SCIENTIFIC COMMITTEE
EIGHTEENTH REGULAR SESSION
10–18 August 2022

Including South Pacific albacore in the WCPFC mixed-fishery harvest strategy framework

WCPFC-SC18-2022/MI-IP-05
23rd July 2022

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Contents

Executive Summary

WCPFC12 agreed to a workplan for the adoption of harvest strategies for WCPO skipjack, bigeye, yellowfin and South Pacific albacore tuna. An important consideration when developing harvest strategies for these stocks is to account for mixed fishery interactions. SC15 agreed to initially consider developing a multi-species modelling framework that can be used for mixed fishery management strategy evaluation (MSE) for the four tuna stocks. This framework involves developing prospective single stock management procedures (MPs) for skipjack, South Pacific albacore and bigeye respectively. The impact of these MPs on yellowfin would then be evaluated.

Work presented at SC17 demonstrated how skipjack, bigeye and yellowfin can be included in the multi-species modelling framework. This report describes a proof of concept implementation of also including South Pacific albacore in this framework by focusing on the albacore and bigeye interactions. This paves the way for all four tuna stocks to be included in the multi-species modelling framework.

In this framework The South Pacific albacore MP sets the fishing opportunities for the southern longline fisheries that also catch some bigeye. Similarly, the bigeye MP sets the fishing opportunities for the tropical longline fisheries that also catch some South Pacific albacore. Fully incorporating these interactions requires the albacore and bigeye simulations to be run simultaneously where the result of each simulation influences the other. This leads to significant computational complexities that are very difficult to resolve. Given the potentially small impact of the South Pacific albacore MP on the bigeye stock, it is suggested that it is not included in the bigeye evaluations. Instead, assumptions about the level of bigeye catches from the southern longline fisheries will be made. These assumptions would need to be carefully monitored in the monitoring strategy. This simplification makes the multi-species modelling framework technically tractable without materially changing the results.

As work progresses, it will be possible to use this approach to determine the impact of the SKJ, BET, and SPA MPs on YFT. These results are sufficiently encouraging to continue developing this approach.

The next steps include:

- Building a full suite of operating models for bigeye and yellowfin;
- Developing candidate MPs for bigeye for the tropical longline fishery;
- Further developing the operating models and MPs for South Pacific albacore;
- Including all four stocks in the multi-species modelling framework, including MPs for skipjack, bigeye and South Pacific albacore; and
- Agreement of multi-species performance indicators.

1 Introduction

WCPFC12 agreed to a workplan for the adoption of harvest strategies for WCPO skipjack (SKJ), bigeye (BET), yellowfin (YFT) and South Pacific albacore (SPA) tuna. These tuna stocks are caught by an overlapping mix of fisheries which means that management measures aimed at one particular stock can have impacts on other stocks (Scott et al., 2019b). An important consideration when developing harvest strategies for these stocks is therefore to account for mixed fishery interactions.

A key component of a harvest strategy is the management procedure (MP), which is a combination of data collection, estimation method (to provide the signal for management action based on estimated stock status), and a decision rule, known as a harvest control rule (HCR), that sets fishing opportunities based on the estimates of stock status (Punt et al., 2014). An MP is adopted on the basis that it is likely to achieve the agreed management objectives. Before an MP is adopted, the relative performance of candidate MPs should be tested using management strategy evaluation (MSE) (Punt et al., 2014; Scott et al., 2019a).

Two possible approaches for modelling mixed fisheries in the harvest strategy MSE simulations have been previously described: the fully integrated modelling approach and the multi-species approach (Scott et al., 2019b). SC15 agreed to initially consider the multi-species modelling framework (WCPFC, 2019). This approach should be regarded as an initial attempt at considering multi-species and mixed fisheries. If this approach is found to be unsuccessful, in terms of achieving objectives for all four stocks, alternative approaches will need to be developed.

Under the multi-species approach, fisheries are managed through single stock MPs for SKJ, BET and SPA. An overview of the multi-species modelling framework is given in Appendix A. The three single stock MPs control the fishing opportunities for different WCPO fisheries by setting catch or effort limits based on status estimates of the associated stock (Table 2). Each fishery is controlled by one of the three single stock MPs. However, that fishery may catch a range of tuna stocks. Purse seine, pole and line, and fisheries of Indonesia, Philippines and Vietnam (subsequently referred to as domestic fisheries, that partially operate in archipelagic waters) are potentially managed through the SKJ MP. The tropical longline fisheries are potentially managed through the BET MP and the southern longline fisheries potentially managed through the SPA MP (Table 2). There is no specific YFT MP, but the YFT stock will be indirectly managed by catches resulting from fishery settings provided by the SKJ, BET and SPA MPs. It is noted that the definition and classification of the WCPO fisheries to different MPs under this approach is an initial proposal, and alternative classifications may also be considered.

An exploratory implementation of the multi-species approach for SKJ, BET and YFT tuna was presented to SC17 (Scott et al., 2021a). This report builds on the previous work and describes how SPA can also be included in this framework by focusing on the interactions between SPA and BET through the tropical and southern longline fisheries. This work paves for the way for including all four stocks in the multi-species modelling framework.

2 Mixed fishery management strategy evaluation framework

In MSE modelling frameworks, the biological dynamics of the stocks and the fishery interactions are simulated by operating models (OMs) (Punt et al., 2014; Scott et al., 2019a). The OMs are used to provide a "virtual true" representation of how the fish stock reacts to different amounts of fishing and allows the simulation of changes to fishery management. Under the proposed multi-species modelling framework, the tuna stocks will have individual single stock OMs, i.e. there will be individual OMs for SKJ, BET, YFT and SPA (Scott et al., 2019b). To capture the key sources of uncertainty about each stock, multiple OMs are developed for each stock where each OM has a different combination of assumptions (Scott et al., 2019a).

Initial progress has been made on developing the multi-species framework through the inclusion of individual OMs for SKJ, BET and YFT into a single MSE framework that simulates the mixed fishery interactions (Scott et al., 2021b). This paper describes how SPA may also be included by considering the interactions between the SPA and BET OMs and MPs.

Progress has been made on developing an individual MSE framework for SPA that uses single stock Multifan-CL models for OMs based on the the 2018 stock assessments (Scott et al., 2022c, 2019c; Tremblay-Boyer et al., 2018) (Section C.2). It is noted that the SPA OM grid may be further developed following the South Pacific-wide 2021 stock assessment (Castillo Jordan et al., 2021). The method presented here to include SPA in the multi-species modelling framework is largely independent of the suite of SPA OMs although some recalculation may be necessary if the OMs are updated.

An exploratory set of OMs for BET that are also single stock Multifan-CL models based on the most recent stock assessment has been developed (Scott et al., 2022b, 2021a; Ducharme-Barth et al., 2020) (Section C.3). These OMs will continue to be developed.

Similar to the WCPO tuna stock assessments, each single stock OM has several regions which contain fisheries representing fishing activity of a particular gear type. The regional and fishery structure of the SPA OMs is different to the BET OMs (Figure 7; Tables 4 and 5).

3 Linking the bigeye and South Pacific albacore operating models

Under the proposed multi-species modelling framework, each fishery is managed through a single stock MP, according to the gear type and area of operation (Appendix A)(Scott et al., 2020a). The details of this approach, including which fisheries are managed through which MPs, are still subject to discussion. In these evaluations, fisheries operating in archipelagic waters are not managed through an MP and their future catch or effort are set at constant status quo levels.

The multi-species simulations presented here are single stock simulations for BET and SPA. To perform the simulations it is necessary to set the future effort or catch of each fishery in the BET and SPA OMs using the output of the MP that manages that fishery. Some fisheries for a stock are managed through the MP of a different stock. For example, the tropical longline (TLL) fisheries in the SPA OMs would be managed through the BET MP and the southern longline (SLL) fisheries in the BET OMs would be managed through the SPA MP. One of the key challenges for the simulations is therefore including the interactions between the OMs and the MPs.

The TLL fisheries in the SPA OMs would be managed through the BET MP and the future dynamics of these fisheries would be determined in the BET simulations, through the application of the BET MP. Similarly, the SLL fisheries in the BET OMs would be managed through the SPA MP and the future dynamics of these fisheries would be determined in the SPA simulations, through the application of the SPA MP.

Fully incorporating these interactions requires the SPA and BET simulations to be run simultaneously where the result of each simulation influences the other. This leads to significant computational complexities that are very difficult to resolve. The additional complexity of using the SPA MP to set the SLL catches in the BET OMs while at the same time using the BET MP to set the TLL catches in the SPA OMs may outweigh the benefit of doing so.

The proportions of catches that would be managed by each MP is calculated from the catches in the recent stock assessment models (Table 1):

- Skipjack (2019 assessment, data up to 2018)
- Bigeye (2020 assessment, data up to 2018)
- Yellowfin (2020 assessment, data up to 2018)
- South Pacific albacore (2021 assessment, data up to 2019)
- South Pacific albacore (2018 assessment, data up to 2016)

OM	BET MP	SKJ MP	SPA MP	SPA & BET MP
BET	42.67	53.22	4.11	0.00
SKJ	0.00	99.99	0.00	0.00
SPA 2018	13.42	0.00	74.73	11.85
SPA 2021	12.68	0.00	87.32	0.00
YFT	14.35	82.56	3.09	0.00

Table 1: Catch percentages, by weight from the last three years of the most recent assessment for each operating model (OM) by management procedure (MP). Note that South Pacific albacore (SPA) has the results from the last two assessments. The BET and SPA column refers to model regions that include both tropical and southern longline fisheries (see maps in the Appendices).

Table 1 shows that the recent catches of BET by fisheries that would be managed by the SPA MP is only a small portion of the total BET catch (about 4%). This means that the potential impact of the SPA MP on the BET stock is likely to be small enough that it can be ignored in the BET evaluations without materially affecting the results. Instead the catches of these fisheries in the BET evaluations can be fixed in advance so that they are not dependent on the SPA evaluations. For example, different scenarios could be explored, such as holding the catches constant at a status quo level.

By making the simplification that the SPA MP does not need to be considered in the BET simulations the inclusion of SPA in the multi-species modelling framework becomes technically tractable. This approach is taken in the analysis presented here. Any assumptions made to this effect would need to be carefully monitored in the monitoring strategy. A similar approach can be taken with the impact of the SPA MP on the YFT stock, given the low proportion of catches of YFT by the SLL fisheries.

The remaining fisheries in the BET OMs are either managed through the SKJ MP or the BET MP (Table 5). By not considering the SPA MP in the BET OMs, the BET simulations can be run independently of the SPA simulations, but will still depend on the output of the SKJ simulations.

The fisheries in the SPA OMs are either managed through the SPA MP or the BET MP. Running the SPA simulations therefore requires the outputs of the BET simulations.

Given the dependencies between the stocks described above and in Scott et al. (2021a), the multi-species simulations can be performed by running the SKJ simulations first, then the BET simulations, and then the SPA and YFT simulations, transferring the resulting fishery dynamics from one model to another.

The BET MP defines future levels of TLL BET catch based on the stock status of BET. The realised efforts of the TLL fisheries to meet the BET catch limits in the BET simulations differ across fisheries, partly because the catch limits are different and partly because the stock abundance in the area they operate is different. The future time series of TLL effort in the SPA OMs needs to reflect the effort made by those fisheries to catch the BET catch limit that is set by the BET MP. The approach here is to calculate the realised effort to take the defined BET catch from the BET simulations, and then transfer it to those fisheries in the SPA OMs, similar to the approach used to link the pole and line fisheries in the SKJ and BET models (Scott et al., 2021a). In this way, the measures stipulated by the BET MP are realised in the SPA simulations.

The future realised effort of each TLL fishery in the BET OMs relative to the average effort in a reference period is calculated. This is the relative effort needed by each fishery to take the BET catch limit that was set by the BET MP. Due to the relatively high variability in historical effort, a relatively long reference period of 2009-2016 is used. Alternative reference periods are possible and will need to be agreed. The relative realised effort is then applied to the SPA OMs to set the future effort.

The regional and fishery structures of the BET and the SPA OMs are different and the fisheries do not directly overlap which makes this process less straightforward (Figure 7). The method used here is to calculate the overlap of each BET TLL fishery with each SPA TLL fishery, based on the historical distribution of fishing effort (see Appendix D). This overlap is used to weight the transfer of relative effort from each BET fishery to the corresponding SPA fisheries. The future effort of the TLL fisheries in the SPA OMs is set by applying the weighted relative effort from the BET results to the effort in the same reference period (see Appendix E).

As noted previously, if the SPA OMs are further developed to be based the 2021 stock assessment, the method presented in Appendix D will still be applicable but the final weights may be different.

4 Running the simulations

In this analysis the BET MP outputs a scalar that is applied to the average catch level in the year range 2016-2018 to set the BET catch limits of the TLL fisheries in the next management period. It is assumed that the catch limits are always taken. As candidate BET MPs are still under development, there is no dynamic BET MP that responds to the BET stock status. Instead, for this proof of concept, a BET MP is simulated by setting the MP output in advance to a square wave that fluctuates between 0.75 and 1.25, with a mean value of 1. The period of the square wave is six years (three years up, three years down), similar to a management period of three years (Figure 1). This level of fluctuation is greater than one would expect from a real BET MP but it provides a signal, the impact of which can be tracked from the BET OMs through to the SPA OMs.

