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Identifying trade-offs for alternative rebuilding polices: Insights from simulations and application to tarakihi

New Zealand Fisheries Assessment Report 2025/39

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PLAIN LANGUAGE SUMMARY

The present study analysed different rebuilding strategies for depleted fish stocks, considering trade-offs between the recovery of fish populations and socioeconomic impacts that are particularly relevant for fishing communities. The analysis included biological and economic factors under different policies to determine minimum rebuilding times relative to generation time for fish stocks with different life histories. Simulations in this study focused on differences between management approaches and their impact on rebuilding timelines. These simulations included an analysis of risks of specific policies to lead to marked stock reductions during the rebuilding. They were also part of an idealised economic performance analysis that assessed the outcomes of different policies in relation to stock life history characteristics. The findings of this analysis were illustrated in a case study for tarakihi in the coastal waters of New Zealand's east coast.

EXECUTIVE SUMMARY

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Recent legal challenges to fisheries rebuilding plans have highlighted the need for a comprehensive evaluation of alternative rebuilding strategies. This report presents an analysis of different approaches to rebuilding depleted fish stocks, considering both biological and economic factors. We compared timeline-based policies based on different definitions (multiples of minimum rebuilding time T_{min} and generation times), which set fixed rebuilding periods, with control rule-based policies that adjust fishing pressure based on stock status.

Our analysis found that T_{min} was similar to generation time at F_{40} (the fishing mortality that produces a spawning biomass at 40% of unfished levels) for fast and moderate life histories, but considerably faster (10 years) than generation time without fishing (39 years) for slow life history species.

Life history characteristics significantly influenced rebuilding strategies. Short-lived species showed faster rebuilding potential but were more sensitive to recruitment variability, while long-lived species had more stable but longer rebuilding trajectories. For short-lived species subject to environmental fluctuations, responsive control rules may be more effective than specific timelines.

Simulations showed differences between management approaches based on fishing mortality (F) and on catch. F-based management during rebuilding led to larger initial catch reductions, nearly matching reductions imposed by harvest control rules, while catch-based management showed smaller initial reductions but resulted in longer and more variable rebuilding timelines. Adaptive rebuilding scenarios, which allowed for adjustments during the rebuilding period, performed better than fixed policies, especially for F-based management with longer timelines.

In terms of risk, control rule-based policies generally showed lower risk of falling below the hard limit (10% SSB_0) compared to timeline-based policies. While catch stability varied between approaches, control rule-based policies and F-based management typically led to large initial catch reductions but allowed for earlier increases during rebuilding. Timeline-based policies, particularly catch-based ones, showed more gradual initial reductions but were more prone to subsequent large adjustments.

The economic performance analysis revealed that the success of different policies was highly dependent on CPUE (catch-per-unit-effort) hyperstability, and per-unit-effort costs. Under base settings, there was no clear advantage between control-rule and timeline-based policies in terms of net present value (NPV). Nevertheless, with CPUE hyperstability or low per-unit-effort costs, longer rebuilding timelines achieved higher NPV, while the opposite was the case with hyper-depleted CPUE or high per-unit-effort costs. These findings were further illustrated through a case study for east coast tarakihi (*Nemadactylus macropterus*), which showed similar patterns in rebuilding times and risk.

Control rule policies generally performed better economically when recruitment was below expectations, highlighting the value of continuous fishing mortality adjustments during rebuilding. While no rebuilding policy can be defined as optimal under all circumstances (all policies involve some level of risk), our study suggests that rebuilding plans could be designed to minimise risk through specified and simulation-tested adjustments during rebuilding.

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1. INTRODUCTION

Rebuilding depleted fish stocks is a critical challenge in fisheries management, balancing the need for stock recovery with socioeconomic considerations (Worm et al. 2009, Hilborn et al. 2012). Although stock rebuilding timelines have been shown to be largely dependent on the degree of reduction in fishing mortality (Murawski 2010, Neubauer et al. 2013), the magnitude of reductions have a direct impact on fishing communities, with significant reductions leading to economic hardship. In contrast, insufficient reductions in fishing mortality lead to uncertain rebuilding timelines due to variable environmental conditions. In this context, recent management decisions and associated legal process surrounding the rebuilding of tarakihi (*Nemadactylus macropterus*) fisheries in New Zealand have highlighted the need for an evaluation of alternative rebuilding policies to inform the development of a revised Harvest Strategy Standard (HSS), specifically relating to the rebuilding of stocks from below limit reference points to the "target" level. The HSS currently sets a default rebuilding timeframe for between T_{min} and $2\times T_{min}$ (Ministry of Fisheries 2008), with T_{min} the minimum time required to rebuild in the absence of all fishing mortality; however, it does not allow for alternative definitions of rebuilding timelines, nor does it explicitly prescribe how T_{min} is calculated.

Rebuilding policies vary internationally, with different approaches to timelines and targets. While many policies are defined in terms of T_{min}, most provide for alternative definitions of rebuilding timelines. For instance, the United States mandates stocks to be rebuilt above levels that produce maximum sustainable yield (MSY) within a maximum time frame (T_{max}) that should not exceed 10 years except where specified conditions dictate otherwise. In the latter case, permissible target rebuilding timeframes include T_{min} plus one generation time (the average time that it takes for a population to replace itself), or the time required to rebuild to the target when fishing at $0.75\times$ the target fishing mortality, or $2\times T_{min}$ (National Oceanic and Atmospheric Administration 1996). United States rebuilding guidelines also explicitly take account of socioeconomic impacts. Canada allows for rebuilding timelines up to three times T_{min}, depending on different factors, including socioeconomic impacts (Fisheries and Oceans Canada 2019), although its aim is to only rebuild to the biomass limit. Australia's harvest policy guidelines suggest a rebuild back to the limit reference point within T_{min}, with provisions for longer stock rebuilding based on studies of costs and benefits of alternative rebuilding timelines (Department of Agriculture and Water Resources 2018). The European Union's Common Fisheries Policy calls for rebuilding all commercially-used fish stocks above B_{MSY}, but without specifying explicitly mandated timelines (European Commission 2023).

