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Mixed-fishery harvest strategy developments

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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. These four stocks are caught by an overlapping mix of fisheries which means that management measures aimed at one particular stock can therefore have impacts on other stocks. 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, in line with the agreed WCPFC harvest strategy workplan. The impact of these MPs on yellowfin would then be evaluated.

This report describes a proof of concept implementation of the multi-species modelling framework based on single stock operating models (OMs) for skipjack, bigeye and yellowfin. Example simulation results are generated that compare the performance of three different harvest control rules (HCRs) for the skipjack MP. The level of future fishing for the purse seine, pole and line and domestic fisheries in the OMs for all three stocks are managed through the skipjack MP. For this proof of concept, no bigeye MP is applied; the tropical longline fishery catch is assumed to remain constant at the average of 2016-2018 levels.

Throughout, where an MP is applied that defines a future catch, or a catch level is assumed, the realised fishery effort required to take that catch is calculated and applied to the corresponding fishery or fisheries in the other tuna OMs, correspondingly influencing stock status. For example, the realised effort made by the tropical longline fisheries to take the bigeye catch is also applied in the yellowfin simulations.

Results of these initial trials are presented here and the impact of the application of the skipjack MPs on bigeye and yellowfin stocks is demonstrated.

Several assumptions are made to run these simulations including the continued application of the current FAD closure period for the purse seine fishery, and the treatment of fisheries in archipelagic waters and territorial seas. It is important that these assumptions are clearly defined and presented to stakeholders in a transparent manner to facilitate input on the modelling, and ultimately management decisions.

This paper demonstrates that the technical challenges involved in implementing the multi-species modelling framework can be addressed and the modelling framework remains tractable. The example results presented here are sufficiently encouraging to support the continued development of this approach. The next steps include:

- Building a full suite of OMs for bigeye and yellowfin;
- Developing candidate MPs for bigeye for the tropical longline fishery; and

- Agreement of multi-species performance indicators.

We invite WCPFC-SC to:

- Note progress in developing the multi-species modelling framework;
- Provide feedback on this initial approach for including mixed fishery interactions when developing and testing harvest strategies for the four main WCPO tuna stocks; and
- Provide suggestions for the initial development of prospective bigeye MPs.

1 Introduction

WCPFC12 agreed to a workplan for the adoption of harvest strategies for WCPO skipjack, bigeye, yellowfin and South Pacific albacore tuna. These tuna stocks are caught by an overlapping mix of fisheries which means that management measures aimed at one particular stock can therefore 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 hierarchical approach (subsequently renamed 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 skipjack, bigeye and South Pacific albacore. 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 4). 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 skipjack MP. The tropical longline fisheries are potentially managed through the bigeye MP and the southern longline fisheries potentially managed through the South Pacific albacore MP (Table 4). There is no specific yellowfin MP, but the yellowfin stock will be indirectly managed by catches resulting from fishery settings provided by the skipjack, bigeye and South Pacific albacore 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.

It is worth noting that managing fisheries through MPs cannot necessarily encapsulate or replace all decisions that need to be made to implement a harvest strategy. There will need to be some over-arching agreements under which all potential MPs would operate, for example, the application and duration of any FAD closure for the purse seine fishery.

This report describes an exploratory implementation of the multi-species approach for skipjack, bigeye and yellowfin tuna, with several fisheries managed through the skipjack MP (purse seine, pole and line, and some domestic fisheries). The tropical longline fishery, scheduled to be controlled by the bigeye MP, is assumed constant for this initial investigation, while South Pacific albacore is not considered in this study. An evaluation framework is developed and tested by exploring the performance of three candidate skipjack MPs and their impact on the skipjack, bigeye and yellowfin stocks.

The paper presents the key elements of the framework. It describes the operating models (OMs) considered for skipjack, bigeye and yellowfin within this exploratory implementation. It describes the approach taken to link the fisheries within these species-specific OMs and summarises the results arising from the application of a small set of skipjack MPs on all three stocks.

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 allow us to simulate 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 skipjack, bigeye, yellowfin and South Pacific albacore (although we do not consider albacore in this study) (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).

Progress has been made on developing an individual MSE framework for skipjack that uses single stock Multifan-CL models based on the most recent stock assessments (Scott et al., 2020b, 2019a; Vincent et al., 2019). In this paper an exploratory set of OMs are developed for bigeye and yellowfin that are also single stock Multifan-CL models based on the most recent stock assessments (Ducharme-Barth et al., 2020; Vincent et al., 2020).

Similar to the WCPO tuna stock assessments, each single stock OM has several areas which contain fisheries representing fishing activity of a particular gear type. The fisheries are not necessarily associated with any particular country. The regional and fishery structure of the skipjack OMs is different to the bigeye and yellowfin OMs which share the same structure (Figure 6; Tables 6 and 7).

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 this paper, individual OMs for skipjack, bigeye and yellowfin are included in a single MSE framework to simulate the mixed fishery interactions. Interactions with South Pacific albacore, through the activities of the southern longline fishery, are not considered at this time but will need to be considered for future evaluations.

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 (average of 2016 to 2018) levels. For future evaluations, as these are sovereign waters, each relevant CCM will decide on their approach (e.g. adopt the MP's decisions, compatible measures, etc.), which can be modelled within the framework. An early indication of proposed approaches, for example whether status quo assumptions are appropriate, will assist in model development.

2.1 Skipjack operating models

The fisheries in the skipjack OMs, based on the 2019 stock assessment, are a mix of purse seine, pole and line and longline as well as the key domestic fisheries of Indonesia, Philippines and Vietnam (Table 6).

The longline fisheries in the skipjack OMs have extremely low catches and are only included to provide size-based information to assist in model fitting. Although under the proposed multi-species approach the longline fisheries would be managed through the South Pacific albacore and bigeye MPs, depending on area (Figure 6), the negligable impact they have on the skipjack stock means they can be effectively ignored when running the skipjack simulations. The longline fisheries are discussed further under the bigeye / yellowfin section below.

The initial evaluations presented in this report use a subset of the full suite of skipjack OMs (Scott et al., 2019a) (Table 1). Unlike the full set of skipjack OMs, only one level of recruitment variability (2005-2014) is used here. Additionally, effort creep in the purse seine fishery is not considered. Combining all levels across the uncertainty grid axes gives 24 OMs.

Table 1: The grid of skipjack operating models, based on Scott et al. (2019a).

Axis	Levels	Options
Steepness	3	0.65, 0.8, 0.95
Tag mixing period (qtr)	2	1, 2
Growth	2	low, high
Hyperstability in CPUE	2	0, -0.5

2.2 Bigeye and yellowfin operating models

In this analysis the bigeye and yellowfin OMs are taken directly from the recent stock assessments and share the same regional and fishery structure (Ducharme-Barth et al., 2020; Vincent et al., 2020). The fisheries of these OMs include purse seine, pole and line, longline, and fisheries in Indonesia, Philippines and Vietnam (Table 7).

Here, the uncertainty grids of OMs for bigeye and yellowfin are based on the grids from the most recent assessment (Tables 2 and 3). An additional axis of recruitment period is included for bigeye only. 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 and 72 yellowfin OMs.

Table 2: 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

Table 3: The grid of yellowfin operating models, based on Vincent et al. (2020).

Axis	Levels	Options
Steepness	3	0.65, 0.8, 0.95
Growth	3	Modal estimate, External otolith, Cond age-at-length
Size freq. weighting	4	20, 60, 200, 500
Tag mixing period (qtr)	2	1, 2

3 Linking the skipjack, bigeye and yellowfin operating models

The mixed-fishery simulations presented here are single stock simulations for skipjack, bigeye and yellowfin, noting that South Pacific albacore is not considered in this analysis. To perform the simulations it is necessary to set the future effort or catch of each fishery in the skipjack, bigeye and yellowfin 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 pole and line fisheries in the bigeye and yellowfin OMs are managed through the skipjack MP. One of the key challenges for the simulations is therefore including the interactions between the OMs and the MPs.

In the analysis presented here, only a skipjack MP is in operation (Figure 1). The fisheries in the skipjack OMs are either managed through the skipjack MP, are not managed through any MP due to being in archipelagic waters, or have very low catches and are ignored in the simulations (the longline fisheries) (Table 6). The skipjack simulations can therefore be run independently of the bigeye and yellowfin simulations.

The purse seine, pole and line, and domestic fisheries fisheries in the bigeye and yellowfin OMs are managed through the skipjack MP. The future dynamics of these fisheries is determined in the skipjack simulations, through the application of the skipjack MP. To run the bigeye and yellowfin simulations, these dynamics need to be transferred to the bigeye and yellowfin OMs (Figure 1).

The tropical longline fisheries in the yellowfin OMs would be managed through the bigeye MP and the future dynamics of these fisheries would be determined in the bigeye simulations, through the application of the bigeye MP. In these evaluations, there is no bigeye MP and the future bigeye catches by the tropical longline fisheries are set constant at the seasonal average of the years 2016-2018. To run the yellowfin simulations, the dynamics of these fisheries need to be transferred from the bigeye simulations to the yellowfin OMs, so that the effort applied to take the bigeye catch is applied in the yellowfin simulations (Figure 1).

Given the dependencies between the stocks described above, the approach taken here is to run the skipjack simulations first, then the bigeye simulations, and finally the yellowfin simulations, transferring the resulting fishery dynamics from one model to another. This process is described below.

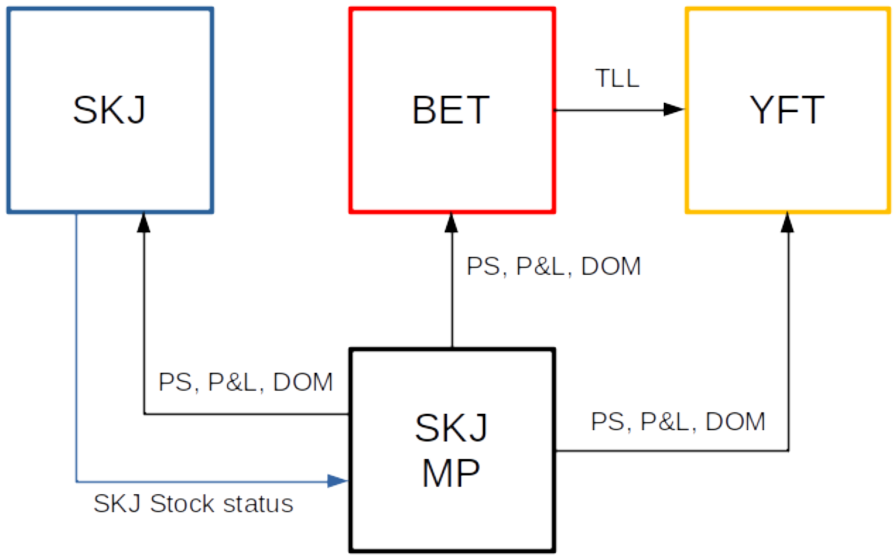

Figure 1: Schematic of the evaluations presented here. The skipjack (SKJ) management procedure (MP) sets the fishing opportunities for the purse seine (PS), pole and line (P&L), and domestic (DOM) fisheries in the skipjack, bigeye (BET) and yellowfin (YFT) models, given the stock status of skipjack. The fishing oportunities of the tropical long line (TLL) are determined by catches of bigeye and need to be transferred to the yellowfin model. Future evaluations will use a bigeye management procedure to set tropical long line catches. The skipjack simulations are run first, then the resulting dynamics of the PS, P&L and DOM fisheries are transferred to the BET and YFT models. The BET simulations are then run and the resulting dynamics of the TLL fisheries are transferred to the YFT models. The YFT simulations can then be run.

An MP may use either catch or effort to set the fishing opportunities for the fisheries it controls (see Tables 6 and 7). In order to transfer the fishery dynamics of one simulation to another, they must be converted to a common metric (i.e. fishing effort). This means that for a catch controlled fishery, the amount of effort required to take the specified catch must be determined so that the effort for that fishery can be used as an input to the next simulation.

The method by which the resulting effort from the skipjack simulations are transferred to the bigeye and yellowfin simulations, and from the bigeye to the yellowfin simulations, is described below for each fishery type. Examples and results of this process using a single example iteration are given in Appendices E and F.

South Pacific albacore is not considered here and the future catches by the southern longline fisheries in the bigeye and yellowfin OMs are set constant at the seasonal average of the years 2016-2018.

3.1 Purse seine

In line with the recent skipjack evaluations, the output of the skipjack MP provides a scalar that sets the future effort in each three year management period of the purse seine fisheries relative to the effort in 2012 (Scott et al., 2019d). All the future effort of the purse seine fisheries in the skipjack OM are scaled equally, apart from fisheries 12 (*S-ID-PH-5*), 19 (*SA-ALL-6*) and 20 (*SA-ALL-6*) which partially operate in archipelagic waters (Table 6). The skipjack MP scalar applied to these fisheries is reduced to reflect that a component of these fisheries is currently unaffected by the MP.

In the bigeye and yellowfin OMs, the skipjack MP manages the future purse seine effort in the same way by applying the output scalar from the skipjack MP to the effort in 2012 (Figure 14). The purse seine fisheries 24 (*S-ID.PH-7*), 25 (*S-ASS-ALL-8*) and 26 (*S-UNA-ALL-8*) in the bigeye and yellowfin OMs partially operate in archipelagic waters (Table 7). These three fisheries correspond to fisheries 12, 19 and 20 in the skipjack OMs and a similar reduction in MP output scalar is applied.

3.2 Pole and line

The skipjack MP defines future levels of pole and line skipjack catch based on the stock status of skipjack. Catches of bigeye and yellowfin from the pole and line fisheries are relatively small (Scott et al., 2020a).

In the skipjack simulations, the MP output scalar is applied to the catch level in 2012 to set the future catch limit for that management period and it is assumed that the catch limits are always taken. The realised efforts of the pole and line fisheries to meet the skipjack catch limits in the skipjack 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 pole and line effort in the bigeye and yellowfin OMs needs to reflect the effort made by those fisheries to catch the skipjack catch limit that is set by the skipjack MP. The approach here is to calculate the realised effort to take the defined skipjack catch from the skipjack simulations, and then transfer it to those fisheries in the bigeye and yellowfin OMs. In this way, the measures stipulated by the skipjack MP are realised in the bigeye and yellowfin simulations.

The future realised effort of each pole and line fishery in the skipjack OMs relative to the average effort in a reference period is calculated. This is the relative effort needed by each fishery to take the skipjack catch limit that was set by the skipjack MP. Due to the relatively high variability in historical effort, a relatively long reference period of 2009-2018 is used. Alternative reference periods are possible and will need to be agreed. The relative realised effort is then applied to the bigeye and yellowin OMs to set the future effort.

However, the regional and fishery structures of the bigeye and yellowfin and the skipjack OMs are different and the fisheries do not directly overlap which makes this process less straightforward (Figure 6). The method used here is to calculate the overlap of each skipjack pole and line fishery with each bigeye and yellowfin pole and line 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 skipjack fishery to the corresponding bigeye and yellowfin fisheries. The future effort of the pole and line fisheries in the bigeye and yellowfin OMs is set by applying the weighted relative effort from the skipjack results to the effort in the same reference period (see Appendix E.3 for an example).

3.3 Domestic

There are four fisheries of Indonesia, Philippines and Vietnam (referred to as domestic) in the bigeye and yellowfin OMs: fisheries 17, 18, 23, 32 (Table 7). Fishery 18 (*HL.IDPH.7*, a handline fishery) and fishery 23 (*Dom.ID.7*, assumed to be equivalent to skipjack fishery 11, *Z-ID-5*) are assumed to fish entirely within the archipelaic waters of Indonesia. As such, in this analysis, they are not subject to an MP. In this analysis, it is assumed that the future catches of bigeye and yellowfin for these fisheries are set at a status quo level (the average of the period 2016-2018). Alternative status quo periods and options for these fisheries are possible and will need to be agreed.

The domestic fisheries in the Philippines and Vietnam (Fisheries 17, *Dom.Z-PH* and 32, *Dom.VN.7*) are equivalent to the skipjack fisheries 10 (*Z-PH-5*) and 16 (*Z-VN-5*) and are managed through the skipjack MP (Table 6). In the skipjack simulations, these fisheries are managed by the skipjack MP through the setting of catch limits of skipjack, relative to the catch in 2012. The future realised effort of these fisheries in the bigeye and yellowfin OMs must reflect the amount of effort made by these fisheries to catch the skipjack catch limit that is set by the skipjack MP.

As with the pole and line fisheries, the future effort of the domestic fisheries 11 and 18 in the skipjack OMs relative to a reference period in the past is calculated. This is the relative effort needed by each skipjack fishery to take the catch limit that is set by the skipjack MP. Here, the reference period is 2009-2018. Alternative reference periods are possible and will need to be agreed.

This relative effort is applied to that in the same reference period of the corresponding fisheries in the bigeye and yellowfin OMs to generate the future effort (see Appendix E.4 for an example). The measures stipulated by the skipjack MP are therefore realised in the bigeye and yellowfin simulations.

3.3.1 Tropical longline

As mentioned above, in this analysis there is no bigeye MP and the future bigeye catches of the tropical longline fisheries are constant at the seasonal average of the years 2016-2018. The resulting effort needs to be transferred to the tropical longline fisheries in the yellowfin OMs. The fishery and area structure of the bigeye and yellowfin models is the same so that each tropical longline fishery in the bigeye OMs has a corresponding fishery in the yellowfin OMs. The same approach as that described above for the domestic fisheries is used where the effort relative to the effort in a reference period of each fishery in the bigeye OMs is applied to the effort in the same reference period of the corresponding fishery in the yellowfin OMs (see Appendix E.5 for an example).

This is a different and improved approach to that used in other recent work that has assumed that changes in tropical longline bigeye catches yield a comparable change in tropical longline yellowfin catches (Pilling et al., 2019).

When candidate bigeye MPs are evaluated in the future, this method will allow the resulting fishing opportunities set by the bigeye MP to be included in the yellowfin simulations.

4 Running the simulations

Three skipjack MPs are tested to demonstrate the approach of linking three single stock OMs together in the mixed-fishery MSE framework. Each MP has the same data collection and estimation method (a Multifan-CL stock assessment) and differ only in the shape of the HCR (Scott et al., 2019a). The HCRs were chosen to provide contrast in the results and their selection does not reflect their suitability at successfully achieving management objectives (Figure 2). They range in terms of how precautionary they are, with HCR 3 setting relatively high levels of catch and effort even when the estimated skipjack $SB/SB_{F=0}$ is close to the LRP, while HCR 4 sets conservative levels, even at high levels of estimated skipjack $SB/SB_{F=0}$.

