

How Persistent Are the Effects of Enforcement?

Evidence from Fisheries Patrols

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Abstract

Governments seeking to protect marine resources face a basic constraint: fishing vessels operate continuously, but costly patrols cannot. Whether intermittent enforcement provides meaningful protection depends on how vessels respond while patrols are active and how quickly they return afterward. I study these responses in The Gambia, combining satellite observations of vessel presence with records of enforcement campaigns. The estimates suggest that campaigns temporarily reduce vessel presence by approximately 12 percent across Gambian waters and 38 percent in the nearshore zone reserved for small-scale fishers, relative to predicted levels without enforcement. Some activity is displaced toward neighboring Senegalese waters. Overall Gambian presence returns close to its predicted no-enforcement level within two to four weeks after the final recorded arrest. These findings suggest that a successful campaign need not deliver lasting protection. Evaluating fisheries enforcement therefore requires considering not only its immediate effect, but also when deterrence must be renewed and where displaced activity goes.

*The University of Texas at Austin. I am grateful to my advisors, Gabriel Englander, Jackson Dorsey, Dan Ackerman, and Robert Town, and to participants in the UT IO Seminar Series for valuable feedback. All errors are my own.

1 Introduction

The canonical economic model of crime treats compliance as a choice: agents weigh the returns to violating a rule against the expected cost of punishment, which depends on both the probability of apprehension and the sanction imposed (Becker, 1968). When enforcement is intermittent, this calculation can change even when the law remains unchanged. An enforcement contact may raise the perceived cost of operating in a location, while the absence of subsequent contacts may allow that threat to recede. For mobile producers, the resulting response need not be a permanent reduction in activity: they can relocate and subsequently return. This paper applies the economic model of crime to industrial fishing, asking how much intermittent enforcement reduces vessel presence, where activity is displaced, and how long deterrence persists.

Marine fisheries make these questions particularly consequential. Fish stocks are common-pool resources: exclusion is costly, and extraction by one vessel reduces the resource available to others. Because individual fishers do not fully internalize these costs, private incentives can generate excessive effort and dissipate resource rents (Gordon, 1954). Advances in machine learning have made growing archives of satellite imagery useful for observing industrial activity across maritime areas that are difficult to monitor from the surface. Radar-based detection can reveal vessels absent from public tracking systems, substantially expanding the activity visible to researchers and regulators (Paolo et al., 2024). International conservation ambitions have also expanded: governments adopted a target under the Convention on Biological Diversity to conserve and effectively manage at least 30 percent of coastal and marine areas by 2030. Whether these commitments protect resources depends not only on drawing boundaries, but also on enforcing the restrictions within them (Convention on Biological Diversity, 2022).

This challenge is particularly acute in West Africa, where productive coastal fisheries coexist with limited resources for maritime surveillance and enforcement. Many countries reserve nearshore fishing grounds for local small-scale fishers, whose livelihoods and access to fish depend on these waters. Nevertheless, industrial vessels repeatedly operate inside restricted areas. Belhabib et al. (2020) document industrial fishing incursions across African inshore waters, with consequences for resource competition and the safety of small-scale fishers. Agarwal and Englander (2026) find substantial differences across countries in whether inshore exclusion zones deter industrial vessel presence. These findings underscore the distinction between a restriction established in law and protection delivered in practice.

Satellite monitoring helps reveal this gap, but observation alone does not impose consequences on violators. Patrols, inspections, and subsequent sanctions remain important components of effective enforcement. I study joint operations between Gambian authorities and Sea Shepherd, a nongovernmental organization that supplies vessels and operational support for at-sea inspections. Gambian officers conduct boardings and arrests for offenses

including fishing in protected waters, using prohibited gear, and failing to maintain required records. The documented operations in 2019, 2020, and 2023 provide repeated enforcement contacts around which to examine changes in the fleet’s spatial distribution. These operations also illustrate why enforcement can affect vessels outside a restricted area: inspections can uncover earlier incursions or other violations that remain punishable after a vessel relocates (Sea Shepherd Global, 2019b).

I combine the arrest calendar with satellite-radar detections and oceanographic conditions over 2017–2023. The radar data provide repeated spatial cross-sections rather than individual vessel histories. I estimate an exposure-weighted spatial-choice model in which vessels respond to environmental conditions, seasonal fishing opportunities, relocation costs, and expected enforcement losses. Documented arrests strengthen an enforcement signal that subsequently depreciates, allowing past contacts to affect current choices without requiring forward-looking optimization. The model jointly describes allocation across Gambian distance bands, neighboring Senegalese waters, and an aggregate outside alternative. Comparing predictions under the recorded arrest history with predictions that remove that signal quantifies deterrence and displacement. This interpretation requires that the controls account for changes in fishing opportunities that might otherwise generate the same retreat-and-return pattern.

The point estimates indicate temporary, spatially uneven deterrence. Across the campaign reporting windows, the model predicts a 12.1 percent reduction in total Gambian vessel presence relative to the no-arrest counterfactual. The estimated reduction is 37.9 percent within nine nautical miles of shore and 5.9 percent in the adjacent 9–25 nautical-mile belt. Overall Gambian presence returns to within 5 percent of its counterfactual path approximately 15–30 days after the final recorded arrest; recovery in the innermost zone takes approximately 31–44 days. The model assigns about 16 percent of the net reduction in Gambian presence to increased presence in neighboring Senegalese waters and the remaining 84 percent to the aggregate outside alternative. These are model-implied net reallocations, not directly observed vessel exits.

The paper contributes to two literatures. First, it contributes to research evaluating marine conservation and fisheries policy. Recent work shows both that spatial restrictions can deter industrial vessels and that behavioral responses can undermine their intended effects. Agarwal and Englander (2026) quantify deterrence from African inshore exclusion zones, while Englander (2023) shows that information conveyed by temporary fishery closures can induce spatial and temporal spillovers. I complement these studies by examining the enforcement of existing restrictions over time. The central objects are the magnitude, geographic reach, and persistence of the response to enforcement contacts—objects needed to distinguish sustained protection from temporary displacement.

Second, the paper contributes to the economics of enforcement and adaptation. Banerjee et al. (2024) show that driver learning and strategic responses affect the performance

of alternative policing arrangements. Gonzalez-Lira and Mobarak (2021) demonstrate that fish vendors adapt to inspections by learning enforcement schedules and developing methods of concealment. I bring this perspective to a mobile extractive industry operating across maritime jurisdictions. Rather than equating an immediate local decline with lasting conservation, the analysis measures how the response evolves across locations and over time. This provides an empirical foundation for asking when enforcement should be renewed and whether its spatial coverage must expand to limit displacement.

2 Institutional Background

2.1 Fishing in The Gambia

The Gambia lies on West Africa’s Atlantic coast at the mouth of the Gambia River. Senegal surrounds the country on land, and Senegalese waters border its exclusive economic zone (EEZ) to the north and south. This geography places neighboring fishing grounds within easy reach of vessels operating in Gambian waters.

The fishery combines small-scale and industrial fleets. Artisanal fishers use small craft and gillnets to catch small pelagic fish, including bonga and sardinella, as well as bottom-dwelling species. Industrial fishing is dominated by trawlers targeting shrimp, cephalopods, and higher-value demersal fish. Much of the licensed industrial fleet is foreign-owned; local and Senegalese fishers also participate in the artisanal sector.¹ A nine-nautical-mile Special Management Area is reserved for artisanal fishing. This paper calls it the inshore exclusion zone (IEZ). Industrial vessels operating farther offshore remain subject to licensing, gear, and reporting requirements. The adjacent 9–25 nm belt is an analytical zone, not a second legal exclusion area.²

2.2 Enforcement campaigns

Sea Shepherd Global is a nonprofit marine-conservation organization that supports enforcement against illegal, unreported, and unregulated fishing. It supplies vessels, crews, and operational support to national authorities that lack sufficient patrol capacity. Similar partnerships operate in other African countries, including Gabon, Liberia, and Benin. Its operations receive support from individual donors and philanthropic organizations. For example,

¹The Gambian Ministry of Fisheries and Water Resources describes the fleets, gears, and principal target species in Key Facts about Fisheries. FAO’s 2023 account of the sardinella fishery describes its importance to coastal communities and competition for small pelagics.