Previous studies have examined various aspects of rebuilding strategies. Benson et al. (2016) evaluated different rebuilding policies in the United States context, finding that life history characteristics significantly influence rebuilding timelines. Wetzel & Punt (2016) focused on "intermediate adjustment" policies (i.e., policies that adjust fishing mortality during the stock rebuild) within overall rebuilding timelines for United States West Coast groundfish, finding that most strategies led to comparable outcomes; i.e., fixed strategies (without updates to fishing mortality settings during rebuilding) performed nearly as well as strategies with intermediate updates. Larkin et al. (2006) conducted bio-economic analyses on idealised stock simulations, demonstrating the importance of discount rates (i.e., the rate at which long-term profits are discounted relative to short-term profits) in determining optimal rebuilding strategies.

Our study aimed to conduct a cost-benefit analysis of alternative rebuilding timelines, combining aspects of previous studies such as stock-based rebuilding metrics (e.g., time-to-recovery and catch during the rebuild) with simple bio-economic calculations to integrate over costs and benefits of alternative rebuilding policies. Specifically, we aimed to:

1. Evaluate a range of rebuilding policies, including timeline-based approaches and harvest control rules (HCRs).
2. Assess the trade-offs between risk, short-term economic impacts, and long-term stock recovery.

3. Examine how life history characteristics and economic factors influence the effectiveness of different rebuilding strategies.
4. Provide insights for the development of effective rebuilding plans.

By combining simulation studies with a case study application (tarakihi), we sought to provide an analysis that can inform policy decisions and contributes to the broader understanding of fish stock rebuilding strategies.

2. METHODS

2.1 Simulation framework

We developed a basic age-structured simulation model (Appendix A) to evaluate the performance of different rebuilding policies across different scenarios. The model incorporated recruitment variability ($\sigma_R = 0.4$), with optional recruitment autocorrelation ($\rho = 0$ or 0.5) to account for the potential impact of autocorrelated recruitment on stock dynamics. Randomness in the simulations was introduced by using Monte-Carlo draws from the distribution of recruitment variability, leading to 1000 individual stock trajectories per scenario and rebuilding policy.

Initial depletion was set to approximately 15% of unfished spawning stock biomass (SSB_0), reflecting an overfished stock. The population was initialised in this state, assuming the population was at equilibrium with the overfished state. The simulations were then run for A_{mat} (age-at-maturity) years with fixed fishing mortality but variable recruitment before rebuilding policies were implemented to allow recruitment variability to influence rebuilding timelines for spawning biomass from the first year of rebuilding.

Three life history strategies were simulated, with short-lived ($A = 6$, $h = 0.95$, $M = 0.8$), moderately long-lived ($A = 20$, $h = 0.90$, $M = 0.20$), and long-lived ($A = 60$, $h = 0.85$, $M = 0.075$) species (also referred to as fast, moderate, and slow life histories, respectively). We ran the model for 10 (20, 70) years for short, moderate, and long-lived species, respectively, to evaluate the long-term performance of the rebuilding policies. Selectivity was assumed to be “knife-edge” at the age of maturity, except for the short-lived life history, where knife-edge selectivity was set at $A_{mat} - 1$ to enable depletion of the stock.

2.2 Rebuilding policies

We evaluated several types of rebuilding policies, broadly categorised as timeline-based or control-rule-based. The timeline-based policies specified a fixed timeframe to rebuild the stock to the target biomass level (40% of unfished spawning biomass; SSB_0) with a certain probability (50%, typically), whereas the control-rule-based policies adjusted fishing mortality or catch based on the current stock status. Most international rebuilding policies require the stock to be rebuilt within a specified timeframe (e.g., $2 \times T_{min}$ or $3 \times T_{min}$), but the choice of the rebuilding timeframe can have a significant impact on the performance of the rebuilding strategy (Staerk et al. 2019). The control-rule-based policies are more flexible and can adapt to changing stock conditions, but they require regular monitoring and adjustment to be effective. Timeline-based strategies can also adapt to changing stock conditions if this aspect is specified in their design.

Both control-rule- and timeline-based policies were evaluated in the context of managing fishing mortality (F) and catch (C). Stocks were assumed to be assessed every five years, except for short-lived stocks, which were assessed every two years. Stock status was assumed to be precisely assessed. If stocks under-performed their expected rebuilding timelines, catch (or F) was reduced by the ratio of the realised stock status relative to the expected stock status. No corresponding adjustment was undertaken when the stock outperformed rebuilding expectations.

In addition, for timeline-based policies, we considered invariable settings as extremes of F and catch-based policies. For these simulations, no assessments were simulated, because we either set catch at the catch that was predicted to meet the rebuilding policy, or as the fishing mortality predicted to achieve the same aim. (Note, that both cases are not meant to simulate policy options, but rather scenarios that bracket the risk and rebuilding timelines: a constant catch during rebuild will likely under-perform relative to performing periodic assessments, re-evaluating progress and adjusting catch.) While a fixed fishing mortality may perform better, at least in some respects, than fixed catch, it is still expected to under-perform with respect to updates to F over the course of the rebuilding period.

2.2.1 Timeline-based policies

- Current ($2 \times T_{min}$),
- $3 \times T_{min}$,
- T_{min} + Generation time (F = 0),
- T_{min} + Generation time (F_{40}),

where T_{min} is the minimum time to rebuild the stock to the target biomass level under conditions of no fishing and average recruitment. For timeline-based policies, initial catch (or F) was set at the catch (or F) that would achieve rebuilding with a probability of 50% (or 70%; see "Sensitivities" below).

Generation time was here calculated following the cohort-based approach at F = 0 (unfished conditions) or F_{40} (i.e., the fishing mortality that would lead to a spawning biomass at 40% of unfished spawning biomass):

$$T_g = \frac{\sum_{a=0}^{A} a S_a m_a}{\sum_{a=0}^{A} S_a m_a},$$

where a is age, A is maximum age, S_a is the survivorship to age a, and m_a is maturity at age a (Restrepo et al. 1998, Staerk et al. 2019). In fished conditions, S_a is the survivorship to age a given the sum of natural and fishing mortality at age.