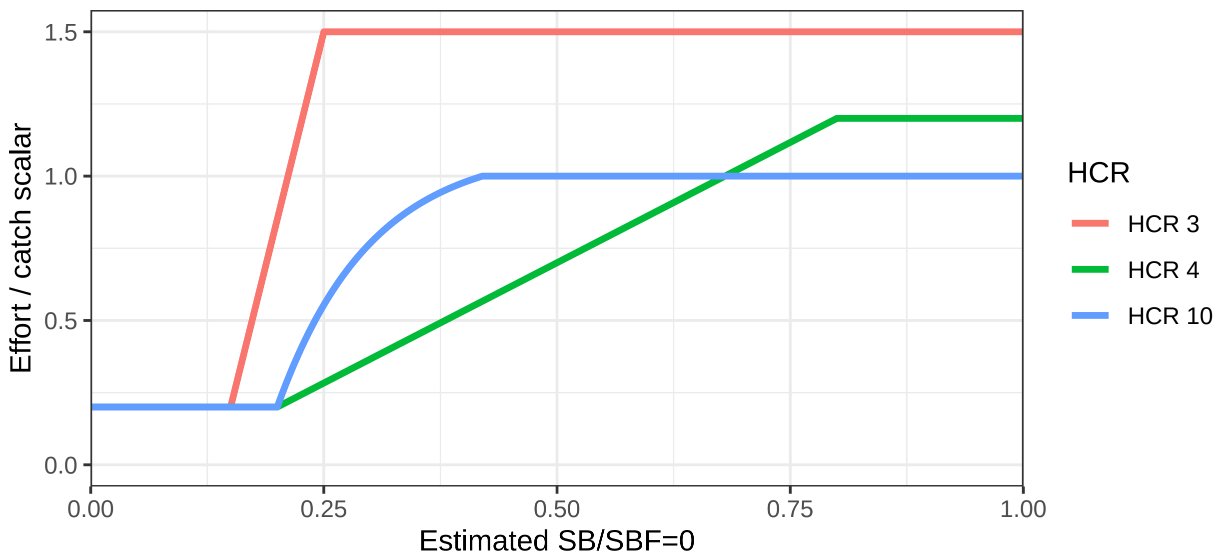

Figure 2: The shapes of the three HCRs used as part of the skipjack management procedure tested in this analysis. HCR 4 can be considered the most precautionary, while HCR 3 is the least precautionary.

The MPs are tested by running 240 stochastic simulations across the model grids of the three stocks (Section 2), 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, 2021). For each skipjack MP tested here, 240 stochastic projection iterations are performed for each of the three stocks where each iteration has different future recruitment variability for each stock. The basis and assumptions for the skipjack evaluations are the same as those used in previous evaluations, for example, regarding the FAD closure period, and using a three year management period (Scott et al., 2019a, 2020b).

In line with the current skipjack evaluations, the 240 iterations are spread equally across the 24 skipjack models in the grid giving 10 iterations per model. For bigeye and yellowfin, 240 OMs are randomly selected with replacement from the model grids and allocated to a corresponding skipjack iteration to give 240 iterations. Future evaluations may also include randomly sampling from the skipjack grid too, rather than allocating a fixed number of iterations to each model.

This random allocation of bigeye and yellowfin models to skipjack 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 skipjack model does not necessarily correspond with a high value for steepness in the bigeye or yellowfin models. The same iteration and OM allocation of the stock models is used across all the skipjack MPs 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 they are only intended to demonstrate that the multi-species approach to developing mixed fishery harvest strategies for WCPO tuna stocks is technically tractable.

Changes in the skipjack status are reflected in the output of the HCR, leading to changes in fishing pressure across all three stocks. Even though the skipjack MP only considers the skipjack stock status, the projected $SB/SB_{F=0}$ of all three stocks is affected by the choice of HCR (Figure 3).

Results are as anticpiated: HCR 4, the most precautionary HCR, results in higher $SB/SB_{F=0}$ levels for all three stocks while HCR 3, the least precautionary HCR, results in lower $SB/SB_{F=0}$ for all three stocks.
These results demonstrate that the mixed-fishery MSE framework presented here is capable of capturing the interactions between the fisheries and stocks.

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

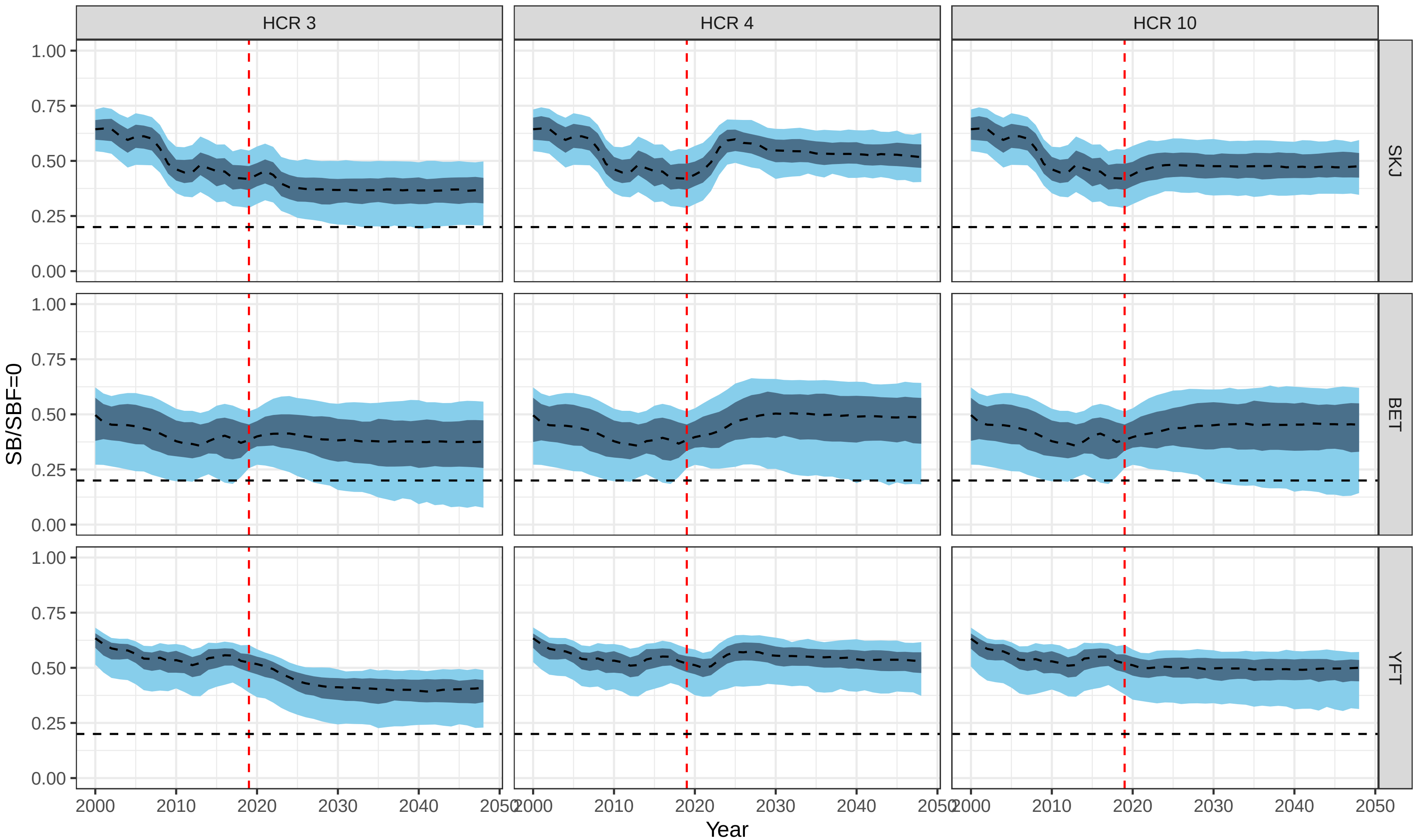

Figure 3: Projected SB/SBF=0 across all iterations and operating models for skipjack (SKJ), bigeye (BET) and yellowfin (YFT) from three skipjack HCRs. The dark blue envelope shows the 20-80 percentiles, the light blue envelope shows the 5-95 percentiles and the dashed line the median. The horizontal dashed line is the limit reference point (0.2). The vertical dashed line indicates the start of the projection period.

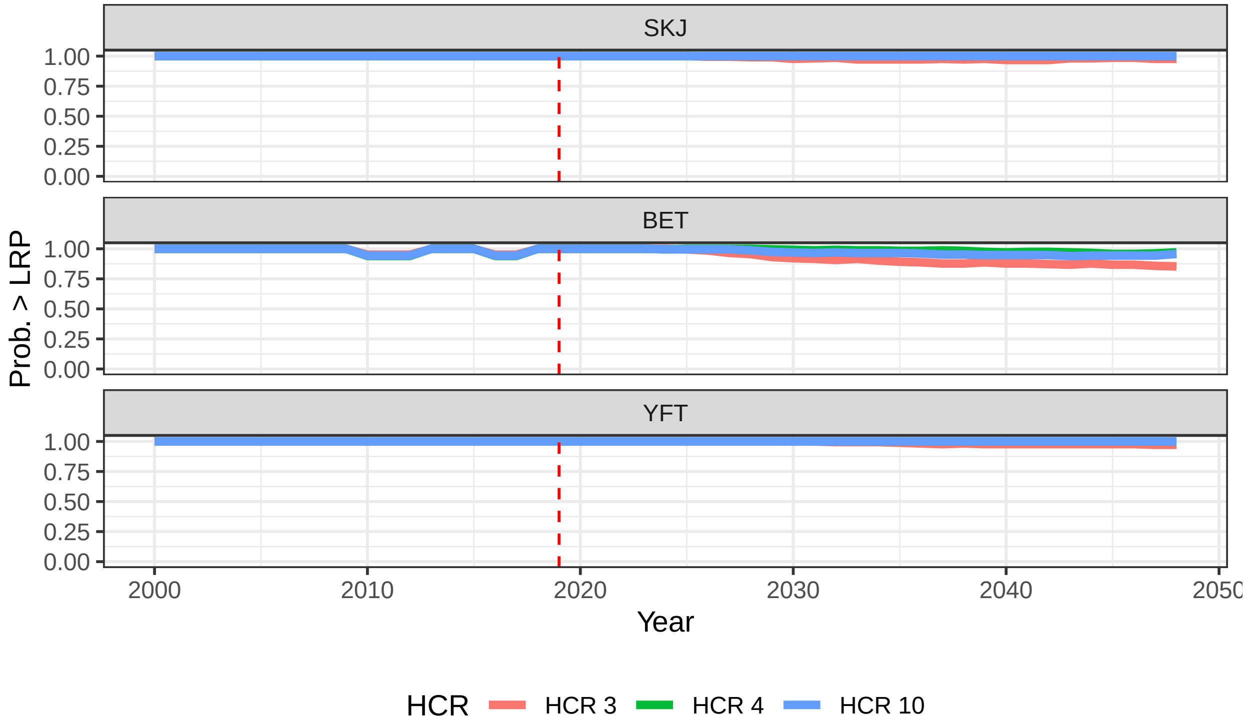

Figure 4: The probability of SB/SBF=0 remaining above the limit reference point for each stock and HCR. The vertical dashed line indicates the start of the projection period.

Only bigeye under HCR 3, the least precautionary HCR, has a non-trivial probability of $SB/SB_{F=0}$ falling below the limit reference point (LRP) of 0.2 (Figure 4). This will be influenced by the recruitment scenarios included within the OMs considered. Even though the simulations are run over a limited range of OMs, these demonstration results suggest that the use of single stock MPs, as described in the multi-species modelling approach, is viable. The results are sufficiently encouraging to continue using this approach to develop mixed fishery harvest strategies for the WCPO tuna stocks, including MPs for bigeye and South Pacific albacore.

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 bigeye and yellowfin 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 bigeye. **Candidate MPs for the tropical longline fishery will need to be generated and tested in the future**. This may include the consideration of empirical and model-based approaches.

The inclusion of South Pacific albacore in the modelling framework and the resulting activities of the southern longline fishery will also be needed.

The multi-species modelling framework will allow the calculation of a range of performance indicators, including multi-species indicators (Yao et al., 2019; Scott et al., 2018; WCPFC, 2017; OFP, 2017). For example, here the probability of depletion being above the LRP is calculated for each stock. It will be necessary to develop additional multi-species indicators that relate impacts on stock status and catches to changes in fishing pressure from the individual single stock MPs. For example, indicators can be developed that evaluate the impacts on the yellowfin and bigeye stocks and catches from changes in purse seine fishing pressure that would be managed through the skipjack MP. **These indicators will need to be developed through consultation with WCPFC members**.

7 Summary

The proposed multi-species modelling framework involves developing prospective single stock MPs for skipjack, South Pacific albacore and bigeye respectively. There is no single stock MP for yellowfin. Instead, the impact of these MPs on yellowfin would then be evaluated using a combined evaluation framework.

This report has described a demonstration modelling approach based on using single stock models for skipjack, bigeye, and yellowfin, with a skipjack MP. The results demonstrate that this modelling approach is tractable and it is possible to determine the impact of the skipjack MP on the bigeye and yellowfin stocks. As work progresses, it will be possible to use this approach to determine the impact of the skipjack, bigeye, and South Pacific albacore MPs on yellowfin. These results are sufficiently encouraging to continue developing this approach.

Acknowledgments

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A Overview of the multi-species modelling framework

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

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).

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

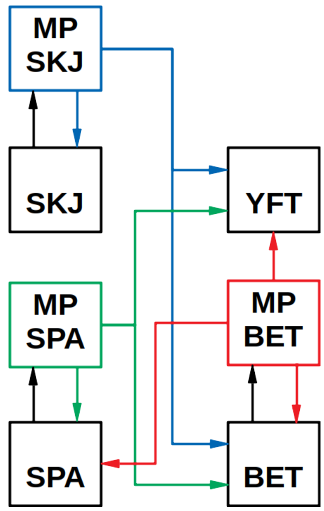

Figure 5: Schematic of the multi-species modelling framework. The skipjack (SKJ) management procedure (MP) sets the fishing opportunities for the purse seine, pole and line and domestic fisheries in the skipjack, bigeye (BET) and yellowfin (YFT) models, given the stock status of skipjack. The BET MP 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 4 and Figure 5). 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 4 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 5. Although Table 4 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 5: 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

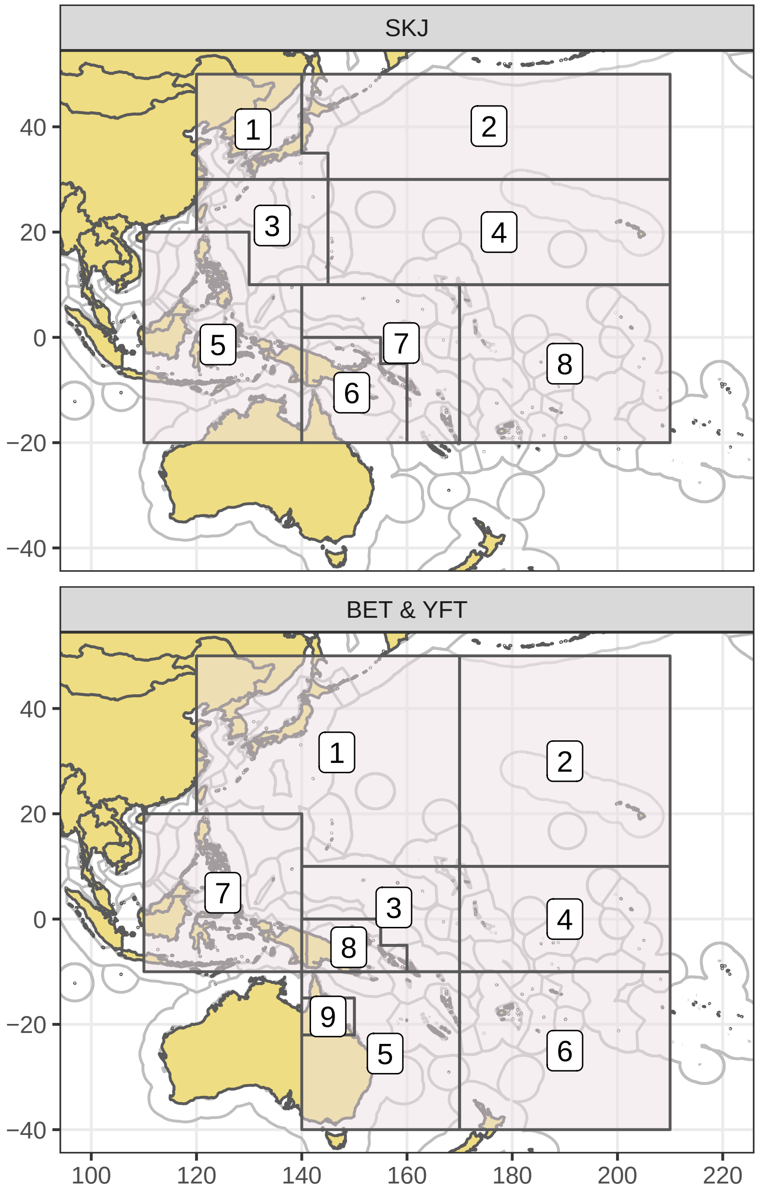

Figure 6: The geographical area covered by the skipjack (SKJ) , bigeye and yellowfin (BET & YFT) operating models and the boundaries of the model areas.

C Tables of fisheries in the operating models

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

Table 6: Fisheries in the skipjack operating model, 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 by the MP through catch or effort limits. Fisheries managed by the BET or SPA MP will have their future effort set by the output of the BET or SPA simulations (not done in this report).

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 7: 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).

D Calculating weights to link the pole and line fisheries of the skipjack and the bigeye and yellowfin models

D.1 Overlap between the skipjack and bigeye & yellowfin operating models

The operating models (OMs) for bigeye and yellowfin have different area structures to the skipjack OMs (Figure 6). In the skipjack OM a pole and line fishery operates in each of the 8 areas. In the bigeye & yellowfin OM a pole and line fishery only operates in areas 1, 3, 7 and 8.