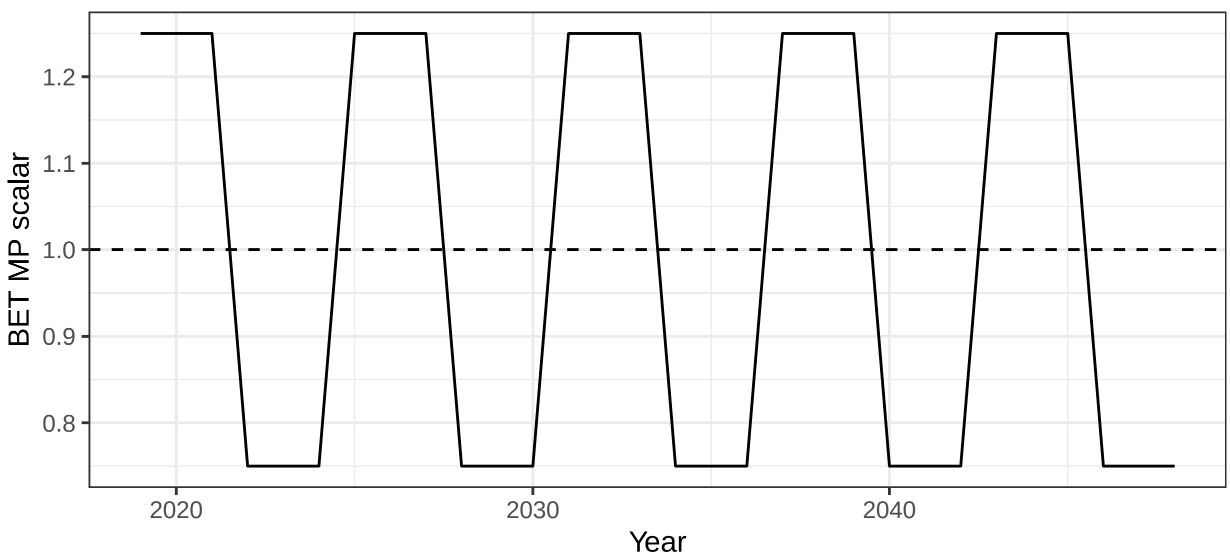

Figure 1: The output of the simulated bigeye management procedure is fixed in advance to a square wave that fluctuates between 0.75 and 1.25, with a mean value of 1 and a period of six years. The output is applied to the average tropical longline catch in the years 2016-2018 to set the catches for the next management period.

To simplify this analysis there is no SKJ MP. Instead, the fisheries in the BET OMs that would be managed by the SKJ MPs have future catches or effort set as the average values in 2016-2018. There are no fisheries in the SPA OMs that would be managed by the SKJ MP.

As SPA MPs are still under development there is also no SPA MP in this analysis. This does not matter here because the focus is on the transfer of the TLL fishing effort from the BET OMs to the SPA OMs. Here, the future catches of SLL fisheries in the BET and SPA OMs that would be managed by the SPA MP are held constant at the average of 2016-2018 levels.

An alternative scenario in which the BET MP outputs a constant value of 1 is also run, i.e. the TLL catches of BET are held constant at the average of 2016-2018 levels.

The two BET MP scenarios (constant status quo and square wave) are tested by running 480 stochastic simulations across the BET and SPA OM grids, using the approach described above to link the stock OMs together. The stochastic simulations include variability in the future recruitment of each stock by sampling from the historic recruitment residuals, similar to the current skipjack evaluations (Scott et al., 2019d, 2021b).

Following the approach described in Scott et al. (2022a), the 480 iterations are spread equally across the 48 BET models in the grid giving 10 iterations per model. 480 SPA OMs are randomly selected with replacement from the SPA model grid and allocated to a corresponding BET iteration to give 480 iterations. This random allocation of SPA to BET models for each iteration makes the assumption that there is no correlation between the OMs of each stock, e.g. a high value for steepness in a BET model does not necessarily correspond with a high value for steepness in a SPA model. The same iteration and OM allocation of the stock models is used across both BET MP scenarios tested here so that the same patterns of recruitment variability are seen and the results are comparable.

5 Results

We do not go into the results in detail here, given that they are only intended to demonstrate how SPA may be included in the multi-species modelling framework.

The catches of BET taken by the TLL fishery is determined by the output of the BET MP, here fixed at a status quo level or as a square wave pattern (Figure 2). Note that in the projections the future catches are set by numbers, but the plots presented here are by weight. Due to variation in stock structure, this contributes to the uncertainty seen in the BET catches, despite those catches being fixed at the same level for all iterations.

The level of catches of SPA taken by the TLL fishery is determined by the output of the BET MP. Figure 3 shows that although TLL catches of SPA are strongly affected by the output of the BET MP (the square wave is clearly visible), the impact of the BET MP on the total catches of SPA is relatively small.

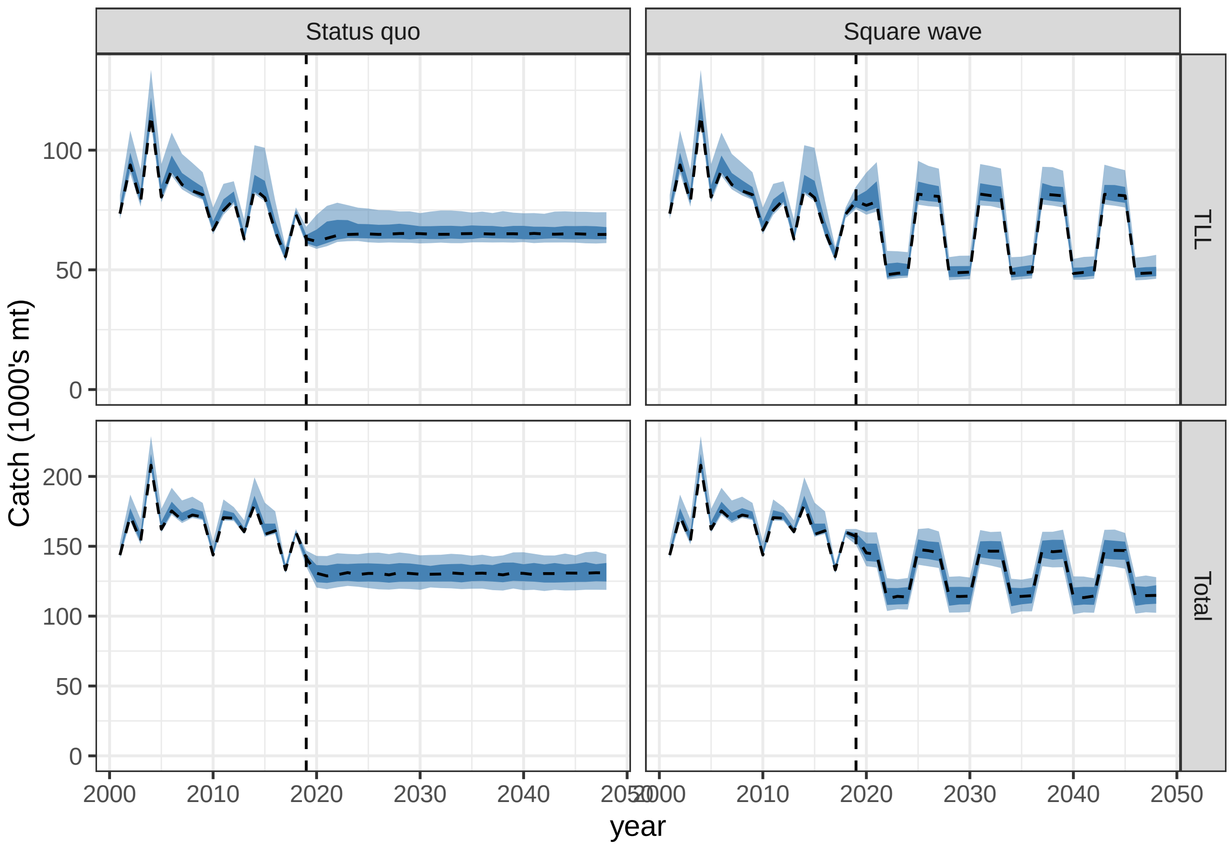

Figure 2: Catches of bigeye by the tropical longline (TLL) fisheries and all fisheries combined for two scenarios: all fisheries at status quo levels of 2016-2018, TLL set as a square wave with an amplitude of 25% around the status quo level. The outer envelope shows the 80th percentile range, the inner envelope the 50th percentile range and the black dashed line is the median level. The start of the projection in 2019 is also shown.

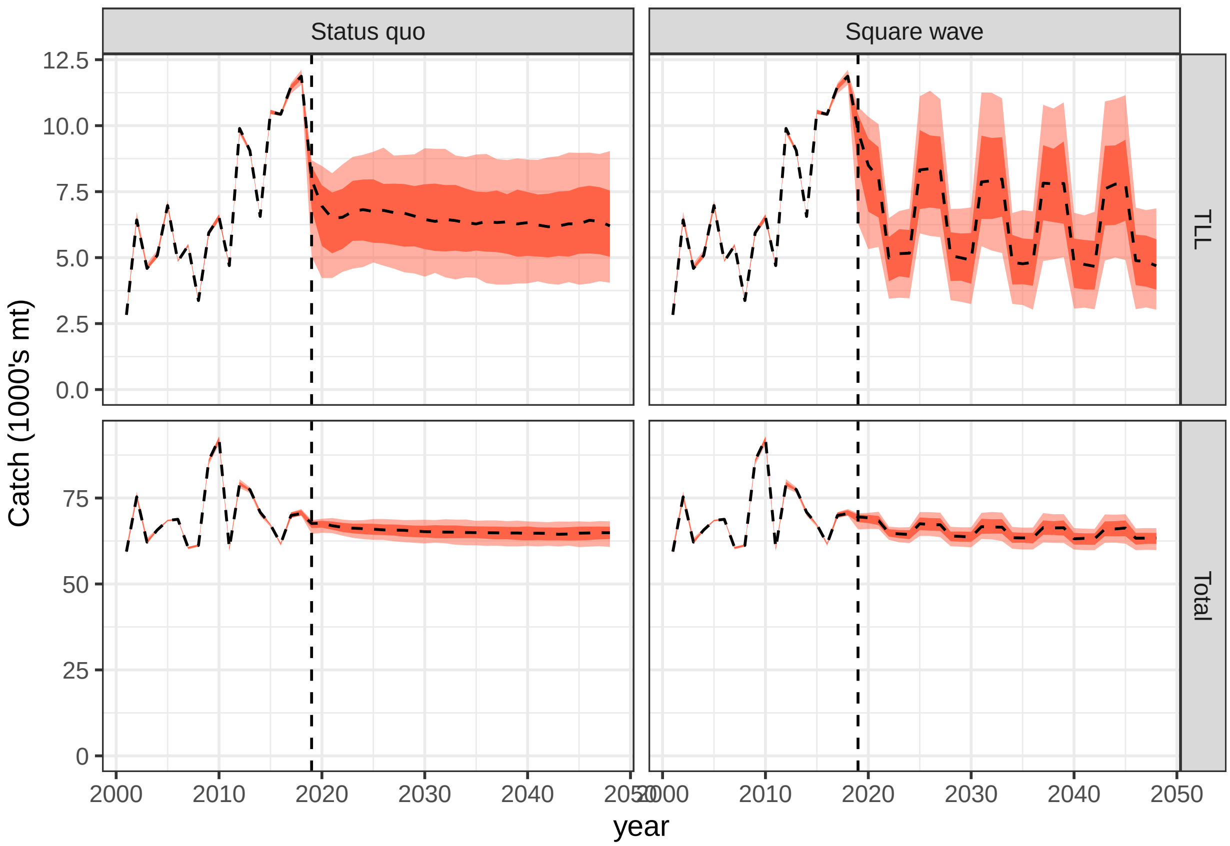

Figure 3: Catches of South Pacific albacore by the tropical longline (TLL) fisheries and all fisheries combined for two scenarios: all fisheries at status quo levels of 2016-2018, TLL set as a square wave with an amplitude of 25% around the status quo level. The outer envelope shows the 80th percentile range, the inner envelope the 50th percentile range and the black dashed line is the median level. The start of the projection in 2019 is also shown.

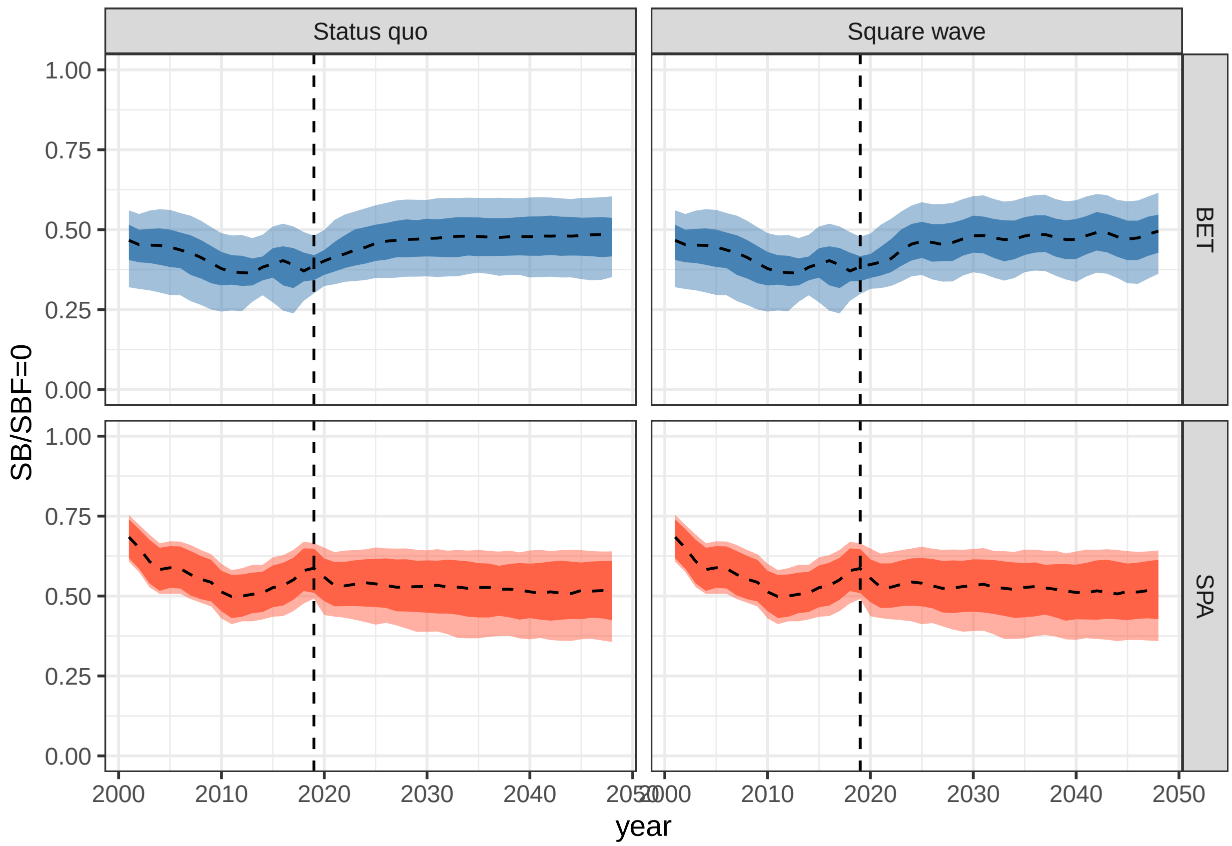

Figure 4: Projected SB/SBF0 of bigeye (BET) and South Pacific albacore (SPA) under two scenarios for the tropical longline fishery: all fisheries at status quo levels of 2016-2018, TLL set as a square wave with an amplitude of 25% around the status quo level. The outer envelope shows the 80th percentile range, the inner envelope the 50th percentile range and the black dashed line is the median level. The start of the projection in 2019 is also shown.