²Sea Shepherd’s September 2019 campaign report describes the nine-mile restriction. The empirical buffers approximate this boundary using distance from shore; vessel-specific license conditions can impose additional limits.

the Age of Union Alliance pledged US\$4.5 million in 2022 to fund three years of operating costs for the *Sam Simon*, which was renamed *Age of Union*.³

Operation Gambian Coastal Defense began in 2019. Sea Shepherd provides the patrol platform, while Gambian fisheries inspectors and naval personnel board vessels and make arrests. The three principal episodes in this study comprise 14 dated arrests in August–October 2019, six in November 2020, and five in July–August 2023. The 2019 episode includes an initial wave and a return in October after the patrol vessel had temporarily left. Reported violations include fishing in protected waters, prohibited nets or undersized mesh, and deficient logbooks or registration. Appendix C lists the dates, vessels, and reported offenses, including the additional January 2020 arrest retained in estimation. Arrest dates document enforcement contacts, not the full duration of patrols.

Figure 1 aligns these contacts with observed vessel presence within 25 nm of the Gambian coast. The 2019 sequence shows two declines separated by a return; the November 2020 decline is followed by recovery in December. The 2023 series also falls and later rises, but its decline begins before the first recorded arrest. These descriptive patterns motivate the estimation without imposing that every fluctuation is caused by enforcement.

³See Sea Shepherd’s description of its mission and operating approach, donor-support page, and January 2022 funding announcement. The pledge supported the vessel’s wider operations, not only its Gambian campaigns.



Figure 1: Arrests and nearshore vessel presence

Notes: The line is SAR vessel presence within 0–25 nm of the Gambian coast, calculated as the sum of exposure-adjusted detections in 0–9 and 9–25 nm. Points are actual orbit-133 acquisitions; connecting segments are visual guides, not daily observations. Bars show the number of documented arrests on each date (right axis). Each row includes 72 days before the first arrest and 72 days after the last. AIS-matched fishing, AIS-matched unknown, and unmatched detections are included; matched nonfishing is excluded. SAR measures presence, not verified fishing or vessel identities. Sources: GFW and Sea Shepherd.

3 Data

3.1 Satellite vessel detections

The main data are Global Fishing Watch’s (GFW) synthetic-aperture-radar (SAR) vessel detections (Global Fishing Watch, 2024). SAR sends microwave pulses toward the ocean and records their reflections. GFW uses machine learning to identify vessel-like objects in these images, estimate their locations and lengths, and match them to Automatic Identification System (AIS) signals when available. Radar operates through clouds and at night, without requiring vessels to transmit their positions.⁴

The sample covers January 2017–December 2023 and contains 411 snapshots and 23,434 retained detections: 5,163 in Gambian waters and 18,271 in nearby Senegalese waters. A snapshot is a collection of images acquired on the same satellite pass, not a daily observation. Locations are assigned to six Gambian coastal-distance bands (0–9, 9–25, 25–40, 40–60, 60–100, and 100–200 nautical miles) and two Senegalese bands (0–25 and above 25 nm) within 100 nm of the Gambian EEZ. Maritime boundaries come from Marine Regions’ World EEZ database. Estimation retains actual acquisition dates and adjusts for the fraction of each zone imaged; Appendix D gives the construction details.

Table 1: SAR sample and snapshot-level descriptive statistics

	Total	Mean	SD
Snapshots	411	—	—
Retained detections	23,434	57.02	37.38
AIS-matched fishing vessels	6,047	14.71	10.11
AIS-matched, vessel type unknown	1,158	2.82	3.08
Unmatched detections	16,229	39.49	27.11
Nonfishing types (excluded)	8,839	21.51	7.67
Other excluded classifications	1,646	4.00	7.40
Average estimated vessel length (meters)	—	35.67	9.85

Notes: Means and sample standard deviations are across 411 snapshots. Counts are raw detections in the observed footprint, before exposure weighting. Length is averaged within each snapshot over retained detections. Fishing/nonfishing denotes vessel type, not activity at imaging. Repeated detections are not unique vessels. Appendix D documents classification harmonization and exclusions.

SAR’s central advantage over AIS for this study is that detection does not depend on a vessel broadcasting. Indeed, 69.3 percent of retained detections have no AIS match. AIS alone would therefore miss much of the observed spatial distribution. I retain matched fishing, matched unknown, and unmatched detections, excluding known nonfishing vessels.

⁴See Paolo et al. (2024) for the detection and matching methodology.

Unmatched status does not establish deliberate disabling, fishing, or illegality. SAR also lacks a complete vessel-identity panel: the analysis characterizes aggregate spatial redistribution, not individual journeys. Presence is not fishing effort, and smaller vessels are more easily missed.⁵

3.2 Environmental inputs, fuel costs, and monetary sanctions

Four environmental controls proxy fishing opportunities and operating conditions: sea-surface-temperature anomaly (NASA/JPL MUR), log chlorophyll-a (NASA Aqua MODIS), wind speed (RSS CCMP), and sea-level anomaly (NOAA/NESDIS). The series are obtained through NOAA CoastWatch’s ERDDAP service at representative locations within each zone and matched to acquisition dates. Zone-specific month-of-year effects account for recurring seasonality; missing-data treatment and source details appear in Appendix D.

Relocation costs combine interzone distances, a reference trawler’s fuel consumption, and annual EIA diesel prices, expressed in 2020 US dollars using US CPI. Appendix A provides the calculation. Monetary losses conditional on apprehension are \$22,147 in 2019, \$21,727 in 2020, and \$41,312 in 2023, each including a \$9,568 lost-trip allowance. The earlier fine component uses reported Gambian fine receipts; the 2023 component is a maintained input, not a verified payment. Table 2 separates these components. Arrest dates and offenses come from Sea Shepherd’s contemporaneous reports and vessel records, listed in Appendix C.

4 Empirical Strategy

I estimate a spatial-choice model in which vessels choose fishing locations in response to environmental conditions, relocation costs, and expected losses from enforcement. Choices are myopic, but enforcement has persistent effects because past arrests influence current perceived risk. The empirical objective is to distinguish the initial response to enforcement from the persistence of that response.

4.1 Vessel location choice

Let i index vessels, o the vessel’s location at the end of the preceding day, j its destination, and t the calendar day. The choice set $\mathcal{J}$ contains six Gambian distance bands—0–9, 9–25, 25–40, 40–60, 60–100, and 100–200 nautical miles from shore—two Senegalese alternatives, and an aggregate outside option, indexed by 0. The outside option includes ports, high seas, and other activity outside the observed regional fishery. Senegal is therefore an explicit alternative, not part of this residual outside option.

⁵See GFW’s data caveats.

The utility from destination j is

$$u_{iojt} = \underbrace{\alpha_j + \xi_{j,m(t)} + X'_{jt}\beta - c_{ojt} - \psi S_t q_{jt}}_{V_{ojt}} + \varepsilon_{iojt}. \quad (1)$$

The intercept α_j captures persistent differences in location attractiveness. The fixed effect $\xi_{j,m(t)}$ allows each zone to have its own calendar-month pattern, where $m(t)$ denotes the month of year. One destination intercept and one month per zone are normalized. The vector X_{jt} contains sea-surface-temperature anomaly, log chlorophyll, wind, and sea-level anomaly. These variables capture changes in the environmental conditions associated with fishing opportunities.

The term c_{ojt} is the utility cost of relocation. For movements between observed locations, it equals ψC_{ojt} , where C_{ojt} is the monetary fuel cost. Movements into and out of the aggregate outside alternative have separate entry and exit costs in utility units, since a single physical distance cannot be assigned to that alternative. Appendix A documents the fuel-cost construction and annual price inputs.

Expected enforcement losses enter through $\psi S_t q_{jt}$. Here S_t is the monetary loss conditional on apprehension, q_{jt} is the perceived apprehension-risk index associated with the recorded enforcement signal, and ψ translates money into utility. Fuel costs and sanctions are expressed in thousands of constant 2020 US dollars, so ψ has the same units in both terms. The extreme-value utility-shock scale is normalized to one. This common monetary coefficient links the enforcement response to the response to observed relocation costs. The model does not infer that every vessel in a regulated zone is committing an offense.

4.2 Enforcement dynamics

Let A_t be the number of documented arrests on day t . Because the arrest input contains dates rather than intraday timestamps, the daily convention places an arrest at the beginning of its recorded day. Perceived risk evolves according to

$$q_{jt} = 1 - \exp(-\lambda_j A_t)(1 - q_{j,t-1})^{\rho_j}, \quad q_{j0} = 0, \quad (2)$$

where $\lambda_j \geq 0$ measures signal strength and $0 < \rho_j < 1$ governs daily persistence. This single state equation replaces separate notation for an enforcement stock and its transformation into risk. It retains only the two economically distinct parameters needed to describe how risk increases and how it dissipates.

Starting from zero, one arrest raises the index to $1 - \exp(-\lambda_j)$. If no further arrests occur over the next h days, the recursion implies

$$q_{j,t+h} = 1 - (1 - q_{jt})^{\rho_j^h}. \quad (3)$$

Thus ρ_j is a daily persistence parameter even though SAR acquisitions are not daily. For small q_{jt} , the path is approximately $\rho_j^h q_{jt}$. A subsequent arrest refreshes the signal. In

particular, the two 2019 arrest pulses enter a continuous history rather than two episodes with independently reset initial conditions.