Under the multi-species approach the pole and line fisheries are managed through the skipjack management procedure (MP). To perform the mixed-fishery simulations the realised future effort of the skipjack pole and line fisheries is transferred to the bigeye and yellowfin pole and line fisheries.

If the area structures of the OMs were the same, or if the pole and line fisheries in the skipjack OM were managed through changes to the relative effort (such as with the purse seine fisheries), then it would be straightforward to apply the same proportional change in effort to the bigeye and yellowfin fisheries. However, the area structures are different and the pole and line fisheries are managed through the setting of skipjack catch limits.

To transfer the pole and line effort from the skipjack OMs to the bigeye and yellowfin OMs the overlapping areas and fisheries between the OMs that have pole and line fisheries area identified (Table 8 and Figure 7).

Table 8: Bigeye (BET) and yellowfin (YFT) areas with pole and line fisheries and the associated skipjack (SKJ) areas and fisheries with which they overlap. The bigeye and yellowfin areas are entirely covered by one or more skipjack area. The fishery numbers are shown in parentheses.

BET & YFT area (and fishery)	SKJ area (and fishery)
1 (F20)	1 (F1), 2 (F4), 3 (F7) and 4 (F22)
3 (F21)	7 (F24)
7 (F28)	3 (F7) and 5 (F13)
8 (F22)	6 (F18)

WCPFC databases are essentially integrated into a single database called LogMaster. The historical pole and line effort data from the LogMaster database is presented as numbers of days at 1x1 degree positions. Superimposing the average annual total of these data on the OM areas describes the historical distribution of effort (Figure 7).

For the bigeye and yellowfin areas that are entirely covered by a single skipjack area (areas 3 and 8), the pole and line effort for the fishery in that area can be modified by the same proportion as the fishery in the corresponding skipjack area, relative to some common reference period. For example, if the pole and line effort in skipjack area 7 increased by 10%, the pole and line effort in

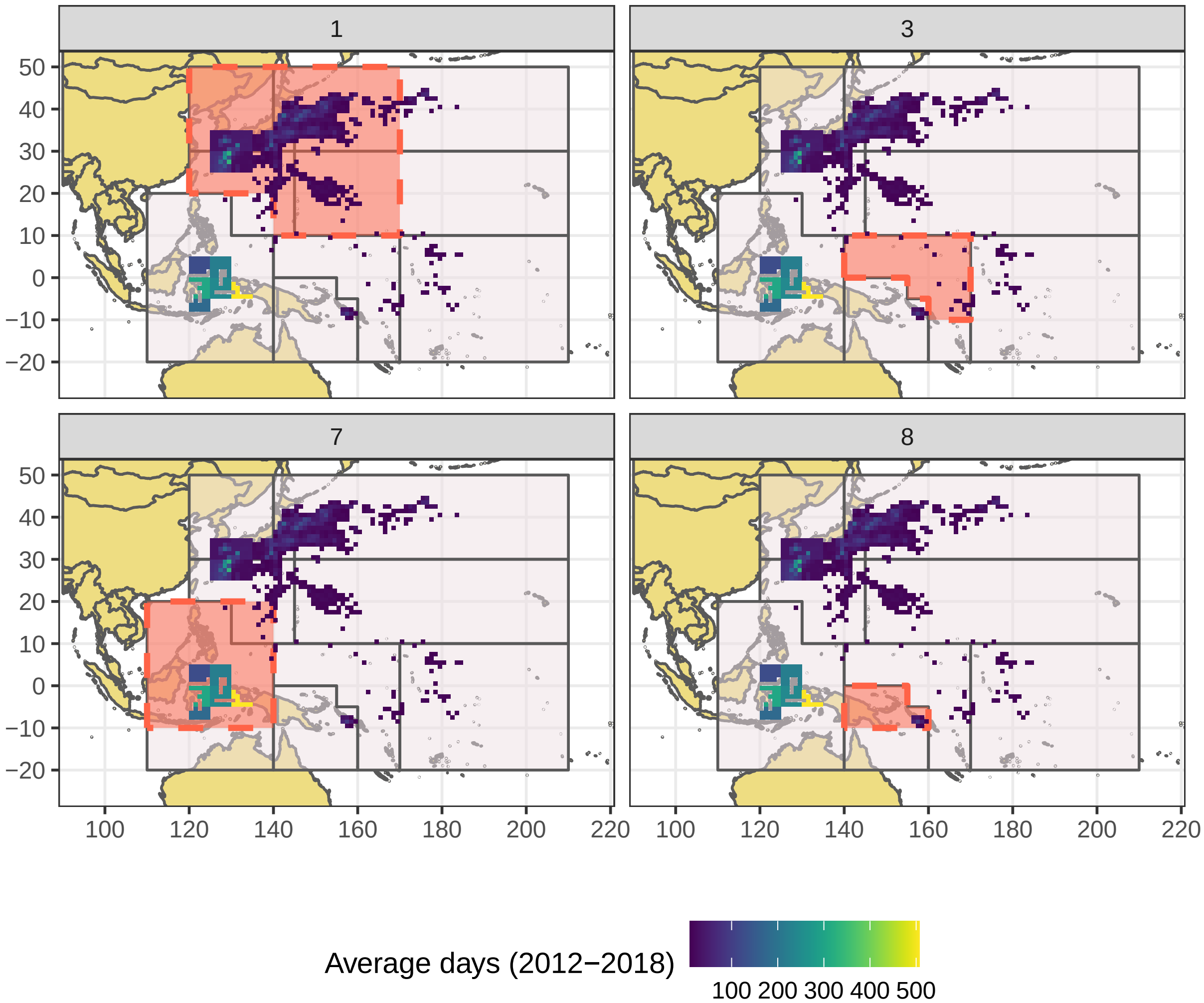

Figure 7: Maps of the overlap between the skipjack and bigeye and yellowfin models. The bigeye and yellowfin model areas with pole and line fisheries (1, 3, 7, 8) are shown in red in each panel, overlaid on the skipjack operating model areas. The points are the average annual effort (measured in days) over the years 2009 to 2018 taken from the LogMaster data (points with less than 10 days are not shown).

bigeye & yellowfin area 3 would also increase by 10%.

For the bigeye and yellowfin areas that are covered by more than one skipjack area (areas 1 and 7) it is more complicated as the proportional changes in effort in the skipjack areas will likely be different. For example, bigeye and yellowfin area 7 is overlapped by the skipjack areas 3 and 5. If the pole and line effort in skipjack areas 5 and 3 increased by 10% and 5% respectively, what would be the overall increase pole and line effort in bigeye and yellowfin area 7?

D.2 Historical effort proportions for the overlapping areas

Here, the historical relative distribution of pole and line effort is used to calculate a weight for each of the parts of a bigeye & yellowfin area that overlap with a skipjack area. These weights are then used as a basis for weighting the future contributions in the MSE projections.

The historical seasonal effort from the LogMaster database is allocated to each of the bigeye and yellowfin areas using the recorded positions (the data is presented at a 1x1 degree resolution). This is then further allocated to each of the parts that overlap with the skipjack areas. From this the proportional contribution of each part can be calculated over time. As there is a strong seasonal component, the historical proportions can be calculated using the seasonal distribution. These analyses are performed for bigeye and yellowfin areas 1 and 7 as areas 3 and 8 correspond to individual skipjack areas.

For bigeye and yellowfin area 1, most of the historical effort has occurred in the parts that overlap with skipjack areas 1, 2 and 3, with comparatively little coming from the part that overlaps with skipjack area 4 (Figure 8). For bigeye & yellowfin area 7, the majority of the historical effort occurred in the part that overlaps with skipjack area 4 (Figure 9.

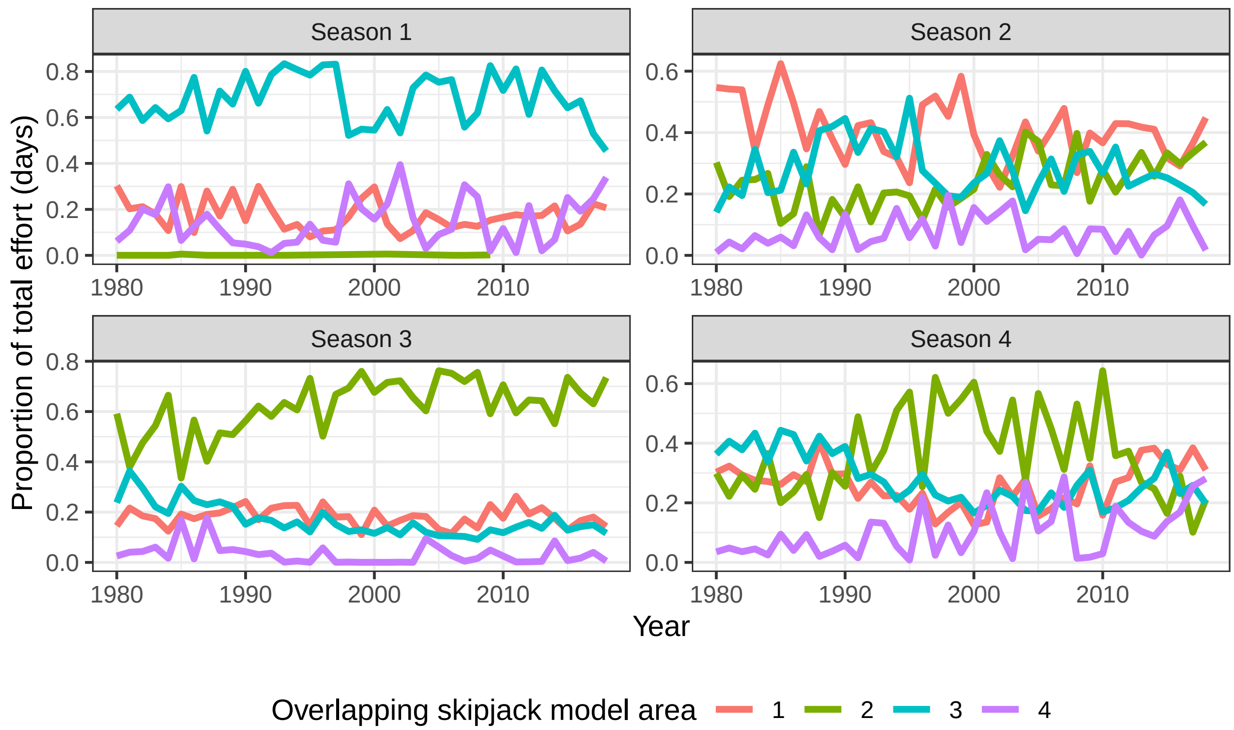

Figure 8: Proportion of historical effort by season in the parts of the four skipjack areas that overlap with bigeye & yellowfin area 1.

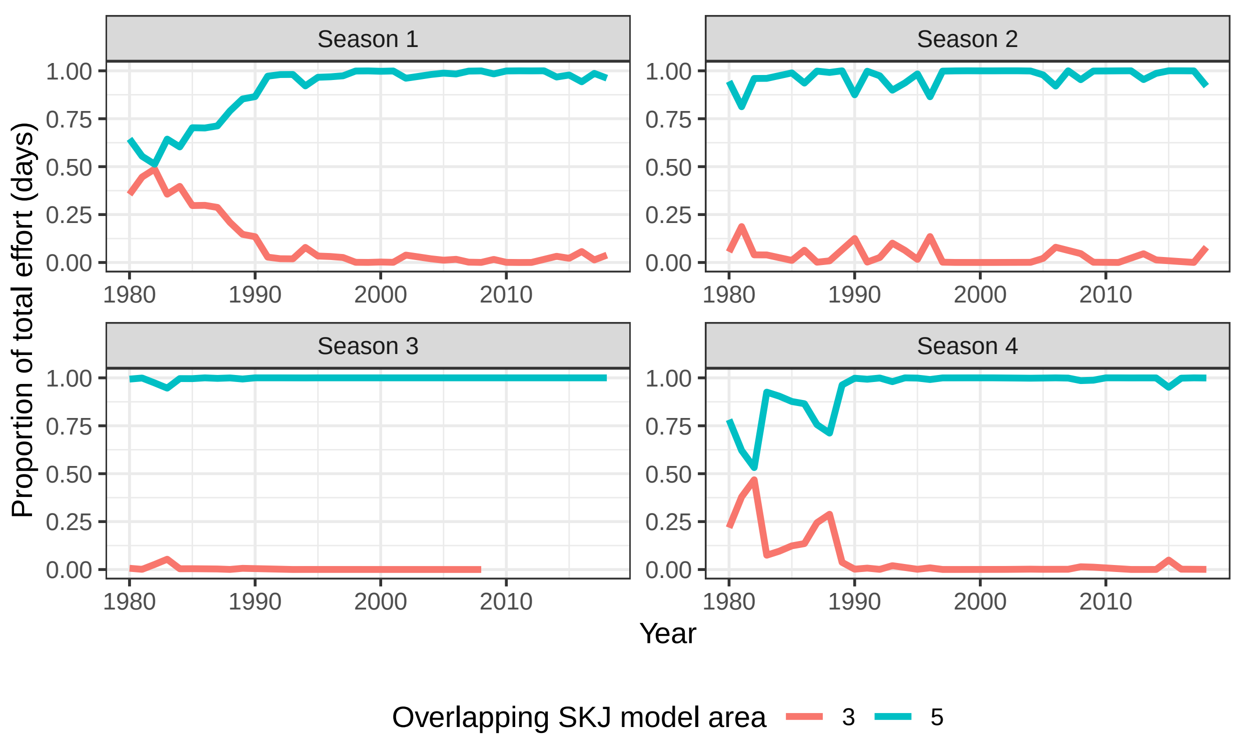

Figure 9: Proportion of historical effort by season in the parts of the skipjack areas that overlap with bigeye & yellowfin area 7.

D.3 Calculating the weights

The weights are calculated by taking the average proportional seasonal contribution over a chosen year range. Given the variability over time, a relatively long year range of 2009-2018 is used for this analysis. Other year ranges are possible and this is something that will need to be agreed by members.

BET & YFT	Season	SKJ 1 (F1)	SKJ 2 (F4)	SKJ 3 (F7)	SKJ 4 (F22)
1 (F20)	1	0.17	0.00	0.68	0.15
1 (F20)	2	0.39	0.29	0.25	0.07
1 (F20)	3	0.19	0.65	0.14	0.02
1 (F20)	4	0.31	0.30	0.25	0.14

Table 9: Weighting of component skipjack areas (and fisheries) for bigeye and yellowfin area 1 (fishery 20), based on average effort distribution 2009 to 2018

BET & YFT	Season	SKJ 3 (F7)	SKJ 5 (F13)
7 (F28)	1	0.02	0.98
7 (F28)	2	0.02	0.99
7 (F28)	3	0.00	1.00
7 (F28)	4	0.01	0.99

Table 10: Weighting of component skipjack areas (and fisheries) for bigeye and yellowfin area 7 (fishery 28), based on average effort distribution 2009 to 2018

The weights for bigeye & yellowfin areas 1 and 7 are shown in Tables 9 and 10. The bigeye & yellowfin areas 3 and 8 overlap with only one skipjack area each (7 and 6, respectively) (Table 8). This means that the skipjack areas, and corresponding fisheries, have a weight of 1 for each season.

E Examples of linking the skipjack, bigeye and yellowfin operating models

To run the mixed fishery evaluations it is necessary to set the future effort and catch of each fishery in the skipjack, bigeye and yellowfin OMs. As mentioned in the main text, the skipjack evaluations are run independently of the bigeye and yellowfin simulations. For fisheries in the bigeye and yellowfin OMs that are managed through the skipjack MP, it is necessary to transfer the realised fishing effort from the corresponding fisheries in the skjpjack OMs.

For fisheries in the skipjack OMs that are managed through effort limits set by the skipjack MP, such as the purse seine fisheries, the output of the HCR is applied in the same way to the corresponding fisheries in the bigeye and yellowfin OMs to generate the future effort.

For fisheries in the skipjack OMs that are managed through catch limits set by the skipjack MP, such as the pole and line fisheries, the realised future effort of those fisheries is transferred to the corresponding fisheries in the bigeye and yellowfin OMs. This is made more challenging when the fishery and area structures of the OMs are different.

It should be noted that the effort values in each stock OM have been internally scaled and do not necessarily reflect number of sets, or number days etc. This means that it is not possible to simply directly transfer the effort values between fisheries in the different stock OMs.

In this analysis there is no bigeye MP. Instead the future catches of bigeye by the tropical longline fisheries are held at a constant status quo level. The resulting future effort of the tropical longline fisheries from the bigeye simulations is transferred to the tropical longline fisheries in the yellowfin OM. Corresponding effort to take the bigeye catch will still vary given fluctuations in the underlying regional biomass due to recruitment variability, for example.

This Appendix provides examples of how this process can be performed. A single example iteration of the stochastic simulations using the skipjack MP with harvest control rule (HCR) 10 are used to illustrate the process. The results from this iteration are given in Appendix F.

E.1 Skipjack results

The simulations for all three stocks start in 2019. For the first three years of the projection the output of the HCR is fixed at 1. The management period is three years, meaning that the output of the HCR is applied for three years before the MP is used again (Scott et al., 2019a). In these simulations, fisheries in the skipjack model that are not managed through an MP, such as those operating in archipelagic waters, have their future catch or effort set at the 2012 level.

The shape of HCR 10 can be seen in Figure 10. The maximum effort and catch scalar is limited to 1 and there is an initially gradual decrease in fishing pressure if the stock $SB/SB_{F=0}$ starts to decrease below 0.42 (the median estimated level of $SB/SB_{F=0}$ in 2012 from the most recent skipjack stock assessment). The output of HCR 10 for the example iteration used in this Appendix can be seen in Figure 11. The resulting skipjack $SB/SB_{F=0}$ and spawning biomass in each model area for this example iteration can be seen in Figures 12 and 13.

