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# Management Strategy Evaluation for Striped Marlin

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Ann Preece

Report for TTRAG32

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# 1 Executive summary

The Tropical Tuna RAG (TTRAG) have provided direction for the Management Strategy Evaluation of a new harvest strategy for striped marlin in the ETBF to replace the previously adopted harvest strategy (Kolody et al., 2010; Hillary et al., 2013) for recommending the Total Allowable Commercial Catch in the Eastern Tuna and Billfish Fishery (ETBF). The new harvest strategy follows the same structure as the ETBF swordfish harvest strategy adopted in 2020.

The operating models and initial harvest strategy results were presented to the TTRAG in 2020 and March 2021, and some final requests for modifications to the operating models and additional information were made. The final set of results are presented here, with a brief description of the operating models against which these harvest strategies were tested.

The striped marlin south west Pacific Ocean (SWPO) stock status is assessed by the scientists from the Pacific Community (SPC) for the Western and Central Pacific Fisheries Commission (WCPFC). The 2019 assessment indicates that the stock is likely to be over-fished (0.196 (range 0.1-0.34, 80%PI) of unfished biomass levels ($SSB_0$)), and catches are close to levels of overfishing (Ducharme-Barth et al., 2019). The stock assessment results show that the stock has been at these low levels since the mid-2000s. Genetic connectivity studies, including recent work by (Evans et al., 2021), have found that the Australian caught striped marlin are linked to the stock in the SWPO. Tag return analysis (Hillary and Patterson, 2019) indicate that the migration rate from the ETBF to the area outside of the ETBF is low, so impact of fishing by the ETBF could be localised. A subset of the stock assessment models, that encapsulate key uncertainties, are used as the starting point for the operating model projections into the future (with additional uncertainty added). The operating models have a 2-area structure (ETBF and non-ETBF) and a single spawning population, with recruitment and migration distributing fish to both areas. The range of uncertainties encapsulated in the operating models and specification of alternative hypotheses, ensures that the harvest strategy is tested against a wide range of potential future conditions.

TTRAG requested that Harvest Strategy 1 (HS1) use the same parameter settings as the swordfish harvest strategy and set the target reference CPUE as the average of the 2012-2015 ETBF striped marlin CPUE (Campbell, 2019). HS1 has been evaluated using 3 sets of operating models: Reference Set 1 which has a 20% migration scenario; Set 2 which has a more localised stock scenario with 1% migration; and, Robustness Set 3 which examines the impact of higher levels of fishing outside of the ETBF area on the HS1 performance (i.e. non-ETBF area effort doubles over 5 years and stays at that level). HS1 responds under each of the these sets of operating models to rebuild the spawning biomass above current (low) levels and increase the CPUE above current levels. HS1 also responds to a localised stock scenario (i.e. 1% migration) or poorer conditions (i.e. higher effort outside the ETBF) to increase or decrease TACC and maintain performance in SSB and CPUE, although the risk of falling below the Commonwealth Harvest Strategy Policy limit reference point guideline is >10% in the increased non-ETBF effort scenario. These results indicate that HS1 responds to feedback from the population dynamics to adjust catches.

TTRAG requested variations to HS1 be evaluated (using reference set 1) to examine if performance is enhanced by using the average CPUE over a shorter or longer period (HS2 and HS4), setting the TACC every 3 years (HS3), or by implementing alternative buffer-zones around the reference CPUE level (within which no TACC change occurs, HS5 & HS6). Results from these additional 5 harvest strategies indicated that there was poor performance relative to the risk of falling below the limit reference point for the alternative buffer zones harvest strategies, and little difference in SSB or CPUE performance for the alternative number of years for averaging CPUE scenarios. HS3, where TACC is set every 3 years, had lowest risk of falling below the limit reference point, and higher median CPUE in 2035, but lower TACCs compared to HS1.

TTRAG also requested constant catch projections. Zero constant catch indicated that the population would increase in the absence of fishing in the ETBF, and the constant catch of 250t, 300t and 351t (which is the current TACC) all showed rebuilding of the stock above current low levels, higher median CPUE in 2035, and a low risk of falling below the limit reference point. HS1 outperforms the constant catch projections in median TAC in 2035 because the HS can take advantage of good stock and respond to bad stock conditions to adjust catches.

# 2 Introduction

At the March 2021 TTRAG31 meeting, the results from Management Strategy Evaluation (MSE) of several alternative harvest strategies for Striped Marlin were presented (Preece, 2021). The TTRAG requested modification to the operating model implementation error, additional diagnostics and alternative constant catch projections to assist future decision making.

# 3 Background

The recent assessment of the striped marlin stock in the SW Pacific Ocean (SWPO) (Ducharme-Barth et al., 2019) indicates that the stock is likely to be over-fished (0.196 (range 0.1-0.34, 80%PI) of unfished biomass levels ($SSB_0$)), and catches are close to levels of overfishing. The median adult depletion estimates have been close to, or below, 0.2 of $SSB_{F=0}$ (recent SSB in the absence of fishing) since the early-mid 2000's (Figure 1). The stock assessment results show that the stock has been at these low levels since the mid-2000s. Genetic connectivity studies, including recent work by (Evans et al., 2021), have found that the Australian caught striped marlin are linked to the stock in the SWPO.

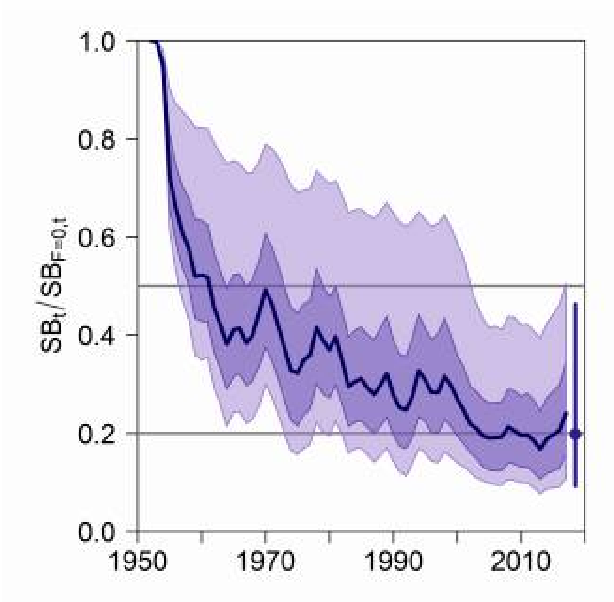


**Figure 1. The estimate of adult depletion across all models in the stock assessment uncertainty grid. Source: Figure 43 in Ducharme-Barth et al (2019).**

The MSE operating models use the most recent assessment model estimates to initialise projections for testing performance of harvest strategies. From the SWPO stock assessment models, 3 key uncertainties (steepness (productivity), natural mortality and CPUE series) were the main drivers of the range of assessment results. These 3 uncertainties were used to select a subset of assessment models as the historical state of the stock and starting point for projections. The other stock assessment factors (growth, size frequency weighting and recruitment penalty cv) are set at the same level used in the stock assessment diagnostic case (Table 1). The operating model structure is described in Preece and Hillary (2020) and builds on previous projects examining performance of harvest strategies for striped marlin and the other key species in Australia's Eastern Tuna and Billfish Fishery (ETBF) (Hillary et al. 2013, Kolody et al. 2010).

# 4 Candidate Harvest Strategies

Candidate harvest strategies use the form of the Harvest Control Rule (HCR) agreed to by the TTRAG members in December 2019 for swordfish (Figure 1). Multiple candidate harvest strategies for striped marlin were developed by varying the parameters of the HCR and presented to TTRAG31 following the advice from TTRAG 29 (Sept 2020) on the types of candidate HCRs to examine, and the scenarios that they should be tested against. Summary figures and statistics on performance of the harvest strategies compare performance primarily in future CPUE, catch and biomass. The TTRAG will consider whether a single harvest strategy should be recommended for implementation.

The TTRAG has agreed to use a single CPUE index (all sizes combined) in candidate harvest strategies for striped marlin. Details on the CPUE standardisation are in Campbell (2019), and the 2020 update is in Dell et al (2020), and no further examination of the CPUE standardisation is considered here.

The CPUE series (all sizes combined) is the only input data to the HCR. A target reference level of CPUE is used to define actions to increase or decrease total allowable commercial catch (TACC). The HCR incorporates an asymmetrical buffer zone around the reference level of CPUE, so that the harvest strategy is not overly reactive to variation in CPUE. The HCR also incorporates a threshold at half the reference CPUE level, which triggers stronger decreases in TACC. The TTRAG defined the reference level as the average CPUE in years 2012-2015 (currently 0.89, all size classes), and the buffer zone lower and upper bounds are 0.8 and 1.25.