The baseline estimates zone-specific signal strength and persistence for the three Gambian bands within 40 nautical miles. Direct arrest-signal effects in the remaining alternatives are set to zero, but their predicted presence can change through substitution. Parameters are shared across campaigns; campaign-specific responses arise from arrest histories, monetary losses, ocean conditions, and the initial spatial allocation. The risk index is a model-implied perception conditional on these restrictions, not an independently observed apprehension probability.

4.3 Aggregate allocation and market size

With independent type-I extreme-value shocks, a vessel starting in o chooses j with probability

$$P_{ojt} = \frac{\exp(V_{ojt})}{\sum_{k \in \mathcal{J}} \exp(V_{okt})}. \quad (4)$$

Let n_{jt} be the population share in destination j after the day- t choice. Starting from the initial distribution, shares propagate according to

$$n_{jt} = \sum_{o \in \mathcal{J}} n_{o,t-1} P_{ojt}, \quad \sum_{j \in \mathcal{J}} n_{jt} = 1. \quad (5)$$

Day- t choices update day- t shares. The initial distribution before January 1, 2017 is the logit allocation implied by that day's destination utilities before relocation costs and enforcement. It is identical in factual and counterfactual simulations. This accounting equation does not require individual identities in SAR. It aggregates the choices of vessels whose origins are distributed according to the preceding day's shares. The implied flows are model predictions, not matched vessel trajectories.

I set the potential population to $M = 617$, the maximum exposure-adjusted supported regional presence during 2017–2018, rounded up from 616.259. This fixed population is a participation normalization, not a count of uniquely identified vessels. The number choosing a location is

$$N_{jt} = M n_{jt}. \quad (6)$$

The reference measure uses supported Gambian and local Senegalese zones, not a sum of repeated detections across a year. The high-seas corridor has no separately usable positive observations and remains part of the residual outside option. With $M = 617$, adjusted counts leave nonnegative residuals on all 411 acquisition dates; the smallest residual is 0.741. This feasibility check does not establish the true number of potential vessels. Gambian participation is $M \sum_{j \in \mathcal{G}} n_{jt}$, where $\mathcal{G}$ is the set of Gambian alternatives. Participation therefore follows directly from the allocation model; a separate participation regression is not required.

Changes in this total describe net changes in Gambian presence, not separately identified gross entry and exit.

4.4 Exposure-weighted maximum likelihood

Let s index actual SAR acquisitions and $t(s)$ their calendar dates. Let Y_{sj} be the number of detections in zone j , and e_{sj} its inclusion probability based on satellite exposure. The exposure-adjusted count and weight are

$$\tilde{Y}_{sj} = \frac{Y_{sj}}{e_{sj}}, \quad w_{sj} = \frac{1}{e_{sj}}. \quad (7)$$

Exposure enters the sampling weights, not vessels' utility. For acquisitions with coverage support for all inside alternatives, the outside count is the residual

$$\tilde{Y}_{s0} = M - \sum_{j \neq 0} \tilde{Y}_{sj}. \quad (8)$$

The weighted choice estimator solves

$$\hat{\Theta} = \arg \max_{\Theta} \sum_s \left\{ \sum_{j \neq 0} \frac{Y_{sj}}{e_{sj}} \log n_{j,t(s)}(\Theta) + \tilde{Y}_{s0} \log n_{0,t(s)}(\Theta) \right\}. \quad (9)$$

The objective is a multinomial pseudo-likelihood with exposure weights. It does not use a Dirichlet-multinomial model. The residual must be nonnegative; this is a required check on the market-size calibration, not a reason to truncate negative residuals mechanically.

Completely unobserved zones are not coded as zero detections. If an acquisition has no exposure in some alternatives, those alternatives and the outside option form one unobserved category. Its model probability is the sum of their shares; its count is the residual after subtracting exposure-adjusted counts in supported zones from M . Writing $\mathcal{O}_s$ for the supported inside alternatives, the implemented contribution is

$$\ell_s(\Theta) = \sum_{j \in \mathcal{O}_s} \tilde{Y}_{sj} \log n_{j,t(s)}(\Theta) + \left(M - \sum_{j \in \mathcal{O}_s} \tilde{Y}_{sj} \right) \log \left(1 - \sum_{j \in \mathcal{O}_s} n_{j,t(s)}(\Theta) \right). \quad (10)$$

This grouped likelihood preserves the distinction between absence and lack of satellite coverage.

The estimation procedure is as follows. For each trial parameter vector, I construct the daily risk paths from the arrest history, evaluate location-choice probabilities, and propagate the aggregate shares. I evaluate the objective only on actual SAR dates, using their exposure weights, and maximize it jointly over the model parameters. All available supported acquisitions enter estimation, including dates outside campaign windows. The daily state recursion does not turn unobserved days into additional observations. Standard errors and recovery intervals are obtained from 200 bootstrap draws of 48-day calendar blocks of acquisition contributions, preserving chronological state paths and re-estimating all coefficients. Calibrated inputs are held fixed.

4.5 Monetary sanctions

Table 2 gives the monetary losses used in the specification, in constant 2020 US dollars. The cash component for 2019 and 2020 is based on the Gambian minister of fisheries’ report of GMD 10 million collected from 16 trawlers: GMD 625,000 per vessel. The source is Dialogue Earth, July 9, 2020. The same nominal benchmark is converted separately for each year; the difference between the 2019 and 2020 real-dollar entries is therefore not evidence of a change in the nominal fine schedule. The report concerns the earlier joint operation, not a separately documented mean payment for the November 2020 arrests.

Table 2: Monetary loss conditional on apprehension

Year	Cash component	Lost-trip component	Total S_t
2019	12,579	9,568	22,147
2020	12,159	9,568	21,727
2023	31,744	9,568	41,312

Notes: Constant 2020 US dollars, rounded to the nearest dollar; the utility specification divides these amounts by 1,000. The 2023 cash component is a maintained model input, not a verified average payment: the underlying records for the three payments attributed to it in the saved input table have not been located. The lost-trip component is an assumed opportunity cost, not observed vessel-specific detention loss.

The lost-trip component is a 17-day interrupted trip valued at \$562.82 per day, or approximately \$9,568. The trip-length benchmark comes from the coastal freezer-trawler example in the FAO review of African fishing units. The daily opportunity value is a maintained monetary input; that source does not establish a Gambian daily loss of \$562.82. No additional confiscated-catch value is added without a documented amount. Fuel-price sources, engine-load assumptions, and the annual cost series are reported in Appendix A.

4.6 Identification

Signal strength λ_j is identified by the change in spatial allocation around documented arrests, conditional on ocean conditions, zone-specific seasonality, relocation costs, and monetary losses. Persistence ρ_j is identified by the evolution of allocation at different elapsed times after those arrests. Repeated pulses distinguish a renewed signal from the continuation of an earlier one. The model uses actual elapsed days between arrests and acquisitions, not a common count of satellite images.

Persistent zone differences identify α_j ; repeated calendar months identify $\xi_{j,m(t)}$; and environmental variation within zones and months identifies β . Variation in fuel prices interacted with origin–destination distances identifies the monetary coefficient ψ , subject to the exclusion that these travel-cost changes are not proxies for omitted differences in fishing

profitability. Given the monetary inputs and this coefficient, the level and timing of the enforcement response identify the risk-path parameters. Monetary sanctions alone do not identify apprehension probabilities.

The enforcement interpretation requires that, conditional on the controls and modeled history, arrest timing is not associated with omitted profitability changes that independently generate the same retreat-and-return pattern. Arrests are not assumed to be randomly assigned merely because they are dated precisely. Exposure weighting additionally requires the inclusion probabilities to represent vessel coverage within each zone. These assumptions are central because both productive fishing opportunities and enforcement can alter the observed spatial distribution.

4.7 Counterfactual deterrence and recovery

The no-enforcement counterfactual sets $A_t = 0$ throughout the modeled history while holding ocean conditions, fuel prices, seasonal terms, sanctions, coefficients, and the initial population distribution fixed. Let $\widehat{N}_{jt}^A$ denote predicted presence under the observed arrest history and $\widehat{N}_{jt}^0$ predicted presence without that signal. Zone-specific deterrence is

$$D_{jt} = 1 - \frac{\widehat{N}_{jt}^A}{\widehat{N}_{jt}^0}. \quad (11)$$

Positive values indicate lower presence under enforcement; negative values indicate increased presence through substitution. The Gambian total is computed from the sums of predicted levels, rather than an unweighted average of zone-specific percentages.

