



RECONSTRUCTING HISTORICAL CATCH SERIES FOR BLUE SHARK (*PRIONACE GLAUCA*) AND SHORTFIN MAKO (*ISURUS OXYRINCHUS*) IN THE INDIAN OCEAN: METHODOLOGICAL APPROACHES AND UNCERTAINTY QUANTIFICATION

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Purpose

This paper has been prepared for discussion within WPEB and presents alternative approaches for reconstructing historical blue shark and shortfin mako retained catches in the Indian Ocean.

Discussion

This paper informs meeting participants of alternative reconstruction approaches for addressing historical non-reporting and generic shark reporting.

Feedback requested

The Working Party is requested to:

- review the reconstruction framework;
- comment on donor hierarchy;
- comment on proposed reconstruction scenarios;
- identify additional information sources that could improve historical reconstruction.

Conclusion

The paper seeks confirmation that the proposed reconstruction framework provides an appropriate basis for estimating historical blue shark and shortfin mako retained catches.

Recommendation

The Working Party is invited to endorse the reconstruction framework as the basis for continued development and evaluation.

Decisions

No formal decisions are requested at this stage.

Abstract

Reliable catch histories are fundamental to stock assessment, yet historical shark catches in the Indian Ocean are affected by changes in taxonomic resolution, species identification, and reporting practices. We developed revised catch reconstructions for blue shark (*Prionace glauca*, BSH) and shortfin mako (*Isurus oxyrinchus*, SMA) using IOTC nominal catch data from 1950–2025, supported by geo-referenced catch-and-effort data where available. Rather than treating all missing species-specific catch as a single problem, the reconstruction distinguished among reporting states, including species-specific reporting, reporting to generic taxonomic categories, and complete non-reporting of sharks. Generic shark catches were allocated using a hierarchical species-composition reconstruction (HSCR), while complete non-reporting was addressed using donor-based shark-to-target-catch relationships matched hierarchically across fleets, fisheries, and periods. For SMA, catches reported as mako sharks *nei* were treated separately and allocated between shortfin and longfin mako using observed mako species composition. Statistical species-composition models using generalized additive models (GAMs) were evaluated as alternative approaches, including leave-one-fleet-out cross-validation and comparisons with catch-area data.

The analyses demonstrated that reconstruction methods should differ between BSH and SMA because the species have different reporting histories and empirical support. For SMA, the empirical hierarchical approach was preferred for both generic shark and mako allocations. The SKH-to-SMA GAM explained substantial in-sample variation but showed modest transferability among fleets and produced substantially greater reconstructed catches than HSCR, particularly through historical backcasting in gillnet fisheries and positive predictions in fisheries and periods with little or no observed SMA composition. The MAK-to-SMA GAM similarly showed poor out-of-fleet predictive performance, whereas observed mako catches were generally strongly dominated by SMA, supporting direct hierarchical allocation based on identified mako composition. GAM results were therefore retained as sensitivity analyses or diagnostics rather than primary SMA reconstructions. The BSH GAM showed stronger overall predictive association than the corresponding SMA model, but predictive support was heterogeneous among fisheries; it was therefore retained as a statistical sensitivity rather than as the preferred reconstruction. The resulting framework explicitly separates taxonomic allocation from complete non-reporting and preserves unsupported catch as unresolved rather than forcing reconstruction. This approach provides a transparent basis for evaluating uncertainty in historical shark catches and for producing species-specific catch histories suitable for subsequent stock assessment.

Keywords: Blue shark; Shortfin mako; catch reconstruction; retained catch; Indian Ocean; IOTC; shark reporting; fisheries statistics

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Introduction

Blue shark (*Prionace glauca*) and shortfin mako (*Isurus oxyrinchus*) are widely distributed pelagic sharks taken in tuna, billfish, and other fisheries throughout the Indian Ocean. Both species are important components of pelagic shark catches and have been subject to stock assessment and management within the Indian Ocean Tuna Commission (IOTC). Reliable estimates of historical removals are therefore essential for stock assessment, ecological analyses, and fisheries management. Despite substantial improvements in reporting over the past two decades, historical catch records for both

species remain incomplete owing to changes in reporting practices, species identification, fleet participation, and the progressive adoption of species-specific reporting by CPCs.

Historical shark catch statistics are affected by two fundamentally different reporting problems. The first is complete non-reporting, in which fishing activity and catches of target species were reported but associated shark catches were not. The second is taxonomic aggregation, whereby shark catches were reported but not identified to the species level. Such catches may occur in broad generic shark categories (e.g., sharks nei or “Various sharks”) or, in the case of shortfin mako, within the more taxonomically specific category mako sharks nei (MAK), which may include both shortfin and longfin mako (*Isurus paucus*).

These problems require different reconstruction approaches. Complete non-reporting requires estimation of the expected species-specific shark catch associated with reported fishing activity, whereas taxonomic aggregation requires allocation of an observed shark catch among species. The latter problem also differs between BSH and SMA. For BSH, the principal taxonomic reconstruction involves estimating the blue shark component of catches reported as generic sharks. For SMA, two levels of taxonomic aggregation must be considered separately: allocation of generic shark catch to shortfin mako and allocation of unresolved mako catch between shortfin and longfin mako. Consequently, the most appropriate reconstruction method need not be identical between species or among reporting categories.

A further challenge is distinguishing the absence of a species-specific catch record from the absence of the species in the fishery. Historical reporting frequently progressed from generic shark categories toward species-specific reporting, and the timing of this transition differed among fleets and fisheries. Species-specific catches may therefore appear to increase as reporting becomes more resolved even where the underlying fishery or species composition has changed relatively little. Spatial and temporal information on the expansion of species-specific reporting can help distinguish these changes in reporting state from changes in the occurrence of the species.

Annual changes in reported or reconstructed BSH and SMA catches should therefore not be interpreted as direct indicators of changes in abundance. Rather, temporal patterns may reflect some combination of:

- improvements in reporting and species identification;
- entry of new fleets or changes in fleet participation;
- changes in fishing behaviour and spatial distribution;
- changes in retention practices;
- target switching, including changes in the importance of sharks relative to tuna and billfish;
- changes in the taxonomic resolution of reported shark catches; and
- retrospective revisions of historical catch statistics.

Consequently, reconstructed catch histories should be interpreted primarily as improvements in fisheries statistics and estimates of historical removals rather than as biological indicators of population change.

A further complication is that historical retained-catch databases continue to be revised as CPCs update historical catch records. These revisions can substantially alter reconstructed shark catch

histories even when the reconstruction methodology remains unchanged. This is particularly important for methods that estimate missing shark catches relative to reported catches of associated target species, because retrospective changes to the denominator can propagate directly into reconstructed catches. For reproducibility and comparability among stock assessments, consideration should therefore be given to maintaining a frozen historical retained-catch baseline for assessment purposes while allowing subsequent data revisions and their effects on reconstructed histories to be evaluated separately.

This study develops a reconstruction framework that explicitly separates complete non-reporting from taxonomic aggregation and evaluates reconstruction methods according to the information available within each reporting state. Empirical hierarchical approaches are compared with statistical species-composition models where sufficient data are available, and independent catch-and-effort information is used to evaluate the consistency of observed species-composition patterns. Rather than imposing a common reconstruction method on both species, the framework allows the preferred approach to differ between BSH and SMA where their reporting histories and empirical support differ.

Previous Indian Ocean SMA assessments have addressed uncertainty in historical catch through both assumptions concerning unresolved taxonomic categories and alternative catch reconstruction. In the 2024 assessment, catches reported as MAK, MSK, AG17, and AG20 were combined with reported SMA and treated as shortfin mako. The principal assumption concerned MAK, which represented most of the unresolved mako catch and was assumed to consist predominantly of SMA because longfin mako is encountered less frequently in oceanic fisheries (Coelho *et al.*, 2024). The assessment also considered an alternative reconstructed catch series based on shark-to-target catch ratios, following methods developed in earlier shark catch reconstruction studies (Murua *et al.*, 2013; Coelho *et al.*, 2019).

The present analysis revisits both assumptions using the expanded IOTC retained-catch and geo-referenced catch-and-effort data now available. Rather than assigning all unresolved mako catch to SMA, the SMA fraction of MAK is estimated from catches identified as shortfin and longfin mako. More broadly, the analysis distinguishes taxonomic aggregation, for which an observed shark catch must be allocated among species, from complete non-reporting, for which the magnitude of shark catch itself must be estimated. This distinction allows information from MAK, generic SKH, and completely unreported shark catch to be treated separately and avoids applying a single reconstruction method to reporting problems that contain different information.

The objectives of this study are therefore to:

1. distinguish complete non-reporting from taxonomic aggregation in historical shark catch records;
2. reconstruct blue shark (BSH) and shortfin mako (SMA) catches using methods matched to the information available in each reporting state;
3. evaluate alternative empirical and statistical approaches to species-composition reconstruction;
4. identify methods with sufficient empirical and predictive support for use in the recommended reconstructions; and
5. provide transparent reconstructed catch histories and sensitivity scenarios suitable for future stock assessments.

Methods

Data sources

Three complementary IOTC databases were used: retained catch (RC), catch and effort (CA), and effort (EF).

The retained catch database formed the primary basis for historical reconstruction because it provides annual retained catches by fleet, fishery, and reported species or taxonomic category. Catch-and-effort data were used to independently evaluate species composition observed in the retained-catch data and to examine the spatial and temporal development of species-specific reporting. Geo-referenced data were used diagnostically to evaluate changes in reporting and fishery distribution, but were not used directly to estimate reconstructed catch. Effort data were used to identify active fisheries and provide additional evidence concerning fishing activity during periods with incomplete shark reporting.

Analyses focused on blue shark (*Prionace glauca*; BSH) and shortfin mako (*Isurus oxyrinchus*; SMA). Historical catches reported under unresolved shark categories were retained separately from species-specific catches so that taxonomic aggregation and complete non-reporting could be treated as distinct reconstruction problems.

Reconstruction framework

Analyses were conducted primarily at the Fleet × Fishery × Year level. Spatial analyses of geo-referenced catch-and-effort data were conducted separately to evaluate the evolution and geographic consistency of reporting and to assess whether temporal changes in species-specific records were consistent with changes in reporting, fishing distribution, or both. Spatial information was not used directly in the reconstruction estimator. The reconstruction framework distinguished two fundamentally different missing-catch processes. Complete non-reporting occurs when fishing activity and target catch are reported but no relevant shark catch is reported. Taxonomic aggregation occurs when shark catch is reported but only under unresolved categories such as sharks nei (SKH) or mako sharks nei (MAK). These processes were treated separately because the first requires estimation of the magnitude of shark catch, whereas the second requires allocation of an observed catch total among species.

Reporting-state labels were used descriptively, but reconstruction eligibility was defined independently for each unresolved catch component. This was particularly important for SMA because MAK and SKH can coexist within a Fleet × Fishery × Year stratum and represent different levels of taxonomic resolution. Their allocations were therefore treated independently rather than assigning each stratum to a single mutually exclusive reporting state.

Complete non-reporting reconstruction was restricted to strata containing reported target catch but no reported catch in the species-specific or unresolved shark categories relevant to that reconstruction. For SMA, for example, complete non-reporting reconstruction was applied only when SMA, MAK, and SKH were all absent. This prevented estimates of completely unreported shark catch from being added to strata in which shark catch was already represented by a species-specific or taxonomically unresolved category.

Relationship to previous catch reconstructions

The complete non-reporting component retains the general rationale of previous pelagic shark catch reconstructions, in which reported catches of tuna and tuna-like target species provide a basis for estimating shark catches in fisheries with incomplete shark reporting (Murua *et al.*, 2013; Coelho *et al.*, 2019). Previous implementations have estimated shark-to-target catch relationships using

information from observer programmes, literature, and fishery-specific information and have applied these relationships according to fleet or métier. The approach has previously been used to construct alternative shark catch histories for stock assessment, including shortfin mako.

The present analysis modifies this framework in two respects. First, donor relationships are estimated directly from the available IOTC reporting data and their application is recorded explicitly according to fleet, fishery, reporting period, and temporal support. Second, the ratio estimator is restricted to complete non-reporting. Catches already reported as SKH or MAK are treated as taxonomic-allocation problems and reconstructed from observed species composition rather than by estimating additional shark catch from target catch. This separation prevents an observed unresolved shark catch and an estimate of unreported shark catch from being treated as equivalent sources of missing species-specific catch.