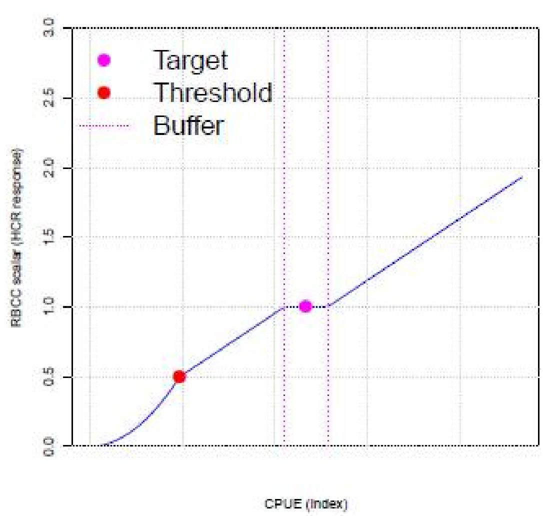


**Figure 2 The form of the harvest control rule. There is an asymmetrical buffer zone around the CPUE reference level, where TACC is unchanged, and a threshold point at half the CPUE reference level, below which TACC multiplier is strongly decreased. Source: Hillary (2020).**

The following alternative candidate harvest strategies, were presented in March 2021 (TTRAG31), and are based on the agreed form of HCR and differ via alternative values for several parameters as requested by TTRAG29:

- HS1 has the same settings as the swordfish HS adopted in 2020 and is the base HCR from which others vary. The reference level of CPUE is the average 2012-2015, 0.89, and lower and upper bounds of the buffer zone are 0.8 and 1.25. The CPUE input to the HCR is the average of the 3 most recent years of data, the maximum TAC change is 10% and TAC is set annually.
- HS2 uses the average CPUE over most recent 2 years as input to the HCR
- HS3 sets the TAC every 3 years, with maximum TAC change of 27%.
- HS4 uses average CPUE over most recent 4 years.
- HS5 uses a narrower and symmetrical buffer zone, set at 10% above and below the target level.
- HS6 uses a narrower and symmetrical buffer zone, set at 20% above and below the target level.
- CC0 A zero constant catch scenario was run to demonstrate whether the stock would rebuild under a hypothetical scenario of zero catch.

# 5 Reference set and robustness sets

A reference set of operating models is used to test performance of the harvest strategies. Robustness sets allow us to examine the effects of alternative or more extreme hypotheses. The previous reference and robustness sets have been simplified into three sets of operating models. Table 1 specifies these alternative sets, the assessment models used to initialise the operating models and the projections settings. The SWPO catch history, and description of spatial structure of the operating models and relationship to assessment models by Ducharme-Barth et al (2019), are provided in Appendix 1 (Figure 10 and Figure 11).

Set 1 (reference set) has migration of 20% per quarter. In contrast, set 2 has migration of 1% per quarter, representing a more localised stock which is less well mixed with the SWPO population. The localised stock hypothesis is supported by Hillary and Patterson (2019) estimates of < 1% per quarter movement of striped marlin from the ETBF to non-ETBF area and 10-21% per quarter movement from non-ETBF into the ETBF. Robustness set 3 explores the impact of doubling effort in the non-ETBF area on HS performance (i.e. a linear increase in non-ETBF effort over 5 years, then held at that level).

The reference and robustness sets also incorporate a revised specification for the TAC implementation error, because the ETBF striped marlin catch has fluctuated around 80% of the TACC in the recent 10 years. Catch estimates in the projections are modified by the implementation error (mean 80%, log sd(0.1)). The projections start from 2017 (the end year of the assessment models), TACs are fixed at 351t through to 2019 and ETBF catches are fixed at actual catches taken through to 2019. The harvest strategy decision rule is used to set the TACC from 2020 onwards. Replicates have been increased to 100.

**Reference Set 1 (1800 models):**

- 18 stock assessment models encapsulating the key uncertainties:
  - 3 values for Steepness (h, productivity of the stock: 0.65, 0.8, 0.95),
  - 3 values for natural mortality (M: 0.3, 0.4, 0.5)
  - 2 CPUE options (Japanese LL 2 CPUE series, and Australian LL CPUE series).
- The other stock assessment factors (growth, size frequency weighting and recruitment penalty cv) are set at the same level used in the stock assessment diagnostic case.
- 100 replicates
- 2 areas, ETBF area and non-ETBF area
- Migration 20% per quarter (both directions)
- Non-ETBF effort is fixed at current levels
- Additional error in future estimates: Implementation error (catches taken can vary from the TAC (mean 80%, log sd(0.1)), CPUE error, recruitment error and autocorrelation, additional error on first 2 age classes at the start of projections, and size sampling observation error.
- The selectivity in the ETBF area is Australian LL and in the non-ETBF area is Japanese LL2.

**Set 2 (1800 models)** – All the same settings as reference set 1, except for an alternative hypothesis for migration: 1% per quarter. This represents a more localised stock with migration rates similar to the tag movement rates estimated in Hillary and Patterson (2019).

**Robustness set 3** – All the same settings as reference set 1 but has an alternative hypothesis for higher effort in the non-ETBF area (effort outside the ETBF gradually doubles over the first 5 years of projections and stays at that level).

**Table 1. Specification of the operating models, including the assessment model starting point and projections settings.**

| Dimension | Reference Set 1 | Reference Set 2 | Robustness Set 3 | Number of Reference Set grid elements |
|---|---|---|---|---|
| **Stock Assessment model**<br>**3 x 3 x 2 grid** | h (0.65, 0.8, 0.95)<br>M (0.3, 0.4, 0.5)<br>CPUE (LL2, Aus6)<br>Other settings: Recr penalty CV 0.2, growth Kopf 2011, size freq wt 1 or 0.5 | | | **18** |
| **Stochastic replicates** | 100 | | | **100** |
| **Recruitment uncertainty**<br>**SD(log(dev));**<br>**autocorrelation** | τ=0.2 ; ρ=0.5 | | | **1** |
| **CPUE obs. error SD(log(dev));**<br>**autocorrelation** | τ=0.2 ; ρ=0.7 | | | **1** |
| **Migration Rate** | 20%/qtr | **1%/qtr** | | **2** |
| **Effort in the non-ETBF fishery** | Constant at 2017 levels | | **Effort outside the ETBF doubles over the first 5 years of projections and stays at that level** | **2** |
| **Additional uncertainty added to Numbers at age 0 and 1 in first yr of projections**<br>**N0 sigma, N1 sigma** | 0.5, 0.25 | | | **1** |
| **Size sampling observation error** | 70% unbiased = 0.7 | | | **1** |
| **TACC implementation error**<br>**Mean; SD(log(dev))** | 0.8 ; 0.1 | | | **1** |

# 6 Harvest Strategy 1 and Performance Measures

Harvest Strategy 1 (HS1) is used as the base model for comparisons of results under alternative reference and robustness sets, and to compare alternative harvest strategies (variants of HS1) under reference set conditions. These are single difference comparisons, only 1 change is investigated in each comparison. Median SSB in 2035 has very similar performance between model runs, therefore results can be compared without further tuning to another performance metric.

At the request of TTRAG, HS1 has the same control rule settings as the swordfish HS adopted in 2020, but with the target CPUE in the harvest control rule equal to the average observed striped marlin CPUE in 2012-2015 (0.89).

HS results are presented in figures and summary tables. The figures indicate the median (red line) and 90% confidence interval (blue area) of the 1800 model estimates over the period 2017-2040. A single black line (worm track) indicates a single model trajectory, highlighting individual variability in model runs that are not visible in the median trajectory summary. Summary tables provide the median estimates of key performance measures SSB, CPUE and TAC, the median of the average annual variability in TAC, and the percentage of the time breaching the limit reference point. The percentage of the time falling below the limit reference point is calculated from the number of times SSB is less than 20% of the initial SSB level, in the years 2030-2040, across all 1800 models. The years 2030-2040 were chosen so that the SSB had an opportunity to rebuild from the current low levels. The Commonwealth Harvest Strategy Policy guidelines (if they apply to this multi-jurisdiction fishery) indicate that a harvest strategy should not breach the limit reference point more than 10% of the time. A corresponding estimate is the percentage of models which breach the limit reference point in more than 10% of the years (within the model). In this case the proportion should be zero to meet the Commonwealth Harvest Strategy Policy. This second option is reported in (**Error! Reference source not found.** Table 5). The TTRAG request to evaluate the performance of each projection over the average of a range of years (2033-2037) gave the same results as the median in year 2035 already reported and has not been included in tables.

In this section, HS1 is evaluated against 3 sets of operating models and is compared with a zero-catch projection which is used to determine likely levels of rebuilding in the absence of ETBF fishing.

## 6.1 Constant Catch 0 projection

The Constant Catch of zero in the ETBF (CC0_stm_2020) provides an estimate of the impact of the ETBF catches on stock indicators and status measures (Figure 3). Effort in the non-ETBF area continue at current (2017) levels (non-ETBF catches can increase).

