Positive outcomes and insights for scaling from a randomized pilot of a gear exchange program to reduce bycatch in small-scale fisheries

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Abstract

Incentive-based conservation programs offer a promising approach for reducing fishing pressure on threatened species while supporting coastal livelihoods, yet causal evidence remains scarce. Modest budgets and small samples are a persistent challenge to evaluating pilots of novel conservation programs. We conducted a 12-month pre-registered randomized pilot of a gear exchange program in Aceh Province, Indonesia, allocating 11 vessels to treatment (N = 4) or control (N = 7) after 26 months of baseline (pre-treatment) monitoring. Treatment vessels were offered fish traps in exchange for gillnets — associated with bycatch of Critically Endangered elasmobranchs. After comparable pre-treatment bycatch rates, treatment vessels recorded zero bycatch across 306 pilot trips while control vessel bycatch declined but persisted (64 individuals, 890 trips), yielding a 95% reduction in bycatch odds (difference-in-differences odds ratio 0.050 [0.002–0.420]). Net income was also $48.62 higher per trip (95% CI: $37.90–$59.35). Bycatch also declined in controls due to opportunistic shifts towards handlining, meaning effects would have been overstated without a counterfactual-based design. Survey data revealed high acceptability and dual conservation-livelihood motivations. Through our randomized mixed-methods pilot we generated credible causal estimates and mechanistic insights that an uncontrolled pilot could not, demonstrating the value of randomized piloting before scaling.

Keywords: bycatch mitigation; causal inference; incentives; alternative livelihoods; elasmobranchs; fisheries management; randomized controlled trial; shark conservation; small-scale fisheries

1. Introduction

Marine biodiversity underpins food security, coastal livelihoods and climate regulation, yet is increasingly threatened by overfishing and habitat degradation [1,2]. Amongst marine taxa, sharks and rays (elasmobranchs) face particularly high overexploitation and extinction risk yet are subject to comparatively limited management despite their critical socio-ecological roles [3,4]. Halting elasmobranch declines requires designing, piloting and scaling interventions that can drive pro-conservation behaviour while equitably meeting the needs of people who depend on marine resources [5,6]. This challenge demands rigorous interdisciplinary evidence on what works, for whom, and why.

Since elasmobranchs are primarily threatened by overfishing [4], halting and reversing population declines to achieve conservation benefits requires reductions in fishing mortality – both in targeted fisheries and fisheries taking elasmobranchs as bycatch or valuable secondary catch [3,7]. However, mortality reductions often entail trade-offs with the consumptive use values of fisheries, in both small-scale and commercial contexts [8,9]. A proven suite of technical solutions exists, including no take zones, quotas and catch limits, bycatch reduction technologies, and safe handling [3,10], but these solutions remain under-adopted as they often bring direct or opportunity costs to fishers [6,8].

Incentive-based programs have the potential to mitigate these trade-offs in small-scale fisheries [11,12], either by compensating for the costs of conservation (e.g., conditional payments for releasing bycatch [13,14]) or by removing barriers to adoption of less damaging but equally valued means of production (aka 'alternative livelihoods') [15,16]. Gear exchanges fall into the latter category: fishers are offered more selective gears in return for giving up unselective or destructive ones [12,17]. This approach relies on the assumption that the primary barrier to adoption is upfront cost rather than fisher willingness or opportunity costs; and works because replacing the gear reduces bycatch while maintaining an acceptable means of production [17].

However, the effectiveness of incentive-based programs is difficult to predict based on theory alone. Such programs operate through behaviorally-mediated pathways in complex coupled human-natural systems and can lead to unintended consequences [14,18,19]. Asymmetric information between those offering and receiving incentives can result in adverse selection (incentives go to people who would act regardless) or hidden actions that undermine conservation goals (such as where a marine compensate-to-release program for shark and ray bycatch induced some fishers to increase catches to secure more compensation payments [14,18]). Incentives can also induce spillover effects; for example, when extractive activities are not reduced but replaced with alternative means of production (as in gear exchanges), pressures may be displaced towards other vulnerable species or ecosystems [14]. For these reasons, rigorous piloting and evaluation with credible estimation of counterfactual behaviours is needed before incentive programs are widely scaled [14,19].

Randomized controlled trials (RCTs) offer a robust approach to evaluation because they guard against confounding [20] yet they remain rare in conservation science [19,21,22] and especially so for behaviorally-mediated and marine interventions. Practical, ethical and logistical challenges have limited their application [23], and to date only a single RCT has evaluated the causal effects of marine conservation incentives [14]. A particular challenge is that conservation pilots are often constrained by modest budgets and small sample sizes, which limits statistical power [23].

Here, we report on a 12-month randomized pilot of a gear exchange program in a small-scale fishery in Aceh Province, Indonesia, in which fishers were offered the opportunity to exchange their gillnets — associated with frequent bycatch of Critically Endangered elasmobranchs — for more selective fish traps. This context is particularly important, as Indonesia is a global hotspot of elasmobranch diversity and endemicity, and the world's largest elasmobranch fishing nation, where more than 95% of vessels are small-scale [24]. Budget constraints limited the pilot to a small sample of vessels; we therefore adopted a randomized experimental design and mixed-methods data collection to maximize the inferential value of the constrained sample and generate evidence on whether gear exchange programs warrant scaling.

2. Methods

2.1 Study context

The study was conducted at Lhok Keluang Daya in Aceh Jaya Regency, Aceh Province, Indonesia (Figure 1). This is one of five Lhoks (traditional coastal territories) included in a multi-site fisheries monitoring and conservation program implemented by Yayasan Kebersamaan Untuk Lautan (KUL), a local NGO. Baseline (i.e., pre-treatment) data were collected for 26 months between September 2022 and October 2024 as part of a wider fisheries study (Figure 1). On 1st November 2024, 11 vessels were randomly allocated to treatment or control in the pilot gear exchange program, with data on outcomes collected from all 11 vessels for a further 12 months between November 2024 and October 2025.

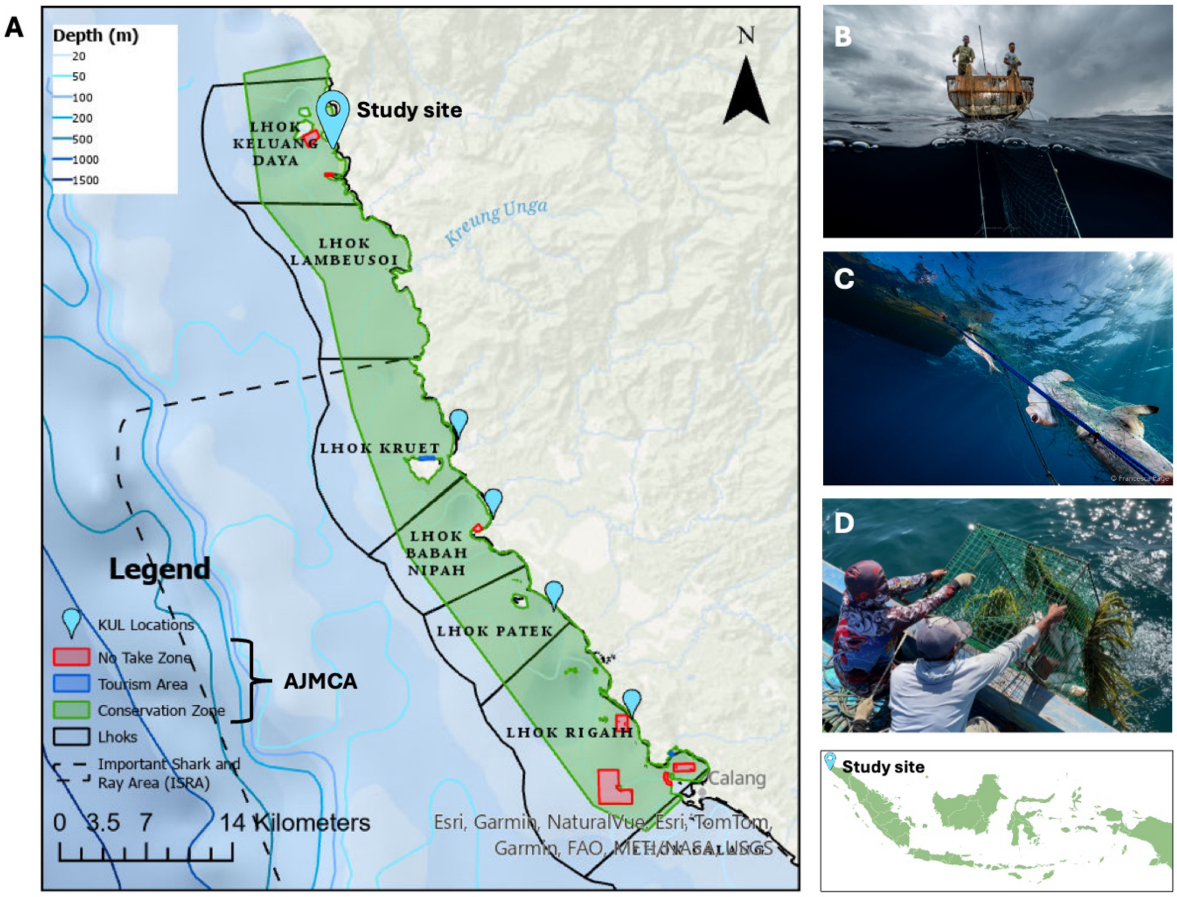

Figure 1 Study site. *(A) Lhok Keluang Daya and the other monitoring locations included in Kebersamaan Untuk Lautan (KUL) fisheries monitoring program, relative to the boundaries of the West Aceh Important Shark and Ray Area (dashed black line) and the Aceh Jaya Marine Conservation Area (AJMCA) (boundary of AJMCA in dark green, with tourism and no-take zones within the AJMCA in dark blue and red, respectively). Lhok (traditional coastal territory) boundaries denoted with solid black lines) (B) a typical gillnet vessel (C), a scalloped hammerhead caught as bycatch (D) fishers using fish traps offered in gear exchange.*

Lhok Keluang Daya borders on the West Aceh Important Shark and Ray Area and the Aceh Jaya Marine Conservation Area (MCA) (Figure 1), designated as critical habitat for elasmobranchs due to its role as a reproductive area for Critically Endangered wedgefish (*Rhynchobatus* spp.) and scalloped hammerhead (*Sphyrna lewini*) [25]. However, these waters also serve as important fishing grounds for small-scale multi-gear mixed-species fisheries along the Southwest coast of Aceh [9,26], with a small portion of the MCA closed to fishing (Figure 1). Small-scale fishers in Aceh Jaya primarily use gillnets and handlines [9,26]; gillnets dominate here and throughout tropical small-scale fisheries due to their low cost and versatility [9,17] but are highly unselective, leading to bycatch of threatened species [9,27]. Wedgefishes and hammerheads both have consumptive use value in Aceh and are legally retained as secondary catch, as only international trade of these taxa is regulated under the Convention of the International Trade of Endangered Species (CITES) [7,9].