Recovery is the first day after the final arrest on which predicted presence is within 5 percent of the no-enforcement path and remains within that band for seven consecutive days. Recovery that lies beyond the observation window is reported as unrecovered within the window, rather than assigned an observed date. Recovery intervals are computed by re-estimating the model in each bootstrap draw. Behavioral recovery can differ from the depreciation of q_{jt} because relocation costs and changing opportunities also affect allocation. The resulting objects describe how much presence changes, where it is redistributed, and how long the modeled effect lasts; SAR presence is not itself a measure of catch, fishing hours, or illegality.

5 Results

I estimate the model on all 411 SAR acquisition dates in 2017–2023, not only campaign windows. The sample contains 2,478 supported zone–acquisition cells and 23,434 eligible detections, excluding matched nonfishing detections. The specification is the exposure-weighted, grouped spatial-choice model in Section 4, with $M = 617$ and same-day updating of choices

and shares. There is no continuation value or additional participation regression. Inference uses 200 converged refits of 48-day calendar blocks, preserving the calendar sequence and recursively recomputing the state paths. All free coefficients are re-estimated in each draw; exposure, market size, and monetary inputs remain fixed.

5.1 Parameter estimates

Table 3 reports the enforcement, cost, environmental, and destination-intercept estimates with bootstrap standard errors. The remaining estimated coefficients, the 88 zone-specific month effects, appear in Appendix B.1; normalized parameters and calibrated inputs are not presented as estimates.

The daily persistence estimates are 0.909 in 0–9 nm and 0.894 in 9–25 nm. In the absence of another arrest, the transformed signal $-\log(1 - q_{jt})$ therefore retains approximately 91 and 89 percent of its preceding day’s level. Its half-lives are 7.3 and 6.2 days. These are properties of the enforcement state, not the time for vessel presence to recover: changing ocean conditions, movement costs, and substitution also affect the latter. The persistence standard errors are 0.216 and 0.254, respectively.

The arrest loadings are 0.00710 and 0.00075 in the two nearshore bands. Starting from zero, a single arrest raises q_{jt} to $1 - \exp(-\lambda_j)$, about 0.00707 and 0.000751, respectively. These levels depend on the monetary normalization and are not externally validated apprehension probabilities. The estimated $\psi = 2.163$ makes a \$1,000 increase in expected monetary loss reduce current utility by 2.163 units; conditional on origin and other utilities, it multiplies the relevant choice odds by $\exp(-2.163) = 0.115$. Its bootstrap standard error is 10.770.

The 25–40 nm loading reaches its upper numerical bound of 50. Raising that cap to 5,000 and allowing persistence to approach zero improves the total log pseudo-likelihood by only 0.10. This destination remains in the allocation system, and Table 3 flags its boundary estimate. A separate bootstrap comparison against a refitted no-arrest model, reported in Appendix B.3, assesses the joint contribution of the enforcement terms.

Table 3: Estimated model parameters

Parameter	Estimate	Bootstrap SE
<i>Enforcement</i>		
Arrest loading, λ_j : 0–9 nm	0.00710	4.733
Arrest loading, λ_j : 9–25 nm	0.00075	5.759
Arrest loading, λ_j : 25–40 nm [†]	50.000	0.363
Daily persistence, ρ_j : 0–9 nm	0.909	0.216
Daily persistence, ρ_j : 9–25 nm	0.894	0.254
Daily persistence, ρ_j : 25–40 nm [†]	0.00167	0.016
<i>Costs and ocean conditions</i>		
SST anomaly, β_1	-0.00773	0.048
Log chlorophyll, β_2	-0.068	0.065
Wind speed, β_3	0.030	0.048
Sea-level anomaly, β_4	0.00505	0.069
Monetary cost coefficient, ψ	2.163	10.770
Entry cost, c^{in}	6.91×10^{-6}	2.33×10^{-7}
Exit cost, c^{out}	2.067	2.028
<i>Destination intercepts</i>		
α_j : Gambia: 0–9 nm	-4.686	0.859
α_j : Gambia: 9–25 nm	-3.503	0.863
α_j : Gambia: 25–40 nm	-5.236	0.920
α_j : Gambia: 40–60 nm	-6.174	0.906
α_j : Gambia: 60–100 nm	-8.251	1.599
α_j : Gambia: 100–200 nm	-7.696	1.130
α_j : Senegal: 0–25 nm	-2.993	0.871
α_j : Senegal: beyond 25 nm	-1.915	0.920

Standard errors are standard deviations across 200 refits of 48-day calendar blocks. January is the omitted month; all 88 zone–month coefficients are reported in Appendix B.1. Ocean covariates are standardized. ψ is per \$1,000 in 2020 dollars; entry and exit costs are utility units. The outside intercept and its month effects are normalized to zero. [†]The 25–40 nm loading is at its upper numerical bound; its standard error does not establish regular identification. Market size and monetary inputs are held fixed.

5.2 Model fit

Figure 2 contrasts observed and predicted shares at actual SAR acquisition dates in every modeled inside zone. The observed counterpart is the exposure-adjusted detection count divided by the calibrated fleet size, $Y_{sj}/(e_{sj}M)$. Comparisons use the same supported cells for the data and the predictions. A zone that was not covered is not assigned a zero. Because the offshore and coastal tracks can be observed on different dates, I do not present a mechanically summed, “observed” daily Gambian total as a fit target.

The model does not fit all spatial margins equally well. In 0–9 nm, the average observed share is 0.70 percent, compared with a prediction of 1.02 percent; in 9–25 nm, the corresponding values are 2.03 and 2.92 percent. The model therefore overpredicts mean presence in both nearshore bands. Means are much closer in 25–40 nm, 40–60 nm, and the local Senegalese alternatives, but this agreement masks substantial acquisition-level variation. Observed–predicted correlations range from 0.12 to 0.43 across the eight zones, and the plots show missed spikes and troughs.

Table 4 reports the means and root mean squared errors without omitting large deviations. These are in-sample diagnostics, not evidence by themselves that arrest timing is exogenous or that the no-enforcement counterfactual is correctly identified. In particular, agreement in average shares is a weaker requirement than explaining the timing and depth of each campaign response. The following counterfactuals should be interpreted in light of these fit limitations.

Table 4: In-sample fit of zone shares

Zone	Acquisitions	Observed mean (%)	Predicted mean (%)	RMSE (pp)
Gambia: 0–9 nm	212	0.70	1.02	0.79
Gambia: 9–25 nm	212	2.03	2.92	1.39
Gambia: 25–40 nm	411	0.53	0.53	0.99
Gambia: 40–60 nm	411	0.23	0.24	0.36
Gambia: 60–100 nm	205	0.07	0.05	0.11
Gambia: 100–200 nm	205	0.05	0.04	0.10
Senegal: 0–25 nm	411	4.81	4.82	4.69
Senegal: beyond 25 nm	411	21.47	21.44	20.41

For each supported acquisition–zone cell, observed share is $100Y_{sj}/(e_{sj}M)$ and predicted share is $100\hat{n}_{j,t(s)}$. Means and root mean squared errors weight supported cells equally within a zone. These are descriptive in-sample diagnostics, not the likelihood weights or an out-of-sample validation. Unsupported cells are excluded.