The projected SB/SBF=0 for both stocks scenarios is shown in Figure 4. When the BET MP has a square wave pattern, a similar pattern can be seen in the BET SB/SBF=0. However, this pattern is barely visible in the SPA SB/SBF=0 suggesting the impact of the BET MP on the SPA stock is small.

Inspecting the SPA spawning biomass in the SPA model area where the TLL operates shows that it is more strongly affected by changes in the TLL catch levels than in the other model areas (Figure 5). This demonstrates that the output of the BET MP is being successfully transferred to the SPA model.

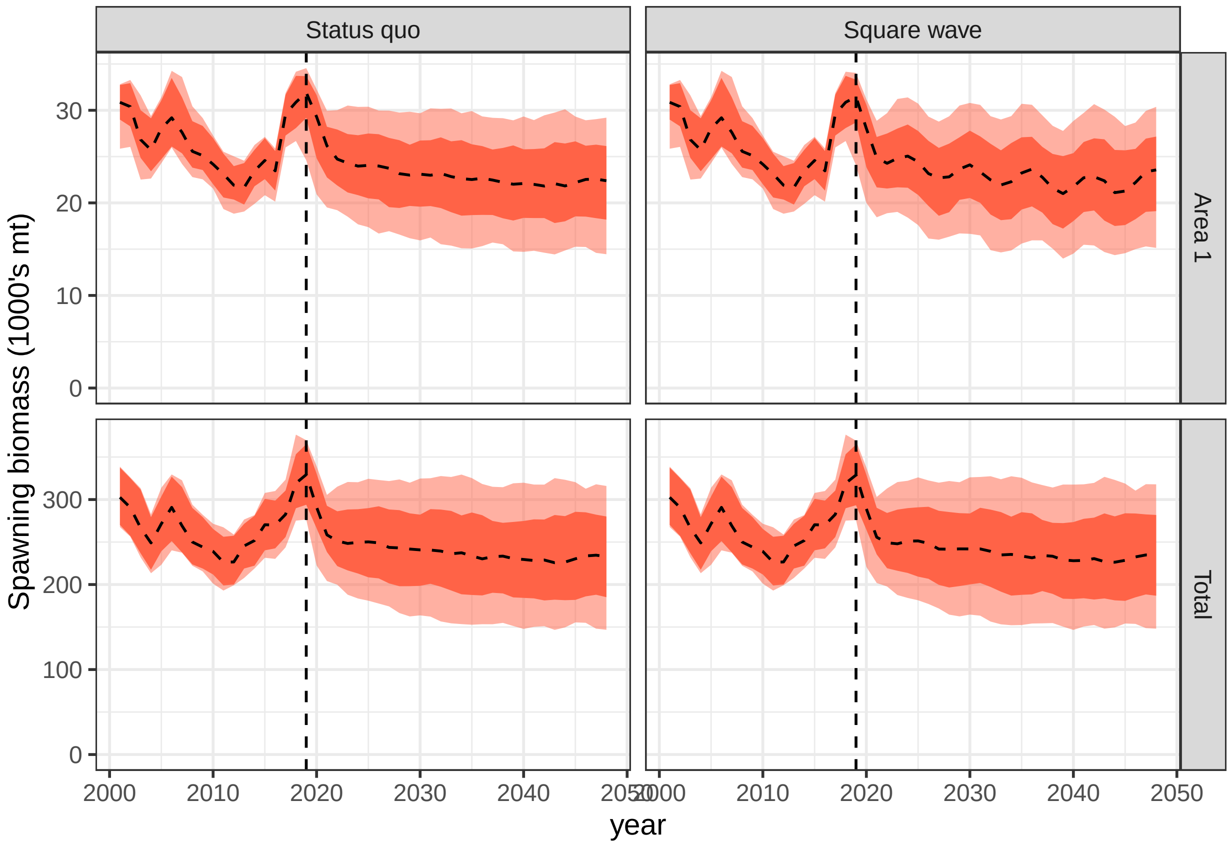

Figure 5: Projected spawning biomass of South Pacific albacore under two scenarios for the tropical longline fishery: all fisheries at status quo levels of 2016-2018, TLL set as a square wave with an amplitude of 25% around the status quo level. The spawning biomass is model area 1 and the total spawning biomass in all regions are shown. The outer envelope shows the 80th percentile range, the inner envelope the 50th percentile range and the black dashed line is the median level. The start of the projection in 2019 is also shown.

Full results, including projected catches by fishery, from a single example iteration are included in Appendix F.

6 Next steps

There are several next steps in developing the multi-species modelling approach.

It will be necessary to develop a full suite of OMs for the BET and YFT stocks. Although these are likely to be based on the most recent stock assessments, they should include a wider consideration of sources of uncertainty.

The analysis presented here did not include an MP for BET. Candidate MPs for the TLL fishery will need to be generated and tested in the future. This may include the consideration of empirical and model-based approaches.

The analysis presented here did not include an MP for SPA. Work has progressed towards developing a set of OMs and candidate MPs for SPA (Scott et al., 2022c). These should be included in the multi-species modelling framework as they continue to be developed.

When all the components are together, including OMs for all stocks and MPs for SKJ, SPA and BET, a full test of the multi-species modelling framework can be performed. Multi-species performance indicators can then be calculated to evaluate possible trade-offs between MPs for the different stocks (Scott et al., 2022a).

7 Summary

The proposed multi-species modelling framework involves developing prospective single stock MPs for SKJ, SPA and BET respectively. There is no single stock MP for YFT . Instead, the impact of these MPs on YFT would then be evaluated using a combined evaluation framework.

Following existing work on using single stock models for SKJ, BET and YFT in a multi-species modelling framework, this report has described how single stock models for SPA can also be included through interactions with the BET models. The results demonstrate that this modelling approach is tractable and it is possible to determine the impact of the BET MP on the SPA stock.

As work progresses, it will be possible to use this approach to determine the impact of the SKJ, BET, and SPA MPs on YFT. These results are sufficiently encouraging to continue developing this approach.

Acknowledgments

We gratefully acknowledge funding for this work from the New Zealand Ministry of Foreign Affairs and Trade (MFAT) funded project “Pacific Tuna Management Strategy Evaluation”.

References

Castillo Jordan, C., Hampton, S., Ducharme-Barth, N. Xu, H., Vidal, T., Williams, P., Scott, F., Pilling, G., and Hamer, P. (2021). Stock assessment of South Pacific albacore tuna. WCPFC-SC17-2021/SA-WP-02, 11–19 August 2021.

Ducharme-Barth, N., Vincent, M., Hampton, S., Hamer, P., Williams, P., and Pilling, G. (2020). Stock assessment of bigeye tuna in the western and central Pacific Ocean. WCPFC-SC16-2020/SA-WP-03 [REV2], 12–20 August 2020.

Pilling, G., Scott, F., and Hampton, S. (2019). Minimum Target Reference Points for WCPO yellowfin and bigeye tuna consistent with alternative LRP risk levels, and multispecies implications. Technical Report WCPFC-SC15-2019/MI-WP-01, Pohnpei, Federated States of Micronesia, 12–20 August 2019.

Punt, A., Butterworth, D., de Moor, C., De Oliveira, J., and Haddon, M. (2014). Management strategy evaluation: best practices. *Fish and Fisheries*, (DOI:10.111/faf12104).

Scott, F., Scott, R., Yao, N., Pilling, G., and Hamer, P. (2022a). Mixed-fishery harvest strategy performance indicators. WCPFC-SC18-2021/MI-WP-07, 10–18 August 2022.

Scott, F., Scott, R., Yao, N., Pilling, G., and Hamer, P. (2022b). Mixed-fishery harvest strategy update. WCPFC-SC18-2021/MI-WP-06, 10–18 August 2022.

Scott, F., Scott, R., Yao, N., Pilling, G., Hamer, P., and Hampton, S. (2021a). Mixed-fishery harvest strategy developments. WCPFC-SC17-2021/MI-WP-05, 11–19 August 2021.

Scott, F., Scott, R. D., Pilling, G., and Hampton, S. (2019a). The WCPO Skipjack MSE Modelling Framework. WCPFC-SC15-2019/MI-IP-02, Pohnpei, Federated States of Micronesia, 12–20 August 2019.

Scott, F., Scott, R. D., Yao, N., Pilling, G., and Hampton, S. (2019b). Mixed Fishery and Multi-Species Issues in Harvest Strategy Evaluations. WCPFC-SC15-2019/MI-WP-04, Pohnpei, Federated States of Micronesia, 12–20 August 2019.

Scott, F., Singh, J., Scott, R., Yao, N., Pilling, G., and Hampton, S. (2020a). Further consideration of the mixed fishery management strategy evaluation framework for WCPO tuna stocks. WCPFC-SC16-2020/MI-IP-06, 12–20 August 2020.

Scott, R., Scott, F., Yao, N., Pilling, G., Hamer, P., and Hampton, S. (2021b). Skipjack management procedure evaluations. WCPFC-SC17-2021/MI-WP-04, 11–19 August 2021.

Scott, R., Scott, F., Yao, N., Singh, J., Pilling, G., Hampton, S., and Davies, N. (2020b). Updating the WCPO skipjack operating models for the 2019 stock assessment. WCPFC-SC16-2020/MI-IP-08, 12–20 August 2020.

Scott, R., Yao, N., Scott, F., and Pilling, G. (2019c). South Pacific albacore management strategy evaluation framework. WCPFC-SC15-2019/MI-WP-08, Pohnpei, Federated States of Micronesia, 12–20 August 2019.

Scott, R., Yao, N., Scott, F., Pilling, G., Hamer, P., and Hampton, S. (2022c). Update on progress and technical challenges for developing the South Pacific albacore MSE framework. WCPFC-SC18-2022/MI-IP-XX, 10–18 August 2022.

Scott, R. D., Scott, F., Pilling, G., Yao, N., and Hampton, S. (2019d). Results of initial evaluations of skipjack harvest strategies. Technical Report WCPFC-SC15-2019/MI-WP-05, Pohnpei, Federated States of Micronesia, 12–20 August 2019.

Tremblay-Boyer, L., Hampton, S., McKechnie, S., and Pilling, G. (2018). Stock assessment of South Pacific albacore tuna. WCPFC-SC14-2018/SA-WP-05, Busan, South Korea, 5–13 August 2018.

WCPFC (2019). Report of the Scientific Committee Fifteenth Regular Session. Technical report, Commission for the Conservation and Management of Highly Migratory Fish Stocks in the Western and Central Pacific Ocean, Pohnpei, Federated States of Micronesia, 12–20 August 2019.

Yao, N., Singh, J., Scott, R., and Scott, F. (2020). HCR design considerations for south Pacific albacore. WCPFC-SC16-2020/MI-IP-05, 12–20 August 2020.

A Overview of the multi-species modelling framework

This appendix is adapted from Scott et al. (2019b), Scott et al. (2020a) and Scott et al. (2021a).

Including mixed fishery interactions in a harvest strategy can be challenging. The agreed WCPFC harvest strategy workplan recognised this and proposed that the initial focus be on skipjack, followed by South Pacific albacore, and then bigeye and yellowfin. This is because skipjack and South Pacific albacore are mainly caught by a single dominant fishery (purse seine and southern longline respectively) and so single stock evaluations could initially be developed. Progress has been made towards developing single stock MSE simulation frameworks for these stocks (Scott et al., 2019c; Yao et al., 2020; Scott et al., 2020b, 2019a, Yao et al. (2020)).

The multi-species modelling framework involves developing prospective single stock MPs for skipjack, South Pacific albacore and bigeye. The impact of these MPs on yellowfin would then be evaluated using a combined evaluation framework to identify whether the multi-species framework can simultaneously achieve management objectives for the stocks. If not, alternative approaches will need to be developed. Any candidate MPs developed using single-species MSE (such as the current South Pacific albacore and skipjack evaluations) will need to be tested with the mixed fishery MSE to fully evaluate their performance. It is worth noting that recent bigeye and yellowfin target reference point evaluations suggest that it is possible for these stocks to be sustainably managed if purse seine and longline fishing levels are kept at recent status quo levels (Pilling et al., 2019).

WCPO fishery	Skipjack	Yellowfin	Bigeye	South Pacific albacore
Tropical PS	SKJ MP	SKJ MP	SKJ MP	
Northern PS	SKJ MP	SKJ MP	SKJ MP	
Tropical LL		BET MP	BET MP	BET MP
Northern LL		BET MP	BET MP	
Southern LL		ALB MP	ALB MP	ALB MP
Pole and line	SKJ MP	SKJ MP	SKJ MP	
ID/PH/VN (non-AW)	SKJ MP	SKJ MP	SKJ MP	
Southern Troll				ALB MP
Archipelagic waters and territorial seas	Aligned to SKJ MP, national plan or local MP	Aligned to SKJ / BET MPs, national plan or local MP	Aligned to SKJ / BET / ALB MPs, national plan or local MP	Aligned to ALB MP, national plan or local MP.

Table 2: Proposed integration of stock-based management procedures (MPs) across fisheries under the multi-species modelling framework (adapted from Scott et al. (2019b)).