Recent national studies and anecdotal evidence suggest that fish traps (Figure 1), which selectively target high-value snapper (Lutjanidae spp.) and grouper (Serranidae spp.) with little-to-no bycatch, could offer a promising alternative to gillnets [28]. Initial consultations conducted by KUL indicated that local fishers were interested in transitioning to fish traps but that the upfront cost of the gear was a barrier. Before proposing a gear exchange as a scalable solution, impacts on bycatch, income, cost-effectiveness and broader ecosystem effects (e.g., [29]) need evaluation.

2.2 Study design

We piloted the gear exchange program using a pre-registered randomised experimental design (AsPredicted #189,965; https://aspredicted.org/n249-46v2.pdf). Vessels were randomly allocated to a treatment or control group, with trip-level data collected across baseline and pilot periods (i.e., a cluster randomized trial with randomization at the vessel level but data collection at the trip level). The pilot was developed through a consultation and design phase conducted by KUL, during which fishers and local leaders in Lhok Keluang Daya gave their consent (S1). Based on these consultations, it was agreed that each treatment vessel would receive eight fish traps in exchange for their gillnets, as this was locally perceived as appropriate, given vessel capacity, and a fair exchange likely to yield similar or higher income. Any fisher using a gillnet in Aceh Jaya MCA with at least one recorded bycatch incident during the baseline period (September 2022 to October 2024) was eligible (N = 11). Due to budget constraints, four vessels were randomly selected for treatment, with the remaining seven allocated to control. Treatment fishers who agreed to participate (N = 4, 100%) signed an agreement with KUL declaring their willingness to stop using gillnets in exchange for traps (S2). Control vessels were not offered traps and continued conventional fishing practices using a mixture of gillnets and handlines. We refer to vessels by their eventual assignment (treatment or control) hereafter.

2.3 Data collection

Trained local enumerators employed by KUL recorded daily fishing trip and catch information from all 11 vessels, including gear types used, for a total of 38 months (26 months baseline, 12 months pilot). KUL were able to collect these data through long-term trust-based relationships with fishers and close collaboration with the *Panglima Laot*, a customary fisheries management institution unique to Aceh Province [9,30].

To assess the conservation benefits associated with the gear exchange, enumerators recorded retained catches of Critically Endangered elasmobranchs (hammerheads and wedgefishes) at the landing site; a proxy for fishing mortality. For livelihood benefits, enumerators recorded catch composition, weight, and ex-vessel (first-sale) price for fish landed from treatment and control vessels. Trip-level revenue was then calculated as the sum of (weight × price per kg) across all fish recorded. Operating costs (fuel, ice, and supplies) were also recorded per trip, and net income was calculated as revenue minus operating costs. Catch data were collected for all fishing trips throughout the study period. Economic data collection began in September 2024, two months before the pilot, providing a short baseline for livelihood indicators, and, unlike catch data, economic outcomes could not be recorded for all trips due to time-intensiveness. Missingness reflected day-to-day variation in enumerator capacity rather than trip outcomes, yielding economic data for approximately 90% of pilot fishing trips (see Section 2.4 for sample sizes), with similar coverage rates across vessels within each group. We recorded program costs following the framework proposed by Iacona et al. [31] (S4) to assess cost-effectiveness and explore scaling potential across other coastal communities bordering the Aceh Jaya MCA.

To gain insights into causal mechanisms and local acceptability of the gear exchange we conducted interview-administered surveys (~45 mins each) combining both closed Likert-style and open-ended questions (S3), supplemented by field observations and informal discussions. All interviews and discussions were conducted in Bahasa Indonesia by trained KUL enumerators with fishers in both conditions at baseline and during the pilot (N = 32 fishers, 62 surveys; S3).

This study received ethical approval by the Interdivisional Research Ethics Committee at the University of Oxford (ref. R66416/RE006) and Indonesia's National Research and Innovation Agency (BRIN) under research permit number (202/SIP.EXT/IV/FR/11/2024).

2.4 Analysis

Our bycatch dataset spanned 38 months of monitoring across all 11 vessels, comprising 26 months of baseline (i.e., pre-treatment) catch monitoring (September 2022 to October 2024; N = 974 treatment and N = 1,573 control fishing trips) and the 12-month pilot period (November 2024 to October 2025; N = 306 treatment and N = 890 control fishing trips). Economic data were available for a smaller subset: 127 trips from the pre-treatment period (September–October 2024, when economic data collection began) and 1,075 trips during the pilot (215 treatment, 860 control).

To estimate conservation benefits, we fitted Bayesian hierarchical logistic regression models with bycatch occurrence as the response. A Bayesian framework was necessary because complete separation (zero bycatch in all treatment trips) caused frequentist estimates to tend to infinity; Bayesian prior regularisation resolves this by constraining posterior estimates to finite values [32,33]. Our primary model specification was a difference-in-differences (DiD) design exploiting the 26-month baseline period, with treatment, period, and their interaction as fixed effects and a vessel-level random intercept. The DiD interaction captures the differential change from baseline to pilot, netting out shared temporal trends, while the vessel-level random intercept accounts for repeated measures within vessels. We placed weakly informative priors: Normal(0, 2.5) on all fixed effects following established recommendations [33], Normal(0, 5) on the intercept, and half-Cauchy(0, 2) on the random effect standard deviation. Models were fitted via Hamiltonian Monte Carlo in Stan [34] using brms [35], with 4 chains of 4,000 iterations (2,000 warmup); convergence was assessed via $\hat{R}$ and effective sample sizes, and the workflow evaluated against the WAMBS-Checklist [36]. We also assessed model robustness through four sensitivity analyses: (i) a pilot-period-only Bayesian logistic regression (without baseline data) to confirm that the treatment effect does not depend on the DiD specification; (ii) a wider Normal(0, 10) treatment prior to evaluate prior sensitivity; (iii) a monsoon season covariate (East (November–March) vs West (April–October)) to account for seasonal variation in catches [9]; (iv) inclusion of vessel-level baseline characteristics (standardised total fishing trips and baseline bycatch occurrence rate) as covariates to assess robustness to observed baseline imbalances between groups and the possibility of regression to the mean.

For livelihood benefits, all monetary values were converted to US dollars (15,800 IDR = 1 USD). We modelled gross revenue and net income at the trip level using a DiD specification incorporating baseline economic data (September–October 2024), with treatment, period, and their interaction as fixed effects and a vessel-level random intercept. Models were estimated using REML, with Satterthwaite's t-tests for the treatment effect and 95% confidence intervals from model standard errors [37]. We assessed robustness through three sensitivity analyses analogous to those for the bycatch model: (i) a pilot-period-only linear mixed model, (ii) a monsoon season covariate, and (iii) vessel-level baseline covariates.

Interview responses were summarised descriptively by group and period. Open-ended responses on attitudes toward fish traps were thematically coded into recurring motivation categories [38].

For cost-effectiveness, we calculated conservation returns based on estimated bycatch averted and program cost per treatment vessel, and economic returns based on additional income generated per trip [31,39]. We also conducted an exploratory scaling analysis by extrapolating bycatch mitigation benefits across all known gillnet-using vessels fishing along the Aceh Jaya MCA coast during the pilot period (3,453 trips from 42 vessels), based on observed mean bycatch rates and the experimental treatment effect. We acknowledge this is extrapolation from a small sample of vessels and the results are therefore indicative only.

All analyses were conducted in R version 4.3.1 using tidyverse, lme4, brms and ggplot2.

2.5 Causal assumptions

Causal inference depends on several assumptions. First, the stable unit treatment value assumption (SUTVA) requires that each vessel's outcomes depend only on its own treatment assignment. SUTVA is plausible given that vessels fish independently and do not share catch. If spillovers did occur (by control fishers shifting to fish traps after observing treatment vessels' success), this would reduce control-group bycatch and attenuate the estimated treatment effect (i.e., bias toward the null), making our estimates conservative. Our observations suggest some shifts in fishing practices did occur in the control group, but due to external market factors rather than spillovers (see Section 3.3). Second, conditional exchangeability requires that treatment and control vessels would have similar potential outcomes without the pilot [23,40]. Exchangeability is supported by random assignment of a relatively homogeneous population operating concurrently at the same site. With a small sample, chance imbalances between groups are possible. We assessed baseline balance by testing for differences in baseline bycatch occurrence between groups using mixed-effects logistic regression and compared other baseline fishing effort and catch characteristics descriptively (S5). The DiD specification also addresses potential baseline imbalances by estimating treatment effects from the differential change within groups over time. However, regression to the mean could still inflate apparent effects. To address this, we conducted a sensitivity analysis adjusting for vessel-level baseline covariates (sensitivity analysis iv), which estimates the treatment effect conditional on each vessel's starting characteristics (baseline bycatch rate and fishing effort).

A conceptual diagram illustrating assumed causal pathways, relevant mediators, and confounders controlled for by the study design is provided in S5.

2.6 Refinements to pre-registered design

The pre-registration was intentionally general given the exploratory nature of the pilot. Key refinements included an expanded sample (additional vessels), an extended pilot duration, inclusion of a baseline monitoring period, and adoption of Bayesian and DiD analytical frameworks, as detailed in S6. All pre-registered outcomes are reported and no pre-registered analyses were omitted.

3. Results

3.1 Conservation benefits: reductions in elasmobranch fishing mortality

The gear exchange pilot was associated with substantial reductions in bycatch of Critically Endangered elasmobranchs (Figure 2A, B). During the pilot period, zero hammerhead catches were recorded by treatment vessels across all 306 monitored trips, while control vessels caught 64 hammerhead sharks across 890 trips (1.57% of trips); zero wedgefishes were recorded in both groups. Bycatch rates were comparable between treatment and control vessels at baseline (estimated difference in bycatch occurrence: OR = 1.06, 95% CrI: 0.16–6.80; Figure 2A, S5), though some variables showed numerical differences between groups, notably total fishing trips and mean hammerhead catch per trip, driven primarily by one treatment vessel (T3; S5). The Bayesian DiD model estimated a 95% reduction in the odds of bycatch occurrence (treatment × period median odds ratio: 0.050, 95% CrI: 0.002–0.420), with a posterior probability of >99% that the treatment effect was negative (Figure 2B; S7). Notably, bycatch also declined among control vessels relative to baseline, likely due to opportunistic shifts towards handline fishing, underscoring the importance of the DiD design in isolating the treatment effect. Results were robust across all sensitivity analyses: alternative prior specification, inclusion of a monsoon season covariate, a pilot-period-only specification (Figure 2B; S7) and inclusion of vessel-level baseline covariates. The covariate-adjusted model produced a near-identical treatment effect (OR: 0.047, 95% CrI: 0.002–0.441, P(effect < 0) > 99%), indicating that baseline imbalances do not drive the result and that findings are not an artefact of regression to the mean (S7). The model passed all ten points of the WAMBS-Checklist (S8), with the sole note being expected prior sensitivity under complete separation.