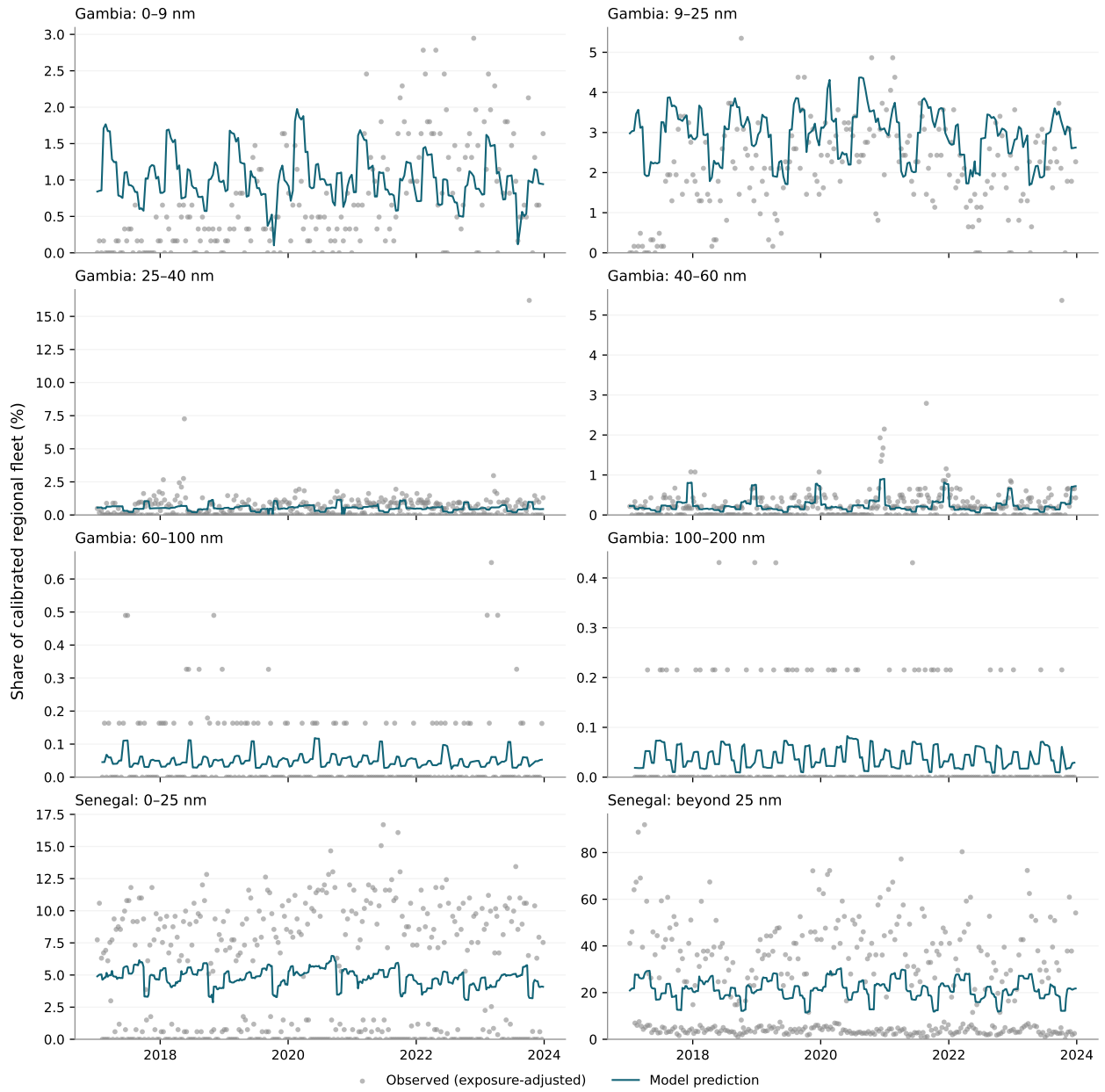


Figure 2: Observed and predicted fleet shares by zone

Gray points are exposure-adjusted SAR counts divided by $M = 617$; blue lines connect fitted shares on the same supported acquisition dates. Connecting lines are visual guides, not additional observations. The vertical scale differs across panels. Senegal denotes the local alternatives included in the market, not its entire EEZ. No directly observed outside-option series is available.

5.3 Counterfactual shares

The no-enforcement experiment sets every documented arrest signal to zero while keeping fitted coefficients, observed ocean conditions, fuel prices, sanctions, seasonal terms, and the initial population distribution unchanged. It is a prediction under the maintained model, not a separately fitted trend. For a reporting window $\mathcal{T}_c$, define

$$\bar{n}_{jc}^a = \frac{1}{|\mathcal{T}_c|} \sum_{t \in \mathcal{T}_c} \hat{n}_{jt}^a, \quad \Delta_{jc} = 100(\bar{n}_{jc}^A - \bar{n}_{jc}^0), \quad R_{jc} = 100 \left(1 - \frac{\bar{n}_{jc}^A}{\bar{n}_{jc}^0} \right), \quad a \in \{A, 0\}. \quad (12)$$

Thus Δ_{jc} is a percentage-point change in the regional fleet share, whereas R_{jc} is a percentage reduction in that destination’s predicted presence. Gambian effects are computed from sums of zone shares, not averages of zone percentage reductions.

For these tables, all destinations in a campaign use the same dates: the first arrest through the day before the last Gambian zone reaches the recovery criterion. This retains the full modeled response in the slowest-recovering Gambian band and makes spatial changes add up. It yields 87 days for August–October 2019, 46 for November 2020, and 47 for July–August 2023. Intervening increases are retained. These windows are fixed at their point-estimate dates when computing the table standard errors. Those standard errors are therefore conditional on the reporting windows; recovery intervals are calculated separately by recomputing recovery in each bootstrap draw. The isolated January 2020 arrest is included in the continuous signal history but not pooled with the three principal campaigns. The two 2019 pulses form one connected episode rather than independent pre–post comparisons.

Table 5 pools the 180 campaign days. Table 6 reports the same objects separately for each campaign. These campaign-specific predictions use common estimated parameters but different arrest histories, sanctions, ocean conditions, and seasonal opportunities. They are not estimates of campaign-specific coefficients.

Across those days, predicted Gambian presence is 4.68 percent of the regional fleet with the arrest signal and 5.32 percent without it. The difference is -0.65 percentage points (bootstrap SE 0.42), or a 12.1 percent reduction (SE 7.3). Campaign-specific reductions over the common spatial windows are 2019: August–October: 12.0 percent; 2020: November: 12.1 percent; 2023: July–August: 12.4 percent.

Within-campaign spatial accounting distinguishes reduced Gambian presence from reallocation among Gambian bands. Increased shares in local Senegal or the residual outside alternative indicate modeled displacement out of the Gambian choice set; neither is evidence that the same unidentified vessel was observed making that move. A share reduction also cannot be equated with a proportional reduction in catch or illegal fishing without additional behavioral and biological assumptions.

The introduction’s suppression-interval reductions use each aggregate’s own recovery endpoint, as defined in the empirical strategy. The tables here use the longer, common spatial endpoint so that regional and zone share changes are additive; consequently their averages

differ without changing the estimated model. Both calculations retain the arrest period and the subsequent response, rather than restricting attention to an arbitrary four-day window.

The estimates are conditional on the identifying assumptions and calibrated inputs in Section 4. The 2023 monetary benchmark, the lost-trip value, and the calibrated potential fleet size are not newly estimated by these counterfactuals. Nonnegative loadings and geometric dissipation are restrictions of the model. Bootstrap standard errors quantify sampling variation under this specification; they do not make those restrictions or the causal interpretation of dated arrests testable by themselves.

Table 5: Average counterfactual share effects across the three main campaigns

	With signal (%)	No signal (%)	Change (pp; SE)	Reduction (%; SE)
All Gambia	4.68	5.32	-0.645 (0.417)	12.1 (7.3)
0–9 nm	0.58	0.93	-0.354 (0.206)	37.9 (16.5)
9–25 nm	3.22	3.42	-0.200 (0.311)	5.9 (8.8)
25–40 nm	0.49	0.58	-0.091 (0.029)	15.7 (3.9)
40–60 nm	0.31	0.31	-0.000 (0.003)	0.2 (0.9)
60–100 nm	0.05	0.05	+0.000 (0.000)	-0.3 (0.9)
100–200 nm	0.03	0.03	+0.000 (0.000)	-0.9 (1.2)
Local Senegal	24.61	24.51	+0.103 (0.219)	-0.4 (0.9)
Outside regional choices	70.71	70.17	+0.542 (0.246)	-0.8 (0.3)

Shares are percentages of $M = 617$, not shares conditional on remaining in Gambia. Change is with-signal minus no-signal share; reduction is $100(1 - \bar{n}^A/\bar{n}^0)$. Negative reductions indicate displacement into a destination. Parentheses report 200-draw block-bootstrap standard errors conditional on the displayed calendar windows. All Gambian zone shares sum to All Gambia. Local Senegal combines the two Senegalese alternatives. Outside is the residual model alternative, not a directly observed count of exiting vessels. The average pools 180 calendar days, weighting each day equally; it is not an equal-weighted mean of campaign percentage reductions.