2.2.2 Control-rule-based policies

- Constant level: $0.75 \times F_{40}$ (F-based) or $0.75 \times C_{40}$ (catch-based),
- 40–10 rule,
- 40–20–10 rule,
- Logistic rule.

The control rules adjust fishing mortality or catch based on the current stock status relative to reference points (e.g., target biomass, soft limit, and hard limit; Figure 1). The 40–10 rule reduces fishing mortality linearly below 40% of the unfished biomass down a level of zero at 10% of initial spawning biomass, while the 40–20–10 rule reduces fishing mortality linearly between 20 and 40% of unfished biomass between 20 and 10%. The 40–20–10 rule can provide for increased fishing opportunity above the soft limit, while restricting fishing more severely between the soft and hard limits. The logistic rule initially imposes only small reductions in fishing mortality as the stock declines below the target biomass level, with a steeper reduction as the stock approaches the soft limit. Constant fishing mortality or catch is not a control rule, but was added for comparison with a precautionary fixed strategy (C_{40} is the theoretical equilibrium catch at 40% of unfished spawning stock). (Note that these control rules are designed to maintain stocks around the target and avoid limits, rather than control rules specifically designed to rebuild already-depleted stocks.)

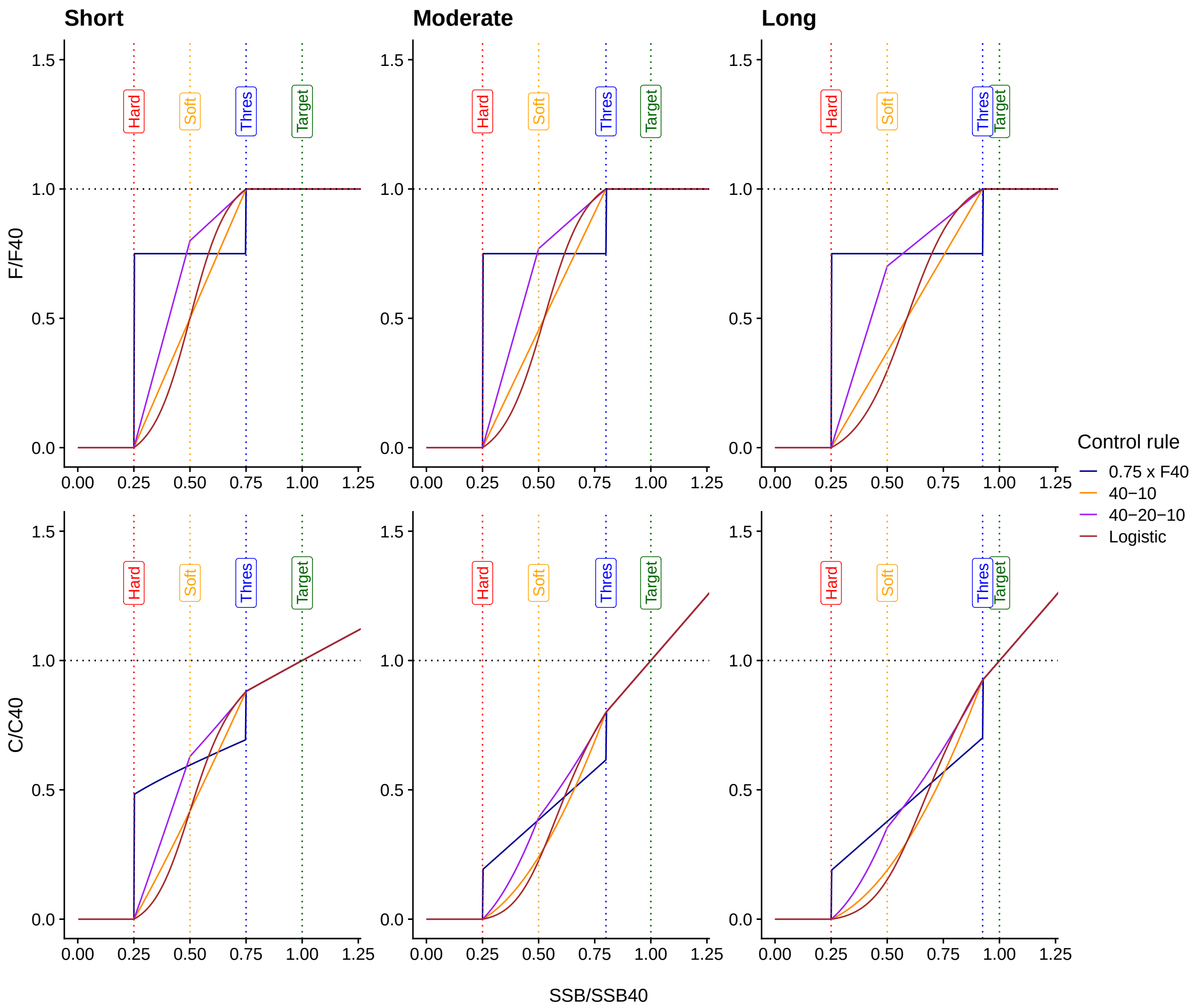

Figure 1: Alternative harvest control rules used for fish stocks with short, moderate, and long life histories. Control rules are in terms of fishing mortality F relative to F_{40}, the fishing mortality leading to a stock status of 40% of unfished spawning stock, and in terms of catch C relative to C_{40}, the theoretical equilibrium catch at 40% of unfished spawning stock.