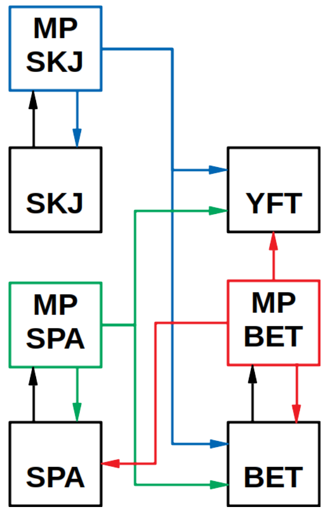

Figure 6: Schematic of the multi-species modelling framework. The skipjack (SKJ) management procedure (MP) sets the fishing opportunities for the purse seine, pole and line and domestic fisheries in the skipjack, bigeye (BET) and yellowfin (YFT) models, given the stock status of skipjack. The BET MP sets the fishing opportunities for the tropical long line fishery in the BET, YFT and South Pacific Albacore (SPA) models, given the stock status of BET. The SPA MP sets the fishing opportunities for the southern long line fishery in the BET, YFT and SPA models, given the stock status of SPA.

The three single stock MPs control the fishing opportunities for different WCPO fisheries by setting catch or effort limits based on status estimates of the associated stock (Table 2 and Figure 6). Each fishery is controlled by one of the three single stock MPs. However, that fishery may catch a range of tuna stocks. It is noted that the definition and classification of the WCPO fisheries to different MPs under this approach is an initial proposal, and that alternative classifications may also be considered.

In Table 2 the longline fisheries are divided into three categories: northern, tropical and southern. Under the multi-species modelling framework these fisheries are managed through different stock-based MPs. An initial proposal for latitudinal range over which these fisheries operate is given in Table 3. Although Table 2 makes a distinction between northern and tropical purse seine, the multi-species modelling framework assumes that they are both managed through the skipjack MP so the latitudinal range of these fisheries does not need to be specified.

Table 3: Proposed latitude range of the different longline fisheries and the associated single stock management procedure that would manage it.

Fishery	Latitude range	Management procedure
Northern LL	20N - 50N	Bigeye
Tropical LL	10S - 20N	Bigeye
Southern LL	South of 10S	South Pacific albacore

B Operating model maps

B.1 Operating model maps

The regional structures of the bigeye (BET), yellowfin (YFT) and South Pacific albacore (SPA) operating models are shown in Figure 7. Under the proposed WCPFC mixed-fishery approach the northern and tropical longline (NLL and TLL) fisheries (north of 10 South, north of the red dashed line) would be managed though the BET MP whereas the southern longline (SLL) fisheries (south of 10 South, north of the red dashed line) would be managed though the SPA MP.

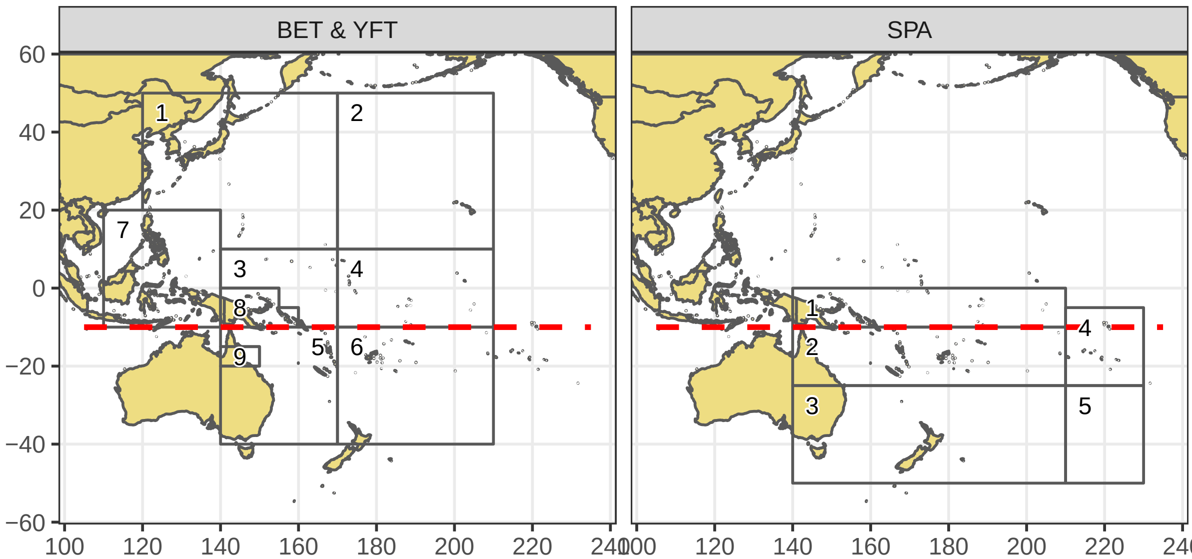

Figure 7: The regional structure of the BET, YFT and SPA operating models. The red dashed line shows the border between the tropical longline and southern longline.

B.2 Overlap of the SPA operating model with the BET operating model

As mentioned above, any longline fisheries north of 10 S are considered to be NLL or TLL and would be managed by the BET MP (Table 3). In the SPA model, these are the longline fisheries in area 1 and part of area 4. To include SPA in the mixed fishery framework it is necessary to transfer fishing effort from the NLL and TLL fisheries in the BET OM to the SPA OM. Figure 8 shows the overlap between the SPA OM areas with TLL fisheries (areas 1 and 4, in red, i.e. those that have a component north of 10 S) with the BET OM. Area 4 of SPA OM does not overlap with any part of the BET OM.

B.3 Overlap of the BET operating model with the SPA operating model

As mentioned above, any longline fisheries south of 10 S are considered to be SLL and would be managed by the SPA MP (Table 3). In the BET model, these are the longline fisheries in areas 5, 6 and 9. To complete the integration of SPA into the mixed fishery framework it would be necessary to transfer fishing effort from the SLL fisheries in the SPA OM to the BET OM. Figure 9 shows

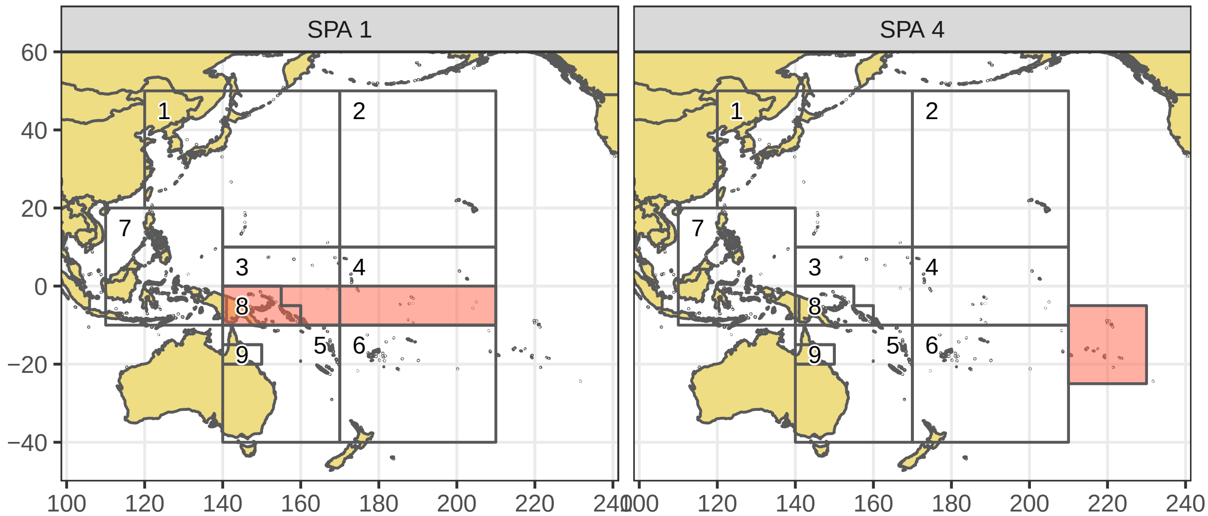

Figure 8: Overlap of SPA operating model areas 1 and 4 (those with TLL fisheries, shown in red) with the BET and YFT operating models.

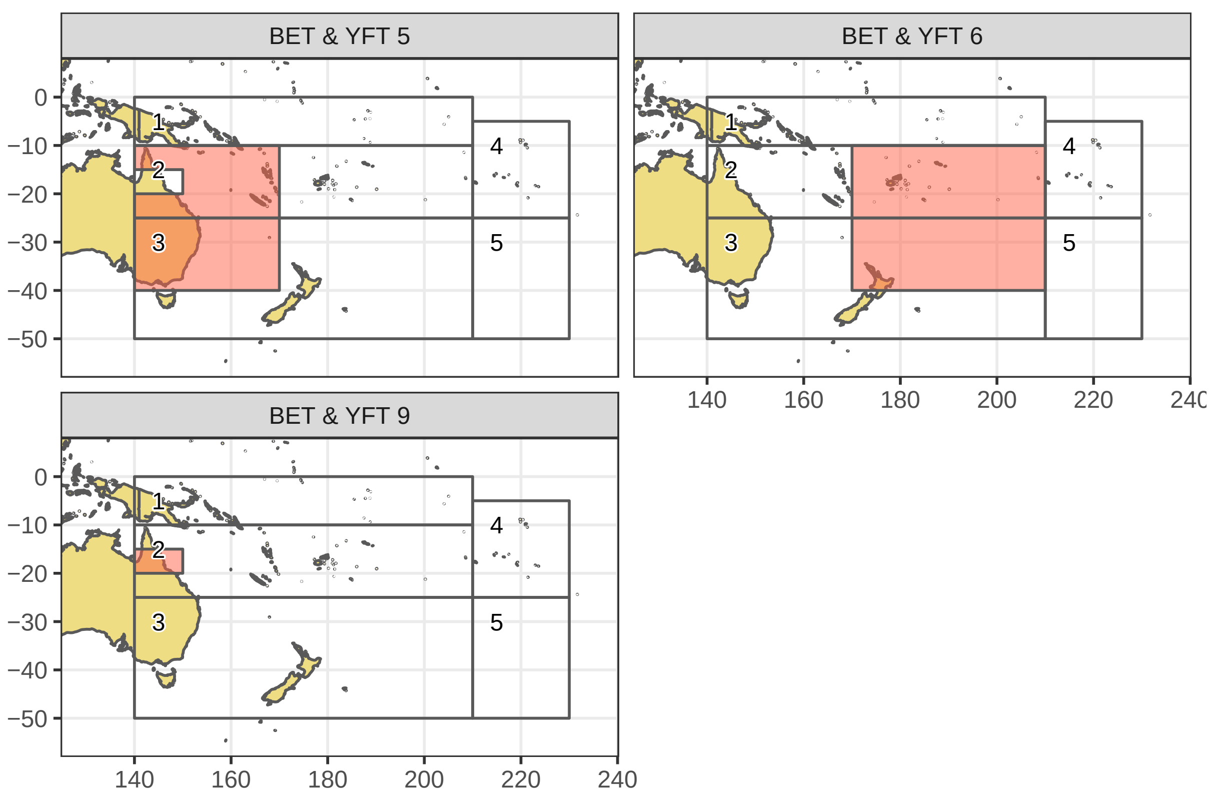

Figure 9: Overlap of BET and YFT operating models areas 5, 6 and 9 (those with southern longline fisheries, shown in red) with the SPA operating model.

the overlap between the BET OM areas with SLL fisheries (areas 5, 6 and 9, in red, i.e. those that have a component south of 10 S) with the SPA OM.

C Bigeye and South Pacific albacore operating models

C.1 Tables of fisheries in the operating models

Fishery	Gear	Area	Name	WCPO fishery	MP	Man. method
1	LL	1	DWFN-LL	Tropical LL	BET	
2	LL	1	PICT.AZ-LL	Tropical LL	BET	
3	LL	2	DWFN-LL	Southern LL	SPA	Catch
4	LL	2	PICT-LL	Southern LL	SPA	Catch
5	LL	2	AZ-LL	Southern LL	SPA	Catch
6	LL	3	DWFN-LL	Southern LL	SPA	Catch
7	LL	3	PICT-LL	Southern LL	SPA	Catch
8	LL	3	AZ-LL	Southern LL	SPA	Catch
9	LL	4	DWFN-LL	Tropical & Southern LL	BET & SPA	Catch
10	LL	4	PICT.AZ-LL	Tropical & Southern LL	BET & SPA	Catch
11	LL	5	DWFN-LL	Southern LL	SPA	Catch
12	LL	5	PICT.AZ-LL	Southern LL	SPA	Catch
13	Troll	3	ALL-TR	Southern Troll	SPA	Catch
14	Troll	5	ALL-TR	Southern Troll	SPA	Catch
15	Driftnet	3	ALL-DN	Driftnet	SPA	Catch
16	Driftnet	5	ALL-DN	Driftnet	SPA	Catch

Table 4: Fisheries in the south Pacific albacore operating model, the associated WCPO fishery and the proposed associated management procedure (MP) (bigeye - BET, South Pacific albacore - SPA). The *Man. method* column describes whether that fishery will be managed through catch or effort limits. Fisheries managed by the BET MP will have their future effort set by the output of the BET simulations.

Fishery	Gear	Area	Name	WCPO fishery	MP	Man. method
1	LL	1	L-ALL	Northern & Tropical LL	BET	Catch
2	LL	2	L-ALL	Northern & Tropical LL	BET	Catch
3	LL	2	L-US	Northern & Tropical LL	BET	Catch
4	LL	3	L-ALL	Tropical LL	BET	Catch
5	LL	3	L-OS	Tropical LL	BET	Catch
6	LL	7	L-OS	Tropical LL	BET	Catch
7	LL	7	L-ALL	Tropical LL	BET	Catch
8	LL	8	L-ALL	Tropical LL	BET	Catch
9	LL	4	L-ALL	Tropical LL	BET	Catch
10	LL	5	L-AU	Southern LL	SPA	
11	LL	5	L-ALL	Southern LL	SPA	
12	LL	6	L-ALL	Southern LL	SPA	
13	PS	3	S-ASS-ALL	Tropical PS	SKJ	
14	PS	3	S-UNA-ALL	Tropical PS	SKJ	
15	PS	4	S-ASS-ALL	Tropical PS	SKJ	
16	PS	4	S-UNA-ALL	Tropical PS	SKJ	
17	DOM	7	Dom.PH.7	ID/PH/VN	SKJ	
18	DOM	7	HL.IDPH.7	ID/PH/VN	AW	
19	PS	1	S-JP	Northern PS	SKJ	
20	PL	1	P-JP	PL	SKJ	
21	PL	3	P-ALL	PL	SKJ	
22	PL	8	P-ALL	PL	SKJ	
23	DOM	7	Dom.ID.7	ID/PH/VN	AW	
24	PS	7	S-ID.PH	ID/PH/VN	SKJ*	
25	PS	8	S-ASS-ALL	Tropical PS	SKJ*	
26	PS	8	S-UNA-ALL	Tropical PS	SKJ*	
27	LL	9	L-AU	Southern LL	SPA	
28	PL	7	P-ALL	PL	SKJ	
29	LL	9	L-ALL	Southern LL	SPA	
30	PS	7	S-ASS-ALL	Tropical PS	SKJ	
31	PS	7	S-UNA-ALL	Tropical PS	SKJ	
32	DOM	7	Dom.VN.7	ID/PH/VN	SKJ	

Table 5: Fisheries in the bigeye and yellowfin operating models, the associated WCPO fishery and the proposed associated management procedure (MP) (skipjack - SKJ, bigeye - BET, South Pacific albacore - SPA). Fisheries operating in archipelagic waters (AW) of Papua New Guinea, Indonesia, Philippines and Vietnam are assumed to be operating independendently of any MP. Fisheries with an asterix next to their MP partially operate in AW. The *Man. method* column describes whether that fishery will be managed through catch or effort limits. Fisheries managed by the SKJ or SPA MP will have their future effort set by the output of the SKJ or SPA simulations (not done in this report).