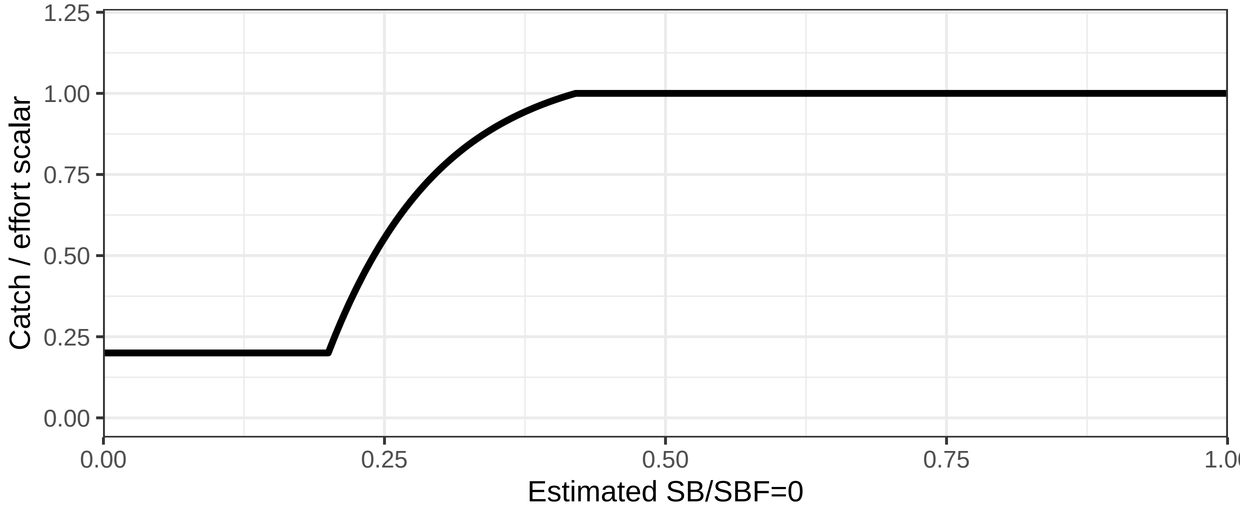

Figure 10: Shape of HCR 10 that is used for the example plots in this section.

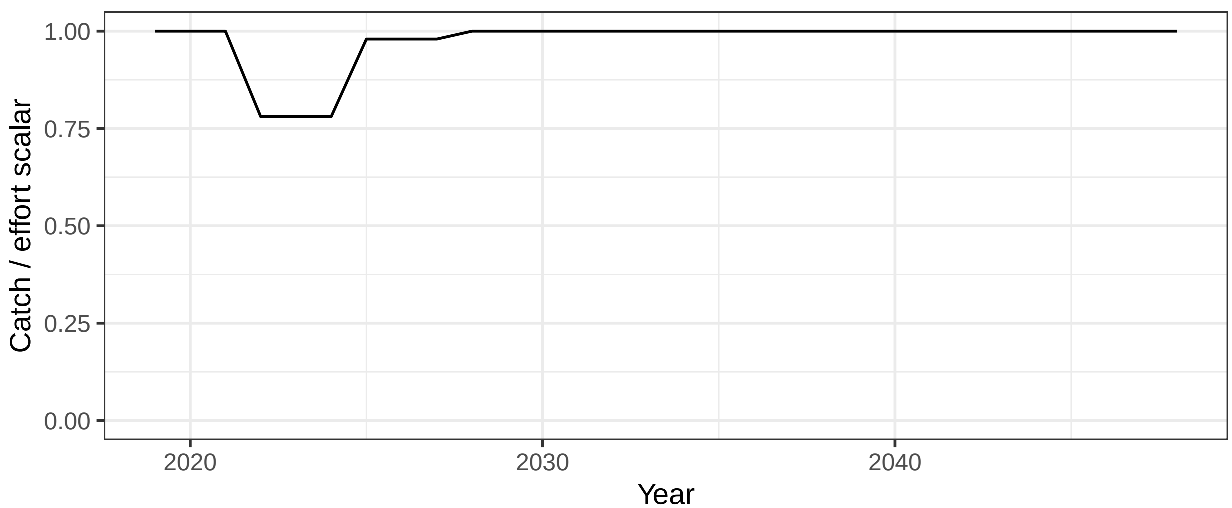

Figure 11: The output of the skipjack MP with HCR 10 from a single iteration. This output scalar is applied to the catch or effort in 2012, depending on the fishery, to set the fishing opportunities in each 3 year management period.

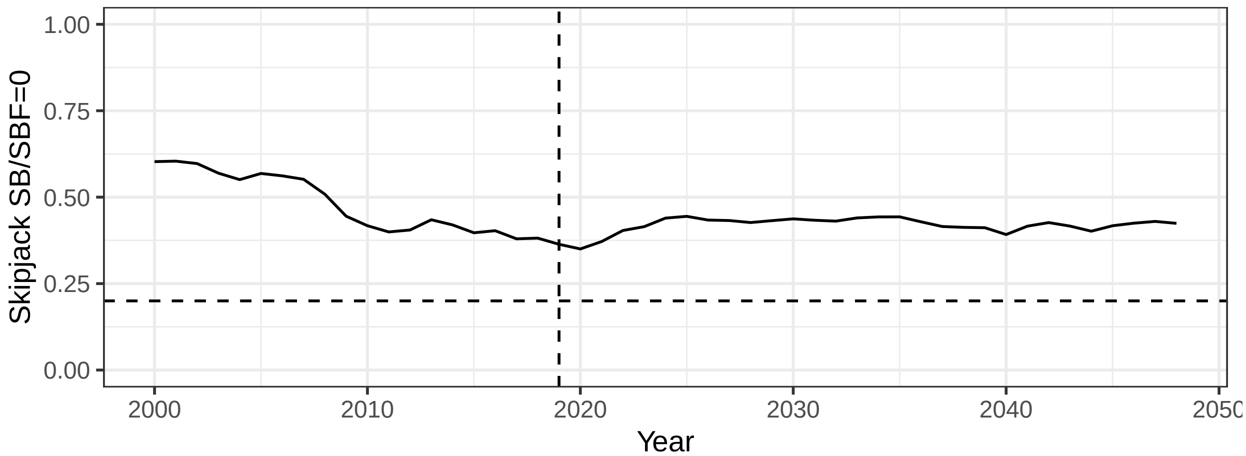

Figure 12: The projected skipjack SB/SBF=0 for the example iteration with HCR 10. The dashed vertical line indicates the start of the projection. The dashed horizontal line is the limit reference point (0.2).

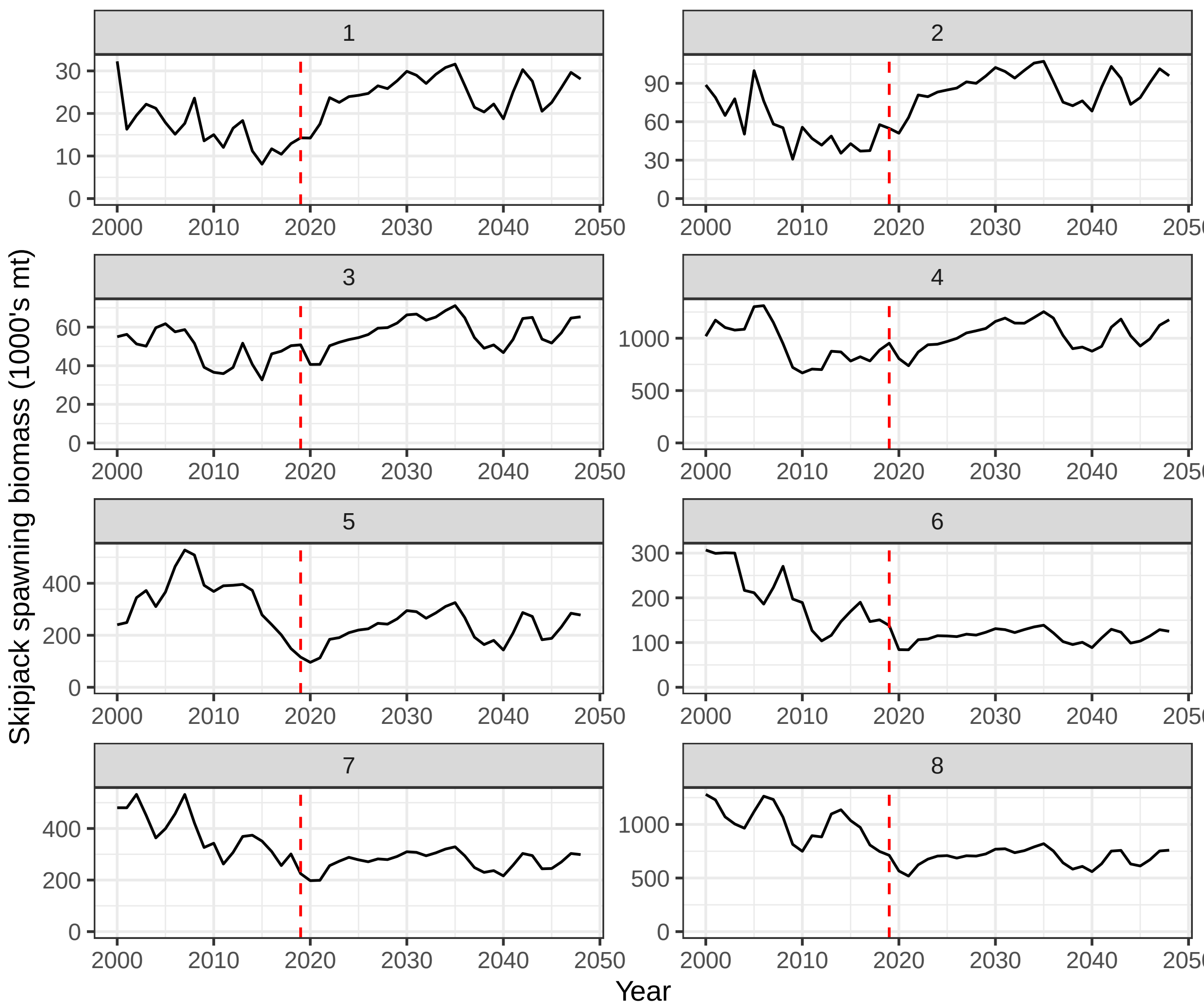

Figure 13: The projected skipjack spawning biomass in each model area for the example iteration with HCR 10. The dashed vertical line indicates the start of the projection.

E.2 Setting up future purse seine effort

The evaluations assume that the purse seine fisheries will be managed through the setting of effort limits, determined by the output of the skipjack MP. To set up the future effort of the purse seine fisheries in the bigeye and yellowfin OMs, the output scalar of the HCR is applied to the 2012 effort, in the same manner as the skipjack evaluations. The future effort of the purse seine fisheries is therefore directly set by the skipjack MP using the estimated skipjack abundance and follows the same pattern as the HCR output (Figure 11). Fisheries 24, 25 and 26 are assumed to partially operate in archipelagic waters and so, as with the skipjack evaluations, the applied scalar is reduced to reflect that a component of these fisheries is unaffected by the MP and remains at 2012 levels of effort (Scott et al., 2019a).

To demonstrate this approach the resulting future effort from the example single iteration is shown for the area 4 purse seine fisheries of the bigeye and yellowfin OMs in Figure 14.

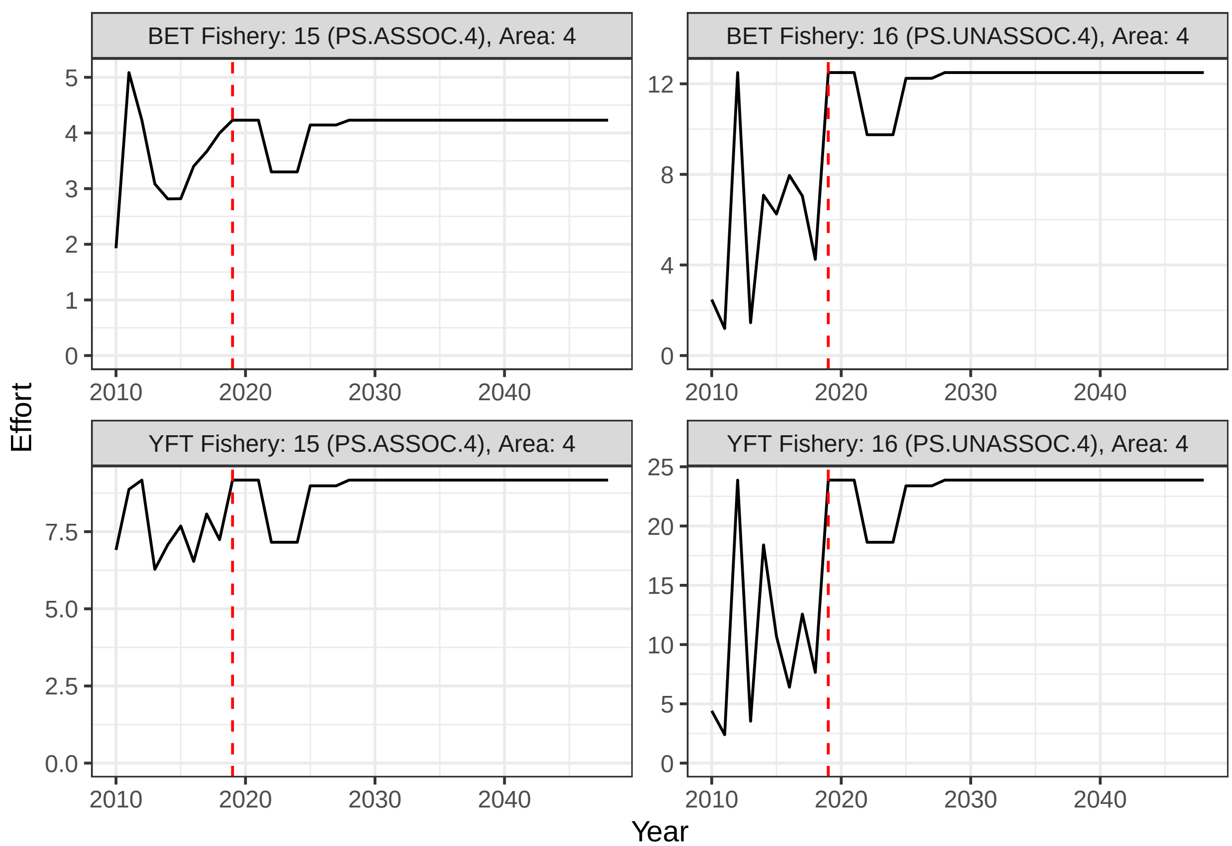

Figure 14: An example of future effort from the example iteration of HCR 10 of the area 4 associated and unassociated purse seine fisheries in the bigeye (BET) and yellowfin (YFT) operating models. The future effort is set by applying the skipjack HCR output to the effort in 2012. Note that the effort values have been internally scaled and do not represent numbers of sets. The dashed vertical line indicates the start of the projection.

E.3 Setting up future pole and line effort

The skipjack MP sets the future skipjack catch limit for each pole and line fishery in the skipjack OMs. The resulting effort made by these fisheries to take this catch limit needs to be tranferred to the corresponding fisheries in the bigeye and yellofin OMs. As explained in the main text, this is made difficult given the different fishery and area structures (Figure 6).

In this analysis, the future effort of these fisheries in the bigeye and yellowfin OMs is set using the weighted relative efforts from the skipjack pole and line fisheries, where the weights are based on the historical distribution of effort in the overlapping model areas (as described in Section 3.2 and Appendix D). The future effort of the pole and line fisheries in the bigeye and yellowfin OMs is therefore a result of the skipjack pole and line catch limits set by the skipjack MP and the skipjack abundance in each model area.

Two examples are shown based on the example single iteration from using HCR 10.

E.3.1 Example 1: Bigeye and yellowfin fishery 28

Due to the spatial overlap, the future fishing activity of fishery 28 in the bigeye and yellowfin OMs is determined by the fishing activity of fisheries 7 and 13 in the skipjack OMs (Appendix D).

The future catches of the skipjack pole and line fisheries 7 and 13 are set by the skipjack MP by applying the output of the HCR to the catch in 2012. Skipjack fishery 13 is assumed to partially operate in archipelagic waters and so the applied scalar is reduced to reflect that a component of the activity of this fishery is unaffected by the skipjack MP and remains at 2012 levels of catch (Scott et al., 2019a).

The resulting effort made by these fisheries to take the catches set by the skipjack MP is determined by the skipjack abundance those model areas. The stock abundance changes through time as a result of fishing pressure from all model fisheries and also through the dynamics of the stock, including variability in recruitment.

The catch, resulting fishing effort and effort relative to the base effort (the average effort in the reference period 2009-2018) from the single example iteration can be seen in Figure 15.

The future relative efforts of skipjack fisheries 7 and 13 are weighted by the values in Table 10 and summed to give the overall relative effort for fishery 28 in the bigeye and yellowfin OMs (most of the weight is applied to fishery 13). This relative effort is then applied to the average effort of the same reference period of fishery 28 in the bigeye and yellowfin OMs to calculate the future effort (Figure 16). The future effort, and subsequent catches, of fishery 28 in the bigeye and yellowfin simulations is therefore driven by the catch limits set by the skipjack MP and the skipjack abundance.