Results show that the SSB rebuilds, with median SSB depletion in 2035 at the 1980s-2000s levels, and the lower bound ($10^{th}$ percentile, blue area) well above median estimates of depletion in 2017 (Figure 3). Historic and future recruitment is highly variable (as shown by the black lines for individual runs) and 2035 median recruitment is at 1980-2000 levels. Estimated CPUE in 2035 (if catches were taken) is higher than the target and recent levels.

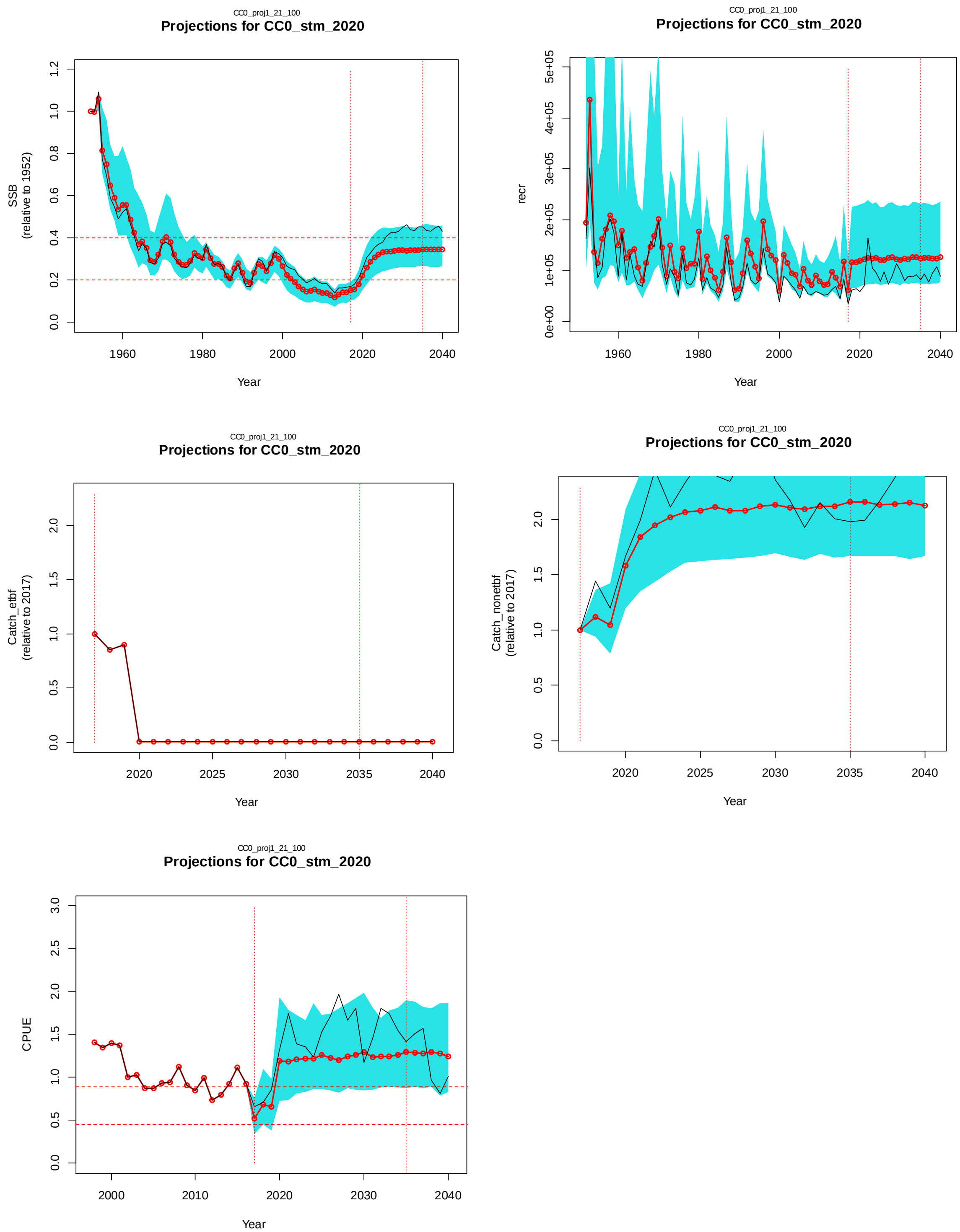


**Figure 3 Examination of recovery of the stock under a constant zero catch in the ETBF, with continued fishing in the non-ETBF area at current effort levels. Red circles indicate the median of 1800 projections, the shaded blue region is the 10th-90th percentiles, the thin black line represents a random trajectory. The vertical dashed lines are at reference years 2017 and 2035. In the CPUE figure the horizontal red dashed lines indicate the target and limit CPUE**

**levels in the HCR, and in the SSB figure red dashed lines indicate 0.4 SSB (a proxy for MSY (the 0.48 MEY proxy is not shown)) and 0.2 SSB reference points.**

## 6.2 Harvest Strategy 1 performance for the reference set

HS1 performance is evaluated under the conditions defined in the reference set of operating models (Figure 4, Table 2).

Results indicate that median SSB depletion in 2035 is above the low estimates at the start of projection period. The lower bound of the estimates (10th percentiles, area in blue) are above 0.2 SSB reference point and above the median estimates for 2017. The probability of breaching the limit reference point in the period 2030-2040 across all models is less than 9%. This meets the Commonwealth Harvest Strategy Policy guideline (of less than 10% probability of breaching the limit reference point).

Median CPUE in 2035 is above the reference CPUE level. Median CPUE tends to sit above the reference level in the HS1 through most of the projection period, as a result of the combination of settings in HS1 (i.e. sitting near to the upper limit of the buffer zone). The single trajectory shows high CPUE variability from year to year. The Australian fishery predominantly catches age 3 fish which means the CPUE is strongly influenced by recruitment variability.

Median TAC in 2035 is above current levels, and has an increasing trend over the projection period, following the initial decrease. The median catch (TACC plus implementation error) in the ETBF has an increasing trend. The median of the average annual variation in TAC is 17t.