Reconstruction of complete non-reporting

For both BSH and SMA, complete non-reporting was evaluated using donor ratios relating species-specific shark catch to associated target catch. Candidate strata contained reported target catch but lacked the species-specific and generic shark categories relevant to that reconstruction. ## Reconstruction of complete non-reporting

For donor set ($d(i)$), the species-to-target catch ratio was

$$\hat{R}_{s,d(i)} = \frac{\sum_{j \in d(i)} C_{s,j}}{\sum_{j \in d(i)} C_{\text{target},j}}.$$

For recipient stratum (i), reconstructed catch of species (s) was

$$\hat{C}_{s,i} = C_{\text{target},i} \hat{R}_{s,d(i)}.$$

where (s) denotes BSH or SMA and

$$R_s = \frac{C_s}{C_{\text{Target}}}$$

was estimated from donor fisheries with observed species-specific reporting.

The target-catch denominator included the principal tuna and billfish species associated with these fisheries. The ratio estimator was intended to reconstruct shark catch where no shark catch total was available; it was not used to allocate catches already reported under unresolved shark categories.

Donor hierarchy and temporal support

Donor ratios were selected hierarchically, favoring the closest available empirical match. The hierarchy prioritized information from the same fleet and fishery before progressively broader donor pools were considered. Each reconstructed value retained information on donor source, donor fleet or fleets, donor period, and the temporal relationship between the donor information and recipient stratum.

Temporal support was classified as within donor period, backcast, or forward extrapolation. This distinction was retained because an estimate based on observations overlapping the recipient period has different empirical support from one requiring extrapolation before or after the period represented by the donor data. Strata for which no suitable donor existed were retained as unresolved fishing activity rather than being assigned an estimate from an increasingly dissimilar donor pool.

For SMA, longline donors required additional stratification because nominal longline fisheries differed substantially in their association with sharks. Deep-freezing longline (LLD), fresh longline (LLF), other

longline (LLO), and shark-targeting longline (SLL, where identified) were therefore not pooled indiscriminately. Broader longline fallback ratios were permitted only within compatible longline classes. This avoided borrowing the high SMA-to-target ratios observed in shark-associated longline fisheries for conventional tuna or swordfish longline strata.

Large observed donor ratios were not mechanically capped because high ratios may represent genuine shark targeting, increased shark retention, or switching between target species. Instead, the reconstruction controlled their application through donor compatibility and temporal support. This approach preserves observed fishery behavior while limiting unsupported transfer of those observations to dissimilar fisheries.

Hierarchical species-composition reconstruction

Taxonomically unresolved shark catches were reconstructed using hierarchical species-composition reconstruction (HSCR). HSCR estimates species composition from observed, species-identified donor strata and progressively broadens the donor pool when information at a finer level is unavailable. This differs from the ratio reconstruction used for complete non-reporting: HSCR allocates an observed unresolved shark catch and does not estimate total shark catch from target catch.

The hierarchy was intended to retain fishery- and fleet-specific information where available while providing a transparent sequence of broader empirical donors when local species-composition information was unavailable. Alternative HSCR scenarios were retained to characterize uncertainty associated with the level of donor pooling. N1 uses the more restrictive empirical hierarchy, whereas N2 permits broader donor support where finer information is unavailable. The exact hierarchy differs where required by the reporting structure of each species.

For donor set $d(i)$, the focal-species proportion was

$$\hat{p}_{s,d(i)} = \frac{\sum_{j \in d(i)} C_{s,j}}{\sum_{j \in d(i)} C_{\text{identified shark},j}}.$$

Generic shark catch was then allocated as

$$\hat{C}_{s,i}^{\text{SKH}} = C_{\text{SKH},i} \hat{p}_{s,d(i)}.$$

The shortfin-mako fraction of identified mako catch was

$$\hat{p}_{\text{SMA},d(i)} = \frac{\sum_{j \in d(i)} C_{\text{SMA},j}}{\sum_{j \in d(i)} (C_{\text{SMA},j} + C_{\text{LMA},j})}.$$

Unresolved mako catch was allocated as

$$\hat{C}_{\text{SMA},i}^{\text{MAK}} = C_{\text{MAK},i} \hat{p}_{\text{SMA},d(i)}.$$

Blue shark

For BSH, the principal taxonomic ambiguity is allocation of generic shark catch (SKH) to blue shark. HSCR therefore provides an empirical species-composition reconstruction based on identified shark catches. A generalized additive model (GAM) of BSH composition was also examined as a statistical alternative using fishery effects, temporal smooths, fleet effects, and covariates describing the composition of associated target catch.

The statistical model was used to evaluate whether broader temporal, fleet, and fishery information provided evidence for species compositions differing from those obtained through hierarchical empirical borrowing. Model performance and extrapolation were evaluated using predictive

diagnostics rather than assuming that improved in-sample fit necessarily represented improved reconstruction of historical unresolved catches.

Complete BSH non-reporting was reconstructed separately using the donor-ratio hierarchy described above. The BSH reconstruction therefore contains three conceptually distinct components: reported BSH, BSH allocated from generic SKH, and BSH estimated for complete non-reporting.

Shortfin mako

SMA requires an additional taxonomic level because historical catches may be reported as either generic sharks (SKH) or mako sharks *nei* (MAK). Three distinct reconstruction components were therefore evaluated.

First, MAK was allocated between SMA and longfin mako (LMA) using observed identified-mako composition,

$$p_{\text{SMA}|\text{mako}} = \frac{C_{\text{SMA}}}{C_{\text{SMA}} + C_{\text{LMA}}},$$

with unresolved mako catch allocated as

$$\hat{C}_{\text{SMA},\text{MAK}} = p_{\text{SMA}|\text{mako}} C_{\text{MAK}}.$$

The identified-mako data were strongly dominated by SMA in the principal fisheries. A GAM was examined as an alternative for MAK $\rightarrow$ SMA, but leave-one-fleet-out validation showed poor transferability, including negative rank correlations within the principal fishery groups. Because the empirical estimator has a direct taxonomic interpretation and stronger predictive support, hierarchical empirical allocation was retained as the recommended MAK $\rightarrow$ SMA method. The MAK GAM was retained as a diagnostic rather than as a reconstruction scenario.

Second, SKH was allocated to SMA using HSCR. A beta-regression GAM was evaluated as a statistical sensitivity analysis. The response variable was the proportion of identified shark catch represented by SMA,

$$p_{\text{SMA}} = \frac{C_{\text{SMA}}}{\sum C_{\text{identified sharks}}}.$$

The final GAM included fishery effects, fishery-specific temporal smooths, a fleet random effect, and covariates describing the composition of associated target catch. Leave-one-fleet-out cross-validation was used to evaluate transferability among fleets. Because the fleet random effect cannot be estimated for an omitted fleet, this effect was excluded during prediction to the withheld fleet, thereby evaluating transferability of the fishery, temporal, and target-composition components of the model.

Third, complete SMA non-reporting was reconstructed using the donor-ratio hierarchy only where target catch was present and SMA, MAK, and SKH were all absent. The three reconstruction components were additive only where they represented distinct unresolved categories, and the complete non-reporting component was explicitly prevented from overlapping reported or taxonomically unresolved shark catch.

Statistical treatment of species-composition proportions

The statistical species-composition models were formulated as beta-regression GAMs because the quantity of interest was a conditional species-composition proportion rather than catch rate or absolute catch. The response represents the fraction of identified shark catch assigned to the focal species within strata for which identified shark catch was available.

Observed proportions included exact zeros and, for some composition datasets, exact ones. Because the beta distribution is defined on the open interval (0,1) , these boundary observations were moved slightly into the interior of the distribution before model fitting. The original zero and one observations were retained for descriptive summaries and model evaluation.

A hurdle or delta formulation was considered conceptually because zero observations were common, particularly for SMA in line and purse-seine fisheries. A conventional fisheries delta model, consisting of a binomial model for occurrence and a continuous model such as a lognormal distribution for positive catch, was not used because the response in this analysis was a bounded species-composition proportion rather than a non-negative catch or CPUE observation. Applying a binomial–lognormal delta model would therefore change the quantity being modeled and would not directly provide an unconditional species-composition proportion without an additional combination step.

A two-part model could instead have been formulated specifically for composition, with one component estimating the probability that SMA occurred in the identified shark catch and a second estimating its conditional proportion when present. Such a model would distinguish structural or sampling zeros from variation in positive species composition. However, the primary objective of the GAM analysis was to evaluate whether a flexible statistical species-composition model provided a useful alternative to empirical HSCR, rather than to develop a new primary estimator.

For SMA, cross-validation indicated that the more important limitation was transfer of species composition among fleets and extrapolation into periods with limited species-specific observations. The beta GAM produced positive predicted SMA composition in some fisheries and periods where observed composition was zero or near zero and generated substantial historical extrapolation in gillnet fisheries. Increasing model complexity through a hurdle formulation would not by itself resolve the lack of empirical support for those fleet and temporal extrapolations. A hurdle model was therefore not pursued for the present reconstruction. The beta GAM was retained as a broad statistical sensitivity against which the empirical HSCR reconstruction could be compared.

This distinction is important when interpreting the GAM results. The beta model should not be viewed as evidence that observed zeros are necessarily generated by the same process as positive proportions. Rather, it provides a smooth statistical alternative that intentionally allows information to be shared across observations. The degree to which that sharing is supported for historical reconstruction was evaluated through cross-validation, temporal support, and comparison with the empirical HSCR estimates.

Comparison of retained catch and catch-and-effort composition

Species composition estimated from retained catch (RC) was compared with composition calculated independently from geo-referenced catch-and-effort (CA) data for matched Fleet × Fishery × Year strata ([Table 1](#)) evaluated whether composition patterns inferred from the retained-catch data were broadly consistent with a separate IOTC reporting system.

Table 1: Comparison of species-composition estimates from retained-catch (RC) and catch-and-effort (CA) data for matched Fleet × Fishery × Year strata. Broad shark composition is the proportion of identified shark catch represented by shortfin mako; mako composition is the proportion of identified mako catch represented by shortfin mako.

Comparison	Fisher y	Matched strata (n)	Median RC proportion	Median CA proportion
Broad shark composition	GN	36	0.024	0.018
Broad shark composition	LI	123	0.000	0.000
Broad shark composition	LL	260	0.054	0.054
Broad shark composition	OT	6	0.000	0.000
Broad shark composition	PS	13	0.000	0.000
Identified mako composition	GN	25	0.793	1.000
Identified mako composition	LI	24	1.000	1.000
Identified mako composition	LL	146	1.000	1.000
Identified mako composition	OT	1	1.000	1.000
Identified mako composition	PS	5	1.000	1.000

For SMA, two comparisons were made. The first examined broad shark composition relevant to SKH → SMA, using the proportion of identified shark catch represented by SMA. The second examined identified-mako composition relevant to MAK → SMA, using the proportion of identified mako catch represented by SMA.

RC and CA showed generally similar broad SMA composition in matched longline and line strata. Identified-mako composition was also strongly dominated by SMA in the principal longline and line fisheries in both datasets. These comparisons provided independent support for the taxonomic allocation assumptions but were not used as direct replacements for RC in the historical reconstruction.

The RC–CA comparison was interpreted as validation of observed species-composition structure rather than validation of historical extrapolation. Agreement between the two datasets in periods with species-specific observations does not demonstrate that the same composition can be extrapolated to fleets or earlier periods lacking species-specific reporting. Donor hierarchy, temporal support, and predictive diagnostics were therefore considered separately when evaluating historical reconstruction.

Spatial analyses of CA data were additionally used to examine the geographic development of species-specific reporting. These analyses helped distinguish the absence of a species-specific record from evidence that the species itself was absent from the fishery.

Temporal aggregation of reporting patterns

Spatial catch and effort data were summarized into six reporting periods: 1950–1963, 1964–1980, 1981–1994, 1995–2004, 2005–2014, and 2015–2025. These periods were used consistently across the spatial analyses and species-composition diagnostics. They were defined as broad reporting eras rather than equal-duration statistical bins.