The interaction between skipjack stock abundance, the skipjack catch limit set by the skipjack MP and the resulting effort of the bigeye and yellowfin fisheries can be complicated. For example, there is an increase in the realised effort of skipjack fishery 13 from 2035 despite the catches of

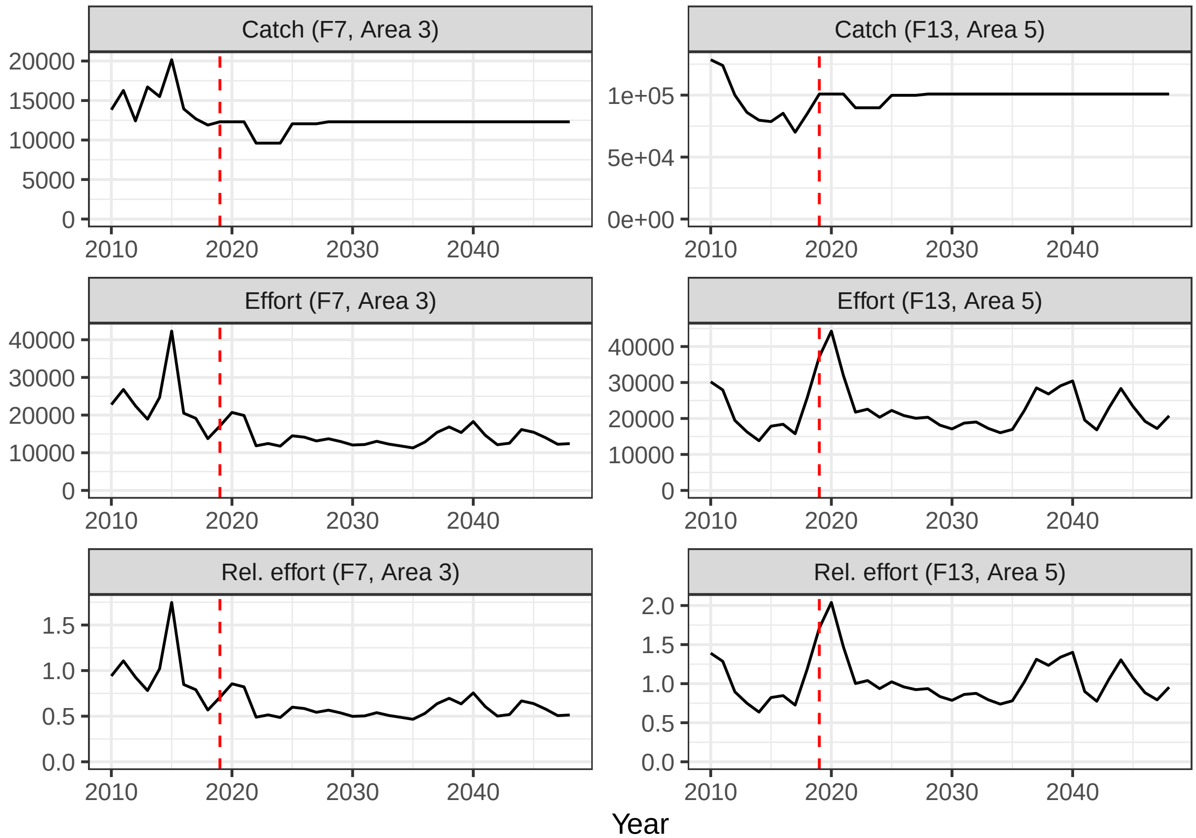

Figure 15: The catch (set by the skipjack management procedure), effort and relative effort for the skipjack pole and line fisheries 7 and 13 from the single iteration of the HCR 10 results. The dashed vertical line indicates the start of the projection.

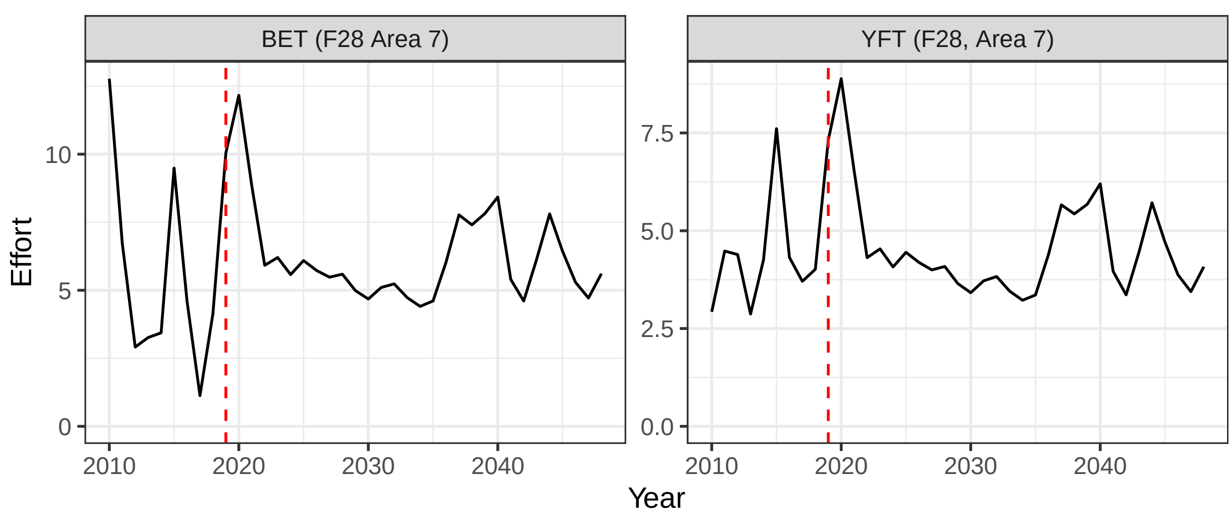

Figure 16: The resulting future effort of the example iteration of the HCR 10 results of the pole and line fishery 28 in area 7 of the bigeye and yellowfin operating models. The future effort is set by weighting the relative efforts of the contributing skipjack fisheries and applying it to the base effort (average effort in the reference period 2009-2018). The future effort is therefore a result of the skipjack MP. The dashed vertical line indicates the start of the projection.

that fishery being constant in time (Figure 15). This increase in effort is driven by a decline in skipjack stock abundance in area 5 in the same period (more effort must be made to catch the same amount when the stock size is lower) (Figure 13). The increase in effort by skipjack fishery 13 is then transferred to the corresponding pole and line fishery 28 in the bigeye and yellowfin OMs in the same period (Figure 16). This has an impact on the catches of bigeye and yellowfin by these fisheries (see below).

E.3.2 Example 2: Bigeye and yellowfin fishery 20

To calculate the future effort for bigeye and yellowfin fishery 20 the same process as in Example 1 above is used, except in this example there are four contributing skipjack fisheries (1, 4, 7 and 22) (Appendix D). The catch, resulting fishing effort and effort relative to the base effort (average effort in the reference period 2009-2018) of the single example iteration can be seen in Figure 17.

As above, the relative efforts of each of the skipjack fisheries 1, 4, 7 and 22 are weighted by the values in Table 9 and summed to give the overall relative effort for fishery 20 in the bigeye and yellowfin OMs. The relative effort is then applied to the the average effort in the same reference period to calculate the future effort (Figure 18). The future effort, and subsequent catches, of fishery 20 in the bigeye and yellowfin simulations is therefore driven by the catch limits set by the skipjack MP and the skipjack abundance.

It is more difficult to link the output of the skipjack MP to the future effort of fishery 20 in bigeye and yellowfin OMs, given the number of contributing skipjack fisheries. However, as above, there is an increase in effort by the skipjack fisheries from 2035 that is driven by the decrease in skipjack stock abundance at the same time (Figure 13). This results in a similar increase in effort for fishery 20 in the bigeye and yellowfin OM.

Pole and line fisheries 18 and 24 in the bigeye and yellowfin OMs each correspond to a single fishery in the skipjack OM (Appendix D). The future effort for these fisheries therefore follow the same pattern as the corresponding skipjack fisheries (not shown here).

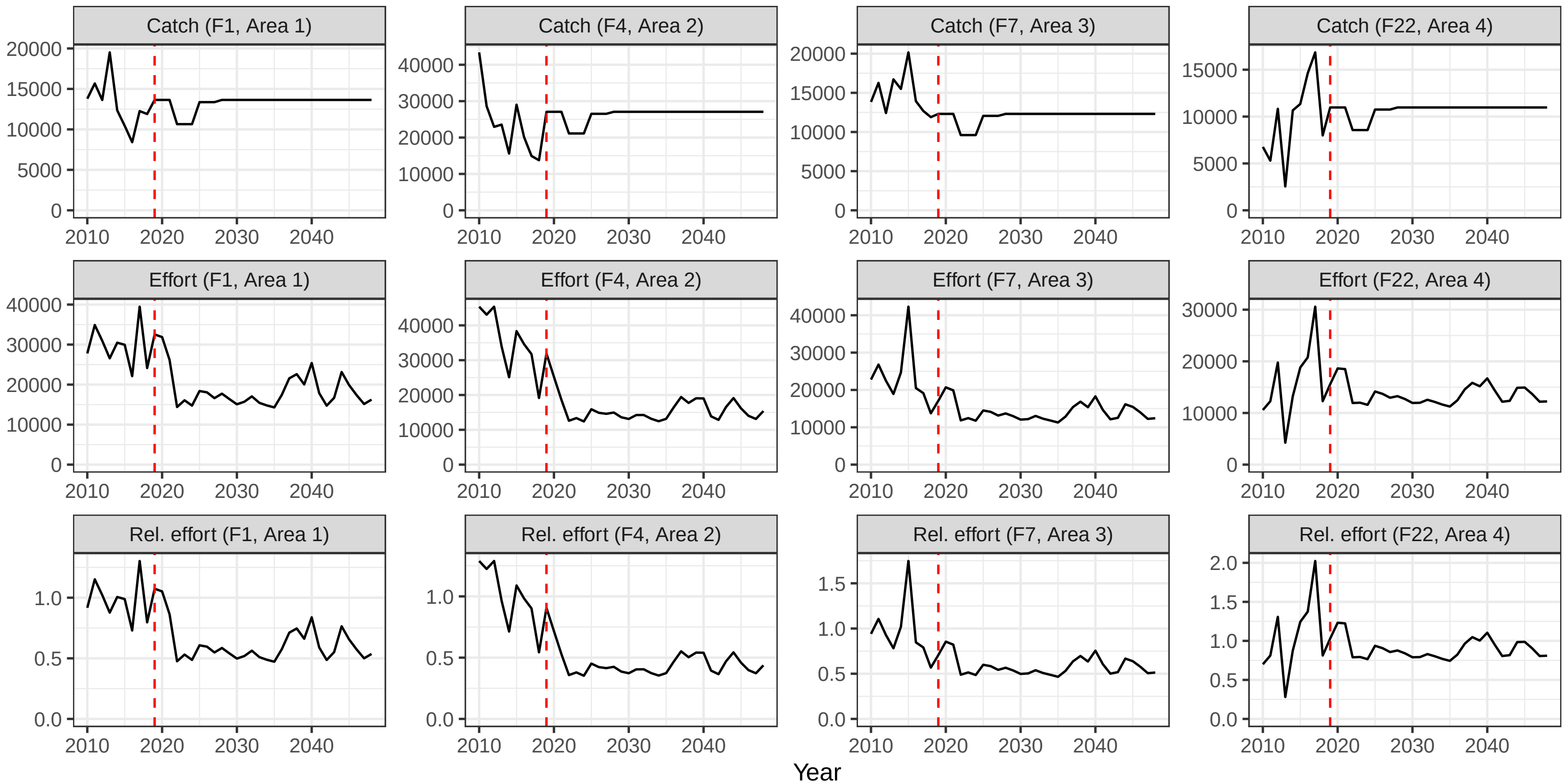

Figure 17: The catch (set by the skipjack management procedure), effort and relative effort for the skipjack pole and line fisheries 1, 4, 7 and 22 from the example iteration of the HCR 10 results. The dashed vertical line indicates the start of the projection.

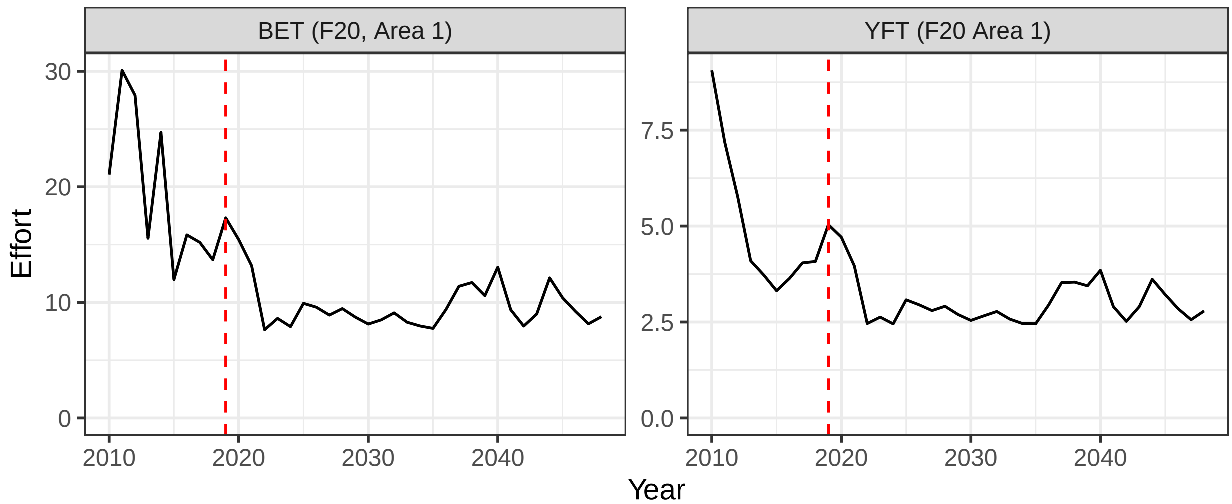

Figure 18: The future effort of the example iteration of the HCR 10 results of the pole and line fishery 20 in area 1 of the bigeye and yellowfin operating models. The future effort is set by weighting the relative efforts of the contributing skipjack fisheries and applying it to the base effort (average effort in the reference period 2009-2018). The future effort is therefore a result of the skipjack MP. The dashed vertical line indicates the start of the projection.

E.4 Setting up future domestic fishery effort

The skipjack MP sets the skipjack catch limit for the domestic fisheries 10 and 16 in the skipjack OMs. These fisheries correspond with fisheries 17 and 32 in the bigeye and yellowfin OMs (Section 3.3). To run the mixed fishery evaluations the resulting effort from taking the catches specified by the skipjack MP must be transferred from fisheries 10 and 16 in the skipjack OMs to fisheries 17 and 32 in the bigeye and yellowfin OMs. In this analysis the effort relative to the average effort in the reference period (2009-2018) of fisheries 10 and 16 in the skipjack OMs is applied to the corresponding fisheries in the bigeye and yellowfin OMs (as described in Section 3.3).

The catch, effort and relative effort for the skipjack fisheries 10 and 16 are shown in Figure 19. The resulting future effort of fisheries 17 and 32 in the bigeye and yellowfin OMs for the single example iteration is shown in Figure 20. The future effort of these fisheries in the bigeye and yellowfin OMs are therefore affected by the skipjack catch limits set by the skipjack MP.

There is an increase in effort for the skipjack fisheries from 2035. As with the pole and line fisheries, this increase is a result of trying to maintain catches while the stock abundance is decreasing (Figure ~13). The increase in effort can be seen in that of fisheries 17 and 32 of the bigeye and yellowfin OMs (Figure 19).

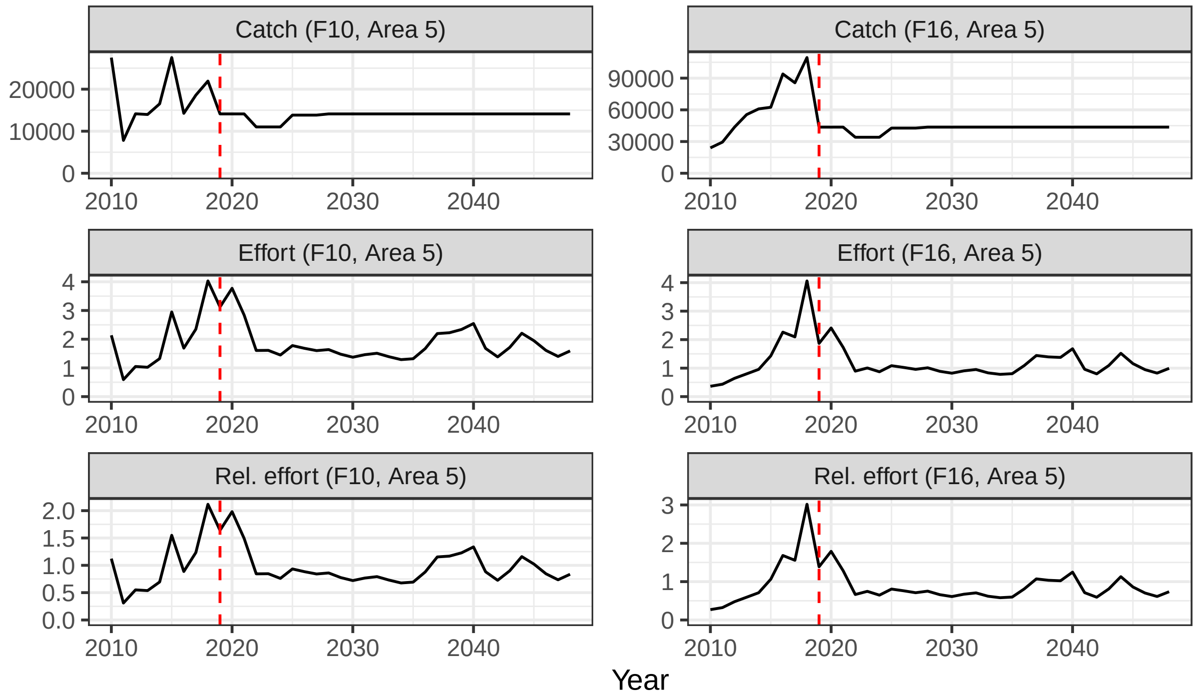

Figure 19: The catch (set by the skipjack management procedure), effort and relative effort for the skipjack domestic fisheries 10 and 16 from the example iteration of the HCR 10 results. The dashed vertical line indicates the start of the projection.