Table 6: Counterfactual share predictions by campaign

	With signal (%)	No signal (%)	Change (pp; SE)	Reduction (%; SE)
<i>2019: August–October; 2019-08-27 to 2019-11-21 (87 days)</i>				
All Gambia	4.65	5.29	-0.634 (0.390)	12.0 (6.9)
0–9 nm	0.58	0.91	-0.328 (0.221)	36.2 (17.2)
9–25 nm	3.18	3.37	-0.194 (0.292)	5.8 (8.6)
25–40 nm	0.57	0.69	-0.111 (0.046)	16.3 (3.5)
40–60 nm	0.25	0.25	-0.001 (0.003)	0.3 (1.1)
60–100 nm	0.05	0.05	+0.000 (0.000)	-0.2 (0.9)
100–200 nm	0.03	0.03	+0.000 (0.000)	-0.9 (1.3)
Local Senegal	21.32	21.25	+0.070 (0.181)	-0.3 (0.9)
Outside regional choices	74.03	73.46	+0.564 (0.252)	-0.8 (0.3)
<i>2020: November; 2020-11-04 to 2020-12-19 (46 days)</i>				
All Gambia	5.11	5.82	-0.704 (0.534)	12.1 (7.9)
0–9 nm	0.79	1.24	-0.446 (0.311)	36.0 (17.0)
9–25 nm	3.20	3.36	-0.159 (0.338)	4.7 (9.2)
25–40 nm	0.46	0.56	-0.100 (0.032)	17.7 (5.7)
40–60 nm	0.57	0.57	-0.000 (0.004)	0.0 (0.8)
60–100 nm	0.06	0.06	+0.000 (0.001)	-0.3 (1.0)
100–200 nm	0.03	0.03	+0.000 (0.000)	-0.5 (1.3)
Local Senegal	28.70	28.58	+0.119 (0.275)	-0.4 (1.0)
Outside regional choices	66.19	65.61	+0.585 (0.326)	-0.9 (0.5)
<i>2023: July–August; 2023-07-30 to 2023-09-14 (47 days)</i>				
All Gambia	4.29	4.90	-0.609 (0.435)	12.4 (8.4)
0–9 nm	0.38	0.69	-0.311 (0.159)	45.3 (17.8)
9–25 nm	3.30	3.55	-0.251 (0.351)	7.1 (9.6)
25–40 nm	0.37	0.41	-0.047 (0.015)	11.3 (3.7)
40–60 nm	0.18	0.18	-0.000 (0.002)	0.1 (0.9)
60–100 nm	0.04	0.04	+0.000 (0.000)	-0.3 (0.9)
100–200 nm	0.03	0.03	+0.000 (0.000)	-1.0 (1.2)
Local Senegal	26.72	26.57	+0.149 (0.258)	-0.6 (1.0)
Outside regional choices	68.99	68.53	+0.460 (0.223)	-0.7 (0.3)

Shares are percentages of $M = 617$, not shares conditional on remaining in Gambia. Change is with-signal minus no-signal share; reduction is $100(1 - \bar{n}^A/\bar{n}^0)$. Negative reductions indicate displacement into a destination. Parentheses report 200-draw block-bootstrap standard errors conditional on the displayed calendar windows. All Gambian zone shares sum to All Gambia. Local Senegal combines the two Senegalese alternatives. Outside is the residual model alternative, not a directly observed count of exiting vessels.

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A Construction of Fuel Costs

This appendix documents the monetary relocation-cost input used in equation (1). Costs are expressed in constant 2020 US dollars and converted to thousands of dollars when entering utility.

A.1 Vessel fuel consumption and travel time

For an origin–destination distance d_{oj} in nautical miles, travel time is $d_{oj}/10$ hours at a maintained speed of 10 knots. The benchmark fuel burn is 0.0842573 tonnes per hour, the median constructed value for 324 trawlers in the saved vessel-registry calibration. With f_t the real price per tonne of fuel, the monetary travel cost is

$$C_{ojt} = \frac{d_{oj}}{10} \times 0.0842573 \times f_t. \quad (13)$$

Vessel-specific fuel consumption is constructed as engine power in kW multiplied by a 0.58 engine-load factor and specific fuel consumption, divided by 10^6 to convert grams to tonnes. Specific consumption is 210 g/kWh below 1,000 kW, 200 g/kWh from 1,000 to 5,000 kW, and 195 g/kWh above 5,000 kW. The engineering benchmark is the Second IMO GHG Study 2009; its trawler-load assumption is reported in Table A1-8. These are engineering assumptions used to translate movement into monetary cost, not observed fuel invoices for the Gambian fleet.

A.2 Annual fuel prices and price conversion

The fuel-price input is the annual mean of daily US Gulf Coast ultra-low-sulfur diesel spot prices, reported by the US Energy Information Administration and distributed through FRED, series DDFUELUSGULF. Prices per US gallon are converted to prices per tonne using 3.785411784 liters per gallon and diesel density of 0.84 kilograms per liter. Annual prices are expressed in 2020 dollars using the US Bureau of Labor Statistics consumer price index, CPIAUCSL. In particular, the conversion from the saved 2019-dollar cost series to 2020 dollars uses a factor of 1.0125293734. The resulting series is shown in Table 7.

Table 7: Annual fuel-price inputs

Year	2020 US dollars per tonne
2017	537.96
2018	663.58
2019	599.93
2020	375.75
2021	606.07
2022	976.07
2023	730.37

Sources: EIA US Gulf Coast ultra-low-sulfur diesel spot prices; BLS CPI; the conversion factors documented above. The series is a common fuel-price benchmark, not a port-specific transaction-price series.

B Additional Estimates and Fit Diagnostic

B.1 Zone-specific month effects

Table 8 reports every estimated month effect. January is zero in each zone; the outside option's intercept and monthly effects are normalized to zero. Standard errors use the same 200 block-bootstrap refits as the main coefficient table.

Table 8: Estimated zone-month coefficients

Zone	Month	Estimate	Bootstrap SE
Gambia: 0–9 nm	Feb	0.726	0.300
	Mar	0.650	0.751
	Apr	0.416	0.562
	May	-0.123	0.475
	Jun	0.205	0.416
	Jul	-0.00701	0.516
	Aug	-0.062	0.476
	Sep	-0.395	0.573
	Oct	0.116	0.606
	Nov	0.387	0.601
	Dec	0.188	0.456
Gambia: 9–25 nm	Feb	0.192	0.355
	Mar	0.027	0.312
	Apr	-0.379	0.433
	May	-0.259	0.397
	Jun	-0.471	0.438
	Jul	-0.090	0.304
	Aug	0.172	0.290
	Sep	0.077	0.313
	Oct	-0.052	0.310
	Nov	0.092	0.339
	Dec	-0.077	0.414
Gambia: 25–40 nm	Feb	-0.087	0.307
	Mar	0.140	0.419
	Apr	0.234	0.393
	May	0.236	0.539
	Jun	-0.745	0.392
	Jul	-1.108	0.419
	Aug	-0.323	0.370
	Sep	-0.270	0.444

Table 8 continued

Zone	Month	Estimate	Bootstrap SE
Gambia: 40–60 nm	Oct	0.518	0.615
	Nov	-0.179	0.408
	Dec	-0.163	0.295
	Feb	-0.421	0.327
	Mar	-0.227	0.368
	Apr	-0.307	0.495
	May	-0.572	0.410
	Jun	-1.173	0.392
	Jul	-0.150	0.392
	Aug	-0.183	0.680
	Sep	-0.558	0.418
	Oct	0.254	0.589
	Nov	0.222	0.395
	Dec	1.155	0.380
Gambia: 60–100 nm	Feb	0.349	2.282
	Mar	0.716	1.494
	Apr	0.256	1.827
	May	0.433	1.576
	Jun	1.167	1.492
	Jul	-0.163	2.278
	Aug	0.142	1.572
	Sep	0.614	1.659
	Oct	-0.012	1.507
	Nov	0.447	1.443
	Dec	0.506	1.417
Gambia: 100–200 nm	Feb	-0.940	3.460
	Mar	-0.981	4.499
	Apr	0.046	1.212
	May	-0.646	5.623
	Jun	0.299	0.999
	Jul	0.226	0.878
	Aug	-0.413	1.343
	Sep	-1.640	5.010
	Oct	0.206	0.924
	Nov	-1.001	4.038
	Dec	-0.564	3.141
Senegal: 0–25 nm	Feb	-0.143	0.217

Table 8 continued

Zone	Month	Estimate	Bootstrap SE
	Mar	-0.099	0.245
	Apr	-0.00322	0.256
	May	-0.043	0.208
	Jun	-0.055	0.202
	Jul	-0.153	0.213
	Aug	-0.052	0.225
	Sep	-0.017	0.218
	Oct	-0.566	0.274
	Nov	-0.137	0.242
	Dec	-0.196	0.263
Senegal: beyond 25 nm	Feb	0.284	0.268
	Mar	0.205	0.280
	Apr	0.292	0.303
	May	-0.00801	0.241
	Jun	-0.207	0.214
	Jul	-0.134	0.233
	Aug	0.050	0.220
	Sep	-0.116	0.276
	Oct	-0.503	0.290
	Nov	0.062	0.252
	Dec	0.013	0.273

B.2 Recovery and region-specific suppression intervals

For comparability with the introduction, Table 9 retains the previously reported region-specific reporting endpoints. Unlike the common-window spatial tables in the main text, these percentages do not have a common denominator of calendar days across destinations and should not be added across zones. Recovery is relative to the changing no-arrest path, not a constant pre-campaign mean.