The temporal aggregation was intended to balance two competing requirements. Individual years are frequently too sparse to characterize historical spatial reporting, particularly for species-specific shark catches, whereas aggregation over the entire time series would obscure the progressive transition from generic to species-specific reporting. The selected periods therefore retain relatively broad intervals during the early portion of the time series, when reporting was sparse, and shorter intervals during the more recent period, when species-specific reporting and spatial coverage increased.

The periods should not be interpreted as biological regimes or as implying abrupt changes in fisheries or reporting at their boundaries. They provide an operational framework for comparing changes in the availability, taxonomic resolution, and spatial coverage of the historical data. Reconstruction calculations were conducted at the Fleet $\times$ Fishery $\times$ Year level; aggregation into reporting periods was used for donor support, diagnostics, and visualization rather than to assume constant catch or species composition within each period.

Spatial evaluation of reporting patterns

Geo-referenced catch-and-effort (CA) data were used to evaluate the spatial and temporal development of shark reporting and to provide additional context for interpreting historical absences of species-specific records. These analyses were conducted separately from the Fleet $\times$ Fishery $\times$ Year reconstruction and were not used to spatially allocate or directly estimate reconstructed catch.

For BSH and SMA, reported catches were summarized spatially through time to compare the geographic distribution of generic shark reporting with the subsequent occurrence of species-specific reporting. Particular attention was given to fisheries with substantial historical shark catches, including longline, line, and gillnet fisheries. The objective was to determine whether generic and species-specific reporting occurred in overlapping fishing areas and whether species-specific reporting progressively appeared within areas where shark catches had previously been reported only at broader taxonomic levels.

The spatial analyses were used primarily to evaluate the interpretation of historical reporting states. Where generic shark reporting preceded species-specific reporting in the same or overlapping fishing areas, the absence of an early BSH or SMA record was not interpreted as evidence that the species was absent from the fishery. Instead, such patterns were considered consistent with a transition from aggregated to species-specific reporting.

Spatial data were also used to identify cases where apparent changes in species composition could plausibly reflect changes in the geographic distribution of fishing activity rather than reporting alone. Consequently, spatial overlap was treated as supporting evidence for the reconstruction framework rather than as sufficient evidence for assigning a species composition to an unresolved catch.

The spatial analyses therefore served as diagnostics of reporting history, fishery distribution, and the plausibility of temporal extrapolation. Reconstruction estimates remained based on the Fleet $\times$ Fishery $\times$ Year donor and species-composition procedures described above, thereby avoiding the assumption that spatial co-occurrence alone provides sufficient information to reconstruct historical species-specific catch.

Reconstruction scenarios

Final reconstruction scenarios retain the individual reconstruction components so that uncertainty associated with different missing-catch processes and allocation methods remains identifiable and can subsequently be propagated into stock assessment analyses.

For BSH, scenarios combine reported BSH, BSH allocated from generic SKH, and BSH reconstructed for complete non-reporting. Alternative species-composition approaches are evaluated according to their empirical support, predictive performance, and the extent of temporal or fishery extrapolation required.

For SMA, the recommended reconstruction combines reported SMA, hierarchical empirical allocation of MAK, HSCR allocation of SKH, and the supported donor-ratio reconstruction for complete non-reporting. HSCR N1 and N2 provide the principal species-composition alternatives for generic shark catch.

The SKH → SMA GAM is retained as a statistical sensitivity rather than a co-equal reconstruction scenario. It is used to characterize the consequences of allowing a smooth statistical model to transfer species-composition information more broadly across fisheries and time than the empirical HSCR hierarchy. The MAK → SMA GAM is retained only as a diagnostic because its predictive performance did not support its use in reconstructing unresolved mako catches.

The resulting scenarios therefore do not impose methodological symmetry between BSH and SMA or among reporting categories. Reconstruction methods were selected according to the information contained in each reporting state and the empirical and predictive support available for transferring species-composition or catch-rate information to unresolved historical strata.

Results

Temporal and spatial development of shark reporting

Changes in retained-catch reporting

The retained-catch data show substantial changes in both the magnitude and taxonomic resolution of shark reporting through time ([Figure 1](#)). Generic Sharks NEI (SKH) occur throughout much of the historical series and account for substantial reported catch during periods when species-specific shark reporting was limited. Reporting of BSH and SMA becomes progressively more prominent later in the time series, while MAK represents an intermediate level of taxonomic resolution relevant specifically to SMA.

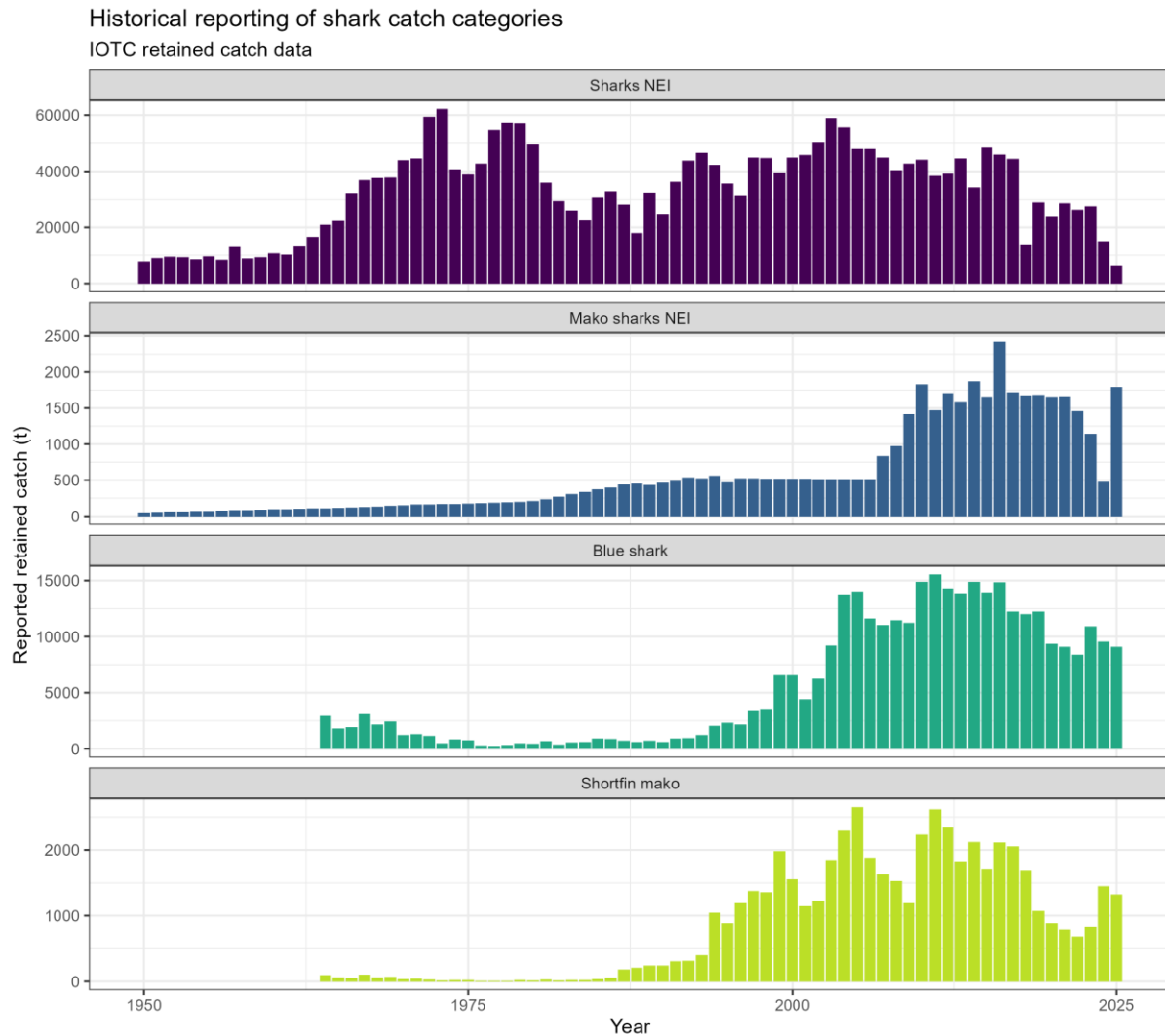


Figure 1: Annual retained catch reported as Sharks NEI (SKH), mako sharks NEI (MAK), blue shark (BSH), and shortfin mako (SMA). Panels use independent vertical scales to show changes in the timing and magnitude of reporting for each category.

The temporal sequence is consistent with a progressive transition from unresolved to species-specific shark reporting rather than an abrupt replacement of one reporting system by another. Generic and species-specific categories overlap for substantial portions of the time series, indicating that changes in reported BSH and SMA catch reflect changes in reporting practice in addition to changes in fishing activity and catch.

The reporting periods used in subsequent analyses capture this transition at a scale appropriate to the amount of information available. The earliest periods contain relatively sparse species-specific information, whereas reporting becomes substantially more resolved during 1995–2004, 2005–2014, and particularly 2015–2025.

Spatial development of generic and species-specific reporting

Generic shark reporting was spatially extensive before species-specific SMA reporting became widespread ([Figure 2](#)). SKH catches were reported across broad portions of the Indian Ocean during the earlier reporting periods and continued to occur in many of the same regions after species-specific shark reporting became more common.

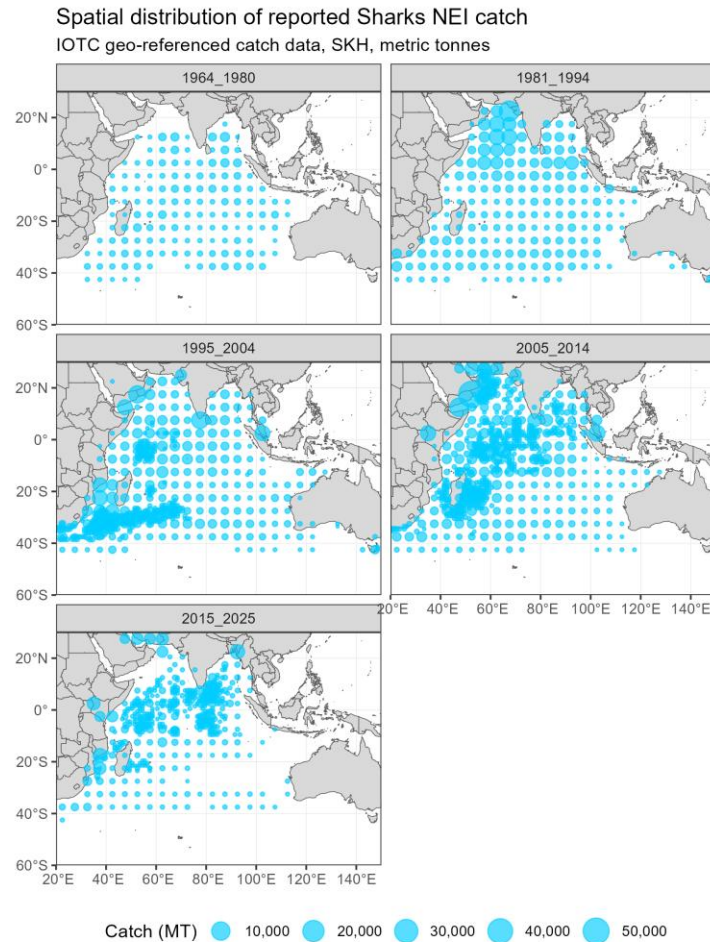


Figure 2: Spatial distribution of reported Sharks NEI (SKH) catch in the IOTC geo-referenced catch-and-effort data by reporting period. Point area is proportional to reported catch.

Species-specific SMA reporting showed a markedly different temporal and spatial pattern ([Figure 3](#)). Spatially resolved SMA records were sparse during the early reporting periods. Reporting expanded during 1995–2004 and became substantially more widespread during 2005–2014 and 2015–2025, including areas of the western, central, and southern Indian Ocean where generic shark catches had been reported previously.