C.2 South Pacific albacore operating models

The South Pacific albacore (SPA) operating models (OMs) used in this analysis are based on the 2018 stock assessment (Tremblay-Boyer et al., 2018). The fisheries in the OMs are a mix of longline, troll and driftnet (Table 4). The overwhelming majority of catches are from the longline fisheries.

The OMs are a subset of the full suite of SPA OMs presented in Scott et al. (2019c) (only the geo-statistics CPUE standardisation method is considered here) (Table 6). Combining all levels across the uncertainty grid axes gives 12 OMs.

Table 6: The grid of South Pacific albacore operating models, based on Scott et al. (2019c).

Axis	Levels	Options
Steepness	3	0.65, 0.8, 0.95
Natual mortality	2	0.3, 0.4
Growth	2	estimated, fixed (Chen-Wells)

C.3 Bigeye operating models

In this analysis the BET OMs are based on the most recent stock assessment (Scott et al., 2022a; Ducharme-Barth et al., 2020) (Table 7). The fisheries of these OMs include purse seine, pole and line, longline, and fisheries in Indonesia, Philippines and Vietnam (Table 5).

An additional axis of recruitment period is included. A full suite of OMs for these stocks that cover a wide range of plausible uncertainties will need to be agreed for future evaluations. Combining all levels across the grid axes gives 48 bigeye OMs.

Table 7: The grid of bigeye operating models, based on Ducharme-Barth et al. (2020).

Axis	Levels	Options
Steepness	3	0.65, 0.8, 0.95
Natural mortality	2	Diagnostic or M-hi
Size freq. weighting	4	20, 60, 200, 500
Recruitment period	2	1962-2014, 2005 to 2014

D Calculating weights to transfer the tropical longline fishing effort from the bigeye operating model to the South Pacific albacore operating model

The operating models (OMs) for bigeye (BET) and yellowfin (YFT) have different regional structures to the SPA OMs (Figure 7). Under the multi-species approach the tropical longline (TLL) and northern longline (NLL) fisheries are managed through the BET management procedure (MP). To perform the mixed-fishery simulations the realised future effort of the BET TLL fisheries needs to be transferred to the SPA TLL fisheries (there are no NLL fisheries in the SPA OM).

To transfer the TLL effort from the BET OMs to the SPA OMs a similar method to that established for linking the pole and line fisheries in the BET and SKJ OMs is used ((Scott et al., 2021a)). The overlapping regions of the BET and SPA OMs that have TLL fisheries are identified (Figure 9).

As noted in Section B, in the SPA OMs TLL fisheries operate in region 1 and part of region 4. Under the mixed fishery harvest strategy approach these would be managed through the BET MP (Table 3). SPA region 1 overlaps with BET regions 3, 4 and 8 so that under the multi-species modelling framework TLL fishing effort from these BET regions needs to be transferred to the TLL fisheries in SPA region 1. SPA region 4 does not overlap with the BET model. The relative importance of TLL fishing within this region is discussed below.

The proportion of SPA catches (average of the last three years, using the SPA 2018 data) by model region is summarised in Table 8.

Region	Percentage
1	13.42
2	47.34
3	22.81
4	11.85
5	4.58

Table 8: South Pacific albacore catch proportions, by weight and model region (average 2016-2018).

D.1 SPA region 4

SPA 2018 region 4 lies completely outside of the BET OM region and there are no overlapping BET TLL fisheries (Figure 9). The proportion of total SPA catches in region 4 is approximately 12% (Table 8). This figure is large enough that we can't just ignore region 4 in the SPA evaluations. However, TLL fisheries would only operate in the 0 - 10 S component of this model region, which is only 25% of the region. The longline fisheries in the remaining 75% are SLL and would be managed by the SPA MP. This raises the possibility of simplifying the SPA evaluations by assuming that all the fisheries in region 4 would be managed under the SPA MP.

WCPFC databases are essentially integrated into a single database called LogMaster. The historical longline catch data from the LogMaster database is presented as numbers and weight at 5x5 degree positions. The validity of assuming that all of the longline activity in region in the SPA OMs would be managed by the SPA MP is checked here by examining the distribution of catches in region 4 using data taken from LogMaster (extracted 10/06/2022).

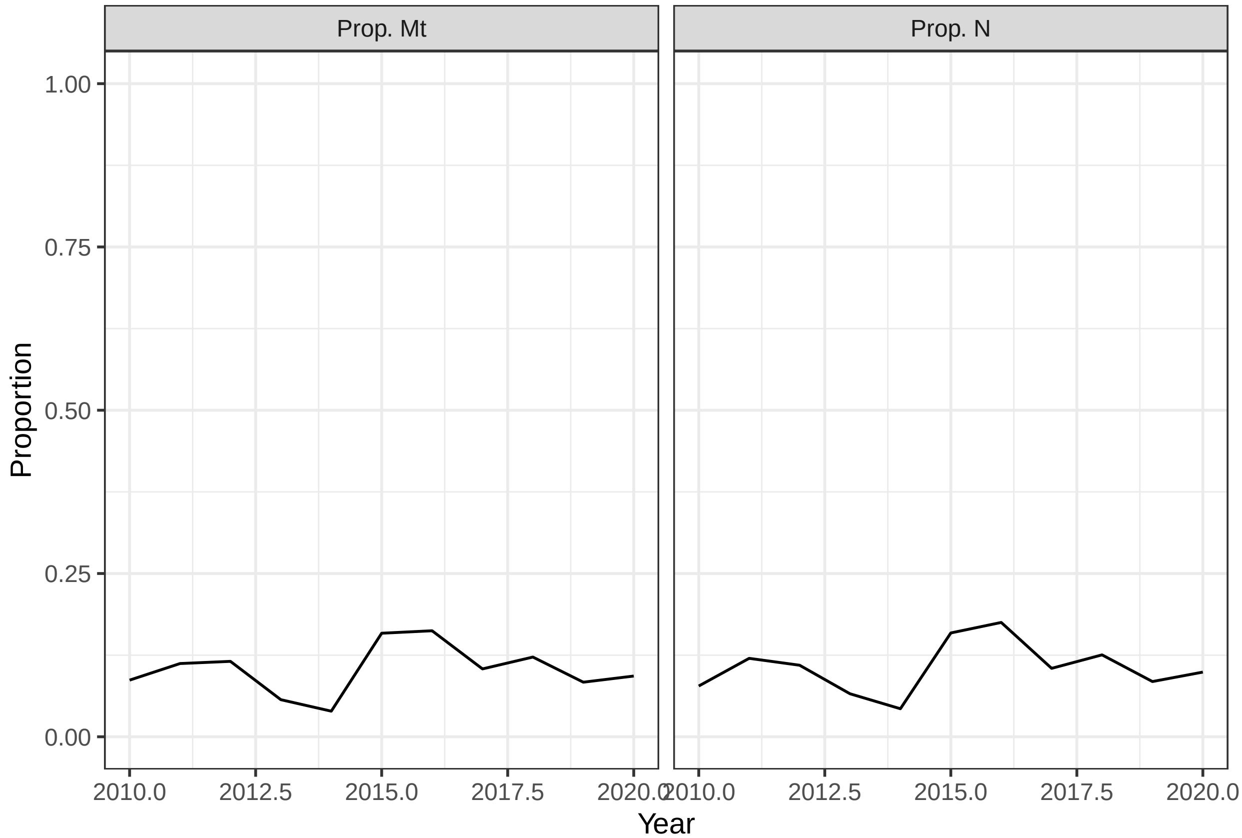

Figure 10: Annual proportion of catches (by N or Mt) in SPA model region 4 that are in the TLL portion (north of 10 S).

The proportion of historical annual catches in region 4 of the SPA OMs, by number and by weight, that occur in the TLL zone (north of 10 S) can be seen in Figure 10. In recent years (2010-2019) the proportion is around 0.10 by weight or number. Additionally, the average proportion of total annual catches (i.e. catches in all model regions) that occur in the TLL zone of region 4 in recent years is around 0.01 by weight or number.

As these proportions are small, it suggests that, for simplicity, during the mixed fishery evaluations the longline fisheries in the TLL zone of region 4 can be assumed to be managed through the SPA MP instead of the BET MP.

D.2 SPA region 1

Region 1 in the SPA OM overlaps with BET OM regions 3, 4 and 8. The fisheries of these regions are described in Tables 9 and 10

Table 9: Longline fisheries in SPA OM region 1. These will be managed through the BET MP and overlap with longline fisheries in regions 3, 4 and 8 of the BET OM.

SPA model region	SPA fishery	Fishery name
1	1	DWFN-LL
1	2	PICT.AZ-LL

Table 10: Longline fisheries in BET OM regions 3, 4 and 8. These overlap with the longline fisheries in region 1 of the SPA OM.

BET model region	BET fishery	Fishery name
3	4	L-ALL
3	5	L-OS
4	9	L-ALL
8	8	L-ALL

Unfortunately, there is not a 1-1 correspondence between the SPA and BET fisheries in these model regions. Instead weightings are calculated from historical distributions of effort taken from the LogMaster data and used to 'map' one region to another. The historical longline effort data from the LogMaster database is presented as numbers of hooks and is reported at 5x5 degree positions. This approach is similar to the one used to transfer the pole and line fishing effort from the SKJ OM to the BET OM (Scott et al., 2021a). However, it is made more complicated by the presence of multiple fisheries in BET region 3 and SPA region 1.

The approach taken here is to weight each of the BET regions to calculate an overall change in effort for the SPA region.

- Assume that fishing effort is spread equally over each model region (in line with the stock assessment model assumptions).
- Use the LogMaster data to calculate the proportion of total effort in SPA region 1 that is in each of the component sub-regions, i.e. the overlapping parts with BET regions 3, 4 and 8.

The proportion of total effort in SPA region 1 that comes from each of the overlapping parts of BET regions 3, 4 and 8 is shown in Figure 11. The majority of effort is from BET region 4 and there is little seasonal variation.

The average proportions over the period 2010 to 2019 by season are shown in Table 11. These proportions can be used as a basis for the weights when transferring effort from the TLL fisheries in BET OM to SPA OM. For example, if the total fishing effort of the longline fishery in BET region 4 increased by 10% in season 1, it would contribute a 6.6% increase in total effort in the LL fisheries in SPA region 1.

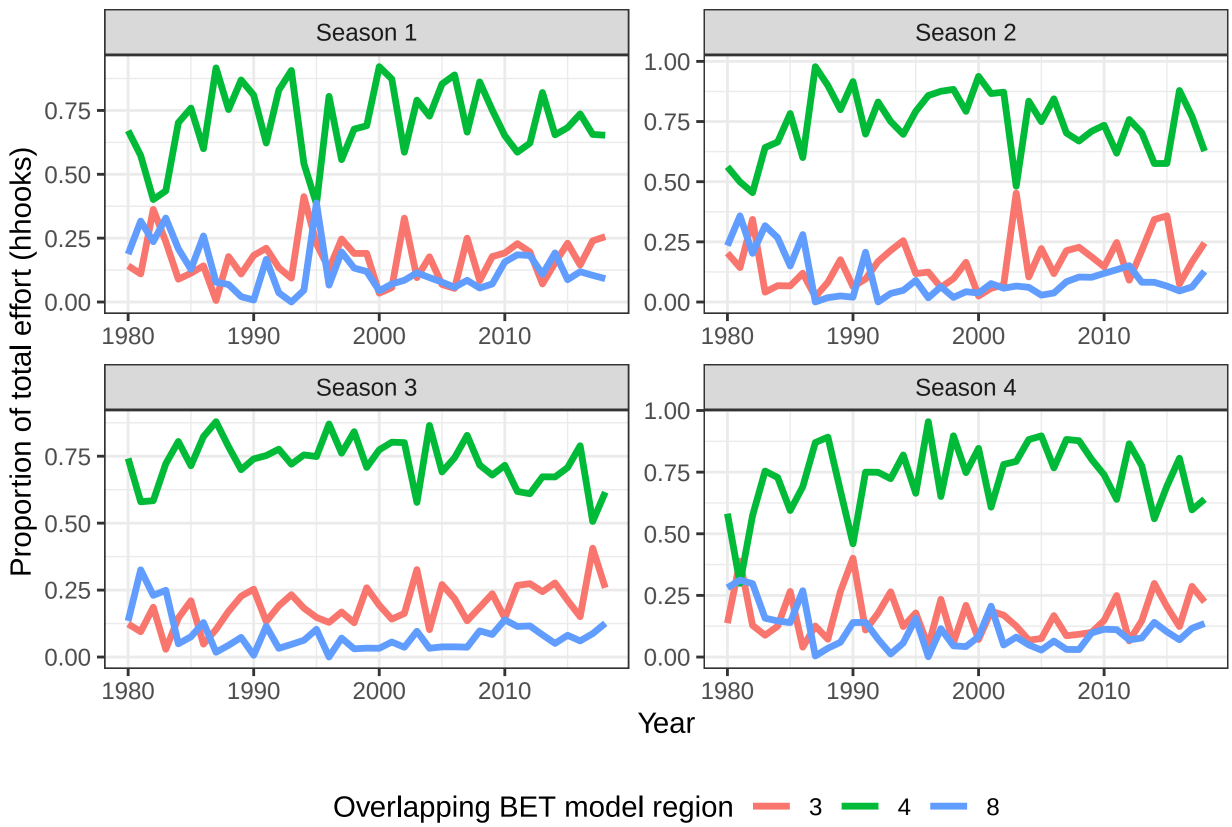

Figure 11: Proportion of effort in SPA model region 1 that occurs in overlapping regions 3, 4 and 8 of the BET model by season.