2.3 Economic evaluation

The economics of rebuilding policies are difficult to model with any accuracy given that there are limited (if any) data on a number of key parameters, such as operating costs of fisheries, and their response to management changes and changes in abundance. We used a commonly-used value, namely the Net Present Value (NPV) as an (idealised) way to integrate over time and illustrate trade-offs, as opposed to aiming to depict realistic economic conditions. Following Clark (1973), we assumed a (potentially non-linear) relationship between yield (Y) per unit effort (E) and available biomass:

$$Y(t)/E(t) = q^{\beta} B^{avail},$$

with a fixed cost k per unit of effort, such that the total cost $C(t) = k \cdot E(t)$. The non-linearity in catch-per-unit-effort (CPUE) is determined by the exponent β of the catchability(q), with $\beta < 1$ leading to a hyper-stable CPUE, and $\beta > 1$ being hyper-depleted CPUE (CPUE declines faster than abundance). Setting catch to a single unit and rearranging gives the cost per unit yield as a function of available biomass, with costs varying with biomass levels and non-linearity between CPUE and biomass (Figure 2):

$$C(t) = \frac{k}{q^{\beta} B^{avail}}.$$

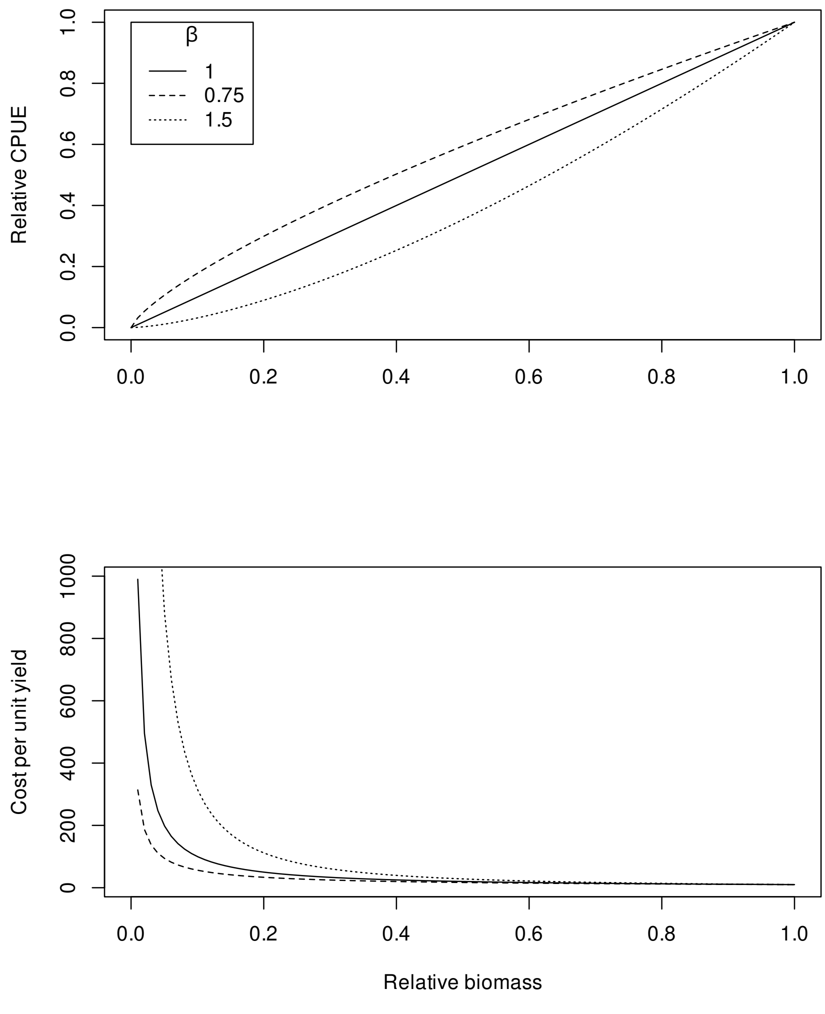

Figure 2: Relative catch-per-unit-effort (CPUE) and cost per unit yield at different levels of available biomass and levels of hyperstability (β).

We used an NPV framework to assess the economic performance of different rebuilding strategies:

$$NPV = \sum_{t=0}^{T} \frac{Y_t(P - C(t))}{(1+\delta)^t},$$

where P is the price per unit yield, Y_t is the yield at time t, and δ is the discount rate. Substituting the above equation for cost gives the NPV as a function of available biomass:

$$NPV = \sum_{t=0}^{T} \frac{Y_t(P - \frac{k}{q^{\beta} B^{avail}})}{(1+\delta)^t}.$$

We considered various scenarios with different cost structures and discount rates:

- CPUE hyperstability parameter (β): 0.5, 1.0, 1.5,
- unit effort cost (k): 0.05, 0.1, 0.2,
- discount rates: constant (3%, 6%), and declining (20 to 3%).

A declining discount rate assumes uncertain discount rates within a range specified by the bounds of plausible discount rates. This assumption leads to a decline in the expected discount rate, with initially high discounts that decline over time. The scenario aimed to reflect high initial costs of rebuilding policies (e.g., socio-economic costs of reduced catch or fishery closures), while maintaining a long-term, inter-generational view (Arrow et al. 2013, Abelson & Dalton 2024).

To enable comparisons of differences in rebuilding timelines and associated trade-offs in catch and rebuilding rate, and to avoid comparisons in terms of post-rebuilding performance of different policies, we set all simulated stock trajectories to the management target once the simulated trajectory reached the target biomass.

2.4 Performance metrics

We evaluated the rebuilding policies based on several performance metrics:

- rebuilding time (years to reach target biomass),
- catch and fishing mortality during the rebuild,
- risk of falling below the 10% SSB_0, or exceeding a harvest rate of 80%,
- NPV of the fishery during the rebuilding period, including the components of NPV expressed as relative costs and profit over time.

2.5 Sensitivity analyses

We conducted sensitivity analyses to assess the impact of recruitment autocorrelation, and rebuilding probability thresholds. Specifically, we used the following alternative parameter settings:

- Increasing the rebuilding probability threshold from 50% to 70% at the outset of the rebuilding plan.
- Introducing recruitment autocorrelation (ρ = 0.5).

2.6 Tarakihi case study

In addition to the theoretical simulations, we applied our evaluation framework to a simplified (single-area) version of the tarakihi (*Nemadactylus macropterus*) stock assessment model (Langley 2022). The terminal year and all inputs were the same as for the most recent stock assessment. The final estimated stock status was slightly lower than in the published final stock assessment due to simplifying assumptions made in the present model.

Although this case study allowed us to compare the performance of different rebuilding strategies in a real-world context, the evaluation was limited, because we could not simulate the assessment process within the assessment framework (SS3) in a straightfoward way without implementing a full management strategy evaluation simulation framework for the model; the latter was beyond the scope of the present study. We were, therefore, only able to evaluate time-invariant (i.e., fixed catch or fixed F) policies. We also did not evaluate alternative control rules for tarakihi.