3.2 Livelihood benefits: increases in income

Treatment vessels achieved substantially higher economic returns than control vessels (Figure 2C). The DiD model estimated that treatment vessels earned $48.62 more net income per trip (95% CI: $37.90–$59.35), a 150% increase relative to the model-predicted control mean of $32.47 (95% CI: $18.62–$46.33) during the pilot period (Figure 2C; S9). Gross revenue was also

$45.01 higher for treatment vessels (95% CI: $34.39–$55.63) relative to a control mean of $54.88 (95% CI: $42.97–$66.79) (S9). Higher net income reflects both increased revenue and reduced operating costs ($15.94 vs $20.66 on average per trip) associated with fish traps (S10). A pilot-period-only specification produced consistent results, and results were robust to the inclusion of a monsoon season covariate and vessel-level baseline covariates (Figure 2C; S9, S10).

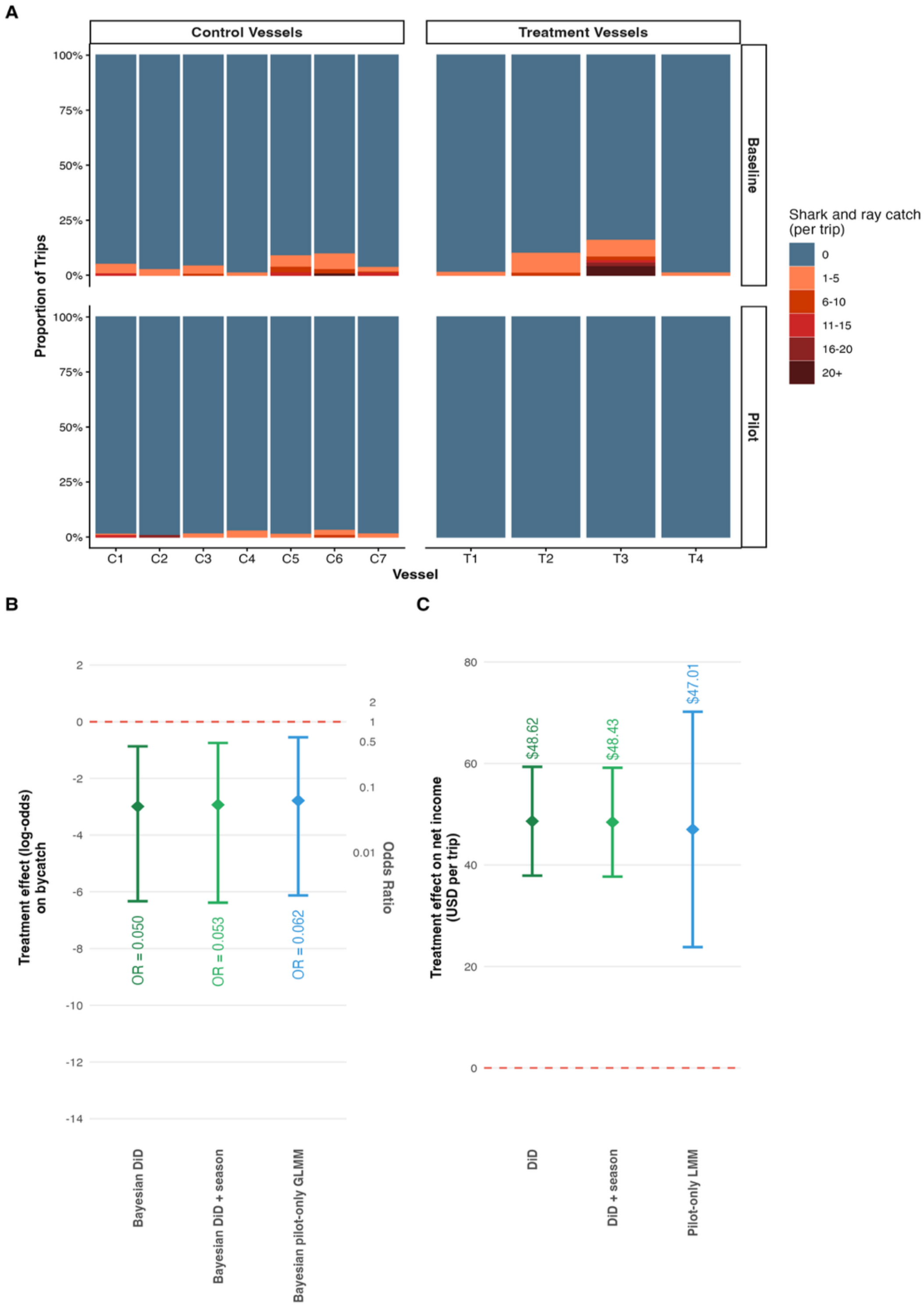

__Figure 2 Treatment effects of the gear exchange pilot on bycatch and income.__ (A) Percentage of fishing trips by shark and ray catch category (individuals per trip) for each vessel, shown for baseline (i.e., pre-treatment) and pilot periods and for control and treatment vessels. (B) Treatment effect estimates on bycatch occurrence across model specifications. Points are posterior medians; vertical bars denote 95% credible intervals. The dashed red line indicates no effect (OR = 1). (C) Treatment effect estimates on net income (USD per trip) across model specifications. Points are coefficient estimates; vertical bars denote 95% confidence intervals. The dashed red line indicates no effect ($0).

3.3 Contextualizing observed outcomes

The fishing trip data and field observations also provide insights into mechanisms for observed bycatch reductions and income gains. Firstly, all fishers in the treatment group (N = 4, 100%) participated, choosing to exchange their gillnets for fish traps, indicating that the pilot program, as designed, is locally acceptable. Secondly, fish traps were highly effective for capturing a small number of large reef fish species (snapper and grouper), which commanded a high price per individual fish. Typical catch numbers were 4-7 individuals per trip, while gillnets catch tens of smaller individual fish (S10). Catch quality is also higher from traps, as fish are captured alive and undamaged. Market observations indicated at-vessel prices of ~$14-24 per fish for snapper and grouper in contrast to prices of ~$1-3 per fish for other fish caught in the gill nets (S10). Third, operating costs for fish traps were lower than for gillnets, with gillnets requiring more fuel for active net deployment and retrieval (S10).

Treatment vessels used fish traps exclusively throughout the pilot, as per their agreement with KUL (S2), and this was verified by the enumerators who interacted with the fishers daily. In parallel, field and market observations indicated that several control vessels opportunistically shifted towards more frequent use of handlines (a simple weighted line fitted with an artificial lure [41]) during the pilot period, targeting octopus in response to increased market demand. Handline fishing does not incur elasmobranch bycatch, which may explain the lower bycatch rates observed in the control condition relative to pre-treatment (Figure 2A), yet this market-driven shift was insufficient to drive a complete transition away from gillnets without the structured support provided by the gear exchange program.

The Bayesian hierarchical model estimated meaningful vessel-level variation in baseline bycatch probability (DiD model random intercept SD = 1.08; S7), confirming that bycatch risk was not uniform across the fleet. Descriptive statistics illustrate this heterogeneity further (Figure 2A, S11). Two treatment vessels (T2 and T3) accounted for the majority of baseline bycatch among treatment vessels, while T1 and T4 recorded little bycatch. Field observations indicated that T3 was almost exclusively using gillnets at baseline, whereas other vessels more frequently switched between gillnets and handlines. This suggests that the conservation impact of the gear exchange was concentrated among more gillnet-reliant vessels.

Interviews and informal discussions revealed strong support for fish traps. All interviewed fishers expressed positive or neutral attitudes towards fish traps before the pilot, reiterating that the primary barrier to adoption was upfront cost rather than aversion to the method (Figure S3A, S12). During the pilot, treatment fishers' attitudes towards the fish traps were entirely positive and predominantly very positive (N = 13, 93%). All treated respondents rated fish traps as better than other gears and expressed practical, economic and conservation motivations — such as ease of use, fuel efficiency, catch quality / value and environmental benefits — as reasons for positive attitudes (Figure S3, S12). These findings complement the experimental evidence, suggesting that easy adoption plus dual conservation-livelihood benefits resonated with fishers, and that direct experience with the traps strengthened support.

3.4 Cost effectiveness and scaling potential

The total cost of the 12-month gear exchange pilot, including staff costs for the local coordinator and enumerators and direct costs for fish trap procurement and maintenance was USD 8,800 (S4), equating to $2,200 per treatment vessel. Based on control group catch rates, the pilot averted fishing mortality of an estimated 22 individuals at a cost of $400 per individual saved (S13). Per-vessel costs would be lower at scale, as fixed program costs (coordination and monitoring) would be distributed across more vessels. The program also generated positive economic returns during the 12-month pilot. Treatment vessels earned $48.62 more net income per fishing trip, generating $14,878 in additional income over 306 trips: a 169% return on investment (S13).

We explored the potential conservation and livelihood returns over a 1–5 year horizon if the gear exchange were extended to all gillnet-using vessels operating in Aceh Jaya MCA. During the pilot period, 42 monitored vessels from five Lhoks caught an average of 0.083 hammerhead sharks and 0.005 wedgefish per trip, equating to approximately 305 individuals annually. At $2,200 per vessel, a district-wide program would require an investment of $92,400, equivalent to $303 per individual saved in the first year. This would decrease to $61 per individual over five years, while also increasing total social benefit. If income gains were to replicate at scale, the estimated additional income across 3,453 fishing trips would total approximately $167,900 in the first year: a 182% return on the $92,400 investment. However, these projections are extrapolated from four treatment vessels over 12 months and assume that both bycatch reductions and income gains would hold at scale, with constant catch rates, stable markets, and no density-dependent effects on snapper and grouper populations from increased trap fishing pressure. Recurring trap replacement costs would also reduce long-term economic returns. Testing these assumptions would require phased expansion with continued monitoring of both bycatch and target species populations.

4. Discussion

This pilot gear exchange program, implemented with a randomized mixed-methods design, yields valuable insights to inform scaling. Treatment vessels captured zero hammerheads and wedgefish while achieving substantially higher income than controls, with bycatch odds reduced by 95% (OR: 0.050) and net income increasing by 150% over the 12-month pilot period. These results demonstrate that well-designed incentive-based programs can deliver conservation and livelihood benefits, and that randomized pilots can offer valuable insights to inform scaling even within the constraints of small budgets and samples. However, there are limits to the inferences that can be drawn from a small sample of vessels in a single context. Careful scaling will be necessary to confirm external validity and guard against negative spillovers on other parts of the socio-ecological systems. We discuss drivers of program effectiveness (4.1), causal claims and limitations (4.2), and implications for policy and scaling (4.3) below.

4.1 Program effectiveness

The substantial reduction of bycatch in the treatment group is likely due to the high selectivity of fish traps for target species. This result is consistent with the gear's design: fish traps passively capture fish that enter through funneled openings and are sized and configured to target reef-associated species rather than larger mobile species such as elasmobranchs. The mechanism of bycatch reduction is therefore primarily technological since the gear simply does not capture elasmobranchs and prioritizes avoidance as per the mitigation hierarchy [3,10]. This distinction has important implications for program design, as gear-based interventions may offer more reliable mortality reductions than interventions in the later stages of the mitigation hierarchy and/or which rely on fisher behaviour change (e.g., safe release). This is particularly important for shark species which exhibit ram ventilation, such as hammerheads, since low post-capture survivability limits the efficacy of post-capture remediation strategies like safe release [14].