BET region	Season 1	Season 2	Season 3	Season 4
3	0.20	0.23	0.23	0.19
4	0.66	0.67	0.67	0.70
8	0.14	0.10	0.09	0.11

Table 11: Average proportion of effort (2010-2019) in SPA region 1 that occurs in overlapping regions 3, 4 and 8 of the BET model.

However, it becomes difficult when there are multiple longline fisheries in a model region. In BET region 3 there are two fisheries, 4 (L-ALL) and 5 (L-OS), and in SPA region 1 there are two fisheries, 1 (DWFN-LL) and 2 (PICT.AZ-LL).

D.2.1 BET region 3

The two BET OM fisheries in model region 3 will have different changes in effort as a result of the BET MP setting catch limits. It is necessary to understand how changes in effort of these fisheries combine to change the effort in the corresponding fisheries in region 1 of the SPA OM. For example, if effort of BET fishery 4 increased by 10% and the effort of BET fishery 5 increased by 5%, what would the resulting impact be on the total effort in SPA regoin 1?

It is possible to see which *Flags* make up each model fishery of the BET OM by looking at the output of MUFDAGR from the recent BET assessment. These are used to distribute the total LogMaster effort in BET OM region 3 between the two longline fisheries, fishery 4 (L-ALL) and fishery 5 (L-OS). The proportion of effort of the two fisheries in the overlapping component with SPA region 1 can then be calculated (Figure 12).

Season	Fishery 4	Fishery 5
Season 1	0.48	0.52
Season 2	0.57	0.43
Season 3	0.67	0.33
Season 4	0.51	0.49

Table 12: Average proportion of effort (2010-2019) of the two longline fisheries in the part of BET region 3 that overlaps with SPA region 1.

Averaging the proportions over the years 2010-2019 gives the values shown in Table 12. These values can be used to weight the contribution of each of the fisheries in BET region 3 to the fisheries in SPA region 1.

For example, if in season 2 the effort, relative to some point in the past, of fishery 4 was 1.5 and fishery 5 was 1.1, the calculation to give the overall relative effort in BET region 3 would be: (1.5 * 0.57) + (1.1 * 0.43) = 1.328. The corresponding contribution to the relative effort in SPA region 1 is calculated using the region weights in Table 11: 1.328 * 0.231 = 0.307.

The contribution to the relative effort of SPA region 1 from BET OM fishery 9 in region 4 and

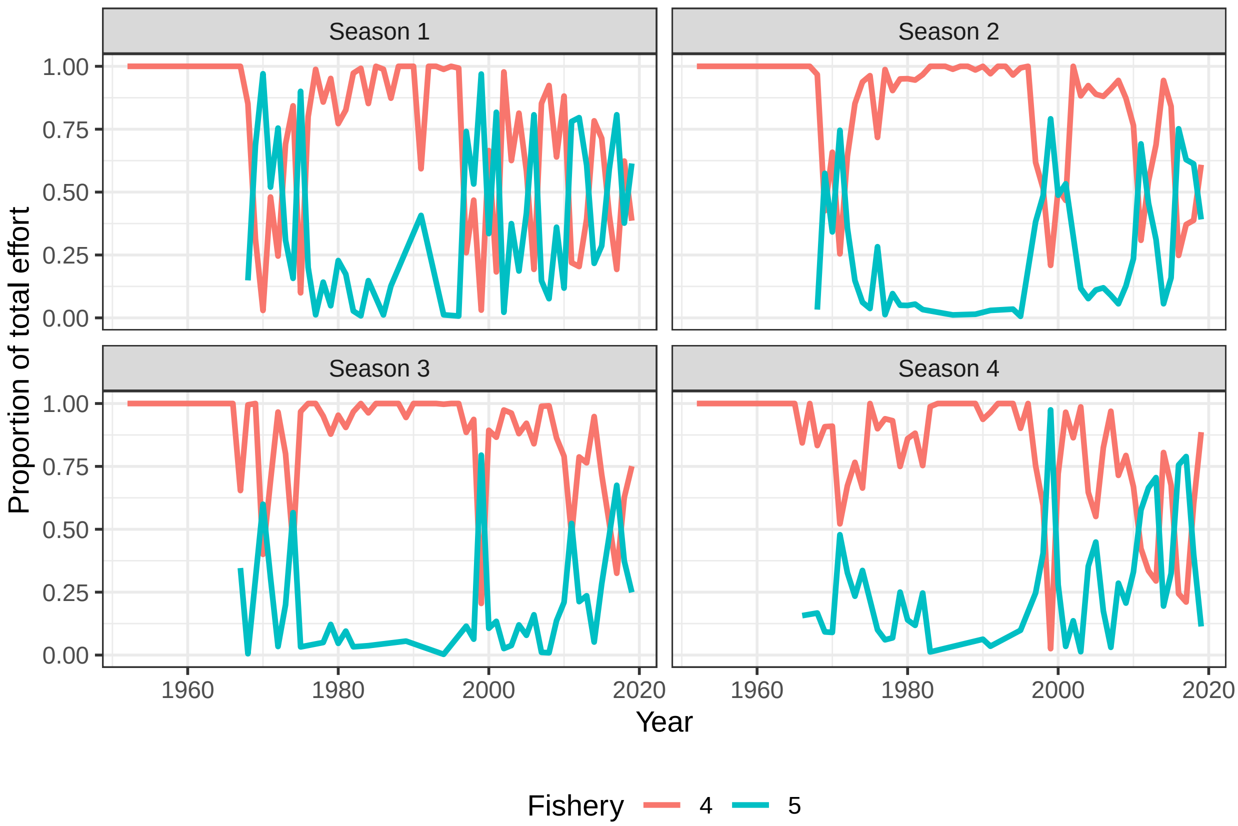

Figure 12: Proportion of effort of the two longline fisheries in region 3 of the BET model that overlaps with region 1 of the SPA model.

fishery 8 in region 8 can be calculated by the relative effort and the weights in Table 11 (there is only one longline fishery each in regions 4 and 8 so this is relatively straightforward).

D.2.2 SPA region 1

The weights calculated above in Tables 11 and 12 can be used to calculate the total relative effort in SPA region 1. There are two longline fisheries in SPA region 1: 1 (DWFN-LL) and 2 (PICT.AZ-LL). The calculated relative effort should be applied to each of the fisheries in SPA region 1. This will ensure that the proportion of actual effort from each of the SPA fisheries will be the same.

D.3 Putting all this together

The weights in Tables 11 and 12 can be used to calculate the contribution of each BET fishery to the total relative effort in SPA region 1 (Table 13).

BET fishery	BET region	Season	Fishery weight	Region weight	Weight
4	3	1	0.481	0.200	0.096
5	3	1	0.519	0.200	0.104
8	8	1	1.000	0.138	0.138
9	4	1	1.000	0.663	0.663
4	3	2	0.571	0.231	0.132
5	3	2	0.429	0.231	0.099
8	8	2	1.000	0.098	0.098
9	4	2	1.000	0.671	0.671
4	3	3	0.671	0.235	0.158
5	3	3	0.329	0.235	0.077
8	8	3	1.000	0.093	0.093
9	4	3	1.000	0.672	0.672
4	3	4	0.514	0.188	0.097
5	3	4	0.486	0.188	0.091
8	8	4	1.000	0.109	0.109
9	4	4	1.000	0.703	0.703

Table 13: Weights for calculating overall change in effort in SPA region 1

D.4 Summary

- For the simulations, assume that the portion in SPA region 4 that would otherwise be managed through the BET MP is managed through the SPA MP. It doesn't actually overlap with the BET OM, and the proportion of total catches in the portion are small. This makes the modelling much simpler.
- For SPA model region 1 where the BET MP specifies longline effort, use Table 13 and apply the total weight equally to both SPA fisheries 1 and 2 in SPA region 1.

E Example of linking the bigeye and South Pacific albacore operating models

This appendix demonstrates how SPA models can be included in the multi-species modelling framework by linking them to the BET models through the activity of the tropical longline (TLL) fisheries.

Following the multi-species modelling framework (Section A), the northern longline (NLL) and TLL fisheries in the BET OMs, i.e. those that range from 50 North to 10 South, would be managed through catch limits set by the BET MP. To link the SPA OMs to the BET OMs the resulting effort of the TLL fisheries needs to be transferred from the BET OMs to the TLL fisheries in the SPA OMs. The corresponding effort by the TLL fisheries to take the SPA catch will vary due to changing catches of BET by the TLL fisheries and also because of fluctuations in the underlying regional BET biomass due to recruitment variability, for example.

In the analysis presented here there is no dynamic BET MP that responds to the BET stock status. Instead a BET MP is simulated by fixing the MP output in advance to a square wave that fluctuates between 0.75 and 1.25, with a mean value of 1 (see Section 4). The period of the square wave is six years (three years up, three years down), similar to a management period of three years. The scalar is applied to the average catch of the TLL fisheries in the years 2016-2018 to set their future catches. This provides a signal, the impact of which can be tracked through into the SPA dynamics.

In Section 3 it is shown that the potential impact of the SPA MP on the BET and YFT models would likely be very small. Therefore, in this example, it is assumed that the there is no SPA MP. Instead, the future catches of the southern longline (SLL) fisheries in the BET and SPA models are set to the average value of the years 2016-2018. This allows the BET evaluations to be run independently of the SPA simulations.

This Appendix provides examples of how this process can be performed. A single example iteration of the stochastic simulations is used to illustrate the process. The results from this iteration are given in Appendix F.

The SKJ and YFT models are not considered here and there is no SKJ MP in this analysis. Instead, the future activity of fisheries that would be managed through the SKJ MP or the SPA MP, such as the SLL, purse seine and pole and line fisheries, are held constant at status quo levels of catch or effort, depending on the gear type where status quo is the average of 2016 to 2018. Linking SKJ, BET and YFT models in the multi-species framework is described in Scott et al. (2021a).

E.1 Bigeye results

As mentioned above, the results shown here are for a single iteration.

The catches of the longline fisheries in the BET OM are shown in Figure 13. The resulting SB/SBF=0 (Figure 14) and region specific spawning biomasses (Figure 15) show the impact of the fluctuating catches. The impact is relatively small because the TLL and NLL fisheries only take approximately 40% of the recent BET catch and all other fisheries are set to fish at mean 2016-2018 effort and catches. Additionally, variation in recruitment has a large impact on the stock levels.

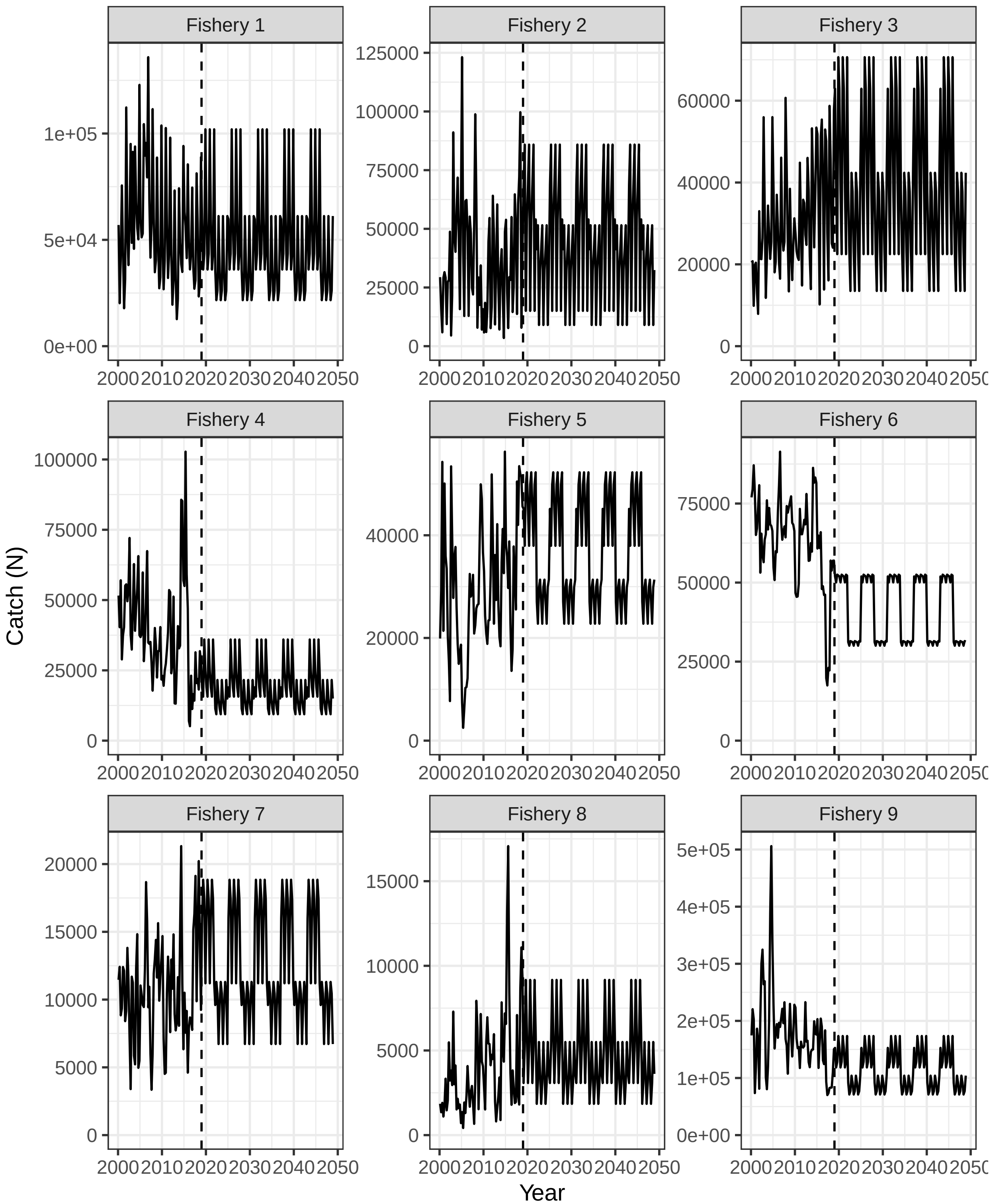

Figure 13: Future catches of the northern and tropical longline BET fisheries set as a square wave with an amplitude of 25% above and below the mean catches in 2016-2018. Note the differing y-axis scales.