3. RESULTS

3.1 Estimates for T_{min} and generation time

Estimates of T_{min} were relatively similar to generation time at F_{40} for moderate and fast life histories (Table 1); however, it was considerably faster (10 years) than generation time without fishing (F = 0; 39 years) and at F_{40} (32 years). (Note, that for the moderate life history, T_{min} plus one generation time at F = 0 is equal to $3\times T_{min}$; for the short life history, $2\times T_{min}$ is equal to T_{min} plus generation time at F_{40}.)

Table 1: Estimates (in years) of minimum rebuilding time T_{min}, generation time without fishing (F = 0) and at the target fishing mortality (F_{40}) for fish stocks with different life histories.

Life history	T_{min}	Gen. time (F = 0)	Gen. time (F_{40})
Fast	3	4	3
Moderate	5	10	7
Slow	10	39	32

3.2 Rebuilding timelines

Across all rebuilding policies, control-rule-based strategies led to faster median rebuilding timelines. This outcome was usually by restricting catch to a small fraction of the originally-applied catch (up to 90% reductions; Figures 3 to 6). Within control rule policies, the logistic control rule often showed the most substantial initial reductions, but led to earlier increases in catch during the rebuilding period. The earlier increases in catch for control rules corresponded with an F-based strategy, and often led to comparable overall rebuilding times to timeline-based policies given F-based management. For example, for long-lived species, rebuilding times for control-rule-based policies were between $2\times T_{min}$ and $3\times T_{min}$.

For the moderate life histories, the rebuilding timelines with control rules were often close to T_{min}, as were rebuilding times under timelines-based policies when F-based management was applied. The short rebuilding times and lack of contrast between policies was due to a lack of opportunity to revise catch to match target fishing mortality for F-based management on a five-year assessment cycle (given that T_{min} was also five years for moderate life histories). Differences between timeline- and control-rule-based approaches were most pronounced for long-lived species, where intermediate adjustments to fishing mortality led to a more differentiated set of outcomes.

The difference between control-rule- and timeline-based approaches was less pronounced for management based on fishing-mortality; the latter tended to lead to greater initial reductions in catch for timeline-based rebuilding policies, which nearly matched the reductions imposed by harvest control rules (Figures 3 & 7). In contrast, catch-based management led to smaller initial reductions in fishing mortality and catch, at the expense of longer median rebuilding timelines and increased variability in rebuilding timelines (Figures 4 & 7). Given the correspondence between F and catch for the harvest control rules applied here, there was no difference in rebuilding scenarios between F and catch-based management for control-rule-based policies.

Compared with fixed policies with invariant catch or F, adaptive rebuilding scenarios led to faster rebuilding than would be expected under timeline-based policies. Rebuilding times faster than initial timelines were particularly evident for F-based management for longer timelines, such as T_{min} plus one generation time. For these longer timelines, there are more opportunities for adjusting F or catch for stocks that do not meet rebuilding expectations (Figures 8 & 9). The difference was most pronounced for the moderate life history with F-based management, where the assessment frequency only allows for infrequent adjustments of catch to match the expected F; in contrast, the fixed F adjusts catch annually, leading to steady increases in catch at the expense of longer rebuilding. For catch-based policies, adjusting catch setting during the rebuild for stocks that did not meet rebuilding expectations did not lead to marked differences in median rebuilding time; however, it led to lower variability in rebuilding timelines and, therefore, lower risk of missing rebuilding targets.