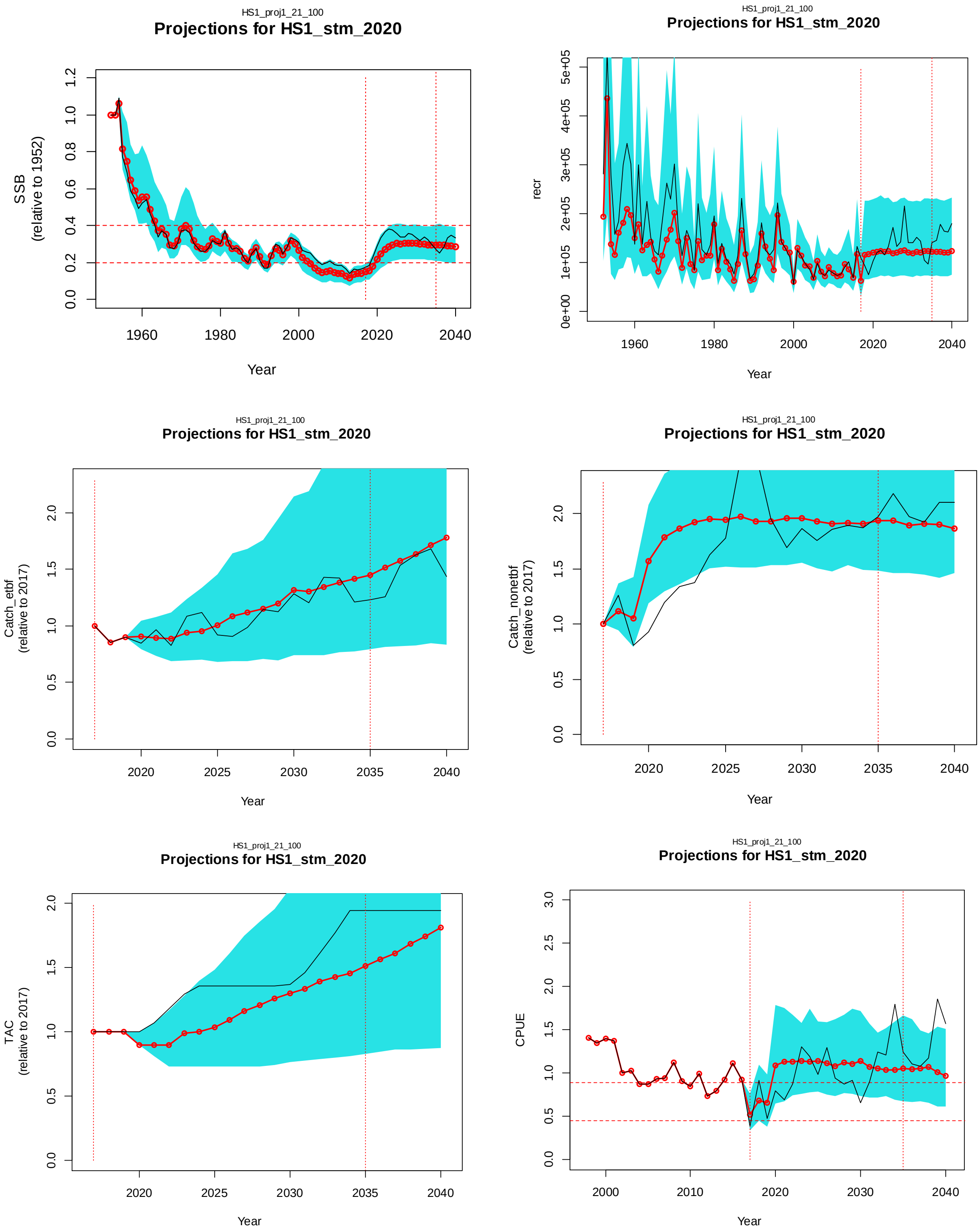


**Figure 4 HS1 performance for the reference set of operating models. Red circles indicate the median of 1800 projections, the shaded blue region is the 10th-90th percentiles, the thin black line represents a random trajectory. The vertical dashed lines are at reference years 2017 and 2035. CPUE horizontal red dashed lines are the target and limit CPUE levels in the HCR, and SSB horizontal red dashed lines indicate 0.4 SSB and 0.2SSB.**

**Table 2 Reference set comparisons of HS performance for HS1 under the reference set (1), localised stock (2) and higher non-ETBF effort scenario (3), and for comparison, the constant catch scenario (CC0). SSB, CPUE and TAC is the median and 80% confidence interval, AAV is the median of the average annual variation in TACC, 'Pr < limRefPt' is the probability of breaching the limit reference point.**

| HS | set | Scenario | SSB 2035/SSB0 | CPUE 2035 | TAC 2035 | AAV (t) | Pr < limRefPt |
|---|---|---|---|---|---|---|---|
| **CC0** | 1 | ref set | 0.35 (0.27,0.46) | 1.29 (0.88, 1.89) | 0 | 0 | 0.00 |
| **HS1** | **1** | ref set | 0.30 (0.21, 0.41) | 1.05 (0.67, 1.66) | 531 (290, 973) | 17 | 0.09 |
| **HS1** | **2** | 1% mig | 0.31 (0.22,0.42) | 1.08 (0.66, 1.76) | 621 (355, 1082) | 23 | 0.06 |
| **HS1** | **3** | 2 x non-ETBF effort | 0.23 (0.15, 0.32) | 0.97 (0.62, 1.51) | 418 (222,779) | 12 | 0.35 |

## 6.3 Effect of a localised stock

Reference set 1 assumes a 20% per quarter migration rate between the ETBF and non-ETBF area. This allows for a gradually well mixed stock. The genetic stock structure research to-date indicates that there is connectivity between the Australian caught striped marlin and those in other locations in the SW Pacific (Evans et al., 2020). Estimation of migration rate from tag returns (Hillary and Patterson 2019) identified a 1 % migration rate from the ETBF to non-ETBF and an asymmetrical migration rate from the non-ETBF to ETBF of ~20%. A 1% migration rate indicates that the ETBF stock is localised, with occasional migration into the area from non-ETBF. Reference set 2 explores HS1 performance under the conditions of a more localised stock in the ETBF area, with low (1% per quarter) migration between areas.

The results of HS1 under the localised stock scenario are very similar to reference set 1 results. SSB and CPUE are slightly higher in the initial period of the projections and gradually decline over time, reaching the same median levels for SBB and TAC as the reference set results in 2035 (Figure 5). A higher median TAC is achieved by 2035, and the risk of breaching the limit reference point is lower under this scenario (Table 2).

These results indicate that if the stock is localised, the ETBF harvest strategy should be able to take advantage of the conditions, maintaining SSB and CPUE above limit reference point levels while increasing catches.

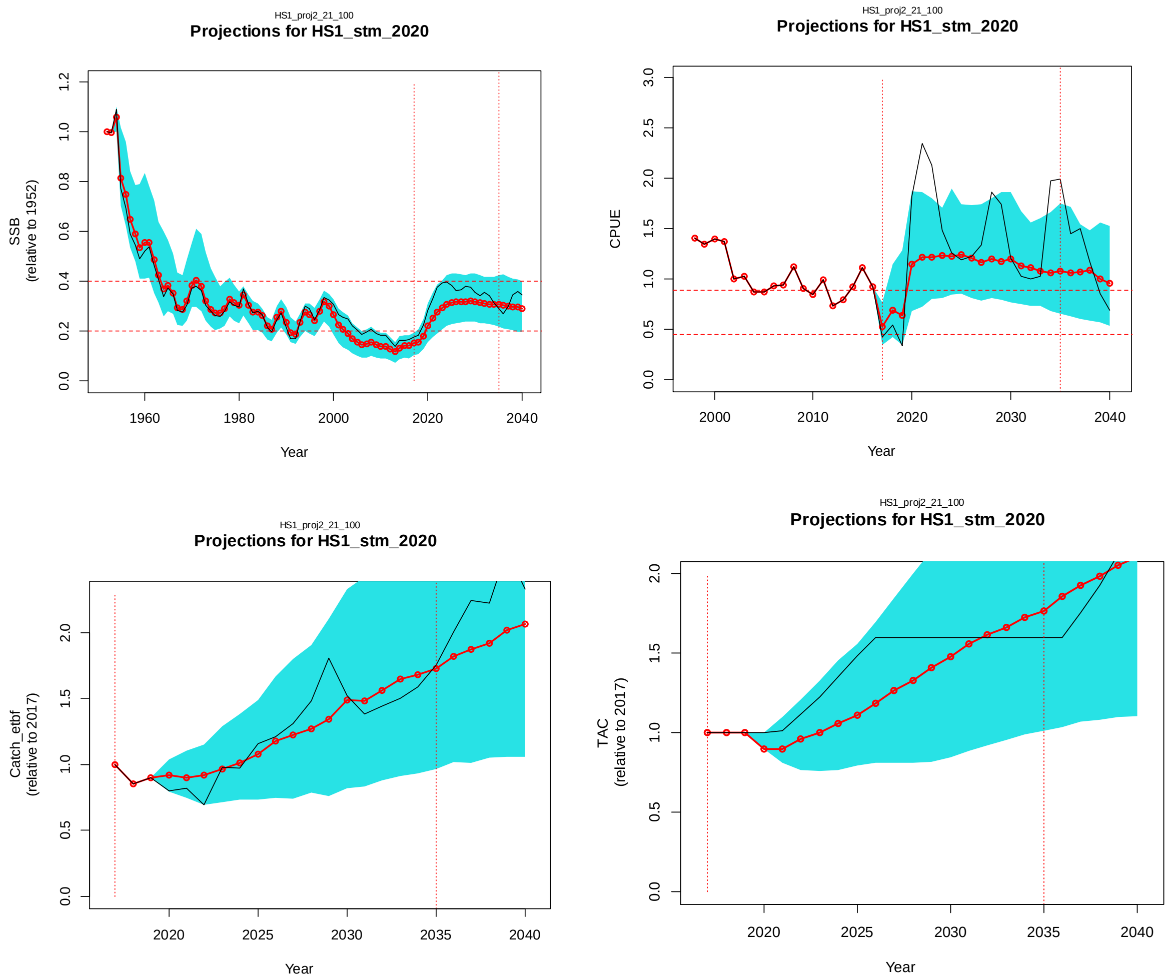


**Figure 5 HS1 performance in a localised stock scenario. Red circles indicate the median of 1800 projections, the shaded blue region is the 10th-90th percentiles, the thin black line represents a random trajectory. The vertical dashed lines are at reference years 2017 and 2035. CPUE horizontal red dashed lines are the target and limit CPUE levels in the HCR, and SSB horizontal red dashed lines indicate 0.4 SSB and 0.2SSB.**

## 6.4 Effect of increased effort outside the ETBF

A key concern of the TTRAG is whether the HS will function if fishing effort outside of the ETBF area increases. Robustness set 3 explores a scenario where non-ETBF effort increase over 5 years to double current levels, and then remains at that level.

Under this scenario of increased non-ETBF effort, the median SSB in 2035 is low but above the limit reference point, the risk of breaching the limit reference point has increased to 35% (Table 2). CPUE is lower than HS 1 performance under reference set conditions. Median TAC increases gradually over the projection period (Figure 6).

Results from this scenario demonstrate that the HS will respond to poorer condition of the stock and the CPUE indicator data. The HS sets smaller TACC increases compared to the reference set results.