Table 9: Region-specific suppression and recovery

Campaign	Region	Reduction, % (SE)	Recovery days	95% interval
2019 Aug–Oct	0–9 nm	36.2 (14.0)	44	[1, censored]
2019 Aug–Oct	9–25 nm	7.2 (11.6)	19	[1, 68]
2019 Aug–Oct	All Gambia	13.7 (7.8)	30	[2, censored]
2020 November	0–9 nm	36.0 (17.9)	31	[1, 151]
2020 November	9–25 nm	7.8 (18.0)	6	[1, 44]
2020 November	All Gambia	17.0 (12.1)	15	[1, 47]
2023 Jul–Aug	0–9 nm	45.3 (18.6)	41	[1, censored]
2023 Jul–Aug	9–25 nm	13.6 (23.9)	15	[1, 62]
2023 Jul–Aug	All Gambia	18.4 (16.5)	23	[2, 112]

Recovery is the first day after the final arrest within 5 percent of the no-arrest path for seven consecutive days. Reductions average from the first arrest through the day before that region’s recovery. Intervals use the original 200 block-bootstrap refits, recomputing recovery in each draw. Follow-up is capped at 180 days, the next campaign, or the sample end. Unrecovered draws remain censored. Daily dates are model-implied between acquisitions, not daily SAR observations.

B.3 Joint contribution of the arrest signal

I compare the fitted model with a restricted model in which the arrest signal is zero and all 103 remaining coefficients are re-estimated on the identical sample with the identical weighted objective. This is distinct from the policy counterfactual, which holds coefficients fixed. The full model’s log pseudo-likelihood is $-204,919.143$, compared with $-204,937.827$ under the restricted model: a gain of 18.684, or 37.368 when doubled.

Because the null places the arrest loadings on a boundary and leaves their persistence unidentified, I do not use a conventional chi-squared likelihood-ratio reference distribution. A parametric null bootstrap generates 199 valid replications with the observed acquisition/exposure structure and the arrest calendar held fixed, and refits both models in each replication. Five statistics exceed the observed value, giving the finite-simulation p -value $(1 + 5)/(199 + 1) = 0.030$. The 95th percentile of the bootstrap null distribution is 32.030. This calculation assesses joint in-sample fit improvement under the simulated null, not an individual-zone effect or a causal test of random patrol assignment.

This diagnostic uses a parametric null bootstrap, whereas the reported coefficient and share standard errors use 48-day block-bootstrap refits. The distinction matters: the null simulation retains the model’s daily allocation transitions but assumes the specified conditional vessel sampling and exposure process. No new out-of-sample exercise is claimed in this section.

C Enforcement Chronology and Observation Calendar

Table 10 reports the vessel-level grounds for arrest and the dates retained in the estimation signal. It preserves the original chronology and its documented source discrepancies.

The inspections could establish earlier misconduct, rather than only an offense observed when a patrol approached. For example, *Mohamed*'s September 1, 2019 arrest concerned 15 reported incursions during the preceding month, corroborated using its logbook and historical AIS. Sea Shepherd reported that its AIS was not transmitting at boarding. This distinction matters economically: moving outside a restricted zone need not remove the expected loss from inspection when earlier catches or records remain on board.⁶

The October operation followed a temporary departure of the *Sam Simon* to Cabo Verde. Sea Shepherd describes the return as clandestine and reports that operators had believed the patrol was over. Its October account attributes nine of the ten arrests to protected-area fishing and one to missing proof of registration. This account motivates a role for changing perceived enforcement, but it does not establish randomized patrol timing or directly measure fishers' beliefs.⁷

The later operations also enforced more than the IEZ boundary. The November reports describe mesh-size violations, logbook and marking irregularities, and a vessel-specific 12-mile license condition, alongside the three *Gorde* protected-area cases. It would therefore be incorrect to classify all six November arrests as nine-mile IEZ intrusions. Similarly, the 2023 reports describe gear and identity cases in addition to three protected-water arrests.⁸

An arrest calendar is a record of enforcement contacts, not a complete patrol-effort series. The first and last arrests need not coincide with arrival and departure, and a day without a documented arrest need not be a day without enforcement. Even the dated contacts are not exhaustive: the January 2020 account mentions an earlier *Atlantide 1* detention for illegal mesh approximately two months before, without an exact date. The 26-record calendar is consequently narrower than all arrests mentioned in narrative reports.⁹ The empirical strategy uses the recorded contacts as signals and estimates their behavioral persistence; it does not equate that persistence with the number of days a patrol vessel was at sea.

⁶Sea Shepherd, September 9, 2019. The report supplies evidence about this vessel; nontransmission is not treated as proof that every AIS-unmatched SAR detection is illegal.

⁷Sea Shepherd, October 17, 2019. The gallery labels all ten as spatial violations; the more detailed contemporaneous narrative is used for the aggregate offense breakdown.

⁸See Sea Shepherd, November 16, 2020, December 9, 2020, August 28, 2023, and September 13, 2023. The last article also discusses *Twenty*'s expired sustainability certification; the paper does not treat certification expiry itself as an established statutory offense.

⁹The January 2020 report describes the previous detention and a paid fine without reporting its amount. Sea Shepherd's December 2020 and August 2023 accounts give 22 arrests for 2019–2020, compared with 21 precisely dated records for those years in the current calendar. No date is imputed for the additional earlier detention.

Table 10: Documented Gambian enforcement operations and grounds for arrest

Operation and patrol vessel	Recorded arrest dates (number)	Reported grounds and vessels
Aug.–Sept. 2019 <i>Sam Simon</i> 4 arrests	Aug. 27 (2); Sept. 1 (1); Sept. 11 (1)	Three spatial-violation cases: <i>Victory 205</i> , <i>Mohamed</i> , and <i>Niam Niokho</i> . <i>Lu Lao Yuan Yu 010</i> : missing fishing logbook and documentation.
October 2019 <i>Sam Simon</i> 10 arrests	Oct. 5 (1); Oct. 7 (1); Oct. 8 (6); Oct. 9 (2)	Nine protected-area fishing cases and one missing-registration case. Vessels: <i>Hazem</i> , <i>Superfly 4</i> , <i>Hansen 01</i> , <i>03</i> , <i>05</i> , <i>07</i> , <i>Qunlong 3</i> , <i>5</i> , and <i>De Hong 2</i> , <i>3</i> . The narrative does not identify which vessel lacked registration.
January 2020 <i>Bob Barker</i> 1 arrest	Jan. 13 (1)	<i>Atlantide 1</i> : shark and ray finning. Retained in the signal history, but not one of the three main campaign-level results.
November 2020 <i>Sam Simon</i> 6 arrests	Nov. 4 (3); Nov. 7 (1); Nov. 15 (1); Nov. 19 (1) ^a	<i>Gorde 105</i> , <i>106</i> , <i>107</i> : protected-area fishing; 105 and 107 also used double-bagged nets. <i>Xing Xi Wang 1</i> : undersized mesh. <i>Jurong Yu 9</i> : logbook and vessel-marking irregularities. <i>Coyah</i> : fishing within its license’s 12-nm exclusion.
July–Aug. 2023 <i>Age of Union</i> 5 arrests	July 30 (2); Aug. 2 (2); Aug. 5 (1) ^b	<i>Abo Islam</i> , <i>Sabrin</i> (listed as <i>Sabin</i> in the gallery), and <i>FK-005</i> : protected-area fishing; reports also describe deficient logbooks and nontransmitting AIS. <i>Twenty</i> : illegal gear and logbook/AIS deficiencies. <i>Majilac 3</i> : fraudulent identification and illegal nets.

Sources and notes: Dates follow Sea Shepherd’s Rogues Gallery; offenses are reconciled with the contemporaneous reports cited in the text. These are reported grounds for apprehension, not a court-disposition dataset. Arrest dates are not patrol start/end dates. The total is 26 precisely dated records; it is not a census of all Gambian enforcement. ^a The gallery dates *Coyah* to November 19, but the December 9 report describes its apprehension as three days after November 15. The table preserves the gallery date used in estimation. ^b The gallery places *Twenty* on August 2 and *Majilac 3* on August 5, whereas the September 13 article calls *Twenty* the fifth 2023 arrest. This sequencing discrepancy remains unresolved; publication dates are not substituted for arrest dates. Sources checked September 25, 2026.

C.1 From documented arrests to the estimation calendar

Figure 3 aligns the November 2020 arrest record with the satellite observations used in estimation. The daily signal is $A_t = 3$ on November 4 and $A_t = 1$ on November 7, 15, and 19. It is zero on the other dates shown because no additional precisely dated arrest is recorded. The gaps between arrest dates are therefore three, eight, and four days. These inputs refresh the enforcement-risk state in equation (2); the state continues to evolve on intervening days, including days without a satellite image. There is no campaign-window indicator or four-day padding in this specification.