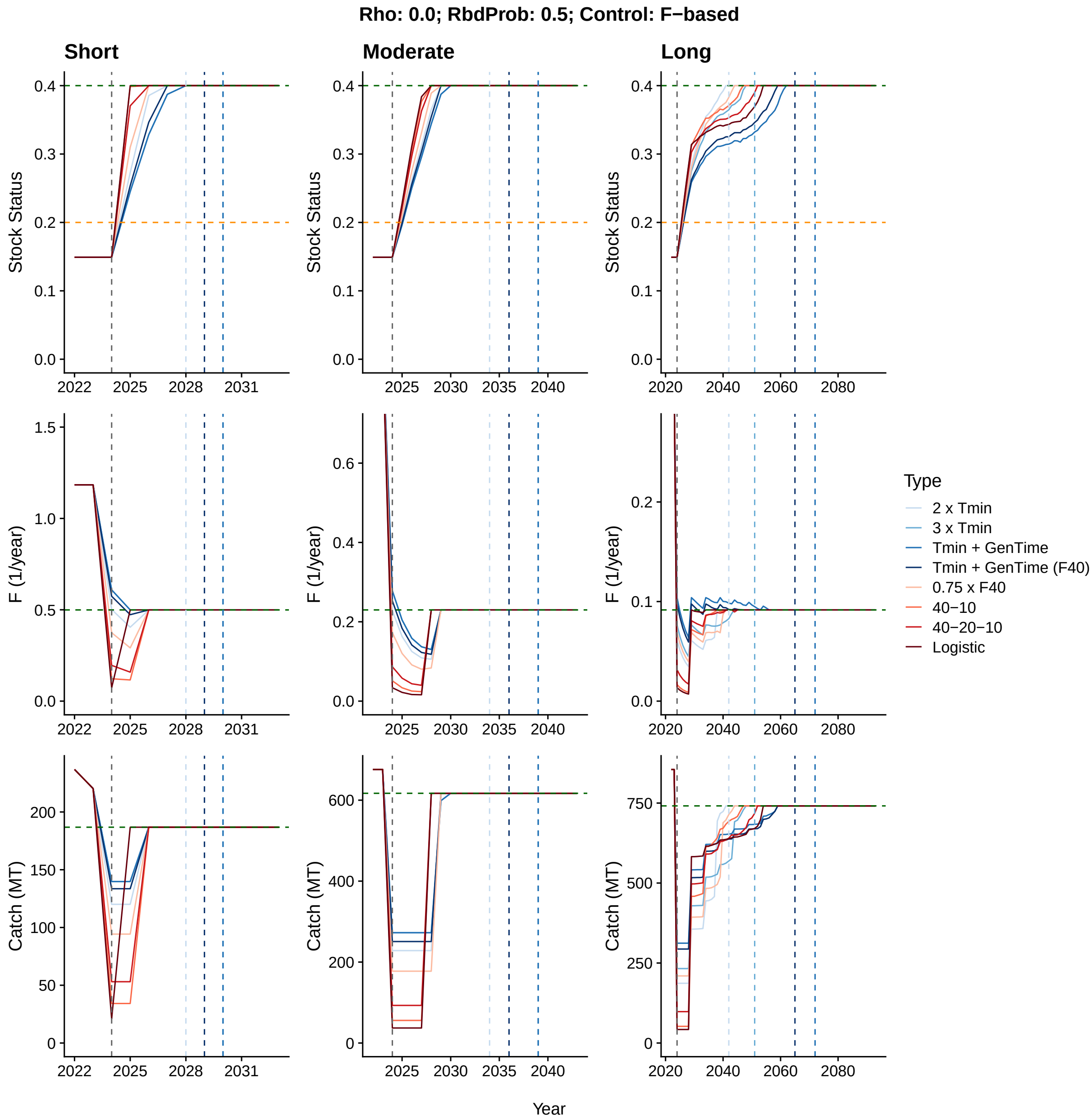

Figure 3: Rebuilding timelines (median of simulated stock trajectories) for management based on fishing mortality (F) across rebuilding policies. Stock status (SSB/SSB_0; top row), fishing mortality (middle row) and catch (C; bottom row) across life histories (columns), for the base scenario without autocorrelation in recruitment (Rho = 0) and with a 50% rebuild probability to estimate T_{min}. Control-rule-based policies are shown in shades of red/orange and timeline-based policies are shown in shades of blue, with corresponding rebuilding targets shown by dashed vertical lines of the corresponding colour.

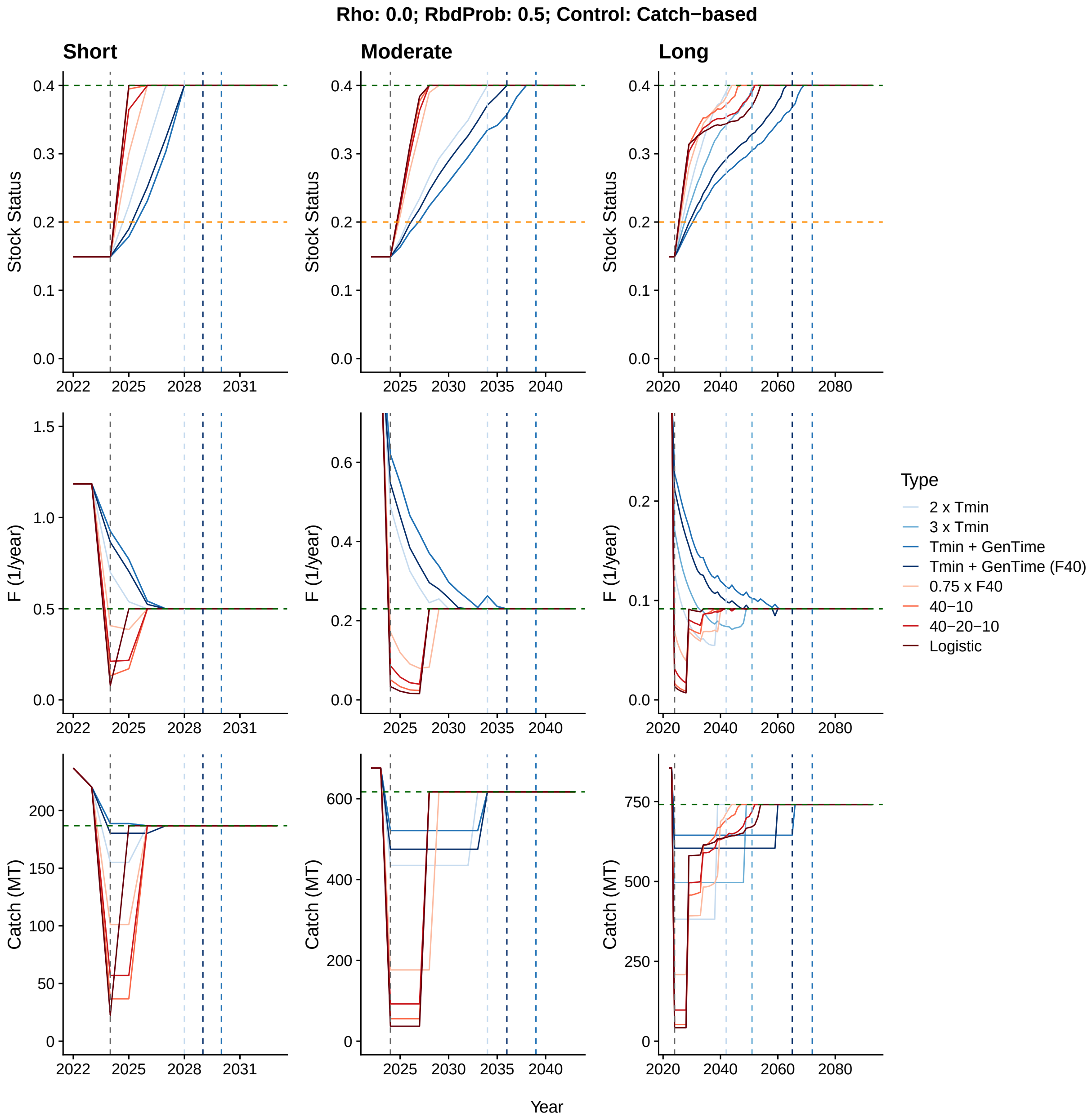

Figure 4: Rebuilding timelines (median of simulated stock trajectories) for management based on catch (C) across rebuilding policies. Stock status (SSB/SSB_0; top row), fishing mortality (F; middle row) and catch (bottom row) across life histories (columns), for the base scenario without autocorrelation in recruitment (Rho = 0) and with a 50% rebuild probability to estimate T_{min}. Control-rule-based policies are shown in shades of red/orange and timeline-based policies are shown in shades of blue, with corresponding rebuilding targets shown by dashed vertical lines of the corresponding colour.