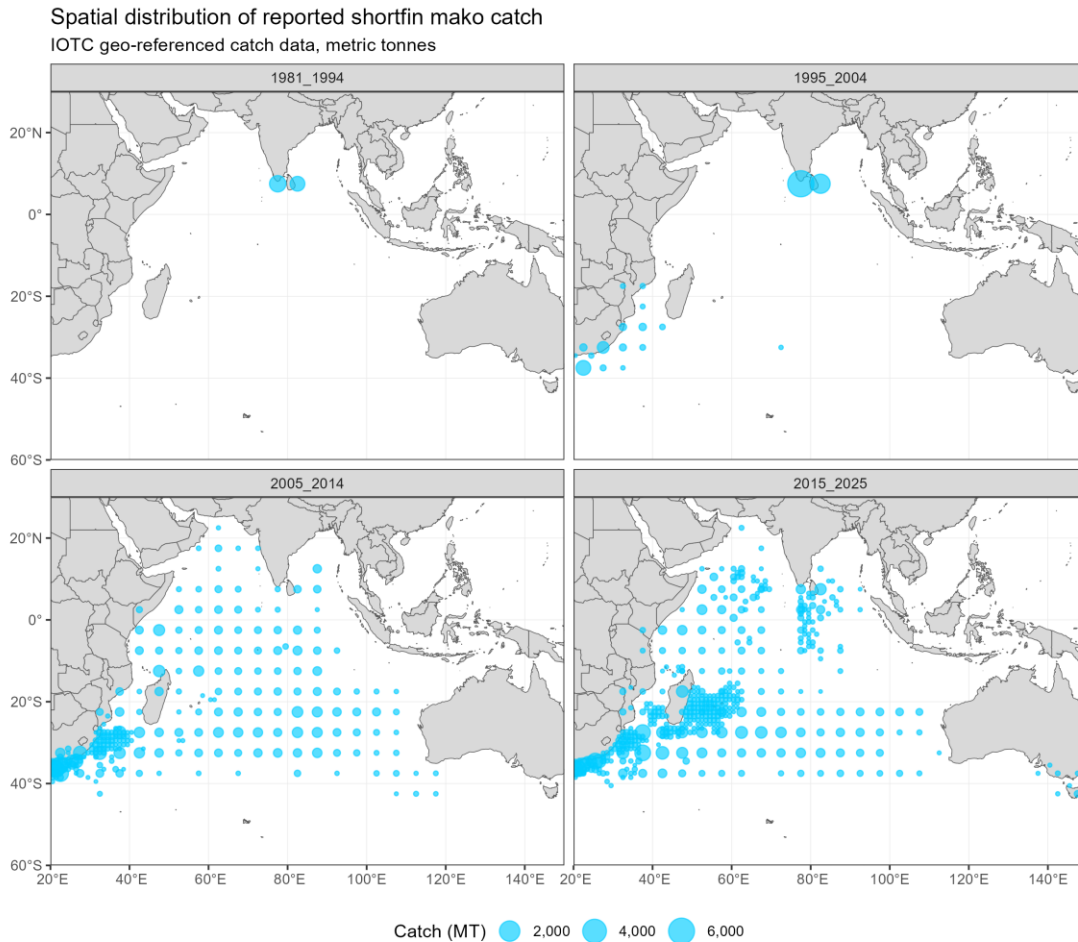


Figure 3: Spatial distribution of reported shortfin mako (SMA) catch in the IOTC geo-referenced catch-and-effort data by reporting period. Point area is proportional to reported catch.

Considering BSH, SMA, and SKH jointly shows the change in reporting resolution more directly ([Figure 4](#)). Earlier spatial records are dominated by unresolved shark reporting, whereas later periods contain increasing numbers of cells with BSH and SMA reported either alone or together with SKH. Generic and species-specific categories continue to coexist during the later periods, demonstrating that the transition toward species-specific reporting differed among fleets, fisheries, and regions.

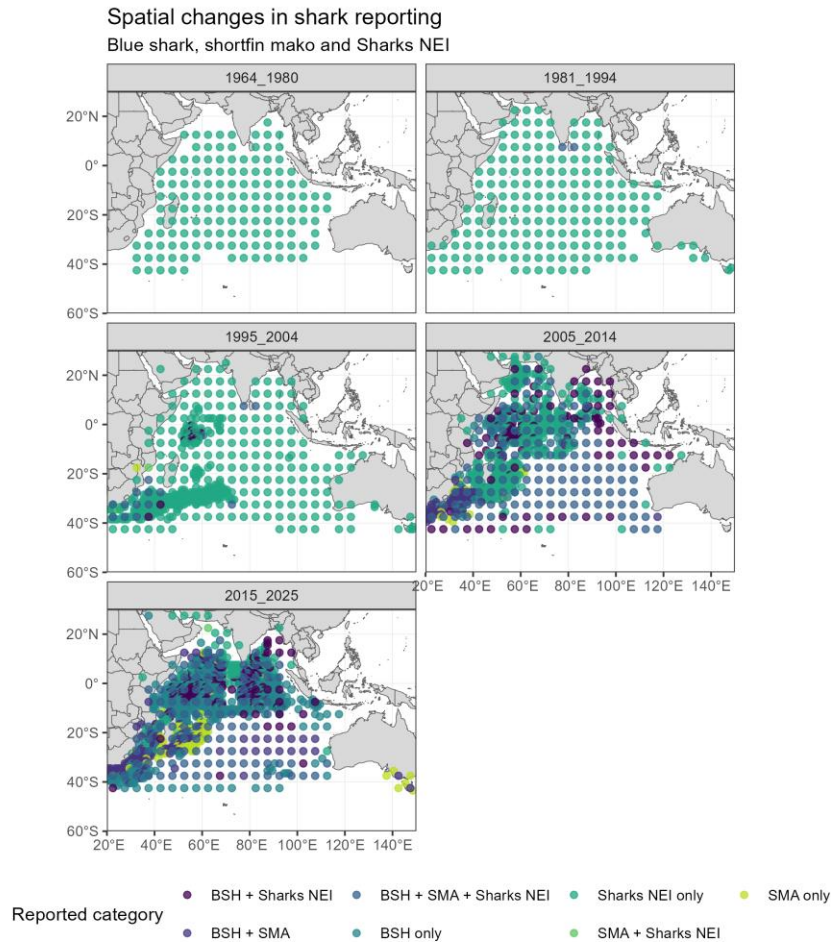


Figure 4: Changes in the spatial distribution and taxonomic resolution of shark reporting through time. Categories indicate whether spatial cells contained reported blue shark (BSH), shortfin mako (SMA), Sharks NEI (SKH), or combinations of these categories during each reporting period.

These patterns support the interpretation that absence of an early species-specific record cannot generally be interpreted as absence of the species from the fishery. Generic shark reporting preceded species-specific reporting in many of the same regions, while species-specific reporting expanded progressively through time.

Spatial distribution of fishing effort

Longline fishing effort was geographically extensive during periods when species-specific shark reporting was sparse ([Figure 5](#)). Substantial effort occurred across areas of the Indian Ocean where BSH and SMA were subsequently reported.

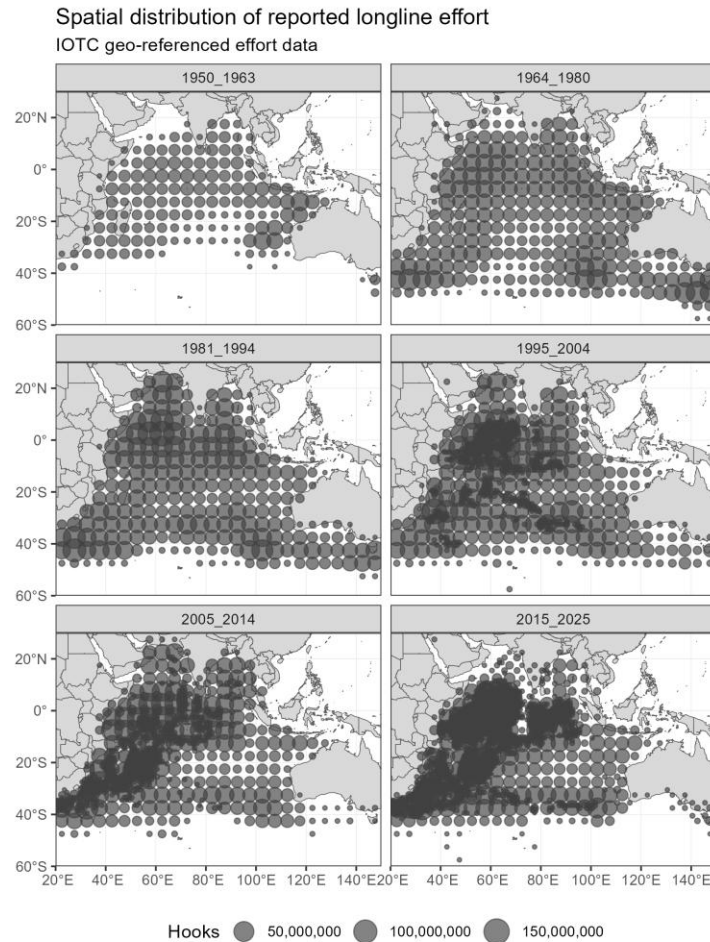


Figure 5: Spatial distribution of reported longline effort by reporting period. Point area is proportional to the number of hooks reported in the IOTC geo-referenced effort data.

The effort distribution distinguishes absence of species-specific reporting from absence of fishing activity. Areas without early BSH or SMA records frequently contained substantial fishing effort or unresolved shark catch. The spatial analyses therefore support the reporting-state interpretation used in the reconstruction but were not used directly to determine species composition or reconstructed catch.

Reporting states

Historical BSH and SMA records could be separated into reporting states that contained different amounts of information for reconstruction. For BSH, the principal states consisted of direct BSH reporting, generic shark reporting, reporting of other identified sharks without BSH, and fishing activity with target catch but no shark reporting. For SMA, the structure was more complex because catch could be reported directly as SMA, under the mako-specific category MAK, under the broader SKH category, or not reported as shark catch.

The same Fleet × Fishery combinations frequently changed reporting state through time. In particular, generic shark reporting often preceded species-specific reporting within fisheries that subsequently reported BSH or SMA. Reporting state was therefore treated as a property of the available information rather than as evidence concerning biological presence or absence.

For SMA, MAK and SKH were not treated as mutually exclusive reporting states because both categories could occur within the same Fleet × Fishery × Year stratum. Instead, eligibility for allocation from each unresolved category was defined independently. Complete non-reporting was treated separately and was restricted to strata containing target catch but no SMA, MAK, or SKH.

Blue shark reconstruction

Allocation of generic shark catch

Allocation of SKH represents the principal taxonomic reconstruction for BSH. Across all generic-shark strata, approximately 2.519 million t of SKH catch were available for allocation. The complete HSCR reconstruction allocated approximately 648.1 thousand t to BSH under N1 and 734.5 thousand t under N2. For the subset of strata for which GAM predictions were available, the corresponding HSCR totals were 648.1 and 734.5 thousand t, respectively, compared with 815.2 thousand t under the GAM sensitivity (Table 1). The GAM therefore exceeded HSCR N1 by approximately 167.1 thousand t and HSCR N2 by approximately 80.8 thousand t. ([Table 2](#)).

The annual trajectories indicate that the differences among methods were not constant through time ([Figure 6](#)). HSCR and the GAM produced broadly similar periods of increased BSH allocation once species-specific information became more extensive, but the magnitude of allocation differed among fisheries and periods. These differences reflect the extent to which the GAM transfers information across fleets and time relative to the more explicit donor restrictions imposed by HSCR.

This matched comparison excluded seven baitboat strata containing approximately 45 t of generic shark catch. Consequently, the matched HSCR totals were 648.1 thousand t under N1 and 734.5 thousand t under N2, compared with 815.2 thousand t allocated by the GAM. The difference between the full and matched HSCR totals is negligible relative to the scale of the reconstruction but is retained explicitly so that totals from the reconstruction and model-comparison datasets are not conflated.

Table 2: Blue shark catch allocated from generic Sharks NEI (SKH) under HSCR and the GAM species-composition sensitivity for the subset of strata with GAM predictions. Full HSCR totals were 648,126 t under N1 and 734,506 t under N2; the matched comparison excludes seven baitboat strata containing approximately 45 t of generic shark catch.