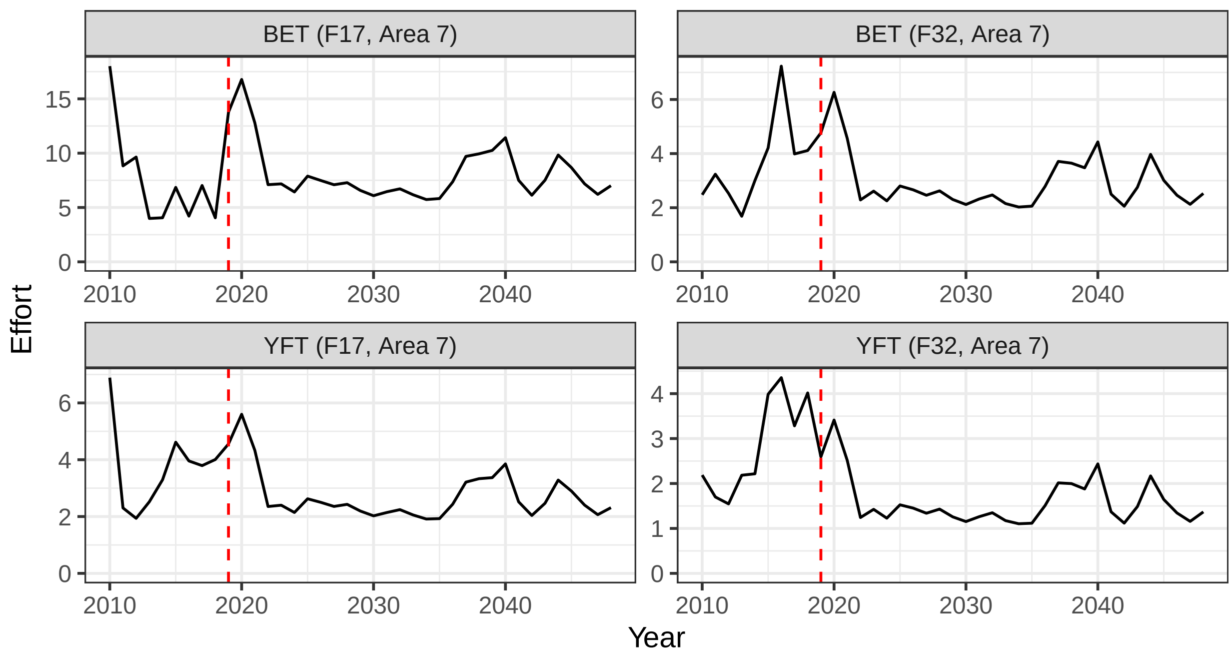

Figure 20: The future effort of the example iteration of the HCR 10 results of the domestic fisheries 17 and 32 of the bigeye and yellowfin operating models. The future effort is set by applying the relative efforts of the corresponding skipjack fisheries (10 and 16) to the base effort (average effort in the reference period 2009-2018). The future effort is therefore a result of the skipjack MP. The dashed vertical line indicates the start of the projection.

E.5 Setting up future tropical longline effort

The future tropical longline catches of bigeye are set at a constant status quo level (average of 2016-2018). In the simulations, the future catches are set as numbers of individuals, rather than biomass. This means that the future bigeye catch biomass, shown in the plots, are not quite constant. The resulting effort of the bigeye tropical longline fisheries is transferred to the corresponding fisheries in the yellowfin OMs by calculating and applying the effort relative to the average effort in the period 2009-2018 (as described in Section 3.3.1).

This process is shown for four example tropical longline fisheries (2, 4, 6 and 9) for the single example iteration of the HCR 10 results (Figure 21).

There is an increase in bigeye fishing effort from 2030, even though the future catches are stable, that is driven by a decrease in bigeye stock abundance (Figure 23). This increase in effort is then transferred to the corresponding fisheries in the yellowfin OM.

This demonstrates that if the tropical longline is managed though a bigeye MP, the effort and subsequent catches of the tropical longline fisheries in the yellowfin model will be affected by the bigeye stock abundance.

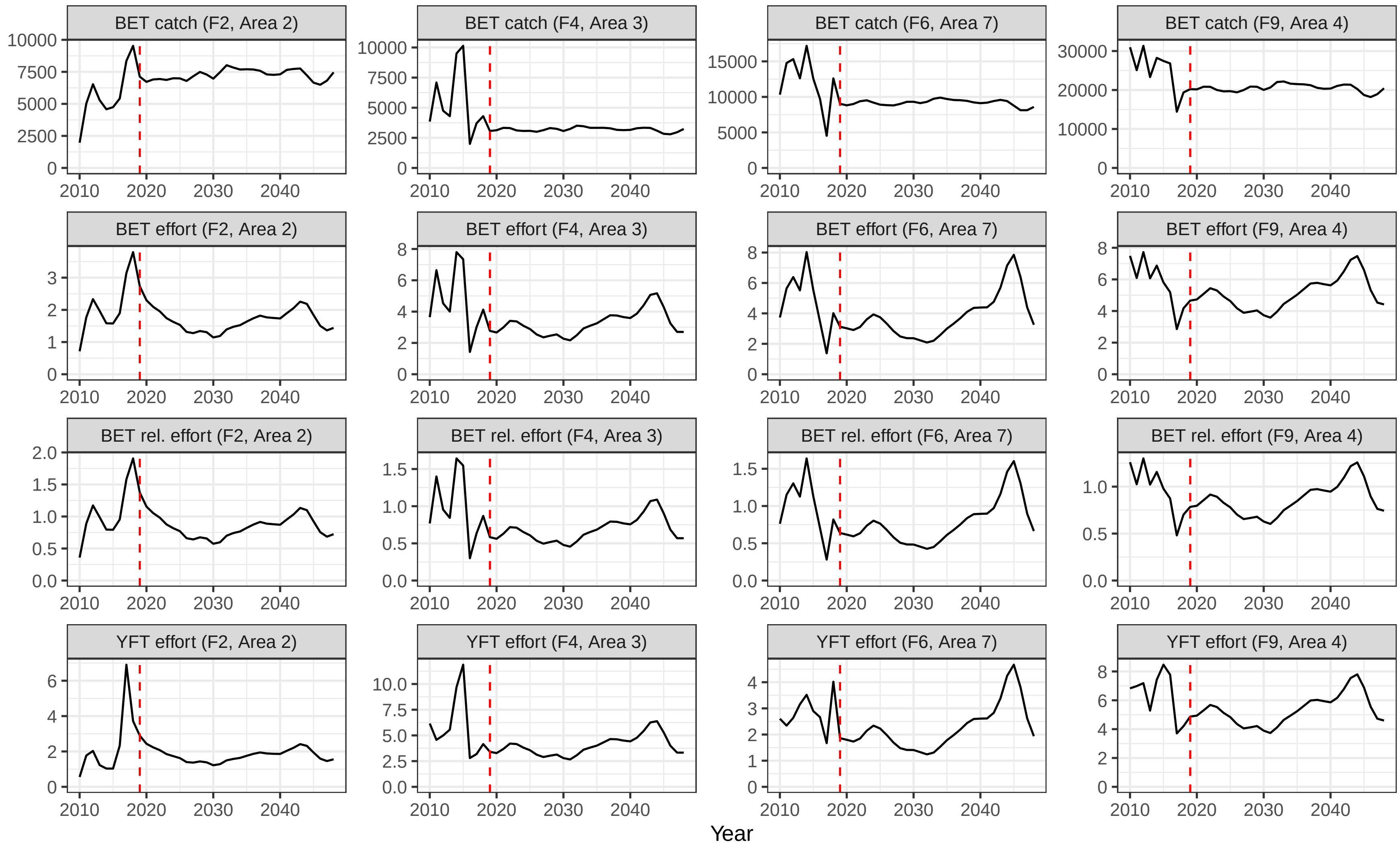

Figure 21: The catch, effort and relative effort for the tropical longline fisheries 2, 4, 6 and 9 in the bigeye operating model from the example iteration of the HCR 10 results. The catches shown here are biomass, whereas they are set as individuals in the projection. This results in not quite constant future catch biomass. The resulting efforts for the same fisheries in the yellowfin model are also shown. The dashed vertical line indicates the start of the projection.

F Example results of a single iteration

In this Appendix the results from the same example iteration and MP (HCR 10) as in Appendix E are reported. These results are included to demonstrate the methodology described above of linking the OMs of the three stocks into a mixed fishery MSE framework. As such they should only be considered as preliminary results.

It is also worth noting that the results presented are a single stochastic iteration and may not represent the behaviour over the full range of iterations.

F.1 Stock status

The resulting $SB/SB_{F=0}$ of the three stocks from the example iteration can be seen in Figure 22. The spawning biomass by model area can be see in Figures 13, 23 and 24. For this example iteration the $SB/SB_{F=0}$ of all three stocks are well away from the limit reference point (LRP) of 0.2.

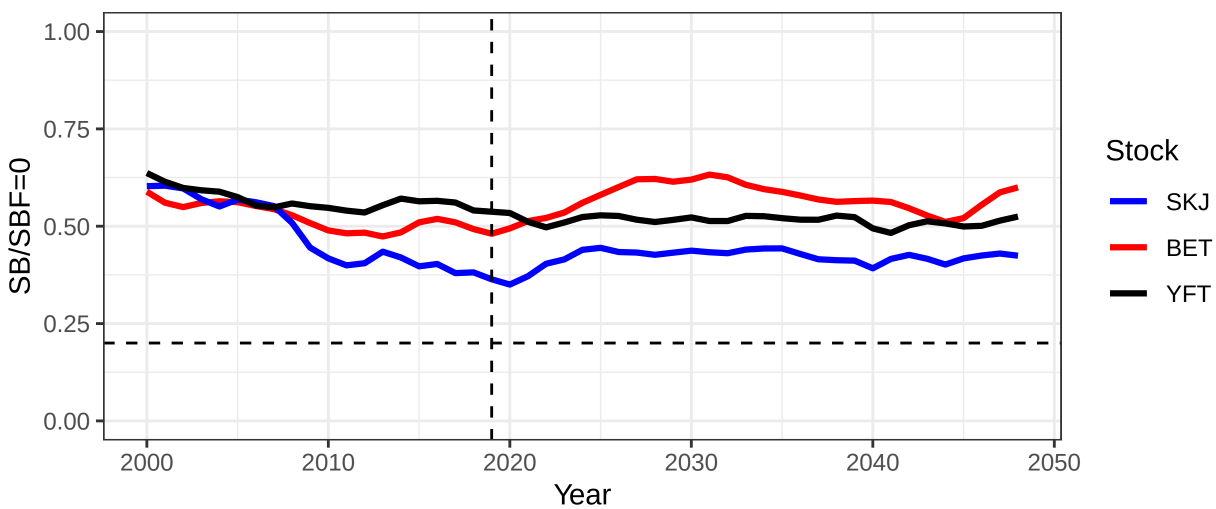

Figure 22: The projected SB/SBF=0 of the three stocks for the example iteration with HCR 10. The dashed vertical line indicates the start of the projection. The horizontal dashed line is the limit reference point at 0.2.

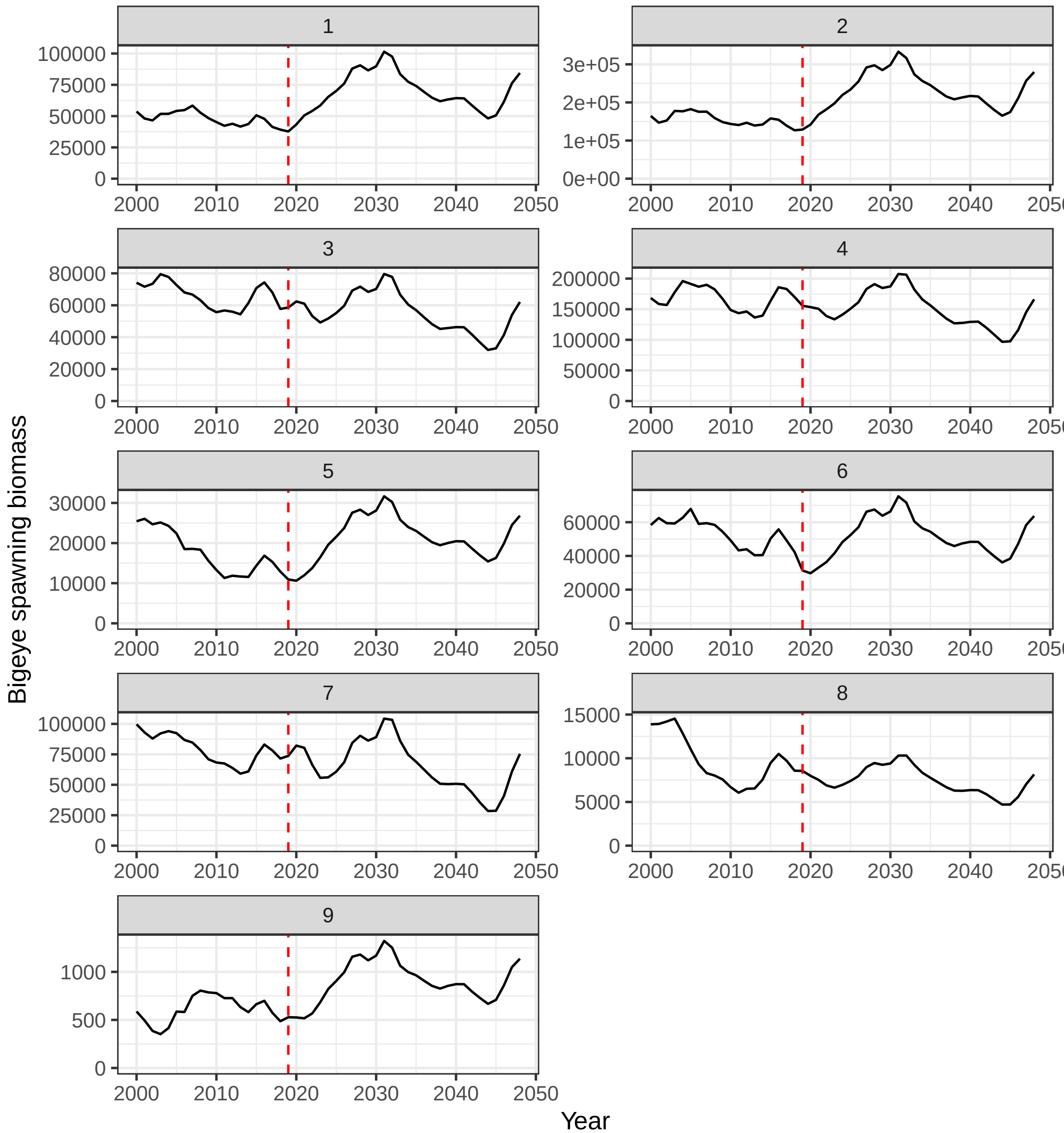

Figure 23: The projected bigeye spawning biomass in each model area for the example iteration with HCR 10. The dashed vertical line indicates the start of the projection.

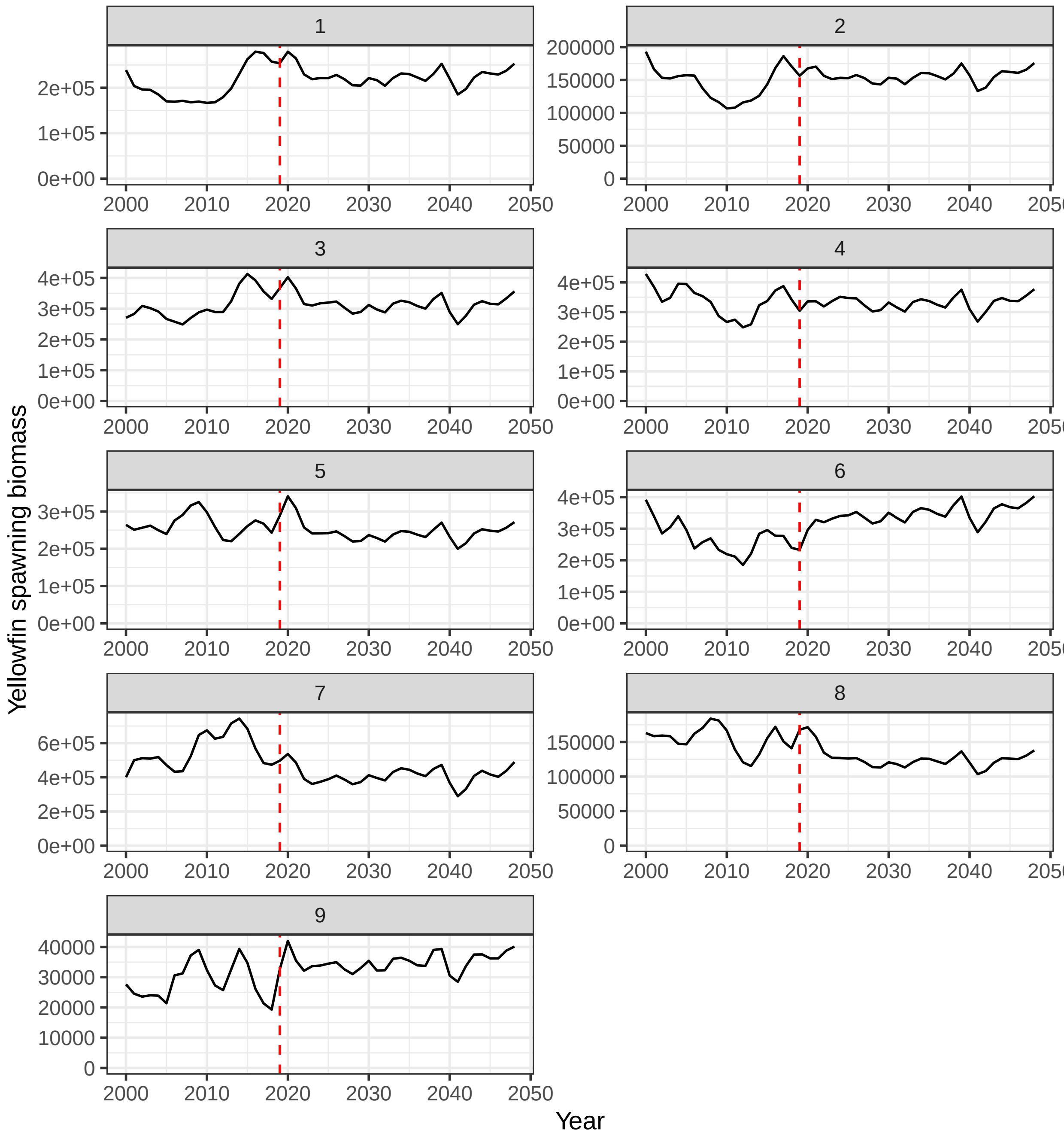

Figure 24: The projected yellowfin spawning biomass in each model area for the example iteration with HCR 10. The dashed vertical line indicates the start of the projection.

F.2 Future catches of the purse seine fisheries

The projected catches of the purse seine fisheries in the skipjack, bigeye and yellowfin OMs for the example iteration are shown in Figures 25, 26 and 27. The catches in all three models are driven by the stock biomass in the corresponding model area and the effort set by the skipjack MP.

Bigeye catches from associated purse seine fisheries are larger than the catches from unassociated purse seine fisheries in the same model area. This result incoroporates the assumption that the FAD closure period will continue into the future. This assumption will need to be agreed by members in the future.