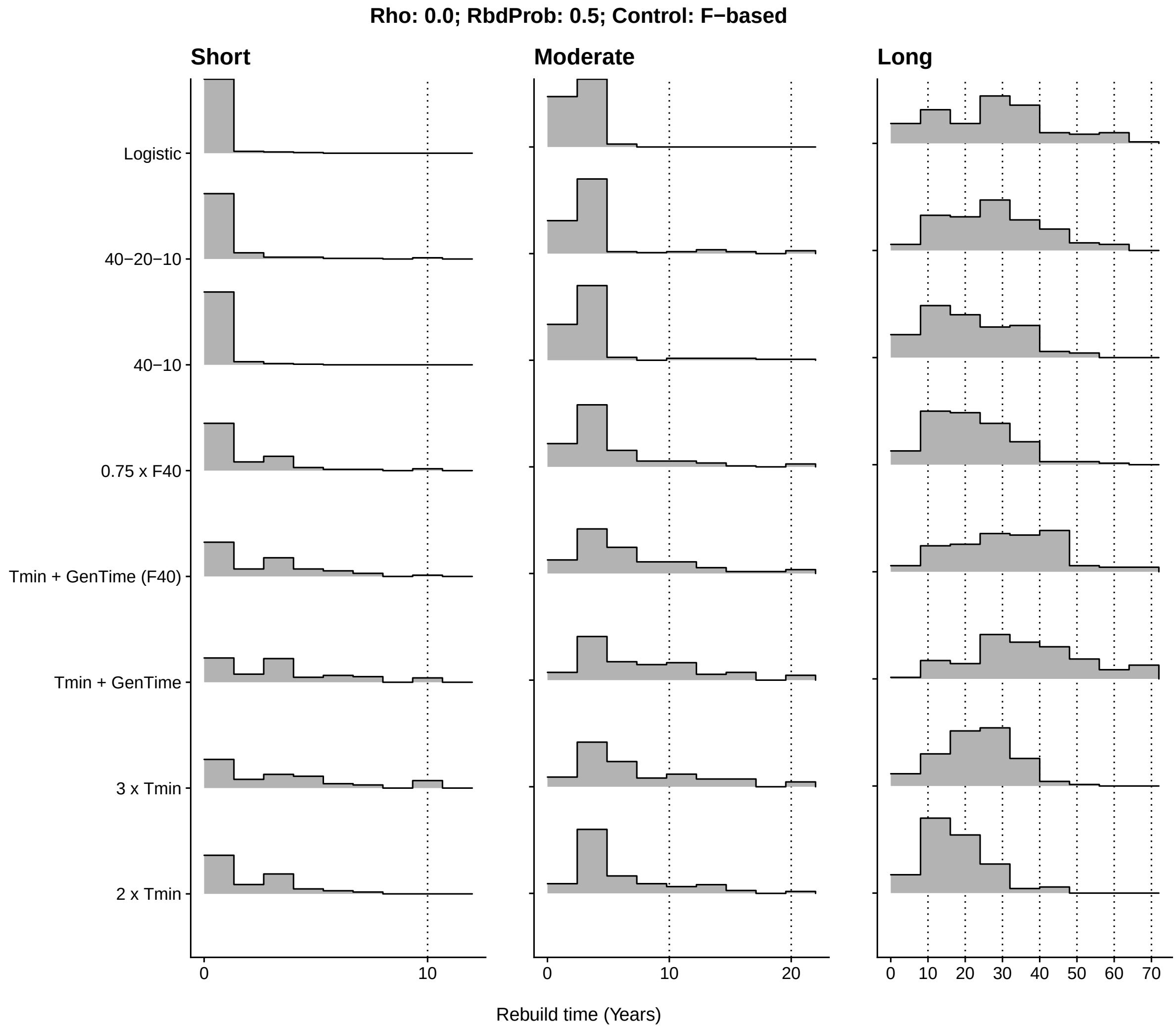

Figure 5: Rebuilding time distribution (in years) for management based on fishing mortality (F) across rebuilding policies.