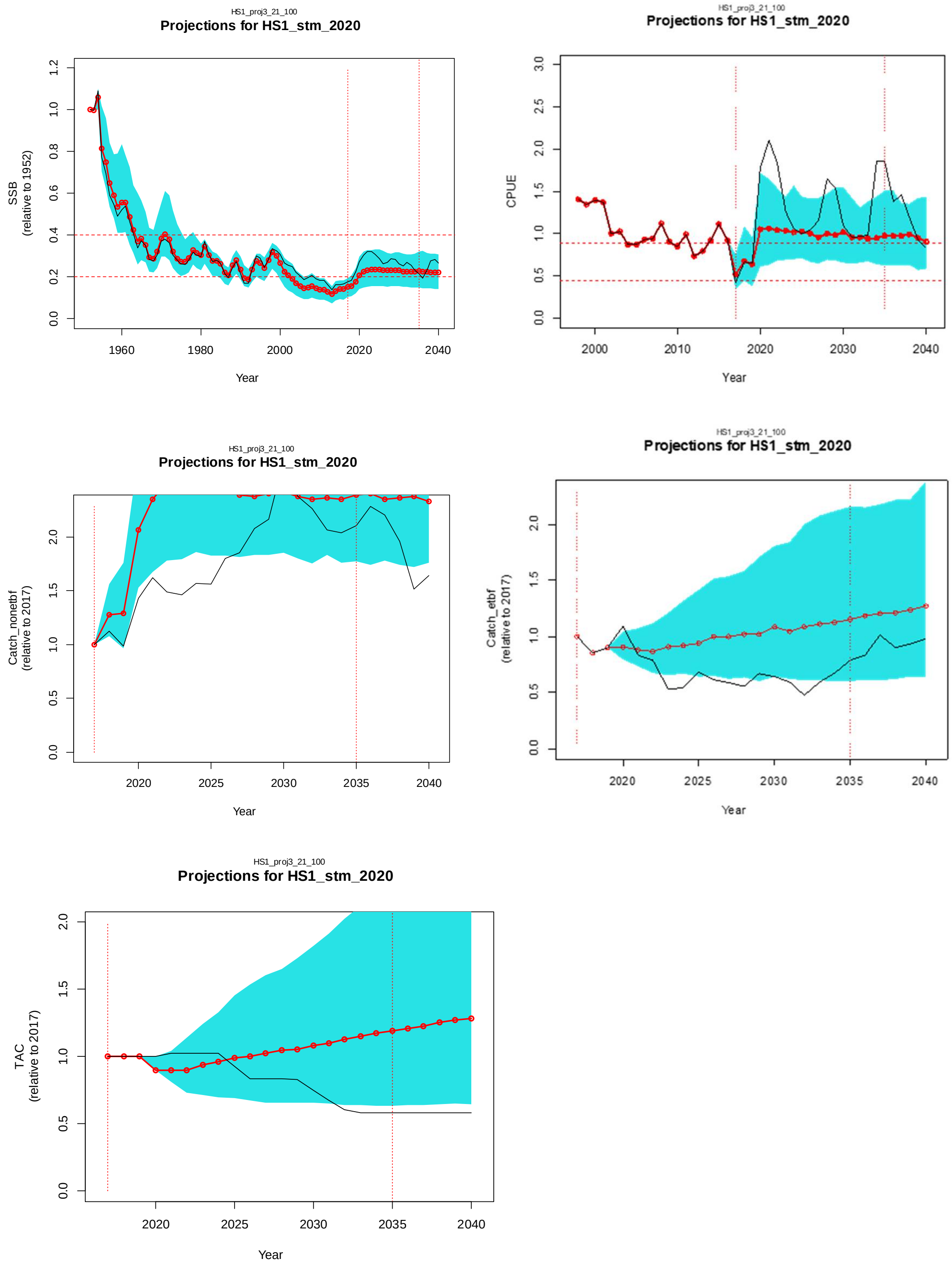


**Figure 6 HS1 performance under the scenario of increased effort in the non-ETBF area. Red circles indicate the median of 1800 projections, the shaded blue region is the 10th-90th percentiles, the thin black line represents a random trajectory. The vertical dashed lines are at reference years 2017 and 2035. CPUE horizontal red dashed lines are the target and limit CPUE levels in the HCR, and SSB horizontal red dashed lines indicate 0.4 SSB and 0.2SSB.**

# 7 Alternative Harvest Strategies

The following alternative harvest strategies (modifications to HS1) were presented in March 2021 (Preece, 2021). Results have been updated using the modified reference set and additional performance measures are reported. Results are summarised briefly below and in Table 3.

HS1 has the same settings as the swordfish HS adopted in 2020.

- This is the base HCR from which others vary. The CPUE input to the HCR is the average of the 3 most recent years from the CPUE index (all size classes), the maximum TAC change is 10% and TAC is set annually.

HS2 uses the average CPUE over most recent 2 years as input to the HCR.

- There is a very small increase in average annual TAC change (AAV), and small decrease in risk of breaching the limit reference point, as the HS is responds to the most recent CPUE values.

HS4 uses average CPUE over most recent 4 years.

- There is very little difference to HS1 or HS2 median results.

HS3 sets the TAC every 3 years, with maximum TAC change of 27%. In comparison, HS1 sets the TAC each year and has a max TAC change of 10%.

- The median SSB depletion in 2035 is very similar to HS1, CPUE performance by 2035 is higher than in HS1, but median TAC is lower. The average annual variation in TAC is lower, and risk of breaching the limit reference point is lower. The improved risk statistic could be a result of a longer period of lower TACs in the early years while the stock is recovering combined with a less reactive harvest strategy (because TAC is set for 3 year periods) (Figure 7**Error! Reference source not found.**).

HS5 uses a narrower and symmetrical buffer zone, set at 10% above and below the target level.

HS6 uses a narrower and symmetrical buffer zone, set at 20% above and below the target level.

- HS5 and HS6 are two alternative settings that were requested by TTRAG29 (Sept 2020) for 10% and 20% symmetrical bounds around the CPUE target (the buffer zone). The HS1 rule has asymmetrical bounds (lower bound of 0.8 and upper bound of 1.25), around the target CPUE of 0.89. HS5 10% bounds are 0.8 and 0.98, and HS6 20% bounds are 0.71 and 1.07. In both these cases the upper bound is lower than the setting in HS1, which means that TAC increases will start to occur at lower levels of CPUE. HS6 will be less responsive to low CPUE levels than HS1 and HS5.
- HS5 and HS6 have very similar results but have different performance to HS1 (Figure 8). Median 2035 SSB depletion estimates are similar for HS1. Median CPUE at 2035 is lower for HS5 and HS6 than HS1, and there is a decreasing trend in CPUE over the projections period. Median TAC in 2035 is higher, average annual variation in TAC is higher and the risk of breaching the limit reference point is above 10% for HS5 and HS6.

In summary:

1. There is no substantial performance improvement from using a smaller (HS2) or larger (HS4) number of years over which the CPUE is averaged for use in the HCR relative to HS1 which uses the average over 3 years;
2. Setting the TAC every 3 years (HS3) results in higher catch rates and reduced risk of breaching the limit reference point, however median TAC in 2035 is lower than in HS1;
3. Changes to the bounds in the HCR (HS5 and HS6) result in higher allowable catches, but poorer performance relative to HS1, with declining trend in CPUE and a greater than 10% probability of breaching the limit reference point (10% is the Commonwealth Harvest Strategy Policy performance guideline).

**Table 3 Results from alternative HSs. The median SSB depletion in 2035 (SSB2035/SSB0), median CPUE in 2035, median TAC in 2035. Numbers in brackets are the 80% percentile range of the estimates from the reference set of operating models (1800 models). Average annual variation in TAC (AAV). "Pr < limRefPt" is the probability of falling below 20%SSB0 in the years 2030-2040.**

| HS | Ref set | HS scenario | SSB2035/SSB0 | CPUE 2035 | TAC 2035 | AAV (t) | Pr < limRefPt |
|---|---|---|---|---|---|---|---|
| **HS1** | 1 | | 0.30 (0.21, 0.41) | 1.05 (0.67, 1.66) | 531 (290, 973) | 17 | 0.09 |
| **HS2** | 1 | CPUE 2 yr average | 0.30 (0.21, 0.41) | 1.05 (0.68, 1.65) | 534 (298, 934) | 18 | 0.08 |
| **HS3** | 1 | Set TAC every 3 yrs | 0.31 (0.22, 0.42) | 1.13 (0.74, 1.73) | 431 (266, 730) | 10 | 0.05 |
| **HS4** | 1 | CPUE 4 yr average | 0.30 (0.21, 0.41) | 1.06 (0.67, 1.67) | 530 (281, 1006) | 17 | 0.08 |
| **HS5** | 1 | 10% buffer zone | 0.30 (0.19, 0.39) | 0.93 (0.56, 1.52) | 791 (411, 1268) | 37 | 0.13 |
| **HS6** | 1 | 20% buffer zone | 0.28 (0.19, 0.39) | 0.96 (0.58, 1.55) | 734 (411, 1202) | 29 | 0.12 |