Yet while the primary mechanism is technological, barriers to adoption had to be addressed for the technological benefits to be realized [6,42]. These barriers can be economic (upfront and opportunity costs) or socio-psychological (fisher preferences, lack of experience with the new gear). In our case, the free gear exchange removed the upfront cost barrier, while the superior economic performance of fish traps, with substantial gains in both revenue and net income (Figure 2C, S10), indicates a clear relative advantage rather than an opportunity cost. As such, while there is a risk of displacing pressures onto vulnerable snapper and grouper populations, fish traps appear to deliver high value per unit effort with relatively low total catch, supporting long-term sustainability. Additional market-based interventions, such as offtake agreements with buyers willing to pay premiums for sustainability, could add further value while creating conditional incentives for sustainability, which may even eventually encourage fishers to transition to fish traps with limited external support.

Complete participation amongst fishers in the treatment sample, combined with the economic advantages of using fish traps, suggests the program offers a clear relative advantage. The gear exchange also retains a similar mode of production differing only in the technology used, with fishers citing ease of use, suggesting easy adoption and learnability. Taken together, these factors are likely to support sustainability and scaling [15,43].

4.2 Causal claims and limitations

The randomized mixed-methods design of this pilot provided valuable insights to inform scaling. By comparing a balanced sample of treatment and control vessels operating concurrently from the same landing site and exploiting trip-level data and 26 months of pre-treatment data in a difference-in-differences framework, we control for confounders that would bias observational comparisons. The estimated effects can therefore be interpreted as causal impacts of the gear exchange program in Keluang Daya, and the consistency of results across model specifications, combined with social survey data and field observations on causal mechanisms, further supports a causal interpretation. However, several limitations warrant consideration.

First, the modest number of vessels (4 treatment, 7 control) limits confidence in our estimated treatment effects. While complete separation required a Bayesian approach, the magnitude of the estimated treatment effect is sensitive to prior specification (S7, S8), even though the direction of the effect is robust across priors. Larger samples in future studies would reduce dependence on prior assumptions. Treatment vessels had higher baseline bycatch rates than controls, driven mainly by one vessel (T3), though the difference was small and imprecise (OR = 1.06, 95% CrI: 0.16–6.80). If treatment vessels were genuinely more prone to bycatch at baseline, the estimated treatment effect is conservative; equally, given the small sample, this imbalance could reflect chance variation. The meaningful vessel-level variation in bycatch probability confirmed by the model suggests that the average treatment effect may obscure heterogeneity in bycatch/conservation impact across vessels.

Second, whether the range of vessel behaviour observed in this small pilot is representative of the broader fleet operating in Aceh Jaya MCA, and therefore whether the findings generalize more broadly, remains an open question. Resolving this would require expanding the sample to capture greater variation e.g., through a phased scale-up across multiple Lhoks with vessel-level monitoring of both bycatch and economic outcomes over 2–3 years, stratified by predominant gear type. This means our exploratory analysis of scaling potential is highly tentative. The strong economic performance of the fish traps in Keluang Daya is promising, but may reflect site-specific factors such as local species assemblages, market conditions, or fisher skill sets that do not transfer to other locations. Moreover, treatment compliance was maintained throughout the pilot, as verified through daily catch monitoring and community-level observations, though sustaining compliance at larger scales where monitoring intensity may decrease would require careful attention.

Third, our 12-month study period may not capture longer-term dynamics. Resource depletion (e.g., a spillover effect where increases in trap use causes the snapper and grouper population to decline) or other environmental shocks or market forces (e.g., climate change, increased market demand for sharks) could alter the relative advantage of the program in future. Gradual scaling with continued monitoring will be essential to assess the scalability and durability of observed benefits [44] and ensure the long-term sustainable management of the fish trap fishery. Fish traps also require periodic maintenance and replacement, introducing recurring costs (Table S1). However, traps proved more durable than gillnets in practice: minor damage appeared after approximately four months and was repairable, with full replacement needed after around 11 months, whereas gillnets require maintenance after nearly every trip and frequent partial replacement due to snagging on coral reefs. The lower maintenance burden reinforces the observed economic advantage, though long-term durability under sustained use warrants continued monitoring.

Fourth, dynamic and opportunistic switching between handlines and gillnets in small-scale multi-gear mixed-species fisheries such as this can impede clear categorization of priority target groups (in this case, gillnet users), leading to implementation challenges for incentive programs due to information asymmetries and lack of additionality [18]. However, this also further highlights the importance of experimental evaluations using randomized designs [19,22]. In our case, the estimated impact of the gear exchange program would likely have been over-estimated in the absence of a concurrent control group, as we would have failed to account for external environmental and market factors that led to a reduction in bycatch in the absence of the program (i.e., more frequent use of handlines amongst control vessels, which reduced bycatch anyway relative to pre-treatment; wedgefish catches declined to zero in both treatment and control conditions during the pilot despite being present at baseline). Rigorous causal inference, with integration of economic, social and ecological data, remains rare in bycatch mitigation research yet is essential for understanding both effectiveness and feasibility. We recommend that more bycatch mitigation programs seek to embed mixed-methods experimental designs to disentangle program effects from background trends, and we hope this study demonstrates that such designs are possible and useful, even under the budget and sample size constraints typical of small-scale fisheries research.

Fifth, we acknowledge that fine-scale heterogeneity in specific fishing grounds may also account for some of the observed vessel-level heterogeneity in bycatch rates. For example, vessels T2 and T3 may have also been fishing in elasmobranch 'hotspots' with higher encounter rates. We cannot test for or verify this in the absence of spatially-explicit data on fishing effort. In the future, GPS tracking of fishing trips would help to understand the role of spatial factors.

Finally, we wish to acknowledge potential sources of reporting and observation bias in the data, though we do not consider them a threat to our conclusions. For the social survey data, self-reported attitudes may be subject to social desirability bias, particularly among treatment fishers aware of KUL's conservation objectives. However, the consistency of survey responses plus corroboration with experimental catch and economic data (e.g., fishers citing economic advantages that are corroborated by income results) provides triangulation, with these data playing a supporting role in interpreting the experimental findings. For the catch data, these were recorded through landing site enumeration rather than onboard observation, with potential for monitoring bias as unreported discarding at sea cannot be fully ruled out. However, we consider discarding highly unlikely in this context given that hammerheads and wedgefishes are legally retained and sold throughout Aceh, with meaningful consumptive use value.

4.3 Implications for policy and practice

Our findings contribute to a growing body of evidence that incentive-based marine conservation can deliver positive outcomes for biodiversity and people when carefully designed and piloted [11,13,14]. The gear exchange program evaluated here represents a form of indirect incentive that provides less damaging but equally (or in our case, more) valued means of production, distinct from direct payment schemes that reward outcomes or compensate for foregone income. Our results suggest that technology-based interventions that seek to avoid bycatch in the first place may offer advantages over approaches that incentivize conservation action at later stages of the mitigation hierarchy e.g., [14]. However, while the gear exchange was effective at the scale of this pilot, it may be infeasible and undesirable to roll out fish traps across the entire population of fishers in Aceh Jaya. For example, doing so could displace fishing pressure onto snapper and grouper populations and cause benthic habitat impacts. As such, a gear exchange should be considered one option within a broader intervention and instrument mix to cost-effectively mitigate mortality of Critically Endangered elasmobranchs in the Aceh Jaya MCA and other similar contexts, rather than a standalone silver bullet.

From a policy perspective, wider implementation of gear exchange programs could complement and strengthen compliance with regulatory approaches. Embedding gear transitions within national and provincial fisheries management plans, CITES implementation efforts, and marine protected area management plans could provide a practical mechanism for translating policy commitments into on-the-ground outcomes (e.g., by supporting behaviour change amongst gillnet-dependent fishers affected by spatio-temporal restrictions within Aceh Jaya MCA and other ISRAs) [7,45]. Moreover, fisheries subsidies in Indonesia and elsewhere often distribute gillnets for free despite their environmental cost. These budgets could be converted into beneficial subsidies, such as provision of more selective gears or incentives for communities that proactively protect marine biodiversity [46,47]. Integration of positive incentives with regulatory frameworks warrants further exploration and, based on our results, could potentially deliver greater total social value than command-and-control approaches alone, at lower cost.

Finally, our study demonstrates the value of randomizing even small-scale conservation pilots. By adopting an experimental design and mixed-methods data collection within the constraints of a limited budget and small sample, we generated evidence on multiple dimensions that a conventional uncontrolled pilot would not have provided: credible causal estimates of conservation and livelihood benefits combined with mechanistic insights into how and why the program appears to have worked in this context. Crucially, the experiment revealed externally-driven bycatch reductions among control vessels and the disappearance of wedgefishes across both groups that would have been misattributed to the program without a concurrent control. While statistical power is inherently limited with small samples, meaning that a smaller true effect might not have been statistically detectable, the combination of experimental and social survey evidence provides a rich basis for informing whether and how to scale. Given the urgency of the biodiversity crisis and the limited availability of funds, we argue that randomized pilot designs — pragmatic, low-budget, and embedded within existing programs — should become standard practice before scaling [14,21], and that many of the often-cited barriers to experimentation in coupled human–natural systems are surmountable with due consideration

[23]. Indeed, the very constraints that limit pilot scale, such as restricted budgets, can provide a natural justification for randomized allocation of scarce resources.

Data accessibility

All data needed to reproduce and evaluate the conclusions in the paper are present in the paper and/or the Supplementary Materials. The deidentified data and code for processing and analysis are available at https://osf.io/z5q6a/overview?view_only=9db5ab85a62f4c649b8d79832f1883e1.

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Supplementary materials

S1 Informed Consent Procedure

1. Ethical Approval

The study protocol was reviewed and approved by the Interdivisional Research Ethics Committee at the lead author's institution (H.B.) (ref. R66416/RE006) and Indonesia's National Research and Innovation Agency (BRIN) under research permit number 202/SIP.EXT/IV/FR/11/2024). All procedures were conducted in accordance with the Declaration of Helsinki and local regulatory requirements.

2. Participant Eligibility

Eligible participants were adult fishers (aged 18 years or older) operating gillnet vessels in Lhok Keluang Daya, Aceh Jaya. Participants were required to have at least one year of active fishing experience and to own or operate a vessel suitable for both gillnet and fish trap fishing.

3. Recruitment and Informed Consent Process

Potential participants were identified through discussions with Panglima Laot and community meetings between fishers and Yayasan Kebersamaan Untuk Lautan (KUL). KUL staff conducted initial information sessions in the local language (Bahasa Indonesia/Acehnese) to explain the study objectives, procedures, and the voluntary nature of participation. Each participant received a detailed explanation of the study, including:

a) The purpose of the research and its potential benefits;
b) The randomised design, including the possibility of being assigned to either treatment (gear exchange) or control (continued gillnet use) conditions;
c) The 12-month duration of the study and data collection requirements, including catch monitoring and economic surveys;
d) The voluntary nature of participation and the right to withdraw at any time without penalty;
e) Confidentiality procedures and data protection measures;
f) Contact information for the research team and ethics committee for questions or concerns.