Generic shark catch (t)	HSCR N1 (t)	HSCR N2 (t)	GAM sensitivity (t)	GAM - HSCR N1 (t)	GAM - HSCR N2 (t)
2,519,278	648,126	734,461	815,247	167,121	80,786

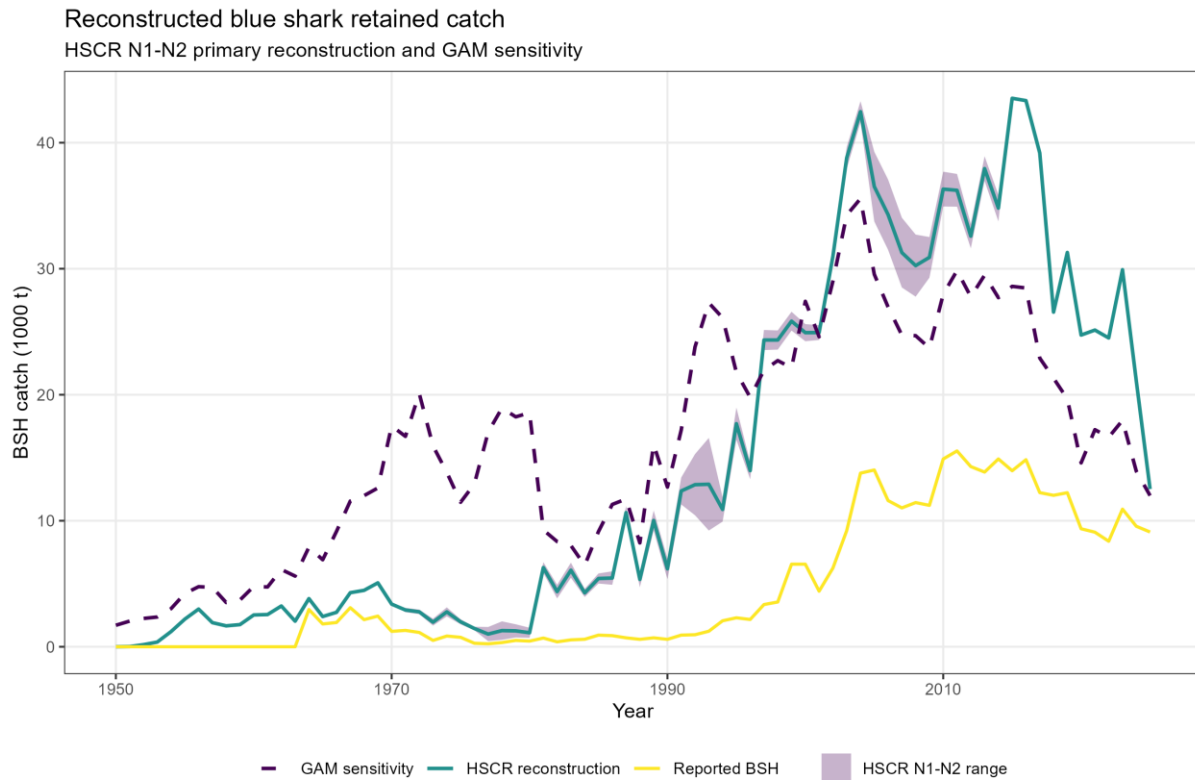


Figure 6: Annual blue shark catch allocated from generic Sharks NEI (SKH) under hierarchical species-composition reconstruction (HSCR) and the generalized additive model (GAM) alternative. The shaded area represents the HSCR N1–N2 range and the central line represents the HSCR midpoint.

Complete non-reporting

Complete BSH non-reporting was reconstructed separately from taxonomic allocation. Candidate strata contained reported target catch but no BSH or unresolved shark catch from which BSH could be allocated. Species-to-target catch relationships from supported donor fisheries were applied hierarchically, with donor source and temporal support retained for each estimate.

Strata without an appropriate donor were retained as unresolved rather than forcing a BSH estimate from increasingly dissimilar fisheries. The resulting complete non-reporting component therefore represents only the portion of historical fishing activity for which an empirically supported BSH-to-target relationship could be identified.

Alternative BSH reconstruction scenarios

The BSH scenarios combine three distinct components: reported BSH, BSH allocated from generic SKH, and BSH estimated for complete non-reporting. Alternative species-composition estimators affect only the allocation of generic shark catch; they do not change the independently reconstructed complete non-reporting component.

This separation allows uncertainty concerning the species composition of reported generic shark catch to be distinguished from uncertainty concerning shark catch that was not reported at all.

Shortfin mako reconstruction

Allocation of mako sharks nei

Reported MAK catch was treated separately from generic SKH because it represents a more restricted taxonomic category. Across the principal fisheries, identified mako catches were strongly dominated by SMA. Application of the empirical SMA/(SMA + LMA) hierarchy allocated approximately 36.3 thousand t of historical MAK catch to SMA.

The result provides empirical support for the assumption used in previous IOTC SMA assessments that much of the unresolved mako catch represents shortfin mako, while avoiding the stronger assumption that all MAK is SMA. Allocation can therefore vary according to the observed composition of identified mako catch rather than assigning the entire unresolved category to one species.

Allocation of generic shark catch

HSCR N1 and N2 produced similar aggregate estimates of SMA from generic SKH. N1 allocated approximately 88.6 thousand t to SMA and N2 approximately 90.6 thousand t. The small difference between the two totals indicates that broadening the empirical donor hierarchy had relatively little effect on total reconstructed SMA, although larger differences occurred within some fisheries and periods.

The similarity of the N1 and N2 totals also indicates that the major uncertainty in SKH → SMA allocation was not the distinction between the two empirical hierarchies. A much larger difference arose when composition was estimated using a statistical model that transferred information more broadly across fleets and time.

Complete non-reporting

The revised SMA donor hierarchy reconstructed approximately 38.9 thousand t from strata with target catch but no reported SMA, MAK, or SKH. Longline donor diagnostics showed substantial heterogeneity among fisheries, with shark-associated longline fisheries producing much larger SMA-to-target ratios than conventional tuna and swordfish fisheries.

Restricting fallback donors to compatible longline classes substantially reduced unsupported transfer of high shark-associated ratios. High observed ratios were retained where supported by the corresponding fishery rather than being arbitrarily capped.

A substantial amount of target catch remained in strata for which no suitable donor could be identified. These strata were retained as unresolved rather than being assigned an estimate from an unsupported donor pool.

Combined SMA reconstruction

The recommended empirical SMA reconstruction combines reported SMA, approximately 36.3 thousand t allocated from MAK, approximately 88.6–90.6 thousand t allocated from SKH, and approximately 38.9 thousand t reconstructed for complete non-reporting.

Using HSCR N1 for the generic-shark component, the combined empirical reconstruction was approximately 217.1 thousand t over the historical series. The corresponding N2 total is slightly higher because of the approximately 2.0 thousand t difference between the two SKH allocations.

Importantly, each additional component represents a different source of unresolved catch. The MAK and SKH components allocate already reported shark catch, whereas the complete non-reporting component estimates shark catch absent from the reported shark categories.

Evaluation of alternative SMA species-composition models

SKH GAM sensitivity

A beta-regression GAM was evaluated as an alternative to HSCR for allocating generic SKH to SMA. The final model included fishery effects, fishery-specific temporal smooths, a fleet random effect, and covariates describing the composition of associated target catch. The model explained 64.9% of the deviance in the observed species-composition data.

Predictive performance was considerably weaker when evaluated outside the fleets used to fit the model. Leave-one-fleet-out validation produced an overall MAE of 0.200, RMSE of 0.280, and Spearman rank correlation of 0.219. Transferability was strongest for longline fisheries and weaker for gillnet and line fisheries.

Application of the GAM to unresolved SKH allocated approximately 351.6 thousand t to SMA, compared with approximately 88.6 thousand t under HSCR N1 and 90.6 thousand t under HSCR N2 ([Figure 7](#)).

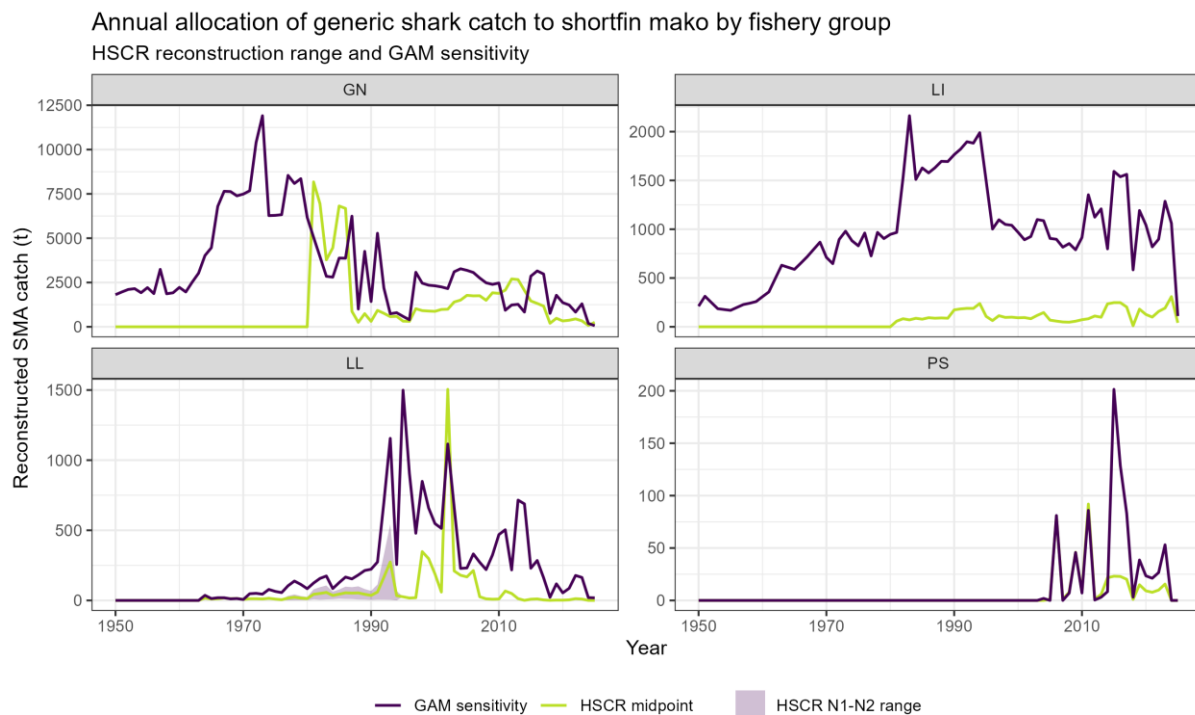


Figure 7: Annual shortfin mako catch allocated from generic Sharks NEI (SKH) under HSCR and the GAM sensitivity. The shaded region represents the HSCR N1–N2 range and the line represents the HSCR midpoint.

The difference was strongly concentrated in the earlier part of the series. During 1950–1963 the GAM allocated approximately 34.8 thousand t of SMA from SKH, while both HSCR scenarios allocated essentially none. During 1964–1980 the GAM allocated approximately 140.0 thousand t, compared with approximately 0.1–0.3 thousand t under HSCR. Thus, approximately 175 thousand t of the total GAM–HSCR difference accumulated before 1981.

After 1980, the difference between the approaches was substantially smaller, although the GAM generally continued to produce greater allocations. The methods were particularly similar for some gillnet periods after species-specific composition information became available.

MAK GAM diagnostic

A separate GAM was evaluated for allocation of MAK between SMA and LMA. Although the fitted model explained variation in the observed mako composition, leave-one-fleet-out prediction was poor. Rank correlations between observed and predicted composition were negative within the principal fishery groups, indicating poor transfer of the fitted relationship among fleets.

The GAM allocated approximately 27.7 thousand t of MAK to SMA, compared with approximately 36.3 thousand t using the empirical identified-mako hierarchy. Given the strong observed dominance of SMA among identified makos and the poor cross-fleet performance of the GAM, the statistical model was not retained as an alternative reconstruction. It is presented only as a diagnostic of whether increased model complexity improved the empirical mako allocation.

Fishery and temporal decomposition of the SKH GAM sensitivity

The difference between HSCR and the SKH → SMA GAM was concentrated in a small number of fishery groups ([Table 3](#); [Figure 8](#)). Gillnet fisheries accounted for approximately 182.1 thousand t, or 69.2%, of the GAM–HSCR N1 difference. Line fisheries accounted for a further 68.0 thousand t, or 25.9%, and longline fisheries approximately 14.0 thousand t, or 5.3%.

Table 3: Decomposition of shortfin mako allocated from generic shark catch (SKH) under HSCR and the GAM sensitivity analysis by fishery group.