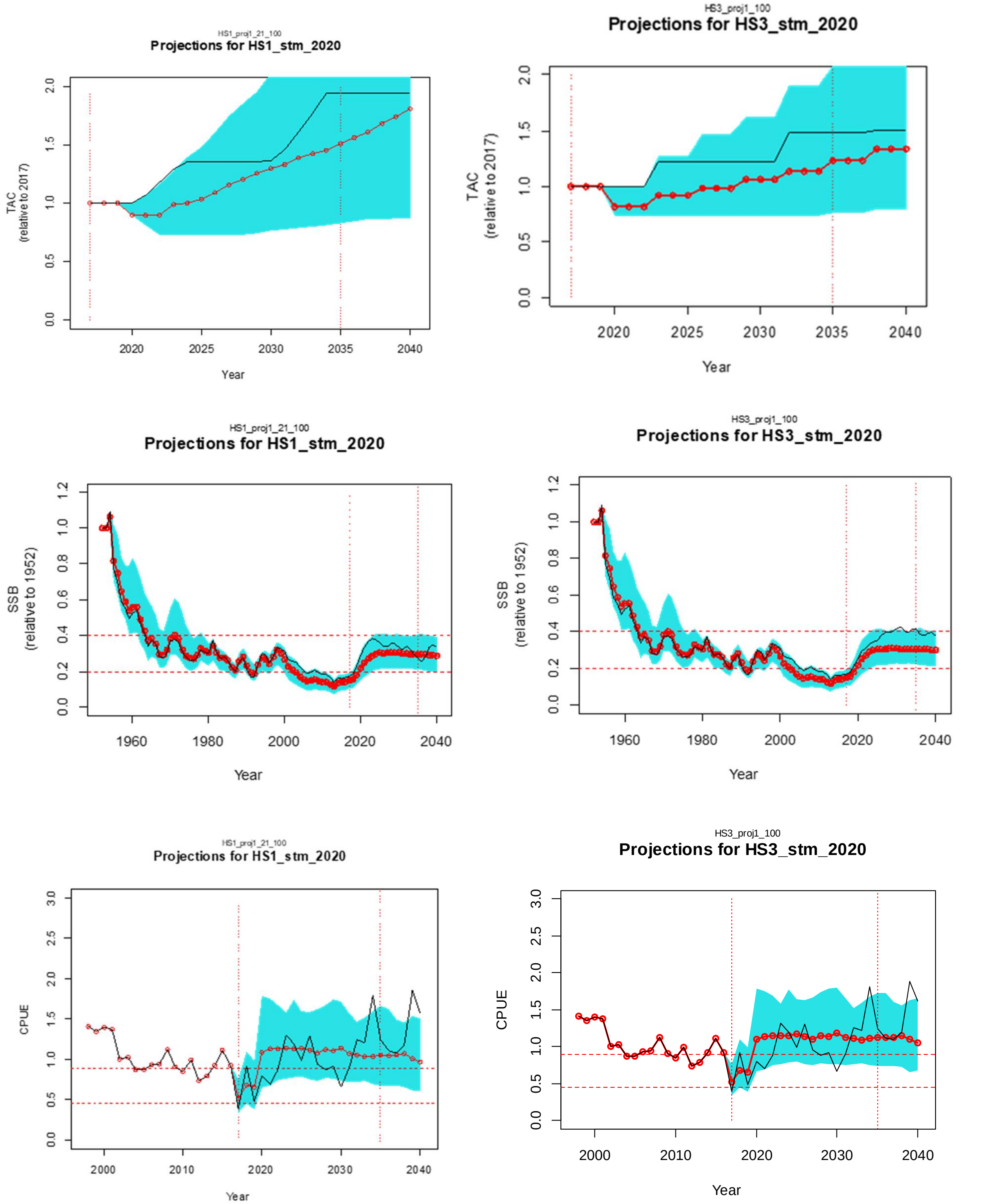


**Figure 7 Effect of frequency of TAC changes. Comparison HS1 (left column, annual TAC changes) and HS3 (right column, TAC changes in 3 yr blocks). Top row TAC, middle row SSB, bottom row CPUE. Red circles indicate the median of 1800 projections, the shaded blue region is the 10th-90th percentiles, the thin black line represents a random trajectory. The vertical dashed lines are at reference years 2017 and 2035. CPUE horizontal red dashed lines are the target and limit CPUE levels in the HCR, and SSB horizontal red dashed lines indicate 0.4 SSB and 0.2SSB.**

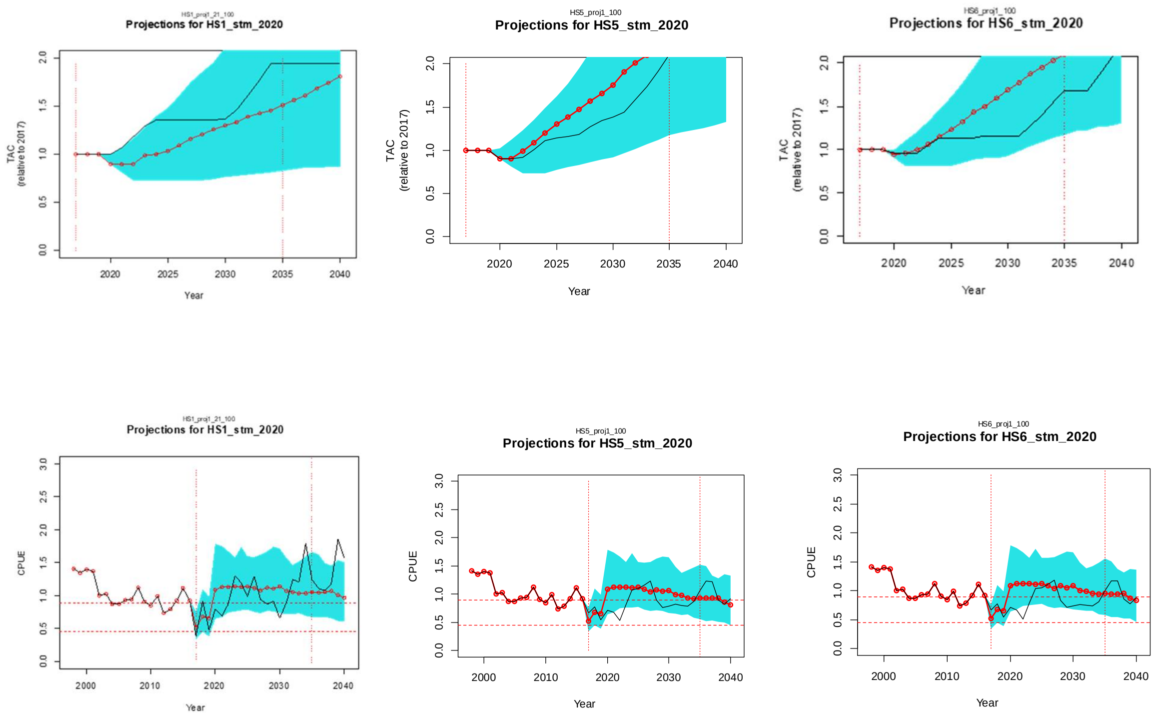


**Figure 8 Comparison of HS1 with HS5 and HS6 (left, middle end columns) which have symmetrical bounds (10% and 20%) to form the buffer zone in the HCR. Top row TAC, bottom row CPUE timeseries. Red circles indicate the median of 1800 projections, the shaded blue region is the 10th-90th percentiles, the thin black line represents a random trajectory. The vertical dashed lines are at reference years 2017 and 2035. CPUE horizontal red dashed lines are the target and limit CPUE levels in the HCR.**

# 8 Additional Constant Catch projections

TTRAG 31 requested additional constant catch projections of 200, 300 and 351t (labelled 350) (Figure 9).

The advantage of HS1 relative to these constant catch options is that the HS will respond to positive and negative changes in the stock. The HS can take advantage of good conditions to increase TAC and will act in poorer conditions (as demonstrated in robustness test set 3) to limit TAC increases, and reduce TAC if needed, to maintain SSB above the limit reference point. There is a substantial TAC performance advantage from HS1 relative to constant catch scenarios under the reference set of operating models (Table 4).