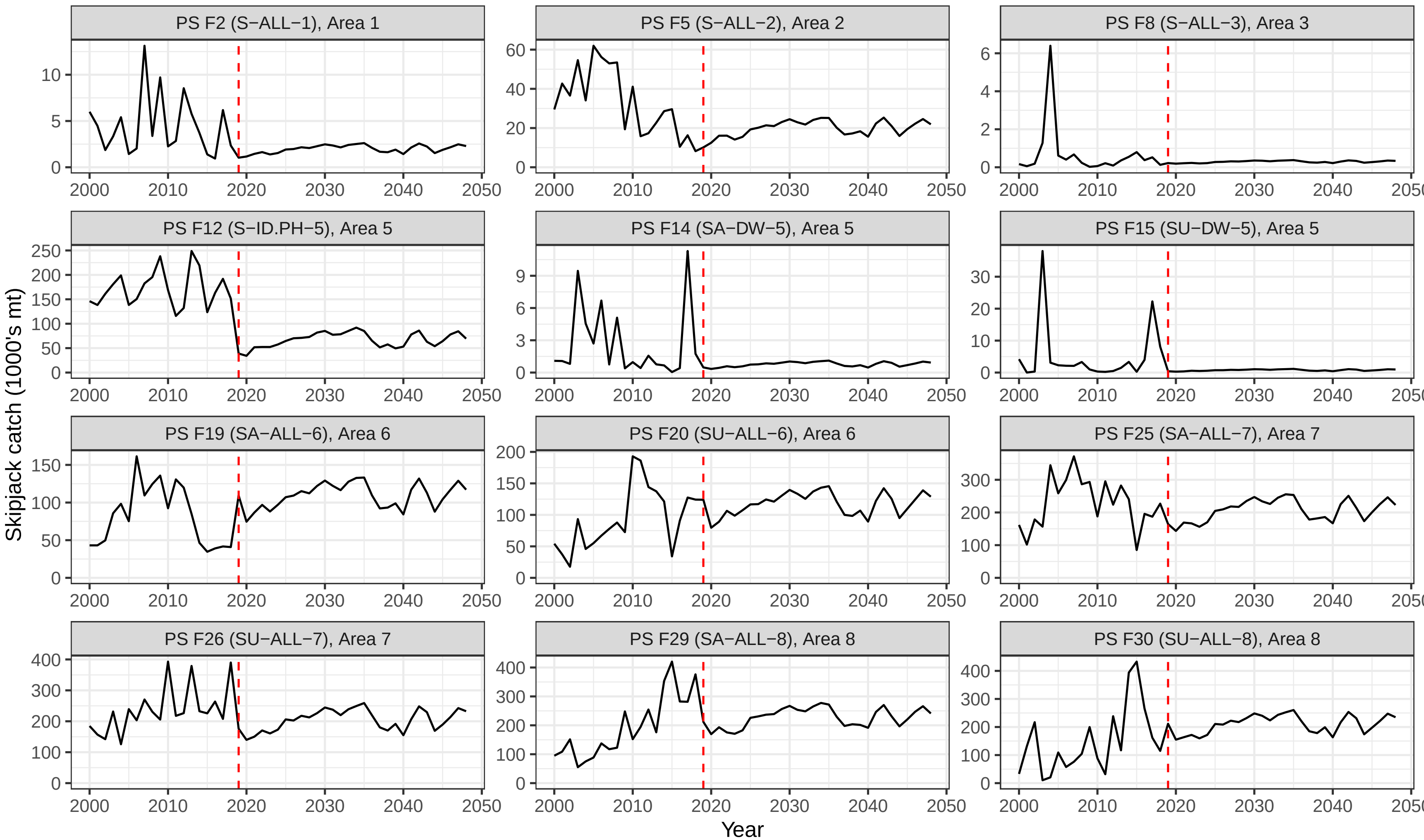

Figure 25: Projected skipjack catches of the purse seine fisheries in the skipjack operating model for the example iteration from the results of HCR 10. The vertical dashed line indicates the start of the projection period.

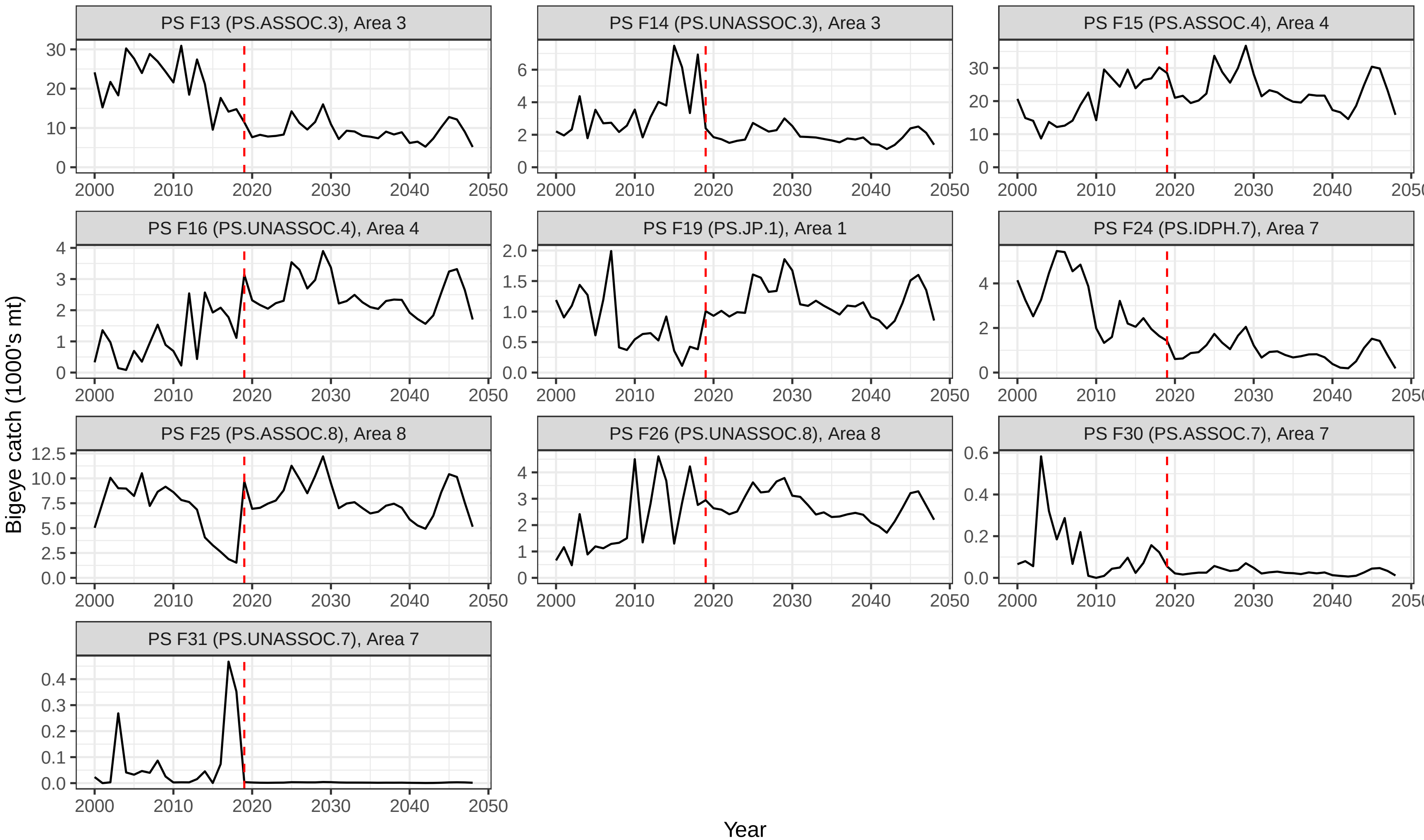

Figure 26: Projected bigeye catches of the purse seine fisheries in the bigeye operating model for the example iteration from the results of HCR 10. The vertical dashed line indicates the start of the projection period.

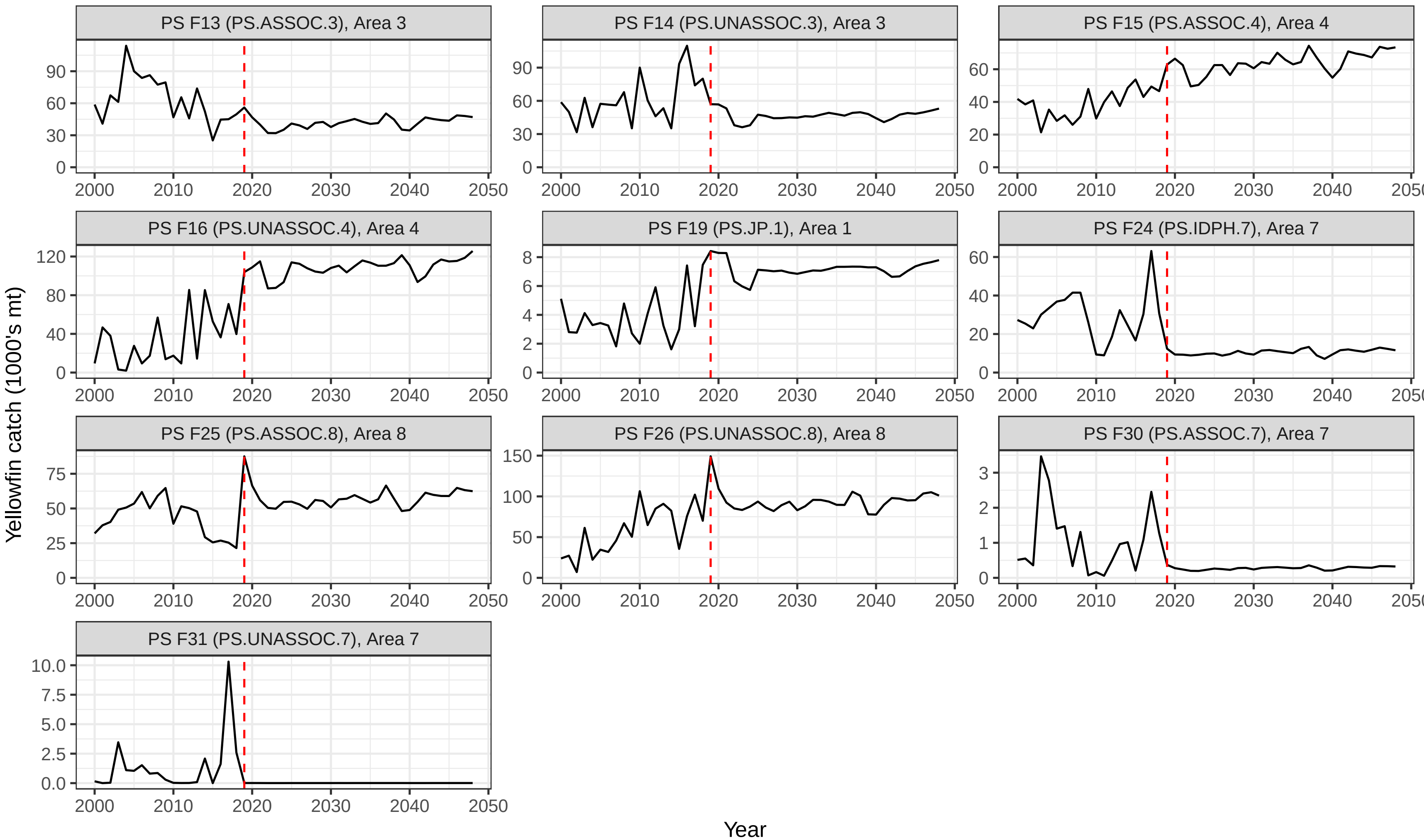

Figure 27: Projected yellowfin catches of the purse seine fisheries in the yellowfin operating model for the example iteration from the results of HCR 10. The vertical dashed line indicates the start of the projection period.

F.3 Future catches of the pole and line fisheries

The catches of the pole and line fisheries in the skipjack, bigeye and yellowfin OMs from the single example iteration can be seen in Figures 28, 29 and 30. The future catches of skipjack are set by the output of the HCR and match the pattern seen in Figure 11. The resulting future catches of bigeye and yellowfin fisheries are given by the effort made by these fisheries (Figures 16 and 18) and the vulnerable stock abundance in that model area.

It should be noted that the pole and line fisheries in the bigeye and yellowfin models catch smaller individuals so that the spawning biomass shown in Figures 23 and 24 is not a good guide to the vulnerable biomass for these fisheries (Ducharme-Barth et al., 2020; Vincent et al., 2020). As such it can be difficult to relate the spawning biomass and the fishing effort to the realised catches for these stocks. For example, the increase in bigeye catches by fishery 28 (area 7) in 2044 is driven by an increase in effort in the same year and an increase in small bigeye individuals not seen in the spawning biomass.

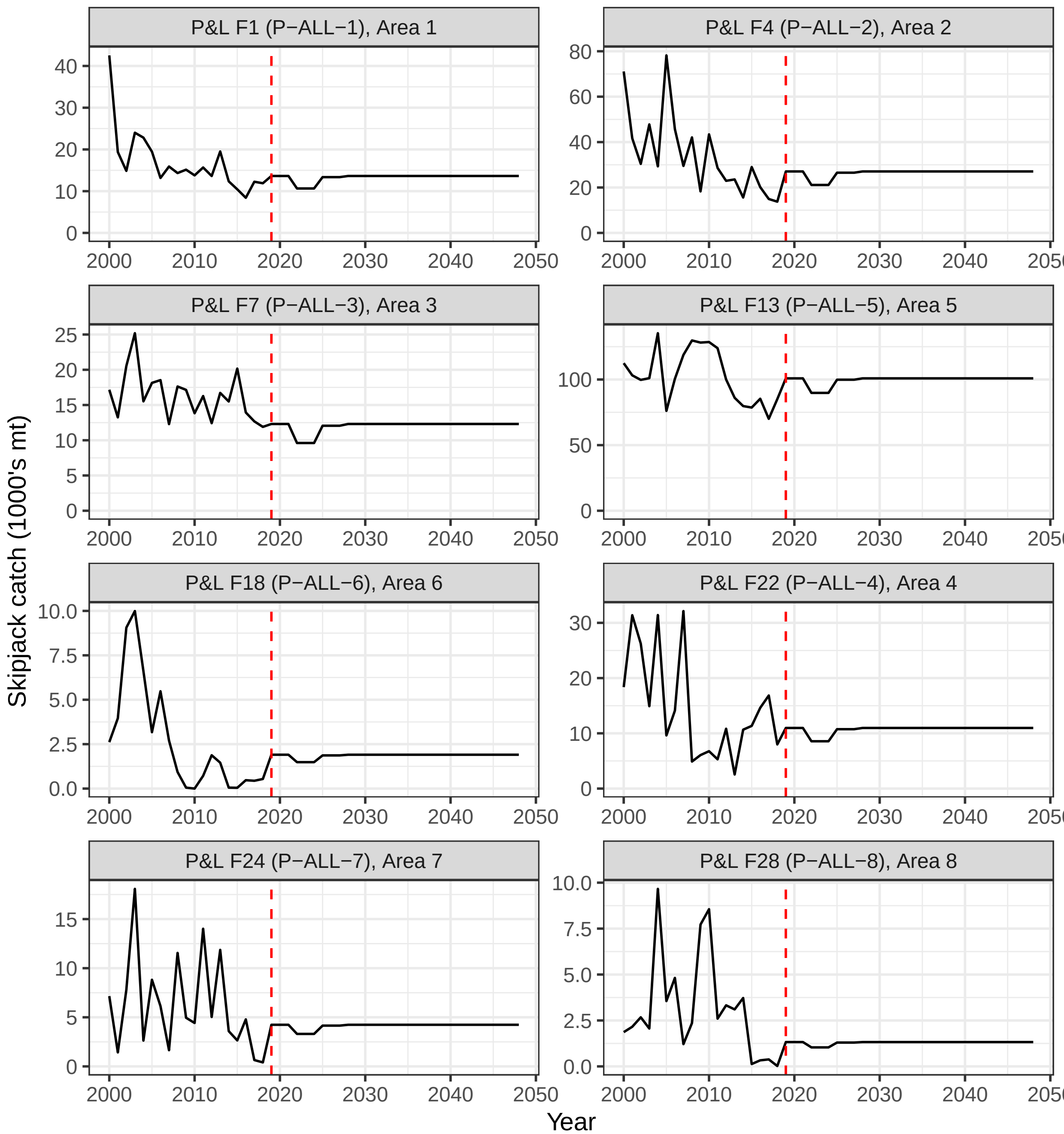

Figure 28: Projected skipjack catches of the pole and line fisheries in the skipjack operating model for the example iteration from the results of HCR 10. The vertical dashed line indicates the start of the projection period.

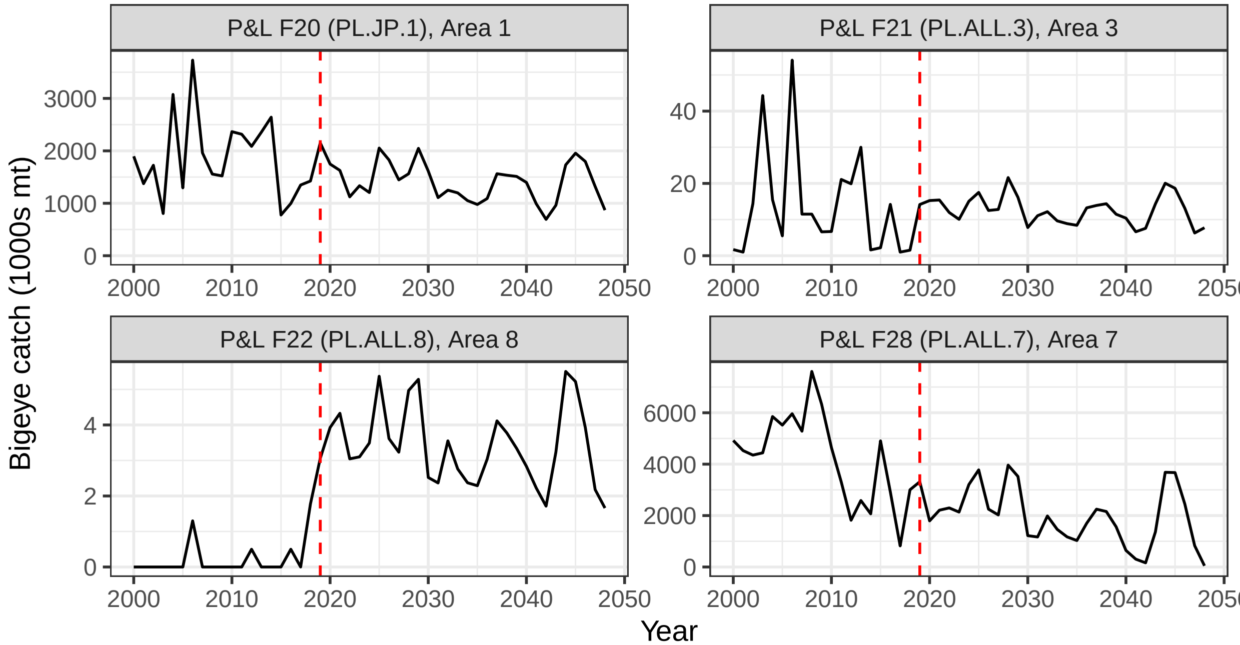

Figure 29: Projected bigeye catches of the pole and line fisheries in the bigeye operating model for the example iteration from the results of HCR 10. The vertical dashed line indicates the start of the projection period.