Fishery	SKH catch (t)	HSCR N1 (t)	HSCR N2 (t)	GAM sensitivity (t)	GAM - HSCR N1 (t)	Share of total difference (%)
GN	1,527,969	77,567	77,567	259,690	182,123	69.2
LI	482,977	5,420	5,420	73,459	68,039	25.9
LL	129,304	3,692	5,705	17,660	13,969	5.3
PS	4,787	390	390	820	430	0.2
OT	374,241	1,484	1,484	0	-1,484	-0.6

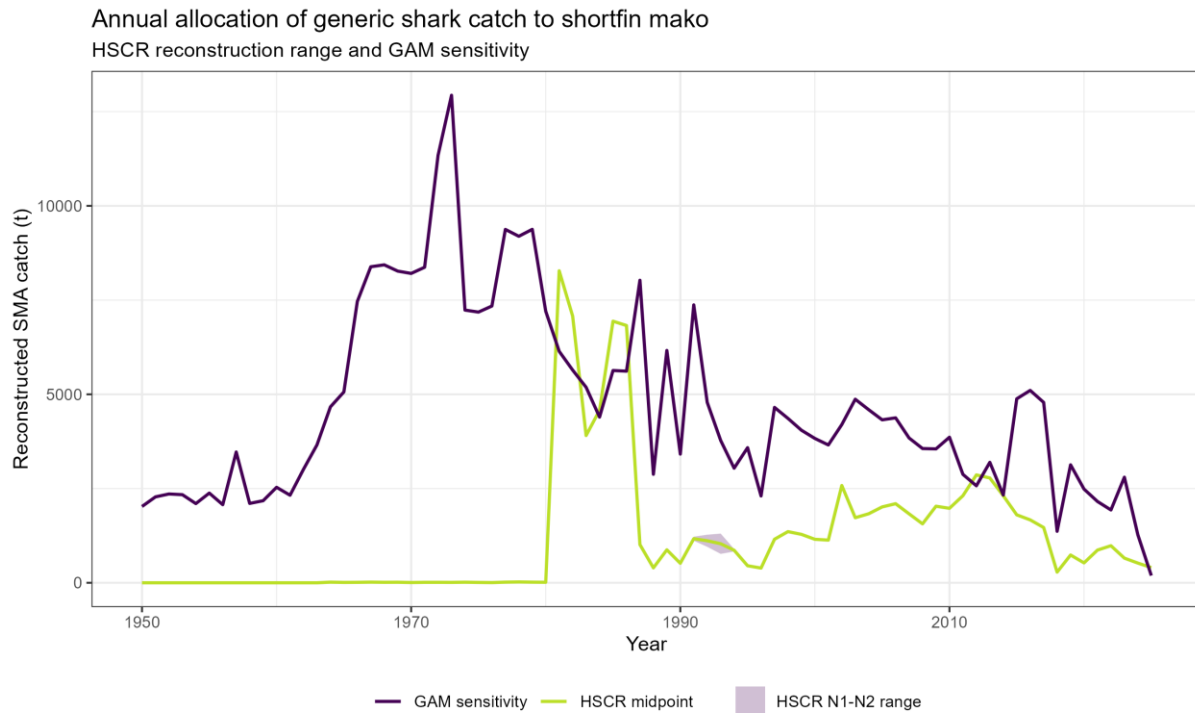


Figure 8: Annual allocation of generic shark catch (SKH) to shortfin mako by fishery group under HSCR and the GAM sensitivity analysis. The shaded region represents the HSCR N1–N2 range.

The gillnet difference was predominantly historical. The GAM allocated approximately 30.8 thousand t more SMA than HSCR N1 during 1950–1963 and approximately 125.5 thousand t more during 1964–1980. During 1981–1994 the aggregate gillnet allocations from the two methods were much closer, indicating that most of the early discrepancy resulted from extrapolation into periods preceding substantial species-specific SMA information.

The line-fishery discrepancy differed in character. Empirical SMA composition in line fisheries was zero or very low in several periods, whereas the GAM generated persistent positive proportions. Consequently, the GAM–HSCR difference remained through much of the time series rather than being restricted to the historical backcast.

Longline fisheries showed smaller differences between empirical hierarchical allocation and the smoother GAM surface. Purse-seine differences were negligible in absolute terms. Other fisheries contributed approximately 1.5 thousand t to HSCR but were excluded from the GAM because there was insufficient model support.

The cumulative trajectories emphasize the effect of the early gillnet allocations ([Figure 9](#)). By the beginning of the period in which substantial HSCR allocations occur, the GAM had already accumulated a large reconstructed SMA catch. The GAM continued to exceed HSCR thereafter, but the rate at which the two trajectories diverged was considerably smaller than before 1981.

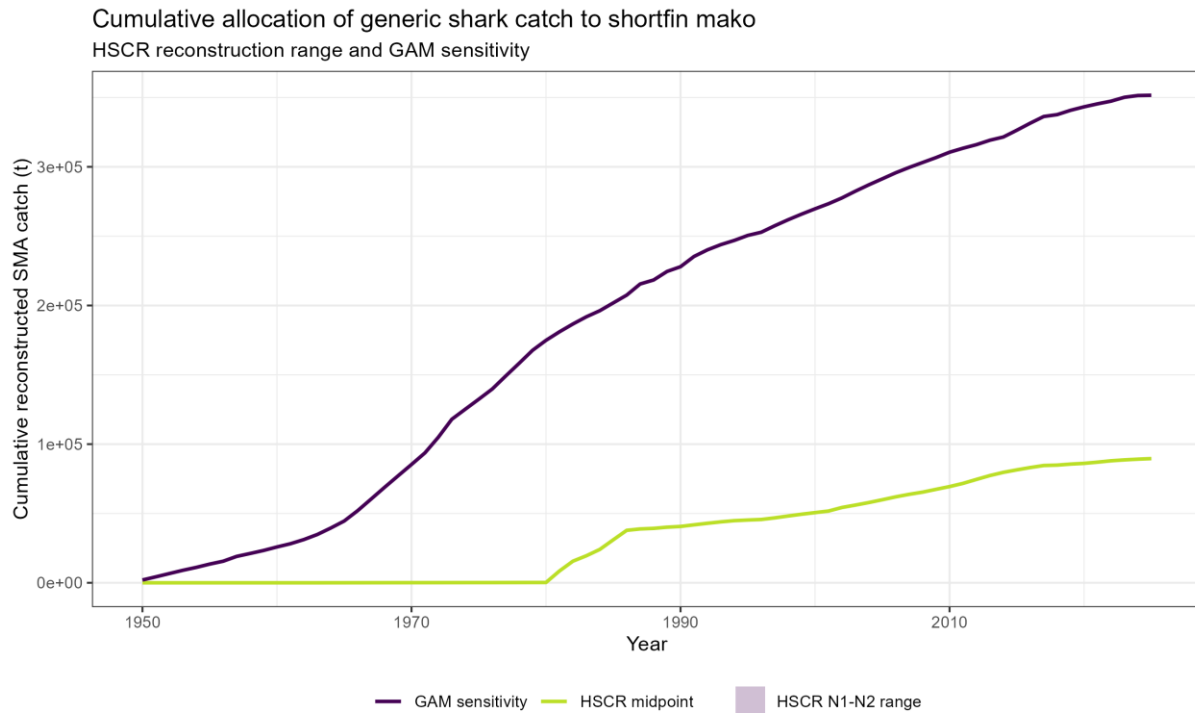


Figure 9: Cumulative shortfin mako catch allocated from generic shark catch under HSCR and the GAM sensitivity analysis. Most of the early divergence accumulates before 1981, primarily in gillnet fisheries.

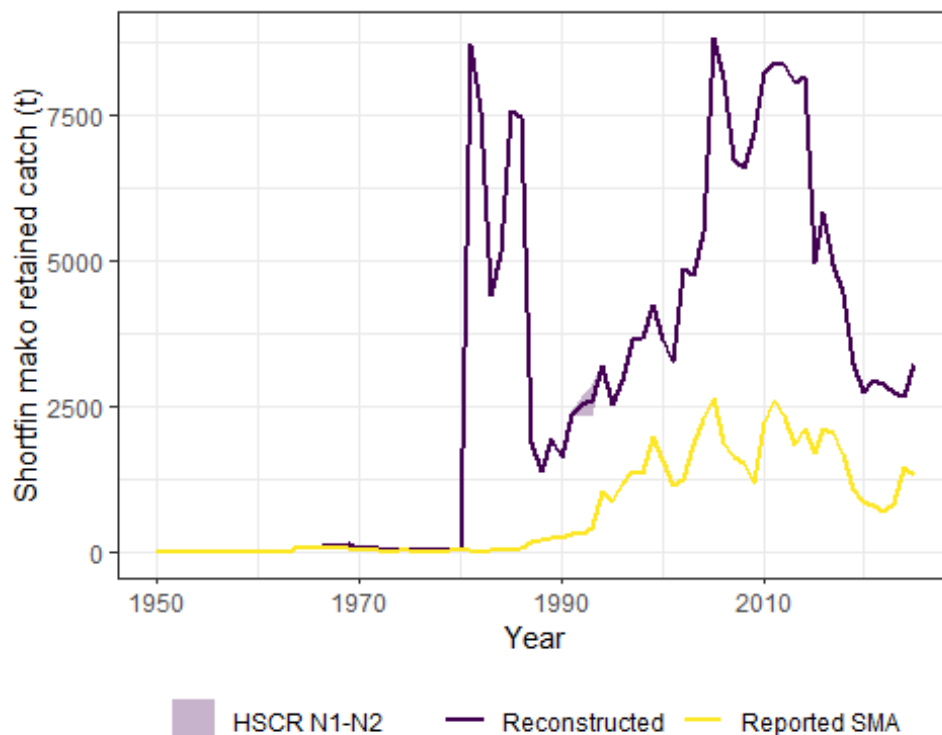


Figure 10: Annual SMA reconstructed-versus-reported catch

Taken together, the cross-validation and reconstruction diagnostics provided little support for replacing HSCR with the SMA GAM. The GAM is retained as a broad sensitivity because it quantifies

the consequence of allowing temporal and fishery relationships to transfer more extensively into unresolved historical strata.

Comparison of retained catch and catch-and-effort composition

Species composition calculated from RC was compared with independently reported CA data for matched Fleet × Fishery × Year strata (Table [Table 1](#)).

Broad SMA composition was generally similar between RC and CA in the principal longline fisheries, while median proportions were low in line fisheries in both datasets. Agreement was stronger for the mako-specific comparison: identified mako catch was overwhelmingly composed of SMA in both RC and CA, particularly in longline and line fisheries. This independent agreement supports allocation of MAK using observed SMA/(SMA + LMA) composition, while not implying that the same composition can be extrapolated without restriction to earlier periods or unsupported fleets.

Agreement between RC and CA was interpreted as support for the observed taxonomic structure rather than evidence that the same composition could be extrapolated without restriction into earlier periods or different fleets. The degree of historical extrapolation therefore remained controlled by donor support and the reconstruction hierarchy.

Species composition calculated from RC was compared with independently reported CA data for matched Fleet × Fishery × Year strata (Table [Table 1](#)). Broad SMA composition was generally similar between RC and CA in the principal longline fisheries, while median proportions were low in line fisheries in both datasets. Agreement was stronger for the mako-specific comparison: identified mako catch was overwhelmingly composed of SMA in both RC and CA, particularly in longline and line fisheries. This independent agreement supports allocation of MAK using observed SMA/(SMA + LMA) composition, while not implying that the same composition can be extrapolated without restriction to earlier periods or unsupported fleets.

Final reconstruction scenarios

The final scenarios retain taxonomic allocation and complete non-reporting as separate reconstruction components.

For BSH, the reconstructed histories combine reported BSH, allocation from generic SKH, and reconstruction of complete non-reporting. Alternative treatment of the generic-shark component is retained where supported by the BSH species-composition diagnostics.

For SMA, the recommended empirical reconstruction combines reported SMA, hierarchical empirical allocation of MAK, HSCR allocation of SKH, and the supported donor-ratio estimate for complete non-reporting. HSCR N1 and N2 represent the principal alternative reconstructions of generic shark catch and produce similar aggregate results.