**Table 4 Constant catch projections. The median SSB depletion in 2035 (SSB2035/SSB0), median CPUE in 2035, median TAC in 2035. Numbers in brackets are the 80% percentile range of the estimates from the reference set of operating models (1800 models). Average annual variation in TAC (AAV). "Pr < limRefPt" is the probability of falling below 20%SSB0 in the years 2030-2040.**

| HS | Ref set | SSB2035/SSB0 | CPUE 2035 | TAC 2035 | AAV (t) | Pr < limRefPt |
|---|---|---|---|---|---|---|
| **HS1** | 1 | 0.30 (0.21, 0.41) | 1.05 (0.67, 1.66) | 531 (290, 973) | 17 | 0.09 |
| **CC250** | 1 | 0.31 (0.24,0.42) | 1.21 (0.79, 1.80) | 250 | 0 | 0.03 |
| **CC300** | 1 | 0.31 (0.23, 0.41) | 1.17 (0.76, 1.77) | 300 | 0 | 0.04 |
| **CC350** | 1 | 0.30 (0.22, 0.41) | 1.14 (0.74, 1.73) | 351 | 0 | 0.05 |

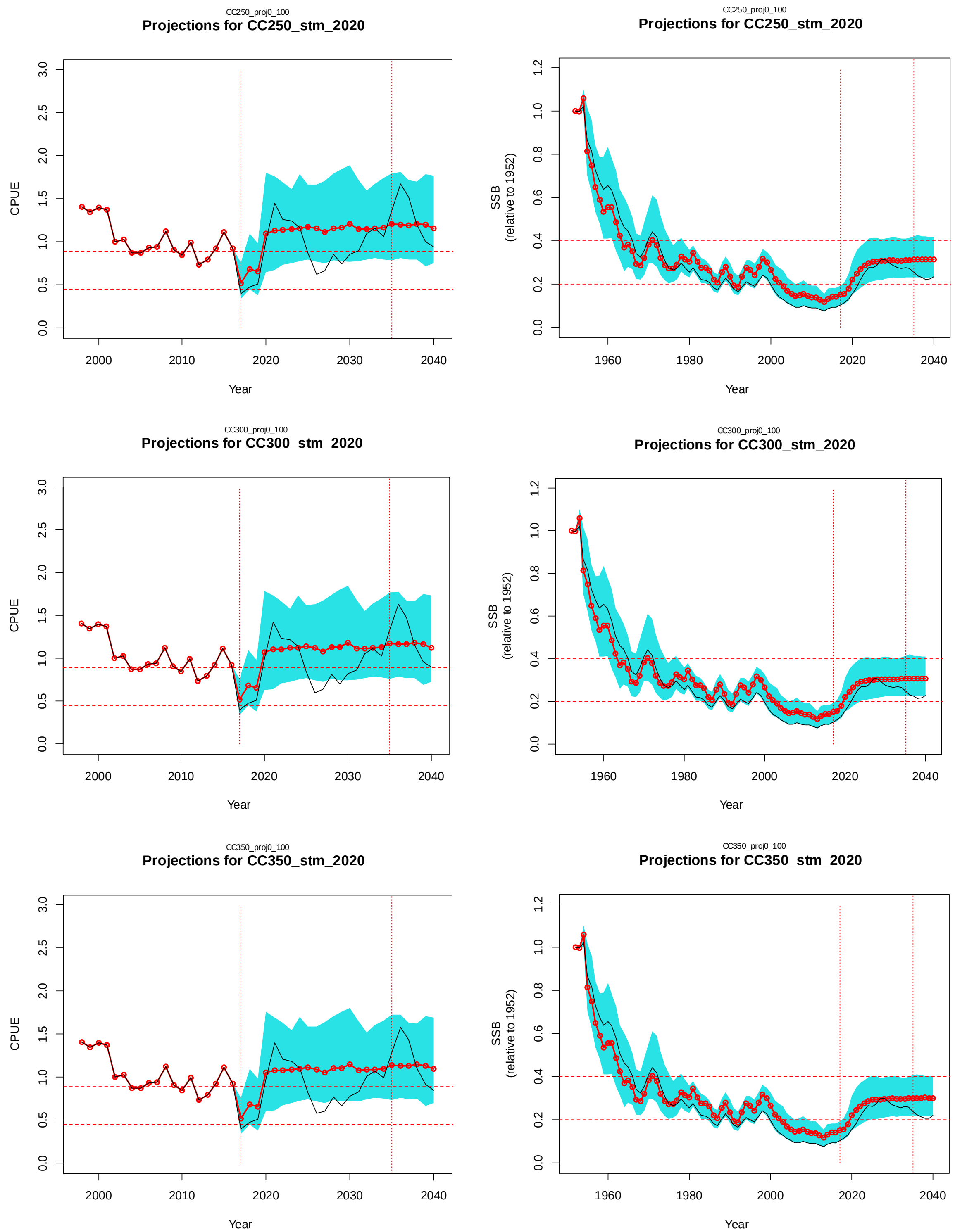


**Figure 9 Constant catch projections. Red circles indicate the median of 1800 projections, the shaded blue region is the 10th-90th percentiles, the thin black line represents a random trajectory. The vertical dashed lines are at reference years 2017 and 2035. CPUE horizontal red dashed lines are the target and limit CPUE levels in the HCR, and SSB horizontal red dashed lines indicate 0.4 SSB and 0.2SSB.**

# 9 Conclusion

Candidate harvest strategies have been evaluated using a reference set of operating models and two alternative future projection scenarios. The MSE operating models are initialised from a set of stock assessment model estimates, that capture key uncertainties in the stock biology and fishery data, and include additional uncertainty in future projections to ensure the HS's are robust to a wide range of potential future stock dynamics. The alternative projection scenarios check for HS1 robustness to the hypothesis that the striped marlin stock is localised, with limited connectivity to the broader SWPO stock, and HS1 performance in the case of increased effort in the non-ETBF.

HS1 demonstrates feedback in that the HS responds to adjust TAC when CPUE, and related biomass, increase or decline. If the stock is localised, the ETBF HS should be able to take advantage of the conditions, maintaining SSB and CPUE above limit reference point levels while increasing catches. Feedback in the HS is also demonstrated in the scenario where non-ETBF effort doubles, and in the scenario when migration is reduced to 1% which mimics a localised Australian stock.

Several alternative HSs were evaluated to determine whether modifications to HS1 would give better performance. As expected, there are trade-offs in performance between higher potential TACs, higher potential CPUE, and risk of breaching the limit reference point more than 10% of the time. SSB results are relatively stable. The modifications included:

1. Using the average of CPUE from the recent 2 or 4 years, rather than 3 year average used in HS1. Neither of these options demonstrated improved performance.
2. Setting TAC every 3 years, rather than annually. Performance gains and losses were mixed. Small gains in CPUE and lower risk to of breaching the limit reference point were attained, but there are larger losses in potential future catches with lower median TAC by 2035.
3. Adjusting the buffer zone in the HCR. These harvest strategies performed poorly relative to HS1 with the limit reference point breached more than 10% of the time in the latter years of projections.

The TTRAG also requested evaluation of several constant catch projections. HS1 outperforms these scenarios in median TAC by 2035. This is because the harvest strategy can adjust TAC to match changes in the stock and optimise catches in the good periods, compared with constant catches which are unrelated to changes in stock size.

The trends in the figures and the median and lower percentile of estimates, summarised in tables, should be considered when selecting a HS.

Acknowledgments

Nicholas Ducharme-Barth, Graham Pilling and John Hampton, at SPC, for access to the striped marlin stock assessment outputs.

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# Appendix A

## A.1 Operating model description from Preece and Hillary (2020):

The estimates from individual stock assessment models of the numbers at age in each year, selectivity of the different fisheries, and natural mortality, steepness and growth rates are used to define the values of the variables and parameters in the individual operating models. The population numbers are then projected into the future, using these population dynamics parameters.

The SWPO assessment models are for a well-mixed single population (Figure 10). Four areas are specified to define fisheries in the assessment, but there is no allocation of a proportion of fish to an area and no movement or migration. In the operating models, the assessment's single spatial structure is split into two areas, an ETBF and non-ETBF area, with hypotheses for connectivity between them. The HS only operates in the ETBF area. The following assumptions have been made to partition the population into a suitable spatial framework in the OM.