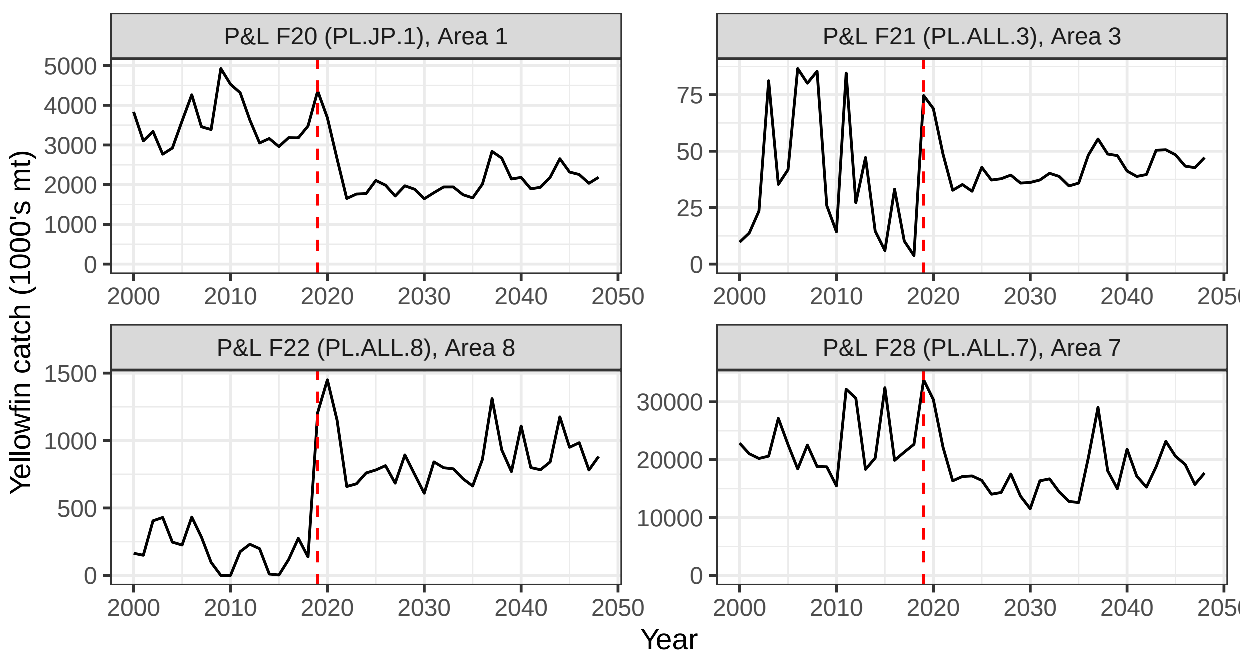

Figure 30: Projected yellowfin catches of the pole and line fisheries in the yellowfin operating model for the example iteration from the results of HCR 10. The vertical dashed line indicates the start of the projection period.

F.4 Future catches of the domestic fisheries

The future catches of the skipjack, bigeye and yellowfin domestic fisheries can be seen in Figures 31, 32 and 33. The future catches of the skipjack fisheries 10 and 16 set by the skipjack MP.

Skipjack fishery 11 and bigeye and yellowfin fisheries 18 and 23 are assumed to operate exclusively in archipelagic waters and are not managed by the skipjack MP. The future catches for these fisheries are set to a constant status quo level.

The effort made by the skipjack fisheries 10 and 16 (Figure 19 has been transferred to the corresponding fisheries 17 and 32 in the bigeye and yellowfin fisheries. This effort, along with the vulnerable stock biomass in the same model areas, determines the catches of these fisheries.

As with the pole and line fisheries, bigeye fisheries 17 and 32 take smaller individuals which means that the spawning biomass shown in Figure 23 is not a good guide to the vulnerable biomass for these fisheries (Ducharme-Barth et al., 2020; Vincent et al., 2020).

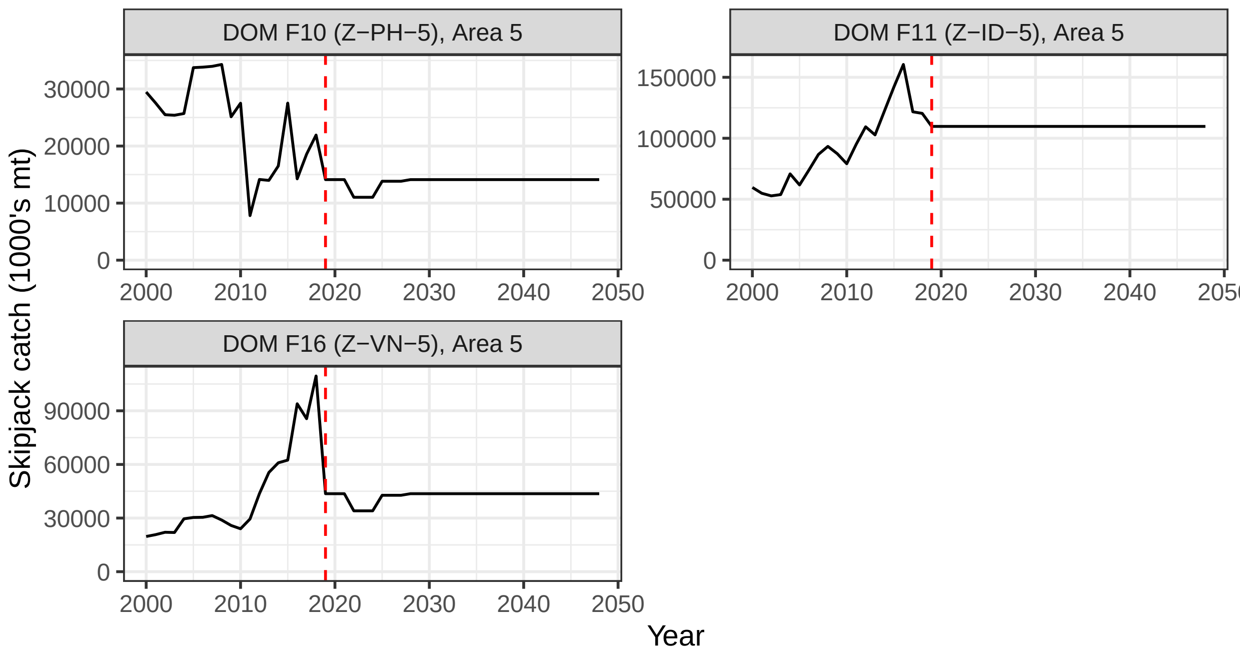

Figure 31: Projected skipjack catches of the domestic fisheries in the skipjack operating model for the example iteration from the results of HCR 10. The vertical dashed line indicates the start of the projection period. Note that fishery 11 operates in archipelagic waters and is not managed through the skipjack MP.

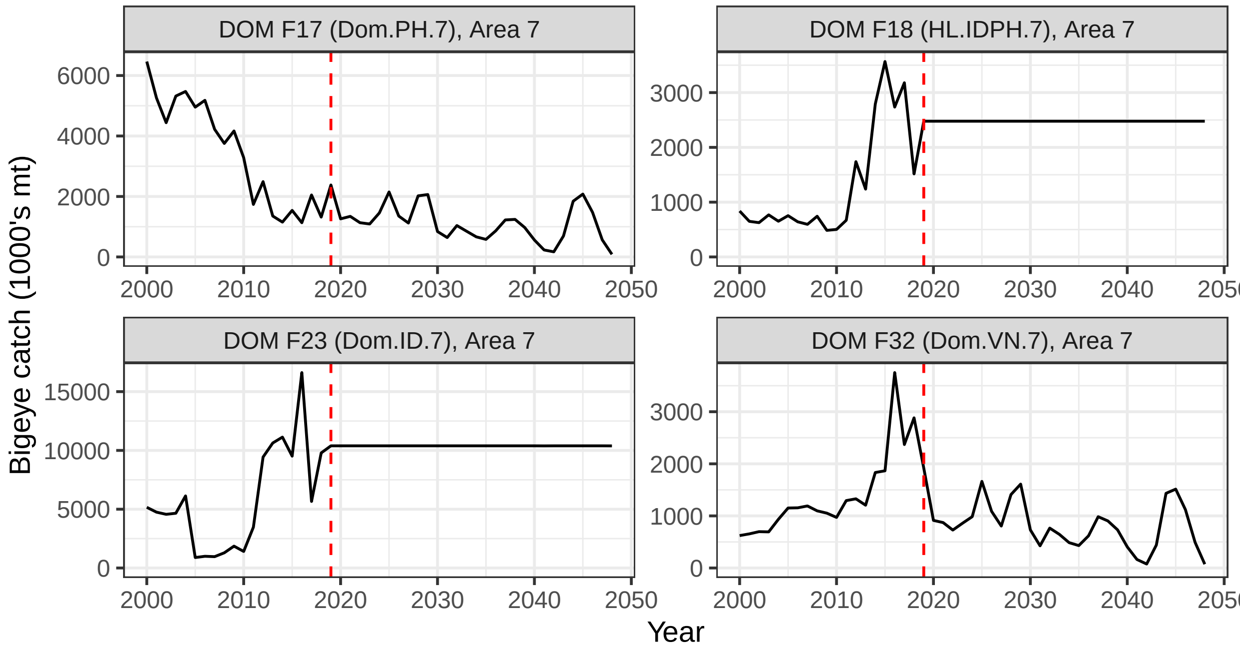

Figure 32: Projected bigeye catches of the domestic fisheries in the bigeye operating model for the example iteration from the results of HCR 10. The vertical dashed line indicates the start of the projection period. Note that fisheries 18 and 23 operate in archipelagic waters and are not managed through the skipjack MP.

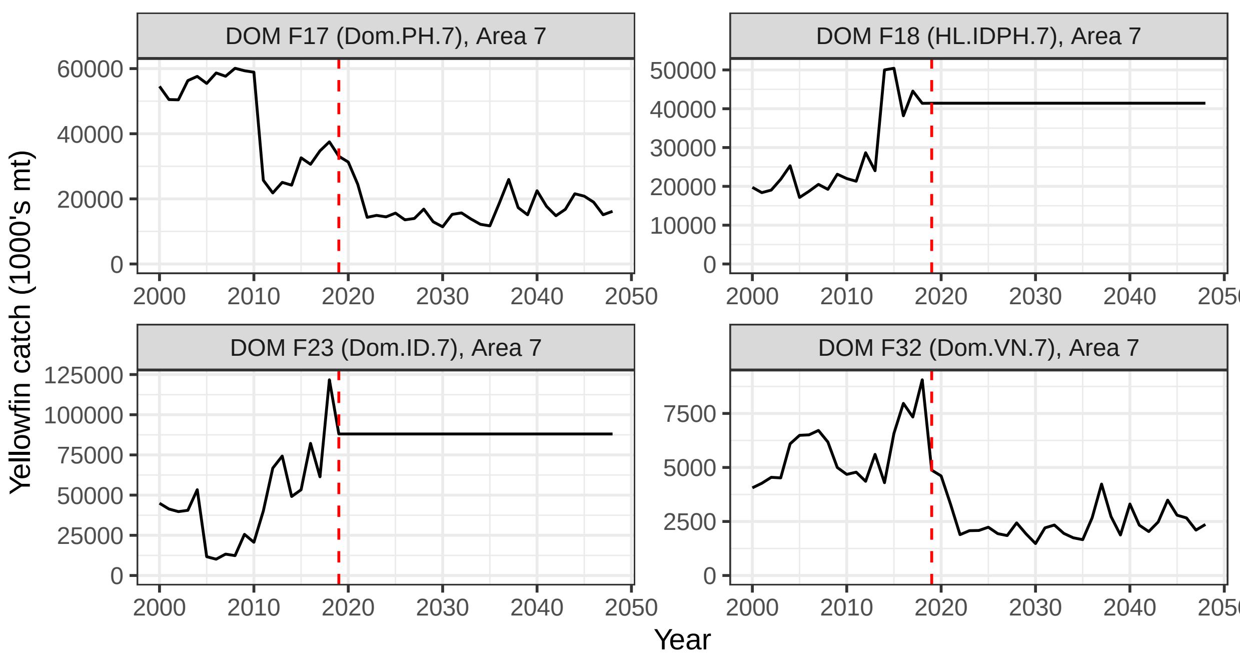

Figure 33: Projected yellowfin catches of the domestic fisheries in the yellowfin operating model for the example iteration from the results of HCR 10. The vertical dashed line indicates the start of the projection period. Note that fisheries 18 and 23 operate in archipelagic waters and are not managed through the skipjack MP.

F.5 Future catches of the tropical longline fisheries

The tropical longline catches of bigeye are set in advance at a status quo level (Figure 21). The effort used to take these catches is transferred to the corresponding fisheries in the yellowfin OMs. The resulting yellowfin catches by these fisheries is shown in Figure 34.

Of the example tropical longline fisheries shown in Figure 21, fisheries 2, 6 and 9 have higher selectivities for the older age classes of yellowfin (Vincent et al., 2020). This means the yellowfin spawning biomass shown in Figure 24 is a reasonable guide to the vulnerable biomass for these fisheries. The future spawning biomass of yellowfin is relatively stable in time for the example iteration. The result is that future catches for these fisheries follows the same pattern as the fishing effort. In this way, it is possible to see how the effort required to take the target tropical longline catches of bigeye also drives the future catches of yellowfin by these fisheries.

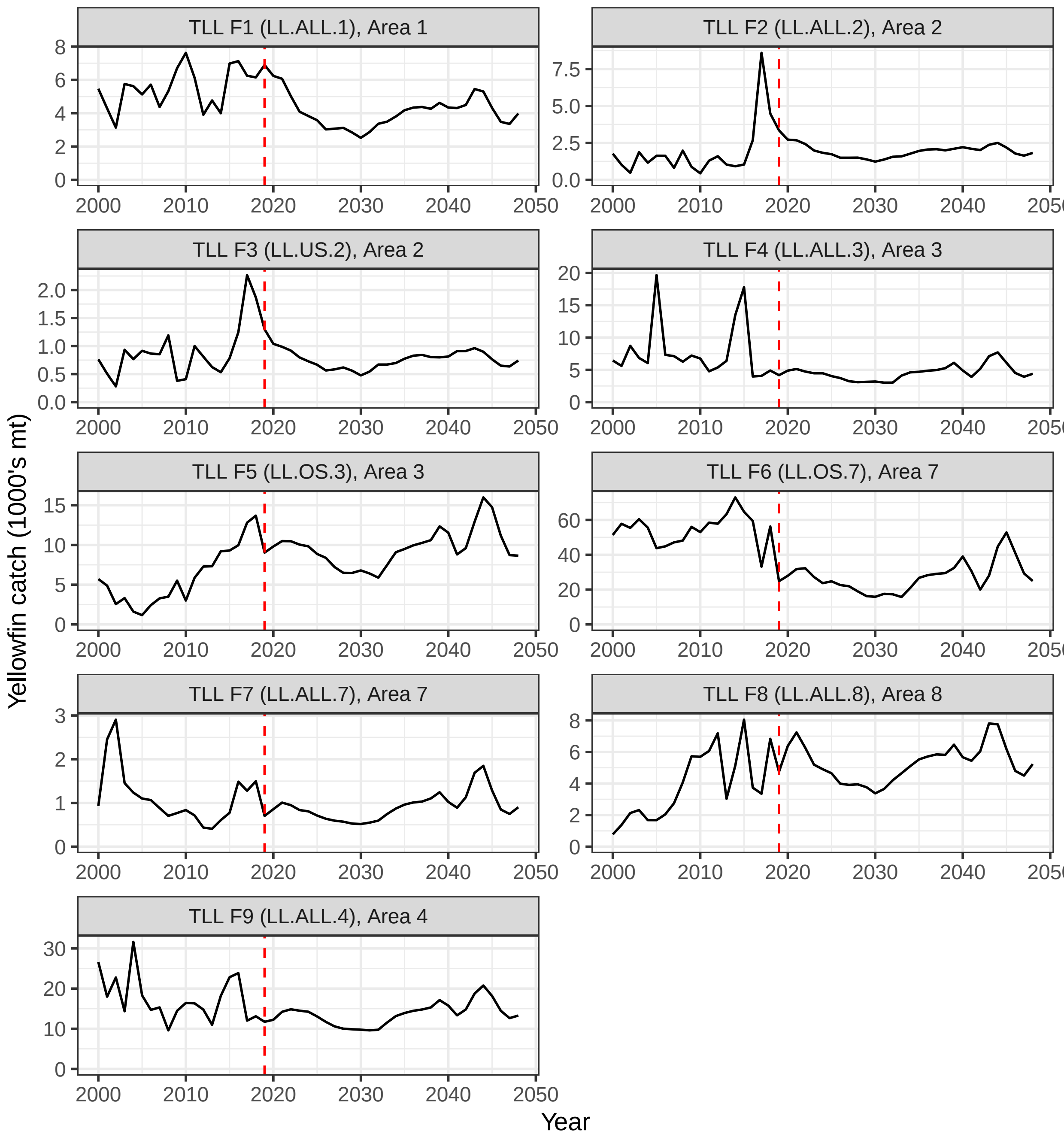

Figure 34: Projected yellowfin catches of the tropical longline fisheries in the yellowfin operating model for the example iteration from the results of HCR 10. The vertical dashed line indicates the start of the projection period.