The SKH → SMA GAM is retained as a sensitivity rather than as a recommended reconstruction because it produces substantially greater historical allocation, particularly through early gillnet extrapolation and persistent positive allocations in line fisheries, while showing only modest out-of-fleet predictive performance. The MAK → SMA GAM is retained only as a diagnostic because it does not improve on the directly observed mako species-composition relationship.

The resulting BSH and SMA scenarios therefore differ according to the information contained in their historical reporting categories. BSH principally requires resolution of generic shark reporting and complete non-reporting, whereas SMA additionally requires allocation of the mako-specific MAK category.

Discussion

Historical reconstruction of pelagic shark catches has generally been motivated by the recognition that shark reporting is less complete and less taxonomically resolved than reporting of the principal tuna and billfish species associated with these fisheries. This problem has been recognized repeatedly in the Indian Ocean, both in reviews of IOTC shark data and in species-specific reconstruction and assessment work (Murua *et al.*, 2013; Clarke, 2015; IOTC Secretariat, 2015, 2016; Coelho *et al.*, 2019). Previous reconstruction approaches have consequently estimated shark catches relative to reported target catch, using fleet-, gear-, or métier-specific information where available (Murua *et al.*, 2013; Coelho *et al.*, 2019). More generally, reconstruction studies have emphasized that reported fisheries statistics may represent only part of historical removals and that assumptions used to reconstruct missing catch should be made explicit (Pauly, 1998; Pauly and Zeller, 2016). This general rationale remains appropriate when shark catch was not reported at all. The present analysis, however, indicates that complete non-reporting should be distinguished from catches that were reported but at insufficient taxonomic resolution.

This distinction builds on earlier Indian Ocean BSH reconstruction work. The BSH assessment of Rice and Sharma (2015) was already dependent on interpretation of an incomplete historical catch series, and subsequent work specifically examined alternative estimates of Indian Ocean BSH catch (Rice, 2021). The IOTC Secretariat has likewise documented substantial uncertainty in historical BSH reporting and the procedures used to estimate catches (IOTC Secretariat, 2016). The present analysis extends this earlier work by distinguishing two different sources of missing species-specific BSH catch: generic shark catch that was reported but not identified to species and shark catch that was not reported at all. This distinction is important because the former is fundamentally a species-composition problem, whereas the latter requires estimation of the magnitude of missing catch.

The same distinction is particularly important for SMA. Previous Indian Ocean analyses have had to contend with limited historical catch information and uncertainty in the species composition of reported shark catches (Brunel *et al.*, 2018; Bonhommeau *et al.*, 2020). The 2024 IOTC assessment constructed the nominal SMA series by combining SMA with several unresolved mako or mackerel-shark categories, including MAK, and treating these catches as shortfin mako (Coelho *et al.*, 2024). The principal assumption was that MAK consisted predominantly of SMA because longfin mako is comparatively uncommon. The present analysis broadly supports the biological basis of that assumption: identified mako catches in the principal fisheries were strongly dominated by SMA. However, the expanded data allow that assumption to be replaced by an empirical allocation based on observed SMA and LMA composition. This retains most unresolved mako catch as SMA where supported by the data while allowing the contribution of LMA to vary among fisheries and periods rather than assuming that all MAK is SMA. The approach is also consistent with previous work emphasizing the importance of explicitly reconstructing the taxonomic composition of unresolved mako catches rather than automatically assigning them to shortfin mako (Coelho and Rosa, 2017).

The treatment of broad generic shark catch represents a larger methodological departure. SKH contains an observed shark catch total but does not identify the species comprising that catch. Estimating additional shark catch from tuna or billfish catch is therefore not necessary for these records; the unresolved quantity is species composition rather than total shark catch. HSCR addresses this problem by allocating observed SKH using species composition from hierarchically matched donor strata. Complete non-reporting is then reconstructed separately using shark-to-target catch relationships. Separating these processes reduces the risk of conflating taxonomic uncertainty with missing total catch and makes the source and degree of extrapolation associated with each reconstructed component explicit. This represents an important refinement of earlier Indian Ocean

reconstruction approaches in which uncertainty in shark reporting and uncertainty in species composition were not always treated as separate estimation problems (Murua *et al.*, 2013; Coelho *et al.*, 2019; Rice, 2021).

The spatial analyses provide additional support for this interpretation of the historical data. Generic shark reporting occurs across broad areas of the Indian Ocean before species-specific BSH and SMA reporting becomes widespread, while later species-specific reporting overlaps many of the same fishing regions. Longline effort was also geographically extensive during periods in which species-specific shark records were sparse. These patterns do not establish historical species composition directly, but they demonstrate that absence of an early species-specific record cannot generally be interpreted as absence of the species from the fishery. This interpretation is consistent with previous descriptions of the development and limitations of Indian Ocean shark reporting (IOTC Secretariat, 2015, 2016; Coelho *et al.*, 2019) and with the historical BSH catch series examined by Rice (2021).

For complete non-reporting, the present results reinforce the importance of fishery comparability when applying ratio-based reconstruction. Previous approaches explicitly recognized fleet and métier as important determinants of the relationship between shark and target catch (Murua *et al.*, 2013; Coelho *et al.*, 2019), while reconstruction of other pelagic fisheries has similarly emphasized the importance of transferring catch-rate information only among sufficiently comparable fisheries (Chambers and Hoyle, 2015). The current SMA analysis shows why this distinction matters. Some longline fisheries have substantially greater SMA-to-target ratios than conventional tuna or swordfish longline fisheries, consistent with shark targeting, increased retention, or target switching. Pooling these fisheries indiscriminately transfers shark-associated catch relationships to fisheries for which they are not representative. Stratifying longline donors and leaving strata unresolved where no suitable donor exists provides a more transparent treatment of this uncertainty than either arbitrary ratio caps or forced extrapolation.

The BSH analysis also illustrates the distinction between statistical model fit and support for historical extrapolation. GAMs provide a flexible framework for representing nonlinear temporal patterns, fishery effects, and other covariates (Wood, 2006, 2011, 2017; Marra and Wood, 2011). The BSH GAM showed stronger overall cross-fleet predictive association than the corresponding SMA model, with leave-one-fleet-out validation producing an MAE of 0.256, RMSE of 0.311, bias of -0.029, and Spearman correlation of 0.586. However, predictive performance was heterogeneous among fishery groups. Performance was substantially poorer for the OT fishery group, for which MAE and RMSE were 0.767 and 0.787, respectively. The aggregate GAM-HSCR difference was also unevenly distributed among fisheries and periods. Consequently, stronger overall predictive performance does not demonstrate that the GAM provides uniformly stronger support for historical BSH allocation. The GAM is therefore retained as a statistical sensitivity rather than treated as a preferred reconstruction.

The SMA statistical species-composition models provide an even stronger example of the limitations of transferring fitted relationships beyond their empirical support. For SKH → SMA, the beta-regression GAM explained substantially more in-sample variation than simpler models but showed only modest transferability in leave-one-fleet-out validation. It also generated a much larger historical SMA allocation than HSCR. Most of this difference arose from gillnet and line fisheries, with a substantial component generated by backward extrapolation before species-specific SMA information was available. In line fisheries, the GAM additionally smoothed positive SMA composition across data containing many zero or near-zero observations. These results do not imply that SMA was absent from those fisheries; rather, they indicate that the available data provide limited support for estimating its historical proportion at the levels predicted by the GAM. The distinction between goodness of fit and predictive support is particularly important for flexible models such as GAMs, for which substantial

flexibility can improve representation of the observed data without necessarily improving extrapolation to poorly sampled fleets or periods (Marra and Wood, 2011; Wood, 2017). The GAM is therefore informative as a broad sensitivity but is not preferred over HSCR for the primary SMA reconstruction.

The MAK → SMA analysis provides a related example. The empirical SMA/(SMA+LMA) composition has a direct taxonomic interpretation and is supported independently by the retained-catch and catch-and-effort data. In contrast, the alternative GAM showed poor transferability among fleets despite fitting the observed data reasonably well. Increasing statistical complexity therefore did not improve the evidential basis for historical allocation. The empirical hierarchical estimator was retained because its assumptions are more directly traceable to observed mako composition. This result also provides additional support for refining, rather than simply discarding, the assumption used in the 2024 SMA assessment that unresolved mako catch was predominantly SMA (Coelho *et al.*, 2024).

The recommended reconstruction consequently differs between BSH and SMA because their reporting histories differ. For BSH, the principal taxonomic reconstruction concerns allocation from broad generic shark catch, supplemented by a separate reconstruction for complete non-reporting. This develops the historical BSH reconstruction problem considered by Rice (2021) by explicitly separating these two sources of uncertainty. SMA requires an additional intermediate taxonomic step in which unresolved mako catch is allocated between SMA and LMA. The resulting framework therefore combines estimators according to the information contained in each reporting category rather than imposing a common reconstruction method across species.

These results also emphasize that reconstructed catch histories should not be interpreted as abundance indices. Changes through time reflect fishing activity, retention, targeting, fleet participation, species identification, reporting requirements, and retrospective revisions to historical catch statistics. Earlier Indian Ocean shark studies similarly identified substantial uncertainty in the historical portion of the catch series, when shark reporting and species-specific information were most problematic (Murua *et al.*, 2013; Clarke, 2015; IOTC Secretariat, 2016; Coelho *et al.*, 2019; Rice, 2021). This distinction is particularly important when reconstructed catch series are subsequently used as inputs to stock assessments, as has occurred for both BSH and SMA in the Indian Ocean (Rice and Sharma, 2015; Brunel *et al.*, 2018; Bonhommeau *et al.*, 2020; Coelho *et al.*, 2024). The reconstructed series should therefore be interpreted as alternative estimates of historical removals rather than as evidence for corresponding changes in population abundance.

Finally, continued revision of historical IOTC retained-catch data presents an important reproducibility issue. The underlying nominal-catch database is itself a living data product that changes as CPCs submit new or revised historical information (IOTC Secretariat, 2021). The 2024 SMA assessment used 55,267 t reported as MAK and 47,515 t reported directly as SMA, illustrating the scale at which unresolved categories contributed to the assessment catch series at that time (Coelho *et al.*, 2024). Similarly, historical BSH reconstructions necessarily reflect the version of the underlying catch database available when they were produced (Rice, 2021). Subsequent revisions can therefore alter reconstructed catches even when the reconstruction algorithm itself is unchanged. Assessment documentation should distinguish changes caused by revised source data from changes caused by reconstruction methodology. Maintaining a documented assessment-specific snapshot of the underlying retained-catch data would facilitate such comparisons while allowing the operational IOTC database to continue to incorporate subsequent revisions.

Table 4: Components of the recommended blue shark and shortfin mako retained-catch reconstructions.

Species	Scenario	Reported catch (t)	MAK allocation (t)	SKH allocation (t)	Complete non-reporting (t)	Final reconstruction (t)
Blue shark	HSCR N1	346,383	NA	648,126	73,926	1,068,435
Blue shark	HSCR N2	346,383	NA	734,506	73,926	1,154,815
Shortfin mako	HSCR N1	53,328	36,333	88,552	38,927	217,140
Shortfin mako	HSCR N2	53,328	36,333	90,565	38,927	219,154

Conclusions

Historical BSH and SMA catch reconstruction in the Indian Ocean requires explicit separation of taxonomic aggregation from complete non-reporting. Earlier Indian Ocean reconstruction and assessment studies established the importance of incomplete shark reporting for both species (Murua *et al.*, 2013; Rice and Sharma, 2015; Coelho *et al.*, 2019, 2024; Rice, 2021). The present analysis extends that work by recognizing that catches already reported under unresolved shark categories contain information on total shark catch and therefore require species allocation, whereas complete non-reporting requires estimation of shark catch associated with otherwise reported fishing activity. Treating these processes separately makes both the source of reconstructed catch and the assumptions required for extrapolation more transparent.

For SMA, the available evidence supports empirical hierarchical reconstruction as the primary approach. Identified mako catches support the central assumption of previous assessments that most unresolved mako catch represents SMA (Coelho *et al.*, 2024), but also provide sufficient information to replace the assumption that all such catch is SMA with an empirical SMA/LMA allocation. HSCR N1 and N2 also produce similar estimates of SMA from generic shark catch. Statistical GAM alternatives showed substantially weaker out-of-fleet predictive performance and, for SKH, produced substantially greater historical allocation through broader transfer across fleets and time. These models are therefore retained as sensitivities or diagnostics rather than preferred reconstructions.