The two satellite tracks supply observations on different dates and cover different parts of the regional choice set. For example, the coastal sequence brackets the arrests with images on October 30, November 11, November 23, and December 5, while the complementary track observes November 4, 16, and 28. The latter observations are not reassigned to coastal dates or treated as complete images of the nearshore fishery. An arrest and an acquisition share November 4, but intraday ordering is not observed: the maintained convention places the arrest signal at the beginning of the day. All supported acquisitions in 2017–2023 enter the likelihood, not only the dates in this example.

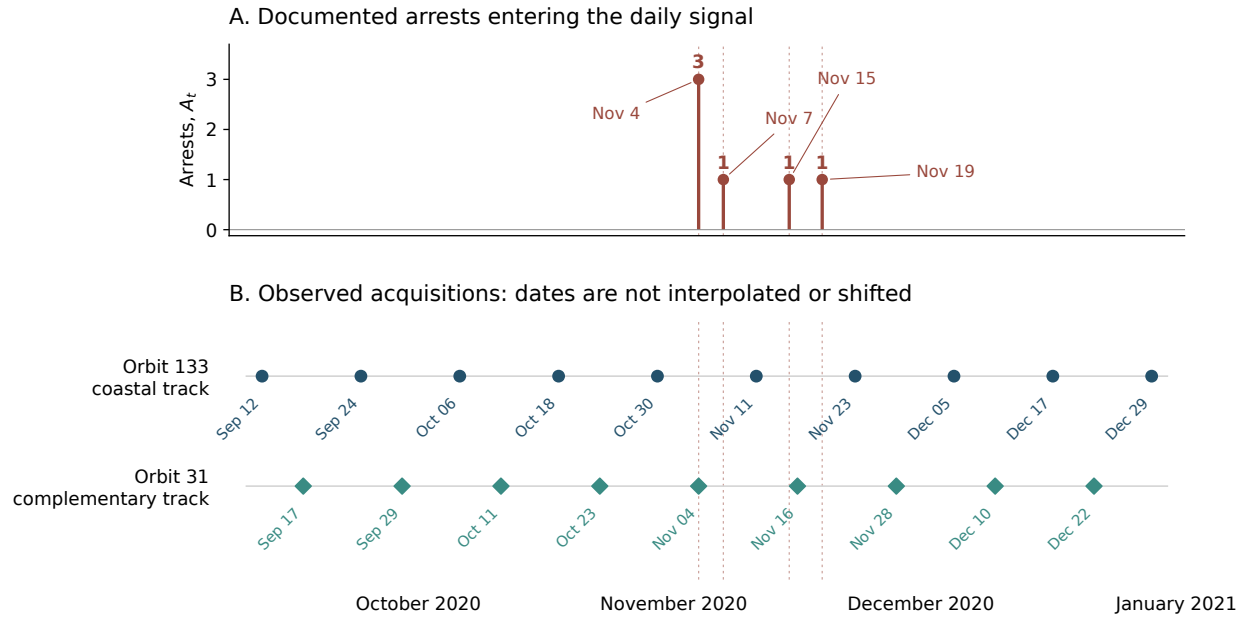


Figure 3: Arrest signals and actual SAR acquisition dates: November 2020

Notes: The upper panel shows the six vessel-arrest records on four dates. The lower panel shows each acquisition date in the regional estimation catalog from September 10 to December 31, 2020, separately for Sentinel-1A relative orbits 133 and 31. Numbers above the arrest stems are counts, not an intensity measure based on patrol hours. Vertical dotted lines align contacts with the observation calendar; they do not define known patrol start or end dates. The model updates its risk state and spatial shares daily and evaluates the likelihood only at the marked acquisitions, using zone-specific exposure. November 19 preserves the gallery date used in the fitted model; the narrative-date discrepancy is documented in Table 10. Sources: Sea Shepherd arrest records and GFW scene identifiers in the estimation files.

D Data Construction and Coverage

D.1 Sample construction and descriptive statistics

The regional extract combines the saved GFW 2017–2021 SAR file, `industrial_vessels_v20240102.parquet`, with the project’s GFW CSV exports for 2022 and 2023. Exact duplicates in scene identifier, timestamp, latitude, and longitude are removed. No additional vessel-length threshold is imposed. The sample runs from January 7, 2017 to December 26, 2023. The 411 snapshots comprise 206 acquisitions on relative orbit 133 and 205 on relative orbit 31, both from Sentinel-1A, with 1,403 scene records. Multiple image tiles from the same pass are not separate choice occasions. Annual snapshot counts are 58, 60, 61, 61, 60, 57, and 54 for 2017–2023, respectively. All years enter estimation.

The full extract contains 33,919 detections. The estimation retains 23,434 in three categories: matched fishing, matched unknown, and unmatched. The descriptive table also shows the excluded records. Its nonfishing row combines 7,099 historical records explicitly labeled matched nonfishing with 1,740 later records labeled cargo, carrier, bunker, passenger, seismic vessel, or support. A further 1,646 records carry the labels other (1,636), noisy vessel (nine), or discrepancy (one) and are shown separately, without inferring fishing status. All 1,158 matched-unknown records occur in the historical extract; the later releases use a more detailed classification. This descriptive harmonization does not change the estimation sample.

Table 1 uses raw counts over the observed footprint, not estimated full-zone totals. All detections lie in supported zone-date cells. Category counts are summed within each snapshot, including zeros, and their means and sample standard deviations are calculated over 411 snapshots. Length is averaged within each snapshot over retained detections, then summarized across snapshots with equal snapshot weights. All retained detections have positive length estimates. For comparison, the detection-weighted mean length is 32.41 meters, with a detection-level standard deviation of 27.37 meters; these differ from the table’s mean and dispersion of snapshot averages.

EEZ boundaries use Marine Regions’ World EEZ version 12 (October 25, 2023). Coastal buffers use the retained `Africa_Boundaries.shp` land file, whose upstream release metadata are not recorded, and are intersected with the EEZ polygons. The nine-mile boundary is an analytical approximation, not a reconstruction of every legal baseline or license condition. The high-seas candidate has no separately usable positive observations and enters the aggregate outside option with ports and more distant fisheries; that outside option is not directly counted by SAR.

D.2 Acquisition timing and exposure

Acquisitions repeat every 12 days on each track, except for twelve 24-day gaps. Combined acquisitions are mostly five or seven days apart, without complete six-day coverage. Actual dates are retained; outcomes are not interpolated. The catalog includes scenes represented in the regional extract before category exclusions, not an independent census that includes completely empty regional images.

Exposure e_{sj} is the estimated fraction of zone j imaged on acquisition s . For orbit 133, available Copernicus product footprints (Copernicus Data Space Ecosystem, n.d.) are intersected with the zone polygons. Exact-date footprints exist for 165 of 206 acquisitions; the remaining 41 use the available footprint closest in day of year. For orbit 31, exposure is reconstructed from GFW’s monthly 0.01° overpass grid. The implied orbit-133 contribution is subtracted, and the residual is divided across the month’s recorded orbit-31 acquisitions. Cell fractions are bounded between zero and one and averaged within each zone. This is a monthly approximation, not an exact offshore footprint on every date.

Exposure below one percent is treated as unsupported. One positive-count zone-date receives a one-percent floor because a detection establishes some coverage despite the lower reconstructed exposure. These rules leave 2,478 supported cells from 3,288 combinations of 411 dates and eight zones. The weighted likelihood uses $1/e_{sj}$; unsupported destinations enter the residual category rather than being coded as zero presence. This correction requires the covered part of a zone to represent its vessel distribution. It does not correct size-dependent detection, classification error, or unobserved concentration within a swath.

D.3 Environmental matching

Controls are obtained at representative zone points through NOAA CoastWatch ERDDAP. SST anomaly uses NASA/JPL MUR v4.2 (jp1MURSST42), saved approximately weekly and matched within eight days. Log chlorophyll uses monthly 4-km Aqua MODIS composites, `erdMH1chlamd` in 2017–2021 and `R2022SQ` in 2022–2023, matched within 20 days. Wind (RSS CCMP v3.1) and sea-level anomaly (NOAA/NESDIS altimetry) use approximately 28-day extracts, matched within 32 days, rather than the source products’ daily or six-hourly frequency.

Dates are matched at noon UTC. Missing values use zone-by-month means, then zone means. Of 2,478 supported cells, chlorophyll is imputed in 581 (23.4 percent) and sea-level anomaly in six (0.2 percent); SST anomaly and wind need no imputation. Controls are standardized, linearly interpolated, and extended at endpoints for the daily recursion, not to create additional SAR observations. Sparse wind and altimetry series capture broad conditions rather than imaging-time sea state; chlorophyll releases differ across years. Absolute SST, currents, and fish prices are not fitted regressors.