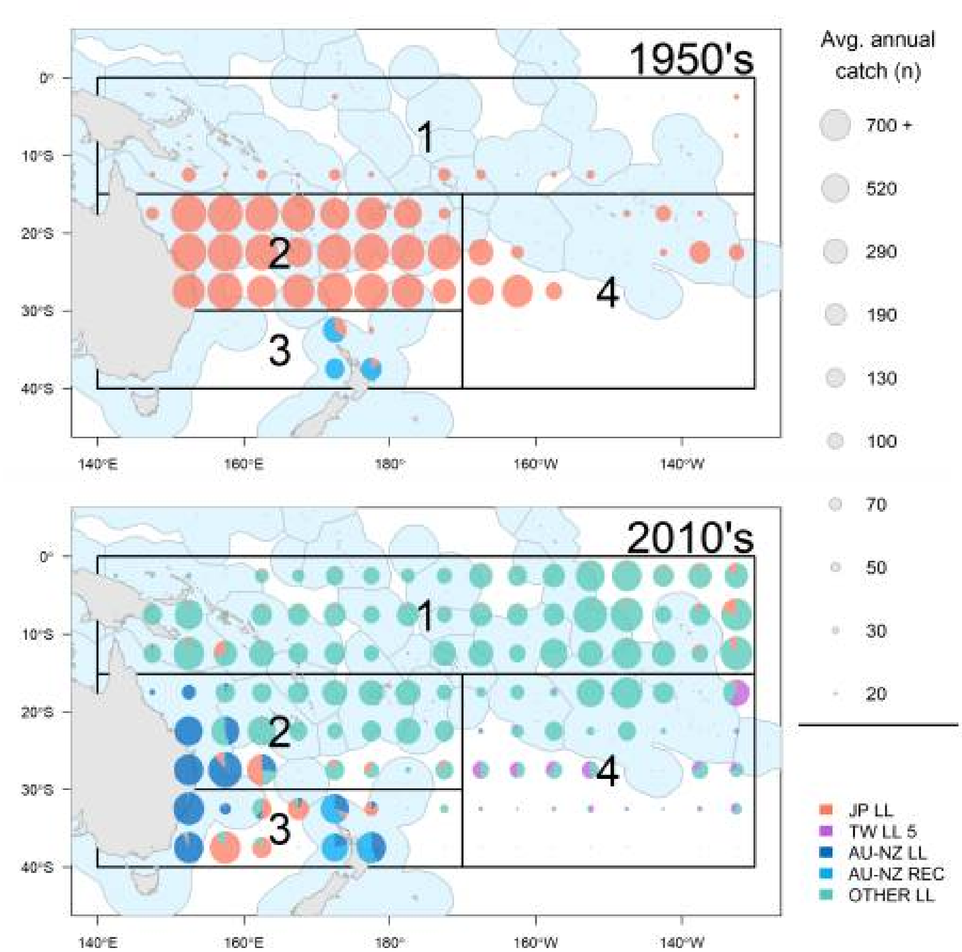
• The operating model (OM) is a two-area model representing the ETBF and non-ETBF areas. The data from the stock assessment (estimates of numbers at age in each year 1950-2017) are partitioned into the two areas based on the geographical surface area of the ETBF in the assessment region (36% was used as the ETBF area in the first MSE OM's, and re-used here).

• A single selectivity vector (by age) is used in each of the OMs 2 areas. The Australian longline fishery selectivity for the ETBF area and for the non-ETBF area in the OM, the Japanese longline 2 fishery selectivity ('LL2' as defined in the stock assessment) is used. The Japanese longline fishery has taken the largest catches over the history of the fishery, but in recent years the catches by non-Japanese fleets have increased substantially.

• The stock assessment model assumes that there is a single well mixed population, and single spawning population. Similarly, the OM assumes that there is a single spawning population (the combination of mature fish from both the ETBF and Non-ETBF areas) and has fixed parameters for distribution of recruits to the 2 areas in the OM.

• The OM allows for migration between the ETBF and non-ETBF areas, and different rates of migration are explored, related to different connectivity hypotheses.

• In the projections of the population into the future, the catch in the ETBF is determined by using the HS decision rules that is being tested, and alternative scenarios for fixed non-ETBF effort are examined.




**Source: Ducharme-Barth et al (2019)**

**Figure 10 Figure from Ducharme-Barth et al (2019): "Average annual catches of striped marlin in the SWPO by 5x5 cell, during the 1950s (top panel) and the 2010s (bottom panel) indicating the large shift in fisheries composition over time. The black lines represent the boundaries of the assessment region (outer lines) for striped marlin in the southwest Pacific Ocean and the four sub-regions used to define the fisheries".**

## A.2 Catch history (from the stock assessment paper (Ducharme-Barth et al., 2019))

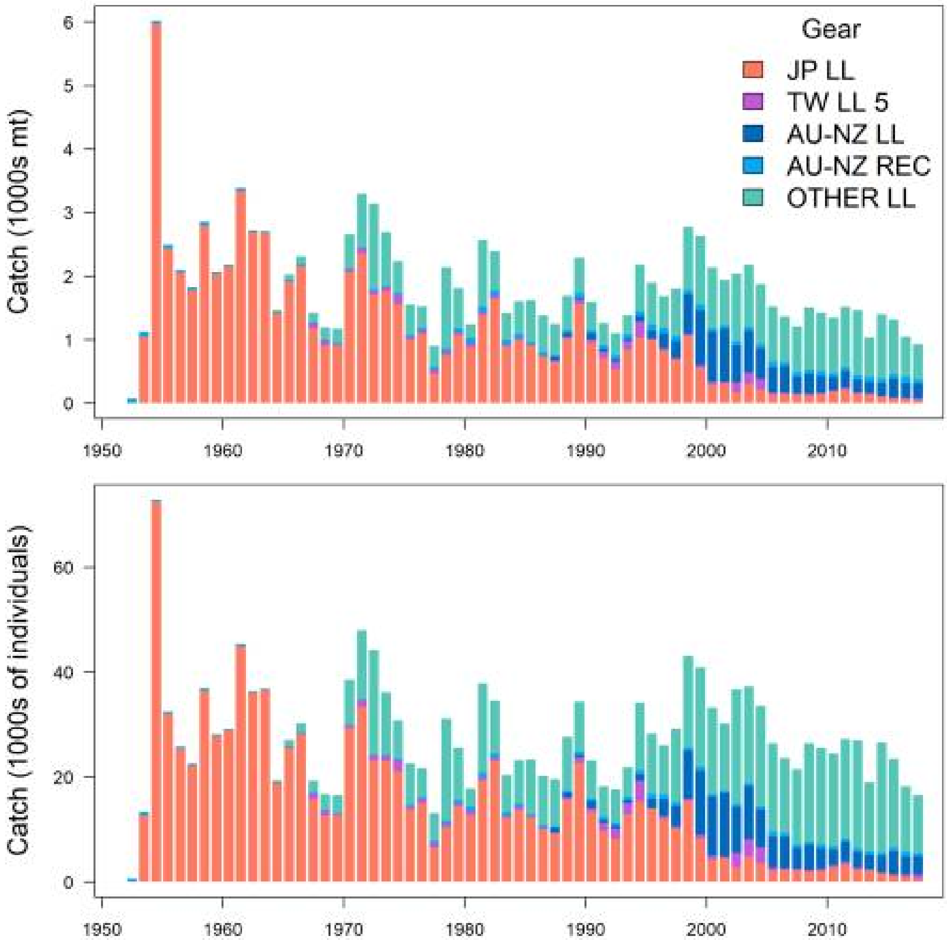



**Figure 11 Source: Ducharme-Barth et al (2019). "Total striped marlin catches (biomass – top; biomass – bottom) grouped by major fisheries in the model region, 1952–2017: JP LL - Japanese longline (red), TW LL 5 – Chinese Taipei longline sub-region 4 (purple), AU-NZ LL – Australia and New Zealand longline sub-regions 2 & 3 (dark blue), AU-NZ REC - Australia and New Zealand recreational sub-region 3 (light blue), OTHER LL – distant water fishing nation and Pacific Island country and territory longline (teal)".**

## A.3 Risk of breaching the Limit Reference Point

**Table 5 The percentage of the time breaching the limit reference point and the percentage of models breaching the limit reference point > 10% of the time. The percentage of the time the estimated SSB falls below the limit reference point is calculated from the number of times SSB is less than 20% of the initial SSB level, in the years 2030-2040, across all 1800 models. The percentage of models which breach the limit reference point in more than 10% of the years within each model is calculated from the SSB estimates in the last decade of each model.**

| Harvest Strategy | Projection set | % of time with SSBy < 0.2SSB0, in years 2030-2040 x 1800 models | % models with SSB < 0.2SSB0 in >10% of the years |
|---|---|---|---|
| **CC0** | 1 | 0% | 1% |
| **HS1** | 1 | 9% | 14% |
| **HS1** | 2 | 6% | 12% |
| **HS1** | 3 | 35% | 50% |
| **HS2** | 1 | 8% | 15% |
| **HS3** | 1 | 5% | 10% |
| **HS4** | 1 | 8% | 14% |
| **HS5** | 1 | 13% | 22% |
| **HS6** | 1 | 12% | 21% |
| **CC250** | 1 | 3% | 6% |
| **CC300** | 1 | 4% | 8% |
| **CC350** | 1 | 5% | 11% |

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**Contact us**

1300 363 400
+61 3 9545 2176
csiroenquiries@csiro.au
www.csiro.au

**For further information**

**Oceans and Atmosphere**
Ann Preece
+61 3 6232 5336
ann.preece@csiro.au
csiro.au/O&A