4. Treatment Allocation Consent

Participants assigned to the treatment condition were asked to provide additional consent to exchange their gillnets for fish traps and signed a written voluntary agreement with KUL in Bahasa Indonesia (see S2: Surat Perjanjian Kerjasama Sukarela) stating that they would not use their gillnet for duration of the program. This process included a demonstration of the fish trap equipment, training on deployment and retrieval techniques, and a clear explanation that the exchange was voluntary and that participants could return to gillnet fishing if they wished to withdraw from the study.

5. Ongoing Consent and Withdrawal

Consent was treated as an ongoing process throughout the study. Research staff maintained regular contact with participants and reaffirmed their Free, Prior and

Informed consent during semi-structured interviews. Participants were reminded of their right to withdraw at any time. No participants withdrew from the study during the 12-month trial period.

6. Compensation

Participants in the treatment condition received fish trap equipment at no cost as part of the gear exchange program.

7. Data Protection

All personal data were stored securely and accessible only to authorised research personnel. Vessel and fisher identities will be anonymised in all published outputs using unique identifiers. Data were stored in accordance with University of Oxford data management policies and applicable data protection regulations.

8. Voluntary Agreement (Surat Perjanjian Kerjasama Sukarela)

See S2.

S2 Voluntary agreement template

KEBERSAMAAN UNTUK LAUTAN

SURAT PERJANJIAN
KERJASAMA SUKARELA

Pada hari ini **Rabu** Tanggal **Satu Oktober Dua Ribu Dua Puluh Empat (01 Oktober 2024)** bertempat di **Aceh Jaya**.

Yang bertanda tangan di bawah ini :

Nama	: …………………………………………………………………………………..
Nama Kapal	: …………………………………………………………………………………..
Jabatan di Kapal	: **Kapten/ABK**

Yang selanjutnya disebut **PIHAK PERTAMA**.

Nama	: Dr Hollie L. Booth
Atas Nama	: University of Oxford & Kebersamaan untuk Lautan
Jabatan	: Ketua Tim Proyek Penelitian

Selanjutnya disebut **PIHAK KEDUA**.

Telah setuju dan bersedia untuk melakukan perjanjian yang bersifat SUKARELA dengan ketentuan-ketentuan sebagai berikut:

1. PIHAK PERTAMA bersedia untuk meninggalkan alat tangkap jaring insang (Gill Net) selama memakai alat tangkap Bubu pada musim barat/timur dan bersedia melepaskan Hiu Martil dan Pari Baji dengan selamat (hidup- hidup) tanpa diberikan kompensasi atas tindakan pelepasan.
2. PIHAK KEDUA setuju memberikan alat tangkap Bubu sejumlah 8 unit yang bersedia meninggalkan sementara alat tangkap jaring insangnya selama memakai alat tangkap Bubu.
3. PIHAK KEDUA akan meminjamkan satu kamera kepada PIHAK KEDUA yang ingin berpartisipasi sebagai perlengkapan untuk merekam bukti video ikan yang tertangkap pada Bubu dan pelepasan hiu/pari dengan selamat.
4. PIHAK PERTAMA mengerti dan bersedia untuk berpartisipasi untuk melaksanan program pertukaran alat dari PIHAK KEDUA **selama 12 (dua belas) Bulan, mulai dari tanggal 02 November 2024.**
5. PIHAK PERTAMA mengerti dan setuju untuk menyerahkan bukti tertangkapnya ikan pada Bubu dan bukti pelepasan hiu/pari kepada PIHAK KEDUA dalam bentuk video menggunakan kamera yang diberikan sebagai salah satu persyaratan untuk mendapatkan alat tangkap bubu tersebut.
6. PIHAK PERTAMA mengerti bahwa bukti video tersebut harus menunjukkan bahwa ikan tertangkap saat hauling Bubu dan ikan hiu/pari yang dilepaskan masih dalam keadaan hidup dan telah berenang jauh dari kapal dengan selamat hingga tidak terlihat lagi dari pandangan.
7. PIHAK PERTAMA dan PIHAK KEDUA mengerti bahwa video tersebut dapat dibagikan di sosial media sebagai salah satu upaya untuk memperluas jangkauan dari proyek.

8. PIHAK PERTAMA mengerti bahwa kamera yang diberikan merupakan pinjaman selama proyek dan harus dikembalikan setelah proyek selesai.
9. PIHAK PERTAMA dan PIHAK KEDUA mengerti bahwa perjanjian ini bersifat SUKARELA, sehingga tidak ada tindakan penegakan hukum atau konsekuensi negatif jika PIHAK PERTAMA tidak lagi ingin berpartisipasi.
10. PIHAK PERTAMA mengerti dan setuju berpartisipasi dengan penelitian terkait program pertukaran alat yang dilaksanakan oleh PIHAK KEDUA seperti mengikuti wawancara tentang pengalaman dan persepsi PIHAK PERTAMA.

Aceh Jaya, 01 Oktober 2024

PIHAK PERTAMA	**PIHAK KEDUA**
(……………………………….)	**(Dr. Hollie L. Booth)**
Kapten Kapal …………………………..	Ketua Tim Proyek
	Perwakilan dari University of Oxford dan
	Yayasan Kebersamaan untuk Lautan

S3 Interview template

The original survey instrument was administered in Bahasa Indonesia. An English translation is provided below.

Original interview template: Bahasa Indonesia

Izin

[BACAKAN SEBELUM SETIAP WAWANCARA & CATAT PERSETUJUAN]

Halo, nama saya ________. Saya adalah peneliti di ________ dan kami sedang melakukan penelitian tentang bagaimana nelayan di Aceh memandang dan berinteraksi dengan hiu dan pari. Kami ingin meluangkan waktu untuk membahas hal ini dengan Bapak/Ibu. Wawancara ini hanya membutuhkan waktu sekitar 30 menit.

Apakah Bapak/Ibu bersedia untuk berpartisipasi? Kapan waktu yang baik untuk berbicara?

Saya ingin memberitahu Bapak/Ibu bahwa:

- Apa yang disampaikan selama pertemuan ini bersifat rahasia.
- Informasi pribadi yang Bapak/Ibu bagikan kepada saya tidak akan diberikan kepada pihak ketiga mana pun.
- Kami tidak akan membagikan jawaban Bapak/Ibu kepada anggota masyarakat lainnya, pihak berwenang setempat, atau pihak berwenang lainnya.
- Kami tidak akan menanyakan hal-hal yang dapat menyebabkan masalah bagi Bapak/Ibu.
- Partisipasi bersifat sukarela dan Bapak/Ibu dapat menghentikan diskusi kapan saja.

Selama wawancara, saya akan mencatat dan mungkin juga mengambil foto, jika Bapak/Ibu memberikan izin. Informasi yang Bapak/Ibu bagikan kepada saya akan disimpan dalam basis data yang aman dan hanya dapat diakses dengan kata sandi. Saya akan menganalisis informasi tersebut dan hasilnya mungkin akan digunakan sebagai bagian dari pekerjaan universitas saya, serta dipublikasikan di jurnal internasional. Di akhir penelitian, saya akan kembali untuk mempresentasikan temuan penelitian saya kepada Bapak/Ibu. Saya tidak akan menggunakan nama Bapak/Ibu dalam laporan atau publikasi apa pun, kecuali Bapak/Ibu menginginkan sebaliknya.

Penelitian ini telah ditinjau dan mendapatkan persetujuan etika dari **University of Oxford Central University Research Ethics Committee** dan **BRIN Klirens Etika**. Jika Bapak/Ibu memiliki kekhawatiran tentang aspek apa pun dari proyek ini, Bapak/Ibu dapat berbicara dengan saya dan saya akan berusaha sebaik mungkin untuk menjawab pertanyaan Bapak/Ibu. Jika Bapak/Ibu tetap tidak puas atau ingin mengajukan keluhan resmi, saya dapat memberikan rincian kontak Komite Etika Penelitian di University of Oxford.

Pertanyaan persetujuan:

- **Apakah Bapak/Ibu setuju?** *(Dapatkan persetujuan lisan dari peserta)*
- **Apakah Bapak/Ibu memiliki pertanyaan atau kekhawatiran sejauh ini?** *(Beri jeda di sini agar peserta memiliki waktu yang cukup untuk berpikir dan berkomentar)*
- **Apakah Bapak/Ibu ingin melanjutkan?** *(Dapatkan persetujuan lisan dari peserta, dan centang lembar peserta untuk mengonfirmasi bahwa persetujuan lisan telah diberikan)*

- **Apakah Bapak/Ibu mengizinkan saya untuk mengambil foto?** *(Dapatkan persetujuan lisan; jika ada yang keberatan untuk direkam atau difoto, jangan rekam pertemuan tersebut)*

[Setelah persetujuan diperoleh, catat persetujuan pada lembar di bawah ini]

Informasi umum

Tanggal Survei	
ID Nelayan	
Nama Enumerator	
Lokasi	
ID Kapal	
Periode	Baseline / Program
Kelompok (saat program)	Perlakuan / Kontrol / Belum ditentukan
Izin diperoleh? N.B. Lembar informasi peserta harus dibacakan kepada peserta dan persetujuan secara lisan harus diperoleh sebelum pengumpulan data dimulai	

Kehidupan nelayan

Pada bagian kami ingin memahami pendapat dan sikap Anda tentang kehidupan dan kegiatan Anda di laut akhir-akhir ini. Tidak ada jawaban yang benar atau salah, kami hanya ingin mengatahui pemikiran Anda.

1. Secara umum, bagaimana kehidupan Anda selama beberapa tahun terakhir ini?				
Sangat buruk	Agak buruk	Biasa-biasa saja	Cukup baik	Sangat baik
2. Mengapa? Silahkan mengambarkan mengapa kehidupanmu baik atau buruk:				

Sikap Terhadap program

Sekarang kami ingin memahami persepsi Bapak/Ibu tentang program pertukaran alat tangkap. Tidak ada jawaban benar atau salah, kami ingin mengetahui pendapat Anda:

3. Bagaimana pendapat Anda tentang program pertukaran alat tangkap ini				
Sangat buruk	Agak buruk	Biasa-biasa saja	Cukup baik	Sangat baik
4. Mengapa? Silahkan mengambarkan mengapa baik atau buruk:				
5. Mengapa Anda tertarik dengan berpartisipasi dalam program ini?				

6. Apakah Anda sudah berpartisipasi dan coba alat bubu?				
Sudah		Belum		
7. Bagaimana pendapat Anda tentang bubu sebagai alat tangkap?				
Sangat buruk	Agak buruk	Biasa-biasa saja	Cukup baik	Sangat baik
8. Mengapa? Silahkan mengambarkan mengapa baik atau buruk:				
9. Bagaimana bubu dibandingkan dengan gill net?				
Bubu jauh lebih baik dari gill net	Bubu sedikit lebih baik dari gill net	Sama saja	Bubu sedikit lebih buruk dari gill net	Bubu jauh lebih buruk dari gill net
10. Mengapa? Silahkan mengambarkan mengapa baik atau buruk:				
11. Apakah Anda bisa menangkap ikan hanya menggunakan bubu saja (tanpa jaring)?				
Pasti bisa	Mungkin bisa	Tidak bisa	Tidak tahu	
12. Mengapa? Silahkan mengambarkan jawaban Anda. Kalau mungkin bisa, jelaskan apa yang diperlukan untuk pasi bisa diggunakan				

Informasi demografis

13. Nama Lengkap					
14. Daerah asal					
15. Desa tempat tinggal sekarang					
16. Umur					
17. Tingkat Pendidikan	SD	SMP	SMA	SMK	S1 atau lebih
18. Status perkawinan	Sudah menikah		Belum menikah		
19. Jumlah anak					
20. Perkiraan pendapatan bulanan (IDR)					

Terima kasih atas partisipasi Anda!