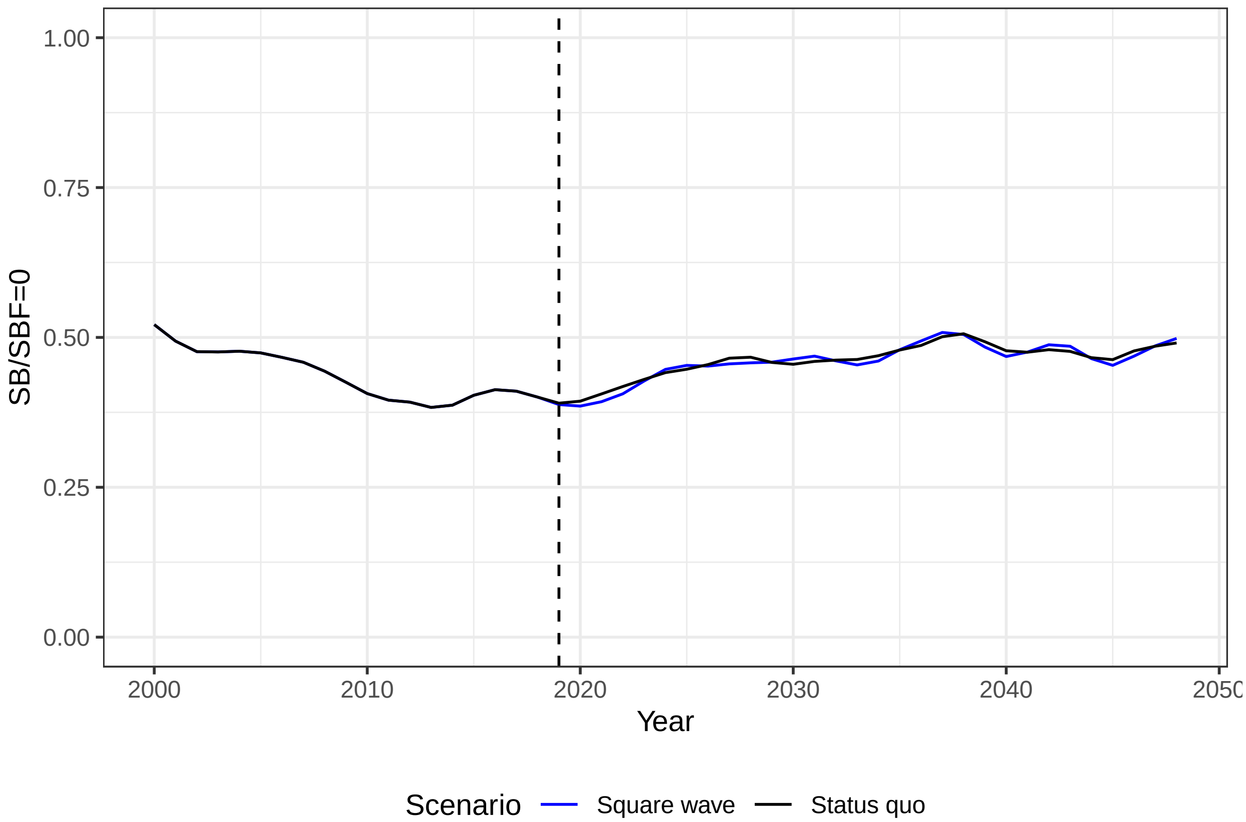

Figure 14: Future bigeye SB/SBF=0 after projecting the tropical longline fisheries with catches as a squarewave (25% around the mean 2016-2018 catches) and with status quo (mean 2016-2018) catches. The variability in the SB/SBF=0 is driven by recruitment variability as well as variability in catches.

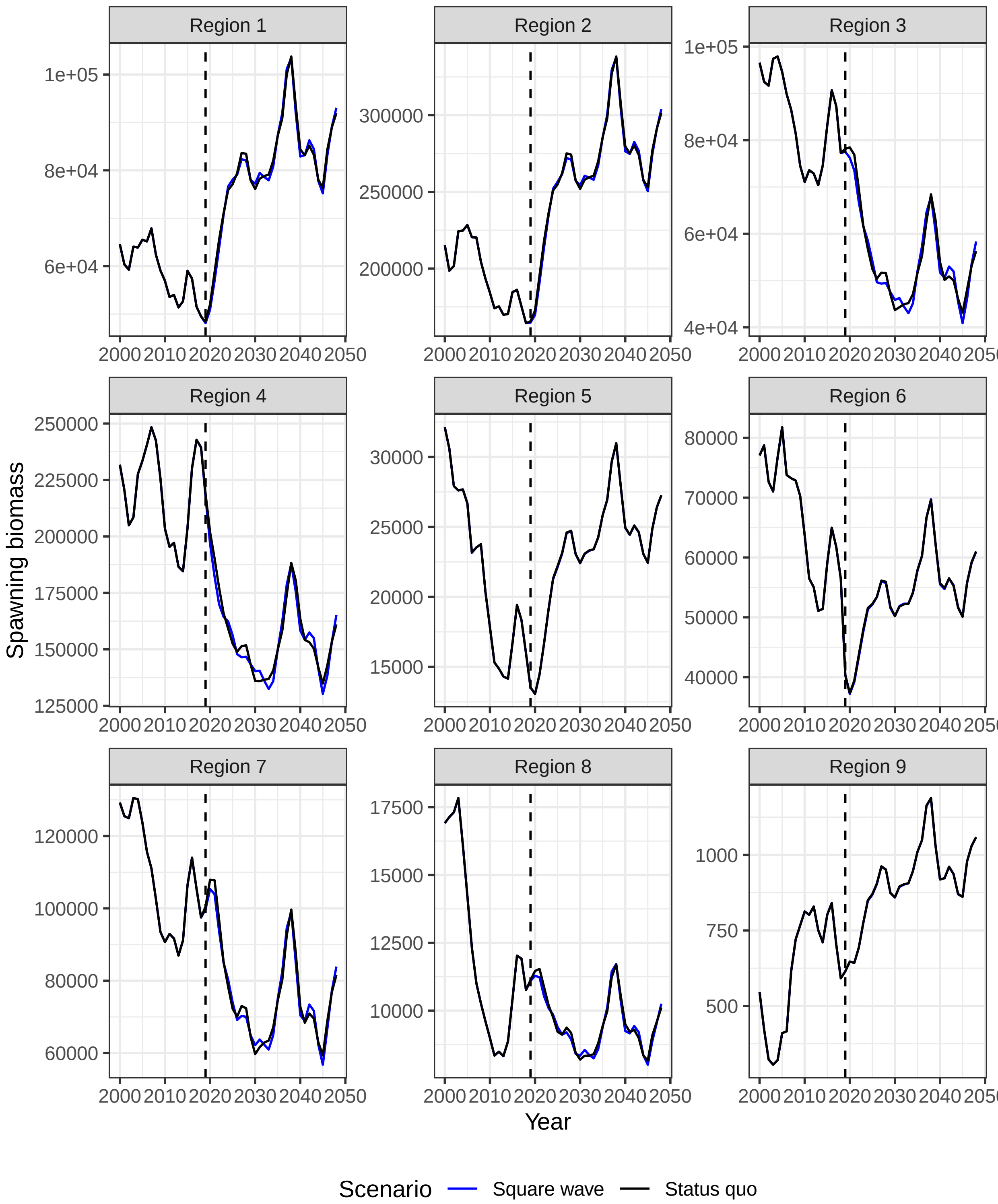

Figure 15: Future bigeye spawning biomass by model region after projecting the tropical longline fisheries with catches as a squarewave (25% around the mean 2016-2018 catches) and with status quo (mean 2016-2018) catches. The variability in the spawning biomass is driven by recruitment variability as well as variability in catches.

E.2 Setting up future tropical longline effort

The resulting effort of the TLL fisheries to take the BET catch is transferred to the corresponding fisheries in the SPA OM. It should be noted that the effort values in each stock OM have been internally scaled and are not necessarily directly comparable nor represent numbers of hooks etc. This means that it is not possible to simply directly transfer the effort values between fisheries in the different stock OMs and the use of relative effort is necessary.

The BET TLL fisheries of interest are those that operate in an region that overlaps with an region in the SPA models: fisheries 4 and 5 (in region 3), fishery 8 in region 8 and fishery 9 in region 4. The catch, effort and effort relative to the average effort in the period 2009-2016 are shown in Figure 16 (alternative year ranges for calculating the relative effort are possible).

The square wave in the catches can be seen in the resulting effort. The effort also changes in time as a result of the biomass in each of the regions changing (Figure 15). For example, if the biomass is decreasing but the catches remain constant, greater effort will be required to take those catches.

The weights calculated in Section D are applied to the relative effort of each of the BET fisheries in Figure 16 to give the relative effort of the SPA fisheries 1 and 2 that operate in the SPA region 1, following the method described in Scott et al. (2021a). The same relative effort is applied to both fisheries to produce their future effort for the projection (Figure 17). The square wave from the BET catches in the TLL fisheries can be seen in the future effort of the TLL fisheries in the SPA model giving confidence that the method is working.

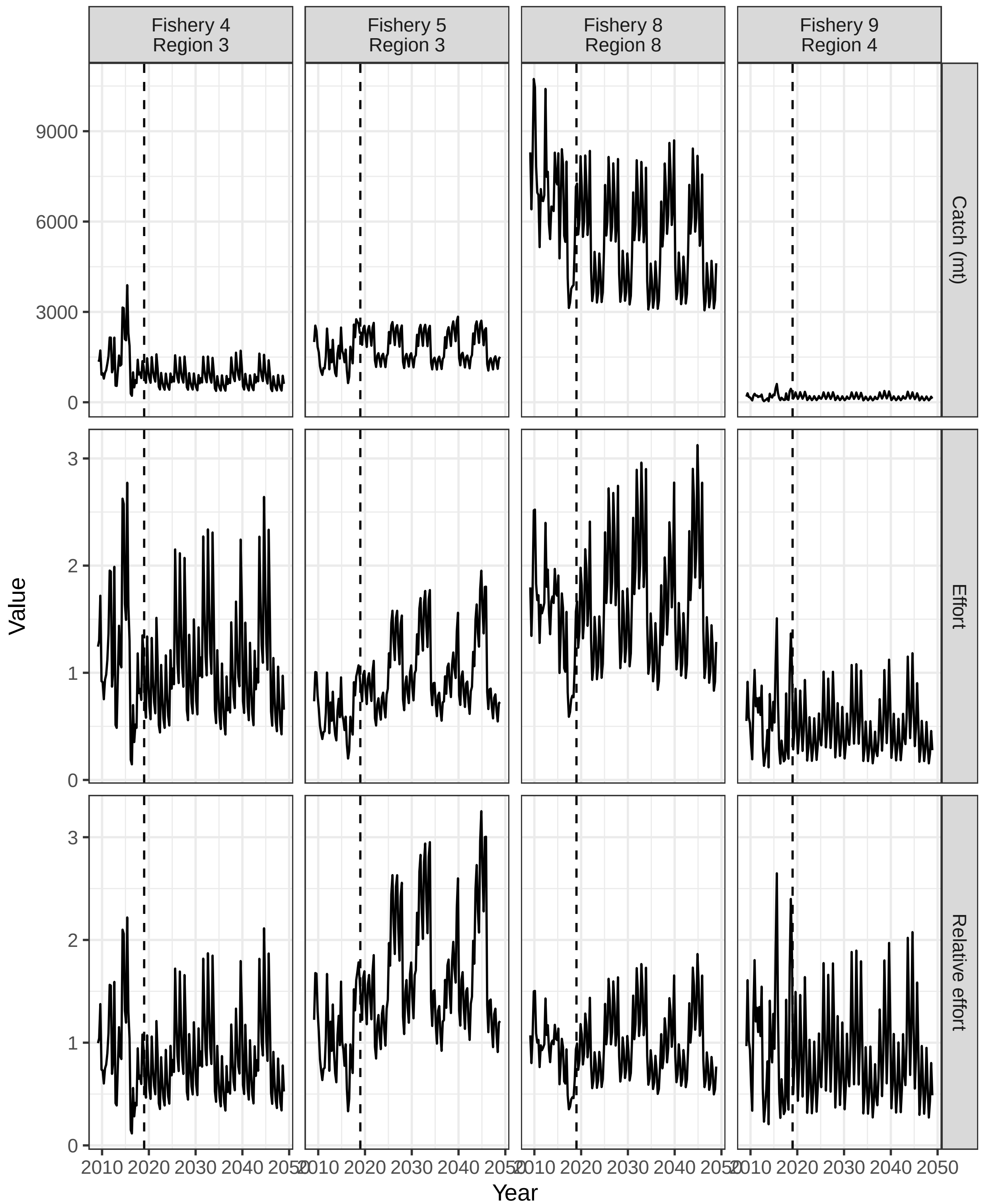

Figure 16: The catches (by weight), resulting effort and resulting effort relative to the average effort in the period 2009-2016 for the tropical longline fisheries in the bigeye model that overlap with the tropical longline fisheries in the South Pacific albacore model.