For BSH, the present analysis builds directly on earlier attempts to reconstruct the Indian Ocean catch history (IOTC Secretariat, 2016; Rice, 2021). The GAM showed stronger overall predictive association than the corresponding SMA model, but support was heterogeneous among fisheries. The GAM allocated more BSH from generic shark catch than either HSCR scenario, while fishery-specific cross-validation identified particularly weak predictive performance for the OT group. The GAM is therefore retained as a statistical sensitivity rather than assumed to provide a uniformly better historical reconstruction. Differences among HSCR scenarios and the GAM provide information about

uncertainty associated with transferring observed species composition among fleets, fisheries, and periods.

The reconstructed catch histories should be interpreted as estimates of historical removals rather than as indices of population abundance. They incorporate information from reported species-specific catches, taxonomically unresolved shark catches, and supported estimates of complete non-reporting, but they do not eliminate uncertainty in strata for which adequate empirical donor information is unavailable. Such strata are intentionally retained as unresolved rather than being assigned catches through progressively weaker extrapolation. This distinction should be preserved when the reconstructed series are used in future stock assessments, including through sensitivity analyses that reflect uncertainty in historical catch. Reproducibility is also essential because the underlying IOTC retained-catch database continues to change as CPCs revise historical submissions. Future assessments should therefore document the reconstruction method together with the specific version of the source catch data used, so that changes in reconstructed histories can be distinguished from changes in the underlying reported catches.

Table 5: Annual reported and recommended reconstructed retained catches of blue shark (BSH) and shortfin mako (SMA). The recommended estimate is the midpoint of the HSCR N1 and N2 reconstructions; N1 and N2 are retained as the empirical reconstruction range.

Year	Reported BSH (t)	Recommended BSH (t)	BSH N1 (t)	BSH N2 (t)	Reported SMA (t)	Recommended SMA (t)	SMA N1 (t)	SMA N2 (t)
1950	0	3	3	3	0	0	0	0
1951	0	17	17	17	0	0	0	0
1952	0	168	168	168	0	0	0	0
1953	0	373	373	373	0	0	0	0
1954	0	1,203	1,203	1,203	0	0	0	0
1959	0	2,192	2,192	2,192	0	0	0	0

5								
5								
1,956	0	2,992	2,992	2,992	0	0	0	0
6								
1,957	0	1,914	1,914	1,914	0	0	0	0
8								
1,958	0	1,659	1,659	1,659	0	0	0	0
9								
1,959	0	1,758	1,758	1,758	0	0	0	0
60								
1,960	0	2,525	2,525	2,525	0	0	0	0
1								
1,961	0	2,557	2,557	2,557	0	0	0	0
2								
1,962	0	3,236	3,236	3,236	0	0	0	0
3								
1,963	0	2,030	2,030	2,030	0	0	0	0
4								
1,964	2,956	3,821	3,821	3,821	96	118	118	118
5								
1,965	1,808	2,399	2,399	2,399	61	75	75	75

1, 9 6 6	1,924	2,733	2,733	2,733	53	72	72	72
1, 9 6 7	3,101	4,290	4,290	4,290	101	129	129	129
1, 9 6 8	2,151	4,478	4,478	4,478	65	111	111	111
1, 9 6 9	2,435	5,072	5,072	5,072	72	125	125	125
1, 9 7 0	1,223	3,384	3,384	3,384	39	74	74	74
1, 9 7 1	1,298	2,917	2,746	3,088	43	72	67	77
1, 9 7 2	1,136	2,772	2,592	2,951	30	59	54	64
1, 9 7 3	504	1,952	1,677	2,227	16	42	35	50
1, 9 7 4	852	2,769	2,409	3,129	26	61	51	71
1, 9 7 5	751	1,982	1,783	2,182	26	49	43	54
1, 9	277	1,449	1,309	1,589	10	30	26	34

7								
6								
1,977	236	1,007	446	1,568	10	28	13	44
1,977								
1,978	333	1,283	550	2,015	11	35	14	55
1,979								
1,979	503	1,261	740	1,782	22	41	26	55
1,980								
1,980	448	1,112	713	1,510	18	33	22	44
1,981								
1,981	692	6,285	5,858	6,713	31	8,729	8,694	8,765
1,982								
1,982	390	4,376	3,838	4,914	16	7,571	7,527	7,616
1,983								
1,983	547	6,074	5,477	6,672	21	4,424	4,374	4,473
1,984								
1,984	595	4,276	3,950	4,603	22	5,139	5,112	5,166
1,985								
1,985	924	5,417	5,018	5,816	39	7,579	7,546	7,612
1,986								
1,986	882	5,453	4,920	5,987	58	7,482	7,438	7,526

1, 9 8 7	709	10,647	10,13 6	11,15 9	180	1,888	1,846	1,930
1, 9 8 8	590	5,342	4,725	5,960	211	1,398	1,351	1,445
1, 9 8 9	709	10,020	9,229	10,81 1	240	1,937	1,900	1,975
1, 9 9 0	589	6,189	5,365	7,014	239	1,630	1,599	1,662
1, 9 9 1	925	12,362	11,29 3	13,43 0	308	2,371	2,317	2,425
1, 9 9 2	955	12,863	10,43 7	15,28 8	313	2,529	2,369	2,688
1, 9 9 3	1,232	12,897	9,225	16,57 0	404	2,604	2,335	2,872
1, 9 9 4	2,061	10,895	9,932	11,85 7	1,046	3,203	3,169	3,236
1, 9 9 5	2,299	17,702	16,42 9	18,97 5	886	2,550	2,550	2,550
1, 9 9 6	2,165	13,978	13,29 5	14,66 0	1,194	2,951	2,951	2,951
1, 9	3,351	24,343	23,54 7	25,13 9	1,380	3,638	3,638	3,638

9
7

1, 9 9 8	3,551	24,342	23,58 2	25,10 2	1,358	3,676	3,676	3,676
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1, 9 9 9	6,554	25,838	25,09 1	26,58 5	1,983	4,243	4,243	4,243
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2, 0 0 0	6,553	24,925	24,24 6	25,60 4	1,558	3,662	3,662	3,662
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2, 0 0 1	4,411	24,932	24,34 7	25,51 8	1,143	3,269	3,269	3,269
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2, 0 0 2	6,245	30,986	30,31 3	31,65 9	1,234	4,874	4,874	4,874
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2, 0 0 3	9,215	38,794	37,94 1	39,64 7	1,846	4,760	4,760	4,760
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2, 0 0 4	13,777	42,459	41,62 8	43,29 0	2,292	5,489	5,489	5,489
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2, 0 0 5	14,028	36,517	33,75 5	39,27 9	2,650	8,847	8,847	8,847
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2, 0 0 6	11,601	34,292	31,50 5	37,07 8	1,881	8,131	8,131	8,131
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2, 0 0 7	11,020	31,279	28,51 3	34,04 4	1,633	6,754	6,754	6,754
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2, 0 0 8	11,443	30,246	27,78 4	32,70 7	1,529	6,621	6,621	6,621
2, 0 0 9	11,221	30,903	29,29 3	32,51 3	1,195	7,187	7,187	7,187
2, 0 1 0	14,900	36,318	34,93 8	37,69 8	2,235	8,240	8,240	8,240
2, 0 1 1	15,541	36,222	34,92 5	37,52 0	2,620	8,408	8,408	8,408
2, 0 1 2	14,297	32,584	31,62 2	33,54 7	2,337	8,373	8,373	8,373
2, 0 1 3	13,862	37,944	36,96 6	38,92 1	1,825	8,068	8,068	8,068
2, 0 1 4	14,904	34,810	33,75 6	35,86 3	2,123	8,161	8,161	8,161
2, 0 1 5	13,968	43,524	43,52 4	43,52 4	1,702	4,958	4,958	4,958
2, 0 1 6	14,845	43,340	43,32 1	43,35 9	2,114	5,841	5,841	5,841
2, 0 1 7	12,231	39,183	39,18 3	39,18 3	2,053	4,933	4,933	4,933
2, 0	12,017	26,554	26,55 4	26,55 4	1,683	4,444	4,444	4,444

1								
8								
2,019	12,224	31,290	31,290	31,291	1,075	3,224	3,224	3,224
2,020	9,362	24,735	24,735	24,736	884	2,736	2,736	2,736
2,021	9,092	25,132	25,131	25,132	793	2,946	2,946	2,946
2,022	8,374	24,505	24,504	24,507	688	2,870	2,870	2,870
2,023	10,923	29,924	29,924	29,924	831	2,729	2,729	2,729
2,024	9,562	21,105	21,105	21,105	1,451	2,677	2,677	2,677
2,025	9,107	12,514	12,514	12,514	1,324	3,248	3,248	3,248

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Appendix A. Supplementary material

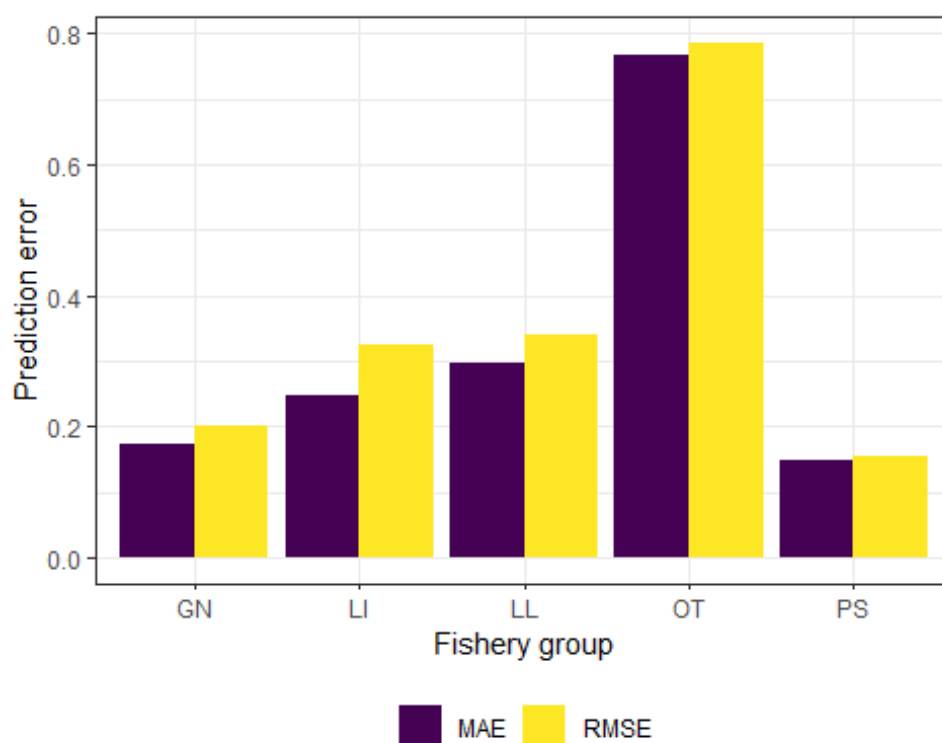


Figure 11: Leave-one-fleet-out predictive performance of the blue shark GAM species-composition model by fishery group.

Table 6: Leave-one-fleet-out predictive performance of the blue shark species-composition GAM by fishery group.

FISHERY_GRO UP_CODE	n	MAE	RMSE	bias
GN	141	0.172	0.200	0.124
LI	262	0.248	0.323	0.013
LL	514	0.296	0.341	-0.099
OT	20	0.767	0.787	-0.371
PS	34	0.148	0.156	0.105

Appendix B. Working Paper Information

Purpose

This paper has been prepared for discussion within WPEB and presents alternative approaches for reconstructing historical blue shark and shortfin mako retained catches in the Indian Ocean.

Discussion

This paper informs meeting participants of alternative reconstruction approaches for addressing historical non-reporting and generic shark reporting.

Feedback requested

The Working Party is requested to:

- review the reconstruction framework;
- comment on donor hierarchy;
- comment on proposed reconstruction scenarios;
- identify additional information sources that could improve historical reconstruction.

Conclusion

The paper seeks confirmation that the proposed reconstruction framework provides an appropriate basis for estimating historical blue shark and shortfin mako retained catches.

Recommendation

The Working Party is invited to endorse the reconstruction framework as the basis for continued development and evaluation.

Decisions

No formal decisions are requested at this stage.