Translated interview: English

Consent

[READ BEFORE EVERY INTERVIEW & RECORD CONSENT]

Hello, my name is ________. I am a researcher at ________ and we are conducting research on how fishers in Aceh perceive and interact with sharks and rays. We would like to take some time to discuss this with you. This interview will only take about 30 minutes.
Are you willing to participate? When is a good time to talk?
I would like to inform you that:
• What is shared during this meeting is confidential.
• Personal information you share with me will not be given to any third party.
• We will not share your answers with other community members, local authorities, or other authorities.
• We will not ask about things that could cause problems for you.
• Participation is voluntary and you may stop the discussion at any time.

During the interview, I will take notes and may also take photographs, if you give permission. The information you share with me will be stored in a secure, password-protected database. I will analyse the information and the results may be used as part of my university work and published in international journals. At the end of the research, I will return to present my findings to you. I will not use your name in any reports or publications unless you wish otherwise.

This research has been reviewed and received ethical approval from the University of Oxford Central University Research Ethics Committee and BRIN Ethics Clearance. If you have concerns about any aspect of this project, you may speak with me and I will do my best to answer your questions. If you remain unsatisfied or wish to make a formal complaint, I can provide contact details for the Research Ethics Committee at the University of Oxford.

Consent questions:
Do you agree? (Obtain verbal consent from participant)
Do you have any questions or concerns so far? (Pause here to allow participant time to think and comment)
Do you wish to continue? (Obtain verbal consent from participant, and tick the participant sheet to confirm verbal consent was given)
Do you give permission for me to take photographs? (Obtain verbal consent; if anyone objects to being recorded or photographed, do not record the meeting)

[Once consent is obtained, record consent on the sheet below]

General information

Survey date | Fisher ID | Enumerator name | Location | Vessel ID
Period: Baseline / Program
Group (during program): Treatment / Control / Not yet assigned
Consent obtained? N.B. The participant information sheet must be read to the participant and verbal consent must be obtained before data collection begins.

Fishing livelihoods

In this section we want to understand your views and attitudes about your life and activities at sea recently. There are no right or wrong answers; we just want to know your thoughts.

1. In general, how has your life been over the past few years? [Very bad / Somewhat bad / So-so / Quite good / Very good]
2. Why? Please describe why your life is good or bad: [open response]

Attitudes toward the program

Now we would like to understand your perceptions of the gear exchange program. There are no right or wrong answers; we want to know your opinion:

3. What do you think about this gear exchange program? [Very bad / Somewhat bad / So-so / Quite good / Very good]
4. Why? Please describe why it is good or bad: [open response]
5. Why were you interested in participating in this program? [open response]
6. Have you already participated and tried the fish trap (bubu) gear? [Already / Not yet]
7. What do you think of the fish trap (bubu) as a fishing gear? [Very bad / Somewhat bad / So-so / Quite good / Very good]
8. Why? Please describe why it is good or bad: [open response]
9. How does the fish trap compare with the gillnet? [Fish trap much better / Fish trap slightly better / About the same / Fish trap slightly worse / Fish trap much worse]
10. Why? Please describe why it is better or worse: [open response]
11. Can you catch fish using only fish traps (without nets)? [Definitely can / Maybe can / Cannot / Don't know]
12. Why? Please describe your answer. If maybe, explain what would be needed to make it definitely possible: [open response]

Demographic information

13. Full name
14. Area of origin
15. Current village of residence
16. Age
17. Education level [Primary / Junior secondary / Senior secondary / Vocational / Bachelor's degree or higher]
18. Marital status [Married / Unmarried]
19. Number of children
20. Estimated monthly income (IDR)

Thank you for your participation!

S4 Program costs

Table S1 Intervention cost reporting worksheet following Iacona et al. (2018).

Intervention characteristics	
Objective of costed intervention	To reduce fishing mortality of threatened sharks and rays whilst maintaining or improving the livelihoods of project-affected people
Methodology of costed intervention	A randomized pilot of a voluntary gear exchange program in Lhok Keluang Daya, Aceh Province, Indonesia
Intervention scale	One village (4 vessels in treatment arm)
Intervention duration (years)	1
Was the objective achieved?	Yes
Organizational level of cost data	Program

Cost category	Description	Unit Cost	Units	Fixed/ Variable	Currency	Date	Totals (IDR)	Totals (USD)
Labour	Project coordinator monthly salary	4,500,000	12	Fixed	IDR	30/10/2025	54,000,000	3,273
Labour	Enumerator monthly salary	3,600,000	12	Fixed	IDR	30/10/2025	43,200,000	2,618
Consumable	Fish traps - initial cost	1,200,000	32	Fixed	IDR	30/10/2025	38,400,000	2,327
Consumable	Fish traps - maintenance and replacement costs	300,000	32	Variable	IDR	30/10/2025	9,600,000	582
Total cost of intervention (IDR)							**145,200,000**	
Total cost of intervention (USD)								**8,800**

S5 Baseline homogeneity and balance check

Table S2 Comparison of vessel characteristics, bycatch rates and income between treatment and control vessels in the baseline period before the gear exchange program

Metric	Treatment (n=4 vessels)	Control (n=7 vessels)
Gear types	Gillnet (primary), handline	Gillnet (primary), handline
Fishing effort	Day trips, 1 set, 12-hour soak time	Day trips, 1 set, 12-hour soak time
Vessel size	<3GT	<3GT
Total fishing trips	974	1,573
Operating costs (USD)	8.93 ± 1.14	9.95 ± 1.19
Revenue (USD)	\$46.70 ± \$17.62	\$48.80 ± \$20.05
Reported monthly income	\$178 ± \$77	\$173 ± \$63
Total survey days recorded	1,499	2,091
Hammerhead catch rate	4.1%	2.2%
Wedgefish catch rate	2.8%	2.5%
Mean hammerhead per trip	0.380 ± 2.822	0.154 ± 1.404
Mean wedgefish per trip	0.039 ± 0.265	0.032 ± 0.212

Note: Bycatch was highly zero-inflated and concentrated among a small number of vessels (see S10 for vessel-level distributions). Treatment vessel T3 accounted for the majority of baseline shark and ray catch among treatment vessels, while several vessels in both groups recorded little or no bycatch throughout the study. The high standard deviations relative to means reflect this skewed distribution. Despite the apparent difference in mean hammerhead catch rates, the estimated difference in baseline bycatch occurrence was small and imprecise (OR = 1.06, 95% CrI: 0.16–6.80; Table S3). Other numerical differences between groups — notably total fishing trips — partly reflect the unequal group sizes (4 treatment vs 7 control vessels) and vessel-level variation in fishing effort, both of which are accounted for by the vessel-level random intercept in all models. These imbalances do not threaten the validity of the DiD design, which identifies treatment effects from within-group change over time rather than cross-group differences in baseline levels. If anything, the somewhat higher baseline bycatch rates among treatment vessels imply that the estimated treatment effect is conservative.

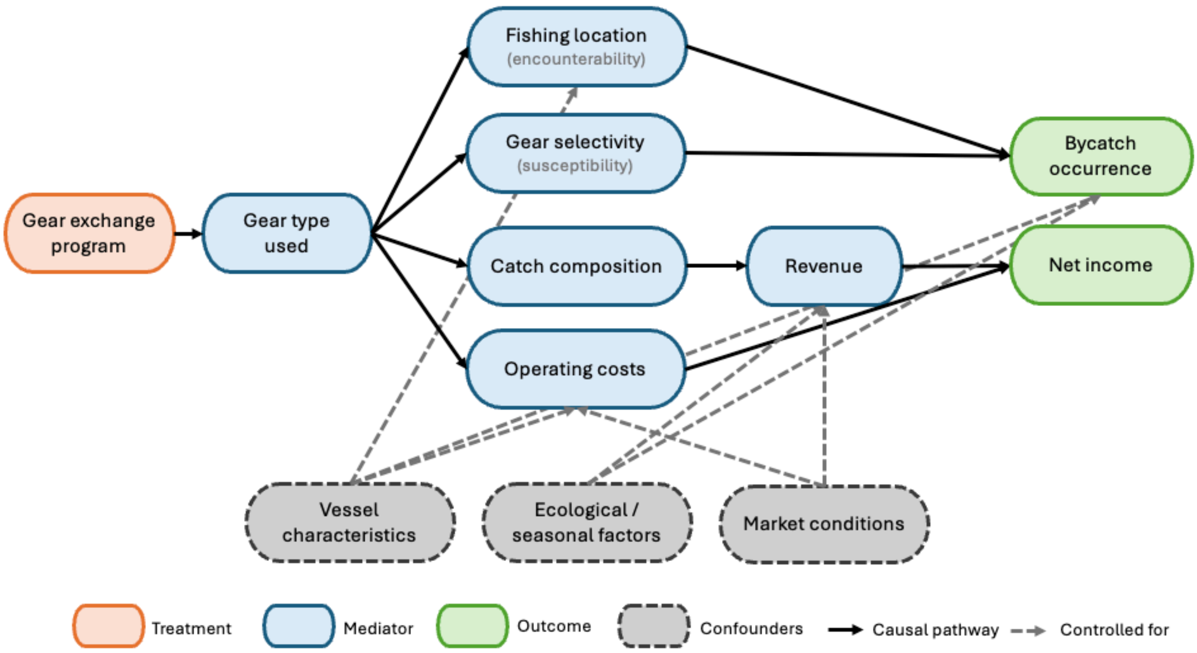

***Figure S1 A conceptual diagram illustrating the assumed causal structure of the gear exchange pilot**. Orange nodes indicate the exposure (random assignment to gear exchange program), blue nodes indicate mediating variables, and green nodes indicate primary outcomes. Dashed grey nodes represent potential confounders controlled by the difference-in-differences design and vessel-level random effects. The primary causal mechanism operates through gear selectivity (susceptibility), which reduces likelihood of elasmobranch capture. Differences in fishing location between traps and gillnets may also influence encounterability. Arrows indicate assumed causal directions; dashed arrows indicate confounding pathways absorbed by the study design.*

Table S3 Model outputs from mixed-effects binomial logistic regression model comparing bycatch rates between treatment and control vessels at baseline

Model A: Bycatch presence ~ Treatment + (1|Vessel), Family: Binomial (logit link)					
Parameter	**Estimate**	**SE**	**z value**	**p-value**	**OR [95% CI]**
(Intercept)	−3.177	0.368	−8.636	<0.001***	0.030 [0.009, 0.097]
Treatment	0.064	0.612	0.105	0.917	1.07 [0.32, 3.53]
Random Effects					
Vessel (Variance, Std. Dev.)	0.821	0.906	—	—	—
Model Fit					
Observations	2,547				
Vessels	11				
AIC	976.1				
BIC	993.7				
Model B: Bycatch presence ~ Treatment + season + (1|Vessel), Family: Binomial (logit link)					
Parameter	**Estimate**	**SE**	**z value**	**p-value**	**OR [95% CI]**
Fixed Effects					
(Intercept)	−2.939	0.382	−7.689	<0.001***	0.024 [0.007, 0.081]
Treatment	0.050	0.620	0.080	0.936	1.05 [0.31, 3.54]
Season (West)	−0.469	0.184	−2.558	0.011*	0.63 [0.44, 0.90]
Random Effects					
Vessel (Variance, Std. Dev.)	0.846	0.920	—	—	—
Model Fit					
Observations	2,547				
Vessels	11				
AIC	971.7				
BIC	995.1				

Note: SE = Standard Error; OR = Odds Ratio; CI = Confidence Interval. Treatment coded as 1 for vessels assigned to treatment condition, 0 for control. Baseline period: September 2022 – October 2024. Non-significant treatment effect indicates balanced bycatch rates between groups at baseline.