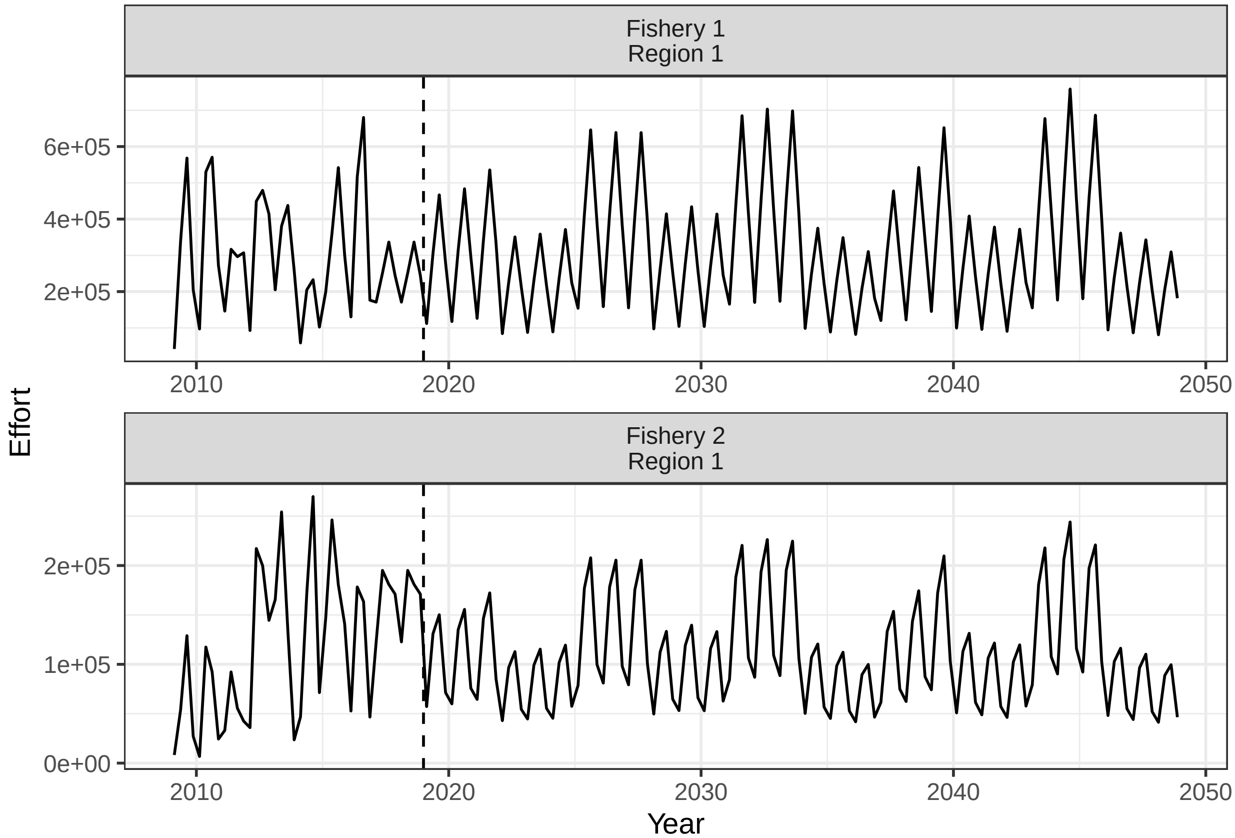

Figure 17: Effort of the tropical longline (TLL) fisheries in the South Pacific albacore model. The effort is set through the transfer of effort that was needed to take the catches of the TLL fisheries in the bigeye model. The future TLL catches in the bigeye model have a square wave pattern, which is then realised in the effort in the South Pacific albacore model.

F Example results

F.1 Catches of South Pacific albacore

The SPA model is projected with the effort of fisheries 1 and 2 set according to Figure 17. As mentioned above the catches of the SLL fisheries that would be managed through the SPA MP are set to a constant catch level equal to the mean of catches in 2016-2018.

Examples of the the resulting catches can be seen in Figure 18. The catches of fisheries 1 and 2 show a square wave pattern, following the square wave in the BET catches of the TLL fisheries. The catches of those fisheries will also be influenced by the stock biomass in region 1. The catches of fishery 3, a SLL fishery, is shown as an example. The total catches of SPA show a faint square wave pattern, indicating the low level of impact that the BET MP may have on catches of SPA.

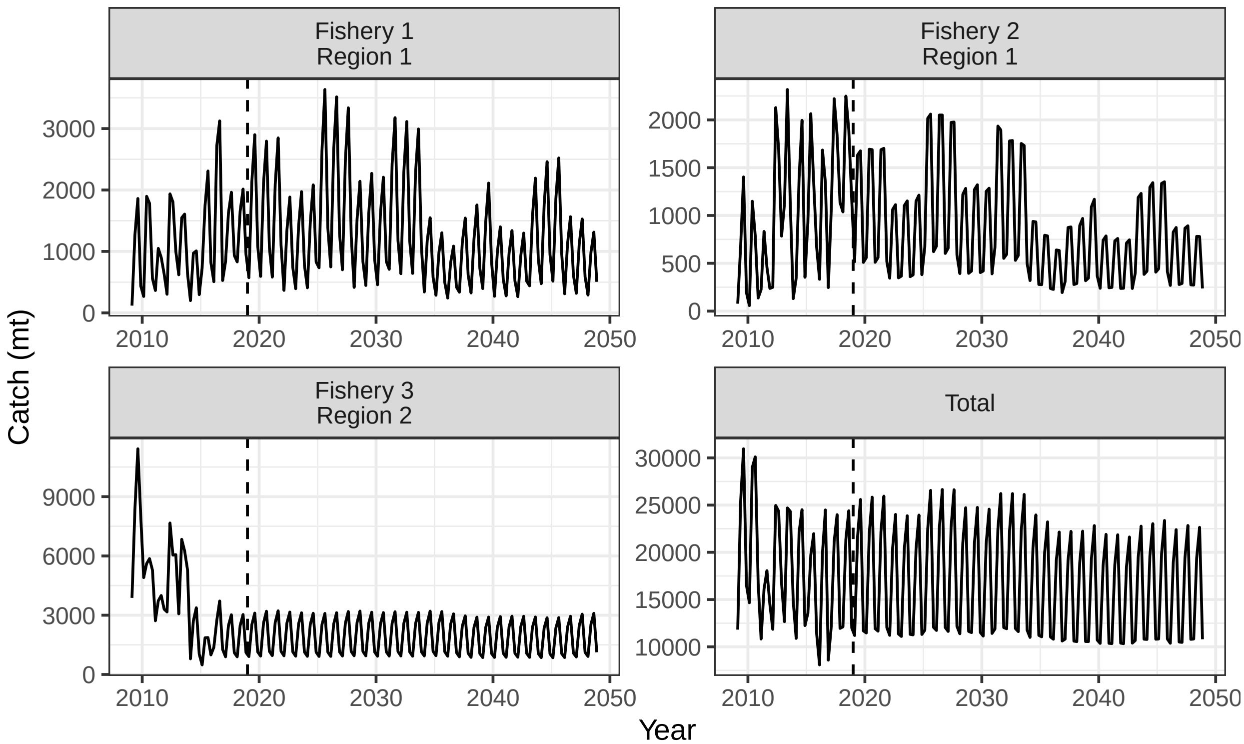

Figure 18: Projected catches of South Pacific albacore taken by fisheres 1 and 2 (tropical longline fisheries with effort transferred from the bigeye model with a square wave applied to the bigeye catch), fishery 3 (an example southern longline fishery with constant catches set at the mean catches of 2016-2018) and the total catch.

F.2 Stock status of South Pacific albacore

The resulting SB/SBF=0 and spawning biomass by region can be seen in Figures 19 and 20. There is little difference between the TLL fisheries in the BET models being set as a square wave and being held constant at the mean of 2016-2018 levels. The biggest difference occurs in region 1, which is where the TLL fisheries operate.

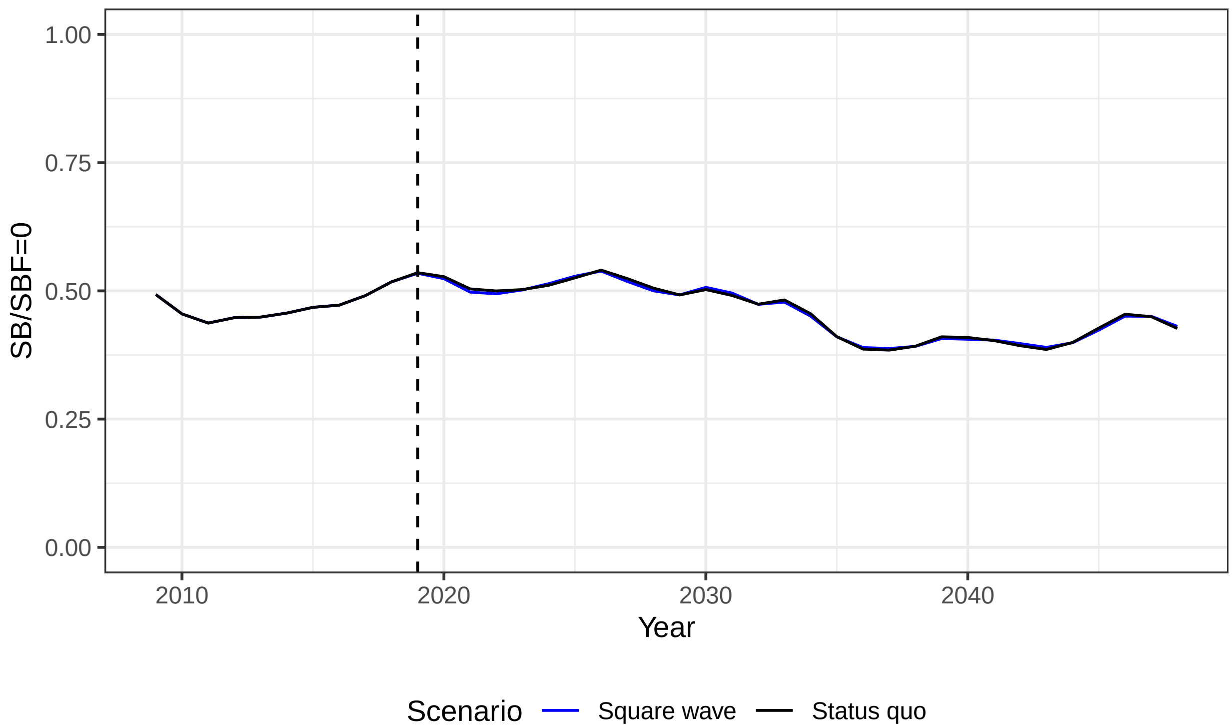

Figure 19: Future South Pacific albacore SB/SBF=0 after projecting the tropical longline fisheries in the bigeye model with catches as a squarewave (25% around the mean 2016-2018 catches) and with status quo (mean 2016-2018) catches.

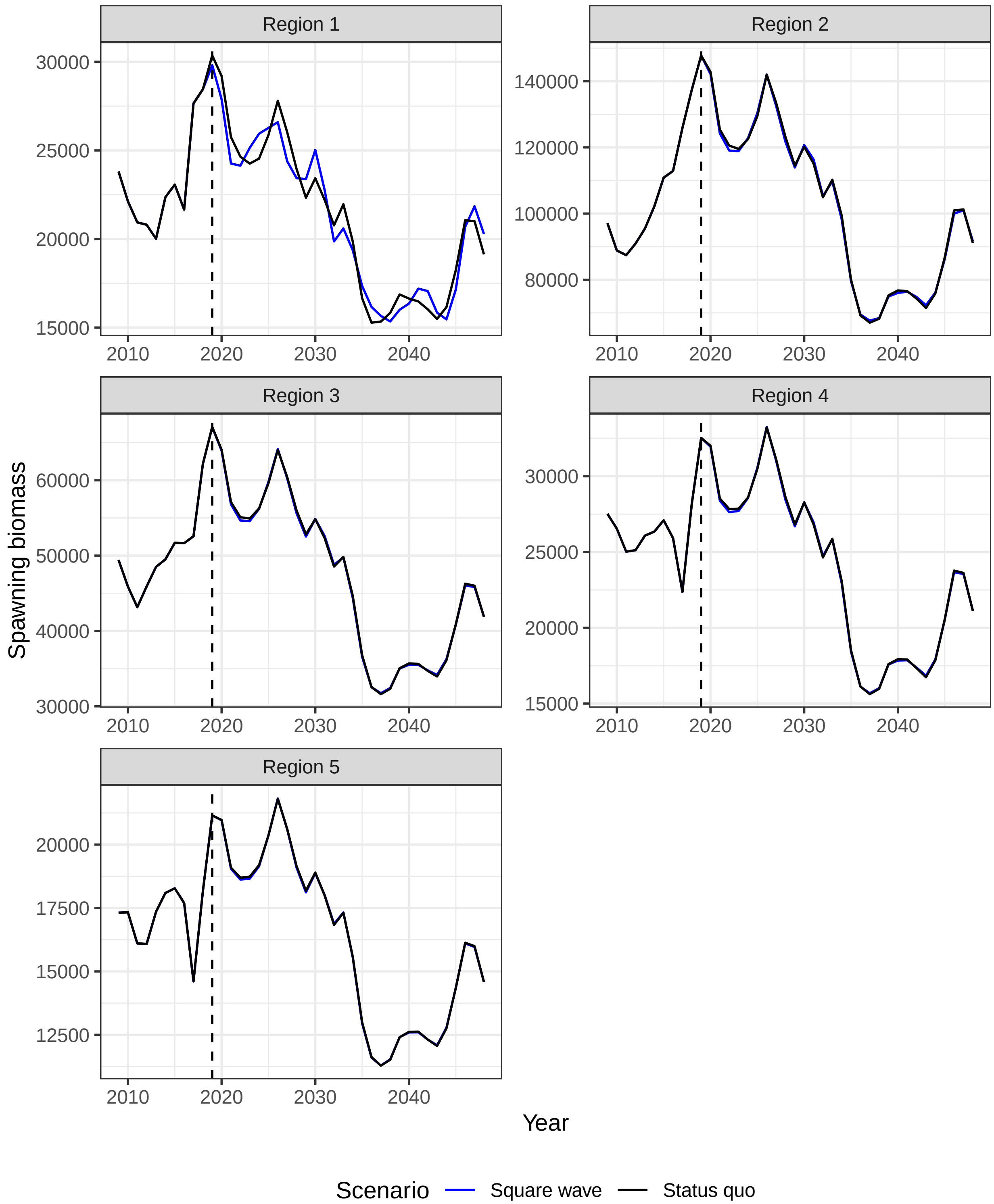

Figure 20: Future South Pacific albacore spawning biomass after projecting the tropical longline fisheries in the bigeye model with catches as a squarewave (25% around the mean 2016-2018 catches) and with status quo (mean 2016-2018) catches.