S6 Refinements to pre-registered design

This study was pre-registered on AsPredicted (#189,965; https://aspredicted.org/n249-46v2.pdf) prior to pilot implementation. The pre-registration was intentionally general given the exploratory nature of the pilot. The reported study refines and expands upon the pre-registered plan in the following ways.

First, sample size and duration were adapted to field conditions. The pre-registered design specified a minimum of four treatment and four control vessels for a minimum of six months but stated “sample size will be determined by budget and feasibility”. In practice, 11 vessels met the eligibility criteria and were included in data collection (4 treatment, 7 control), and the pilot ran for 12 months. These changes increased statistical power and were consistent with the pre-registered intention to "increase the number of participants and the amount of time in the trial if the pilot runs smoothly."

Second, the pre-registered "regression analyses" were refined in response to data characteristics that could not have been anticipated. Complete separation in the bycatch data (zero events across all 306 treatment trips) caused frequentist regression estimates to tend to infinity, necessitating a Bayesian hierarchical logistic regression framework. Additionally, a difference-in-differences specification was adopted to exploit the 26-month baseline monitoring period and control for shared temporal trends — a stronger design than the simple between-group comparison implied by the pre-registration.

Third, all pre-registered outcome variables — retained catch of threatened species, income, and subjective wellbeing — are reported. The social survey data on fisher attitudes and motivations represent additional exploratory analyses not specified in the pre-registration.

No pre-registered analyses were omitted.

S7 Biodiversity outcomes: model outputs and sensitivity analyses

Table S4 Model outputs from Bayesian hierarchical logistic regression of bycatch outcomes (primary specification; DiD): bycatch_present ~ treatment × period + (1|vessel_id).

Parameter	Median (log-odds)	95% CrI	Median OR	95% CrI (OR)	R̂
Intercept	−3.12	−3.99, −2.25	0.044	0.019, 0.105	1.00
Treatment (main effect)	0.00	−1.40, 1.39	1.01	0.25, 4.00	1.00
Period (main effect)	−1.33	−1.95, −0.75	0.27	0.14, 0.47	1.00
Treatment × Period (DiD)	−2.99	−6.33, −0.87	0.050	0.002, 0.420	1.00
Vessel RE SD	1.08	0.61, 1.87	—	—	1.00
Observations	3,743				
Vessels	11				

Family: Bernoulli (logit link)
Prior on treatment: N(0, 2.5); Intercept: N(0, 5); Vessel SD: half-Cauchy(0, 2)
MCMC: 4 chains x 4,000 iterations (2,000 warmup) = 8,000 posterior draws

Table S5 Sensitivity analyses for models of bycatch outcomes

Model specification	Prior on treatment	Median (log-odds)	95% CrI (log-odds)	Median OR	95% CrI (OR)	P(β < 0 | data)
DiD	N(0, 2.5)	−2.99	[−6.33, −0.87]	0.050	[0.002, 0.420]	0.998
DiD	N(0, 10)	−7.89	[−22.53, −1.80]	0.000	[0.000, 0.165]	1.000
DiD + season	N(0, 2.5)	−2.93	[−6.38, −0.75]	0.053	[0.002, 0.474]	0.998
DiD + season	N(0, 10)	−7.59	[−22.21, −1.55]	0.001	[0.000, 0.212]	0.999
Pilot only	N(0, 2.5)	−2.78	[−6.13, −0.55]	0.062	[0.002, 0.577]	0.995

Models identical except for the prior on the treatment coefficient. All other priors: Intercept N(0, 5); Vessel SD half-Cauchy(0, 2). The wider prior permits the estimate to move further toward −∞ (the maximum likelihood direction under complete separation), resulting in a more extreme point estimate but qualitatively identical inference. All other priors held constant. Both priors show the entire 95% CrI below zero (OR < 1) and P(beta < 0) > 0.99.

Table S6 Sensitivity analysis adjusting for vessel-level baseline covariates: bycatch_present ~ treatment × period + baseline_trips_z + baseline_hh_rate_z + (1|vessel_id)

Parameter	Median (log-odds)	95% CrI	Median OR	95% CrI (OR)	R̂	P(β < 0)
Intercept	−3.05	[−3.67, −2.47]	0.047	[0.025, 0.084]	1.00	—
Treatment	−0.27	[−1.42, 0.83]	0.76	[0.24, 2.29]	1.00	—
Period	−1.35	[−1.97, −0.78]	0.26	[0.14, 0.46]	1.00	—
baseline_trips_z	−0.26	[−0.93, 0.36]	0.77	[0.39, 1.43]	1.00	—
baseline_hh_rate_z	0.64	[0.03, 1.29]	1.89	[1.03, 3.63]	1.00	—
Treatment × Period	−3.18	[−6.31, −0.82]	0.047	[0.002, 0.441]	1.00	0.999

Covariates are vessel-level baseline characteristics (standardised): total fishing trips during the baseline period and proportion of baseline trips with hammerhead bycatch. All other model specifications identical to primary DiD model. The treatment × period interaction (OR = 0.047) is near-identical to the primary model (OR = 0.050), indicating that baseline imbalances do not drive the estimated treatment effect. This analysis also addresses the possibility of regression to the mean by directly adjusting for baseline bycatch levels.

S8 WAMBS-Checklist

Table S7 WAMBS-Checklist (Depaoli & van de Schoot, 2017) applied to the primary Bayesian DiD model of bycatch occurrence: bycatch_present ~ treatment × period + (1 | vessel_id)

Point	Criterion	Status	Evidence
1	Do you understand the priors?	**PASS**	Weakly informative priors: N(0, 2.5) on treatment×period, treatment, and period; N(0, 5) intercept; half-Cauchy(0, 2) RE SD
2	Does the model converge?	**PASS**	All $\hat{R} < 1.01$ (max = 1.0018)
3	Does doubling iterations change results?	**PASS**	Relative bias (treatment×period) = 0.85% (threshold: 5%)
4	Does the posterior have enough precision?	**PASS**	Min Bulk ESS = 2,014; Min Tail ESS = 2,782 (treatment×period: Bulk 6,216, Tail 4,260)
5	Is autocorrelation low?	**PASS**	ESS/N ratio (treatment×period) = 0.78; HMC/NUTS sampler minimises autocorrelation
6	Does the posterior make substantive sense?	**PASS**	DiD OR = 0.050 ≪ 1; consistent with 0/306 treatment trips having bycatch during pilot
7	Do variance priors influence results?	**PASS**	half-Cauchy vs exponential: 0.32% change in treatment×period estimate
8	Is the prior influential vs non-informative?	**NOTE**	64.90% change with wider prior N(0,10); expected with complete separation
9	Are results stable across specifications?	**PASS**	$P(\beta < 0)$ range: [0.998, 1.000] across 5 DiD specifications
10	Is Bayesian reporting used?	**PASS**	Full priors, posteriors, CrI, P(hypothesis), diagnostics reported

Status: PASS = criterion fully met; NOTE = expected behaviour, documented and justified; WARN = potential concern requiring attention.

S9 Livelihood outcomes: model outputs and sensitivity analyses

Table S8 Model outputs from mixed-effects models of livelihood outcomes (primary specification; DiD): Outcome ~ treatment × period + (1|vessel_id), fitted using REML

A. Net Income (USD per trip)

Parameter	Estimate	SE	df	t value	p-value	95% CI
Fixed Effects						
(Intercept)	44.026	7.790	13.35	5.652	<0.001***	[28.76, 59.29]
Treatment	−1.612	12.647	12.27	−0.127	0.901	[−26.40, 23.18]
Period	−11.552	3.663	1195.63	−3.154	0.002**	[−18.73, −4.37]
Treatment × Period	48.624	5.473	1194.69	8.885	<0.001***	[37.90, 59.35]
Random Effects						
Vessel (Variance, SD)	343.1	18.52	—		—	—
Residual (Variance, SD)	711.0	26.66	—		—	—
Model Fit						
Observations	1,202					
Vessels	11					
REML criterion	11,322.2					

B. Gross Revenue (USD per trip)

Parameter	Estimate	SE	df	t value	p-value	95% CI
Fixed Effects						
(Intercept)	54.648	6.890	14.79	7.931	<0.001***	[41.14, 68.15]
Treatment	-1.597	11.124	13.29	-0.144	0.888	[-23.40, 20.21]
Period	0.232	3.626	1196.86	0.064	0.949	[−6.88, 7.34]
Treatment × Period	45.014	5.419	1195.90	8.307	<0.001***	[34.39, 55.63]
Random Effects						
Vessel (Variance, SD)	253	15.88	—		—	—
Residual (Variance, SD)	698	26.41	—		—	—
Model Fit						
Observations	1,202					
Vessels	11					
REML criterion	11,297.1					

*Note: SE = Standard Error; CI = Confidence Interval. Treatment coded as 1 for offered gear exchange, 0 for control. Models fitted using REML (Restricted Maximum Likelihood) with vessel as random intercept to account for repeated observations. CIs computed using Wald method. Exchange rate: 15,800 IDR = 1 USD. ** p < .01; *** p < .001*

Table S9 Sensitivity analyses for models of livelihood outcomes

Model specification	Estimate	SE	df	t value	p-value	95% CI
Income DiD	48.62	5.473	1194.69	8.885	<0.001***	[37.90, 59.35]
Income DiD + season	48.43	5.471	1193.62	8.852	<0.001***	[37.71, 59.16]
Income pilot only	47.01	11.832	9.30	3.973	0.003**	[23.82, 70.20]
Revenue DiD	45.01	5.419	1195.90	8.307	<0.001***	[34.39, 55.63]
Revenue DiD + season	45.56	5.382	1194.89	8.465	<0.001***	[35.01, 56.11]
Revenue pilot only	43.41	10.190	9.29	4.260	0.002**	[23.44, 63.38]

Table S10 Sensitivity analysis adjusting for vessel-level baseline covariates: Outcome ~ treatment × period + baseline_trips_z + baseline_hh_rate_z + (1|vessel_id)

Model specification	Estimate	SE	df	t value	p-value	95% CI
Income DiD + baseline covs	48.28	5.47	1193	8.83	<0.001***	[37.55, 59.01]
Revenue DiD + baseline covs	44.53	5.42	1194	8.22	<0.001***	[33.92, 55.15]

Covariates are vessel-level baseline characteristics (standardised): total fishing trips during the baseline period and proportion of baseline trips with hammerhead bycatch. The treatment effect estimates are near-identical to the primary DiD models (Net income: $48.62; Revenue: $45.01), confirming that baseline imbalances do not influence the estimated treatment effects.

S10 Economic performance metrics

Table S11 Descriptive statistics comparing catch and economic performance between vessels during the pilot program in the treatment and control conditions. 15,800 IDR = 1 USD.

Metric	Treatment	Control	Difference
Catch per trip (kg)	27.9 ± 11.8	12.0 ± 5.3	+133%
Catch per trip (individual)	4-7	20-40	-82%
Price per fish	$14-24	$1-3	+850%
Operating costs per trip	$15.94 ± $5.92	$20.66 ± $7.88	−23%
CPUE (kg/USD cost)	2.10 ± 1.47	0.60 ± 0.29	+248%
VPUE (Revenue/Cost)	7.33 ± 5.32	3.70 ± 3.78	+98%

S11 Vessel-level heterogeneity

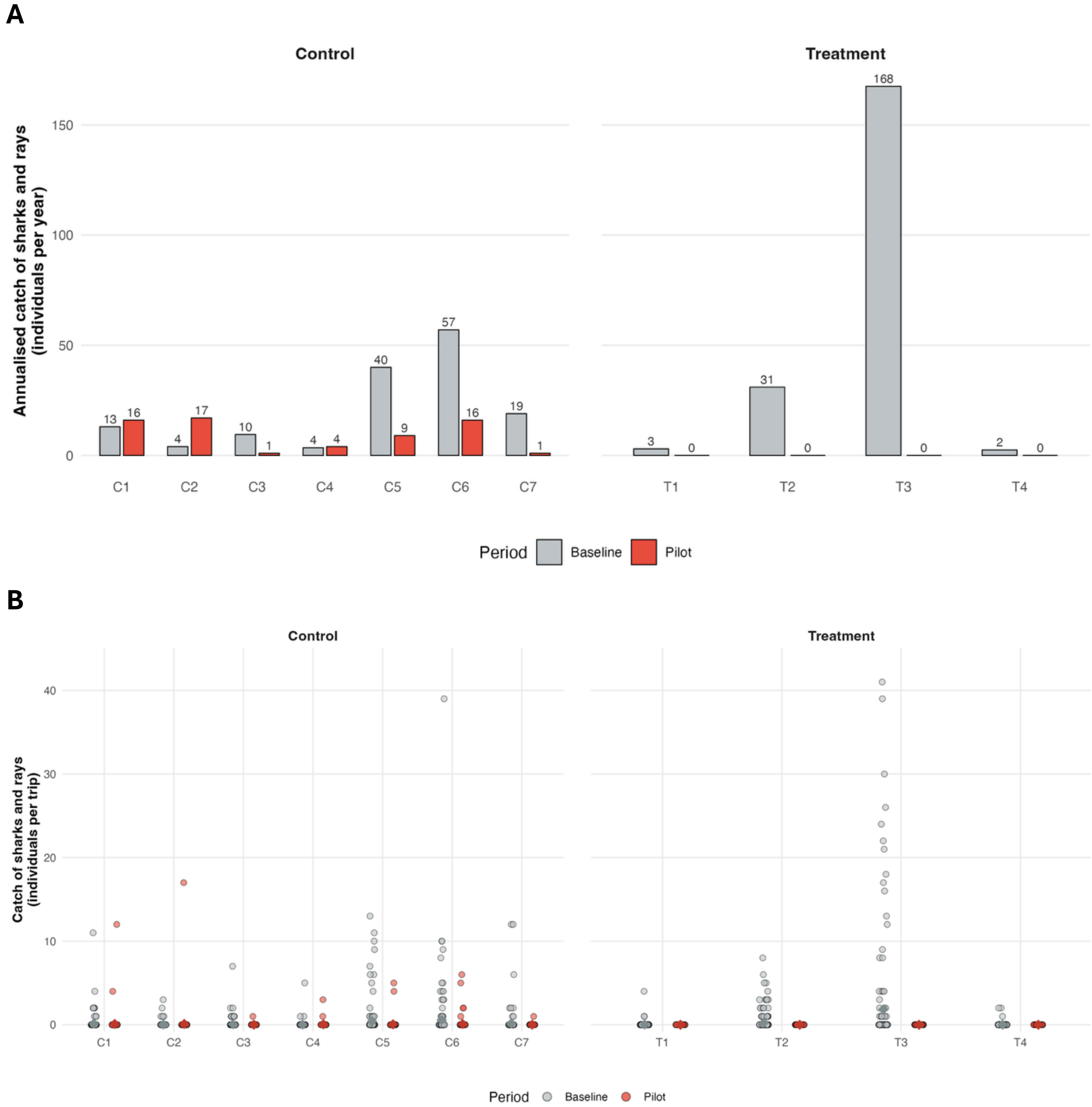

Figure S2 Descriptive statistics showing vessel-level heterogeneity in bycatch. *Vessels grouped by experimental condition (control vs treatment), with baseline (grey) and pilot (red) periods shown side by side (A) shows total (annualised) catch of sharks and rays per vessel, baseline values are annualised from 26 months of data (September 2022 – October 2024) for comparability with the one-year pilot period (November 2024 – October 2025). (B) shows catch of sharks and rays per trip. Bycatch was concentrated among a small number of vessels, with one treatment vessel (T3) accounting for the majority of recorded shark and ray catch at baseline.*

S12 Key descriptive statistics from interview-administered surveys

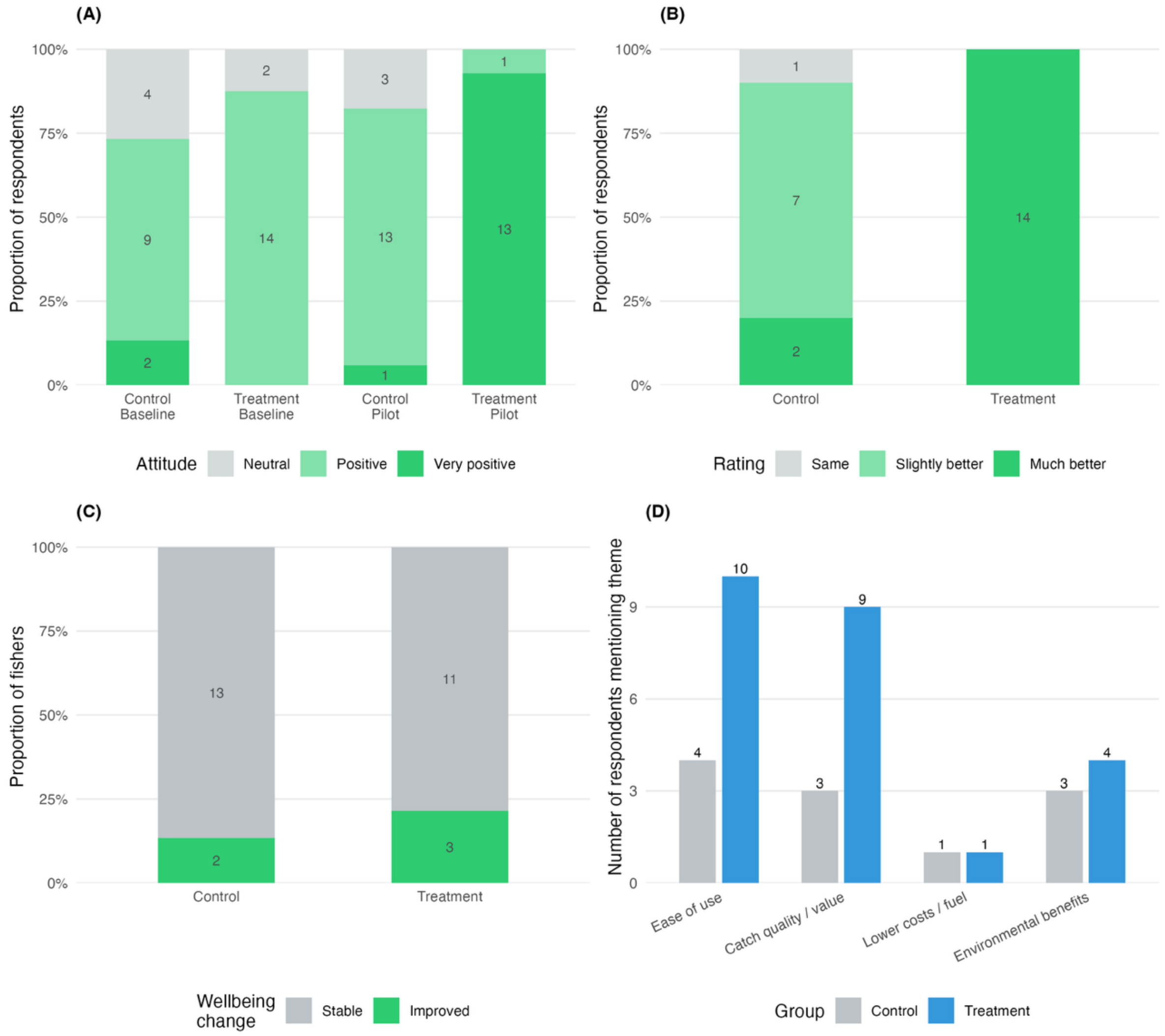

Figure S3 Social survey data by group and period (N = 32 fishers, 62 surveys). **(A)** Fisher attitudes toward fish traps (bubu), classified as neutral, positive, or very positive (no negative responses were recorded). **(B)** Fisher ratings of fish traps compared to other gears during the pilot period. **(C)** Change in self-reported subjective wellbeing from baseline to pilot among fishers surveyed in both periods (N = 30). **(D)** Thematic coding of open-ended responses on reasons for positive attitudes toward fish traps during the pilot period; each individual response could be coded to multiple themes.

S13 Cost-Effectiveness metrics

Table S12 Metrics on biodiversity and livelihood return-on-investment, based on $8,800 total program investment (including program team staff time plus new gear and maintenance for 4 vessels) = $2,200 per vessel. These costs would come down as the program scaled. N.B. these metrics are for Keluang Daya only.

Outcome	Metric	Value
Biodiversity returns	Bycatch during pilot (treatment)	0 individuals
	Bycatch during pilot (control)	64 individuals
	Estimated bycatch averted*	22 individuals
	Cost per individual saved	$400
	Individuals saved per $1,000	2.50
Livelihood returns	Additional income per trip	$48.62
	Total additional income during pilot	$14,878
	Return on investment	169%
	Income per $1 spent	$1.69

*Estimated bycatch averted is calculated by applying the control group's pilot-period bycatch rate to the number of treatment trips: 64 individuals × (306 treatment trips / 890 control trips) = 22 individuals. This represents the expected number of sharks and rays that treatment vessels would have caught had they continued using gillnets, based on observed bycatch rates in the concurrent control group.