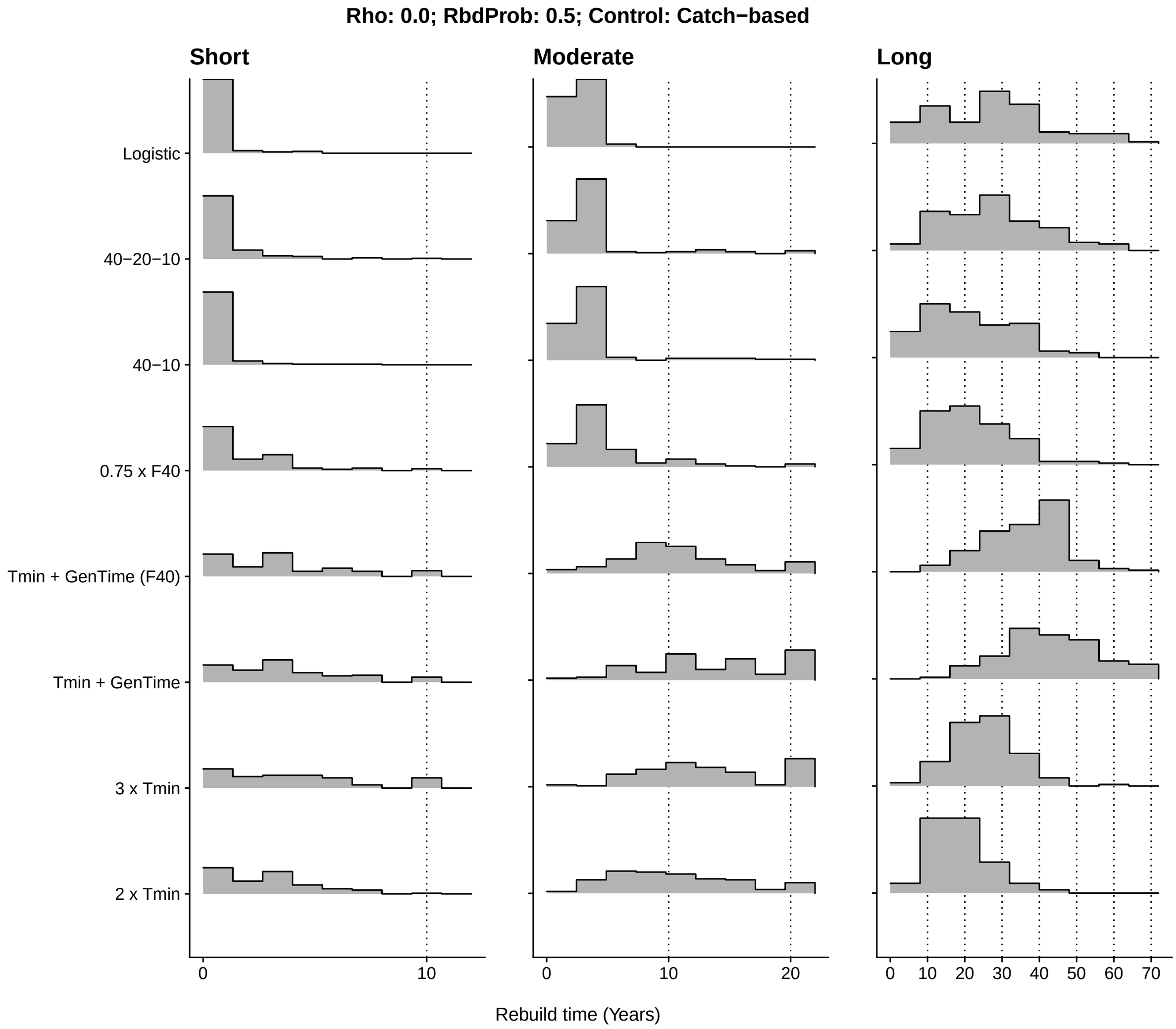

Figure 6: Rebuilding time distribution (in years) for management based on catch across rebuilding policies.

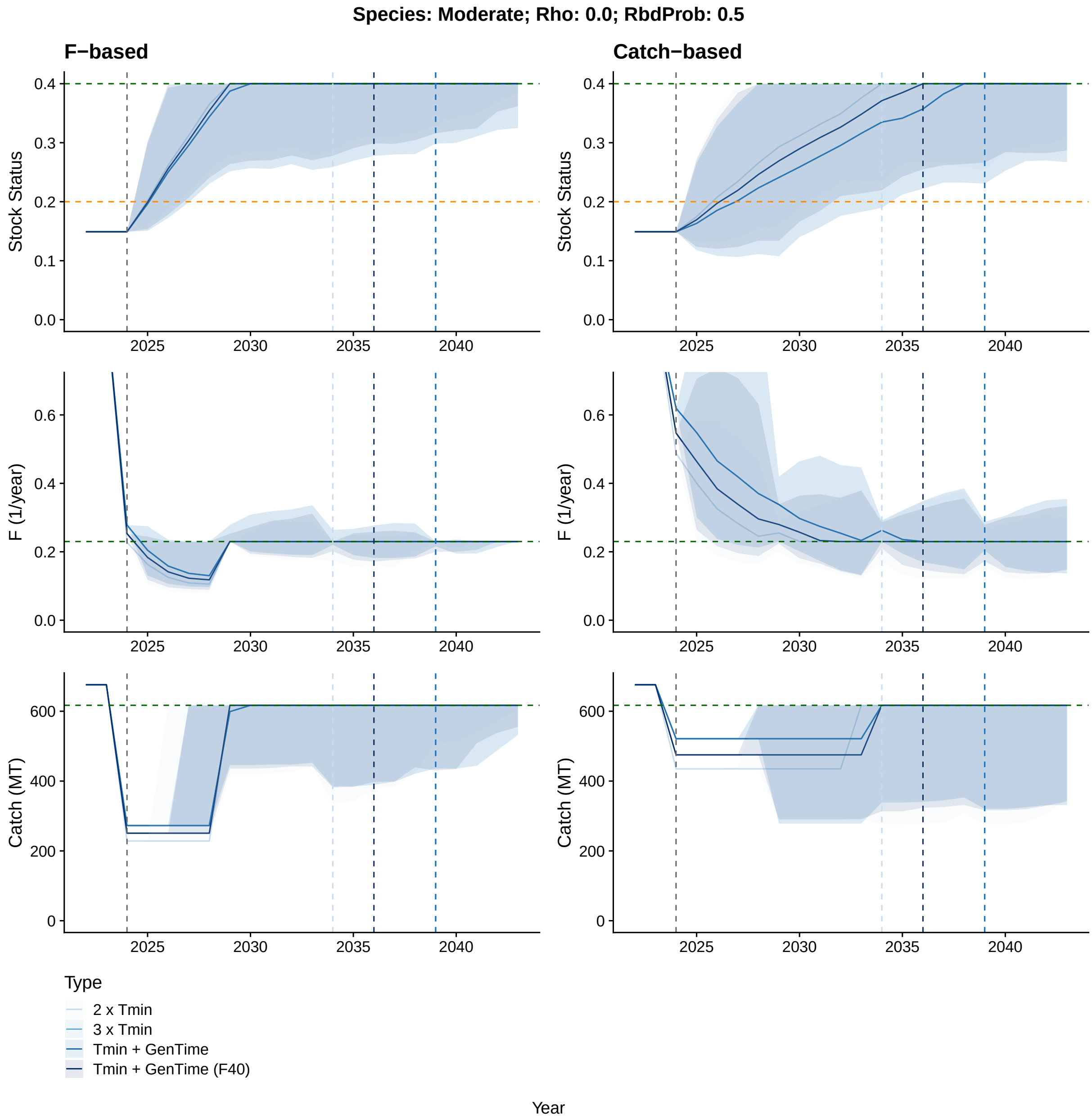

Figure 7: Difference between management based on fishing mortality (F) and based on catch (C), illustrated for fish stocks with a moderate life history. The timeline-based rebuilding policies are compared with corresponding rebuilding targets shown by dashed vertical lines of the corresponding shading.

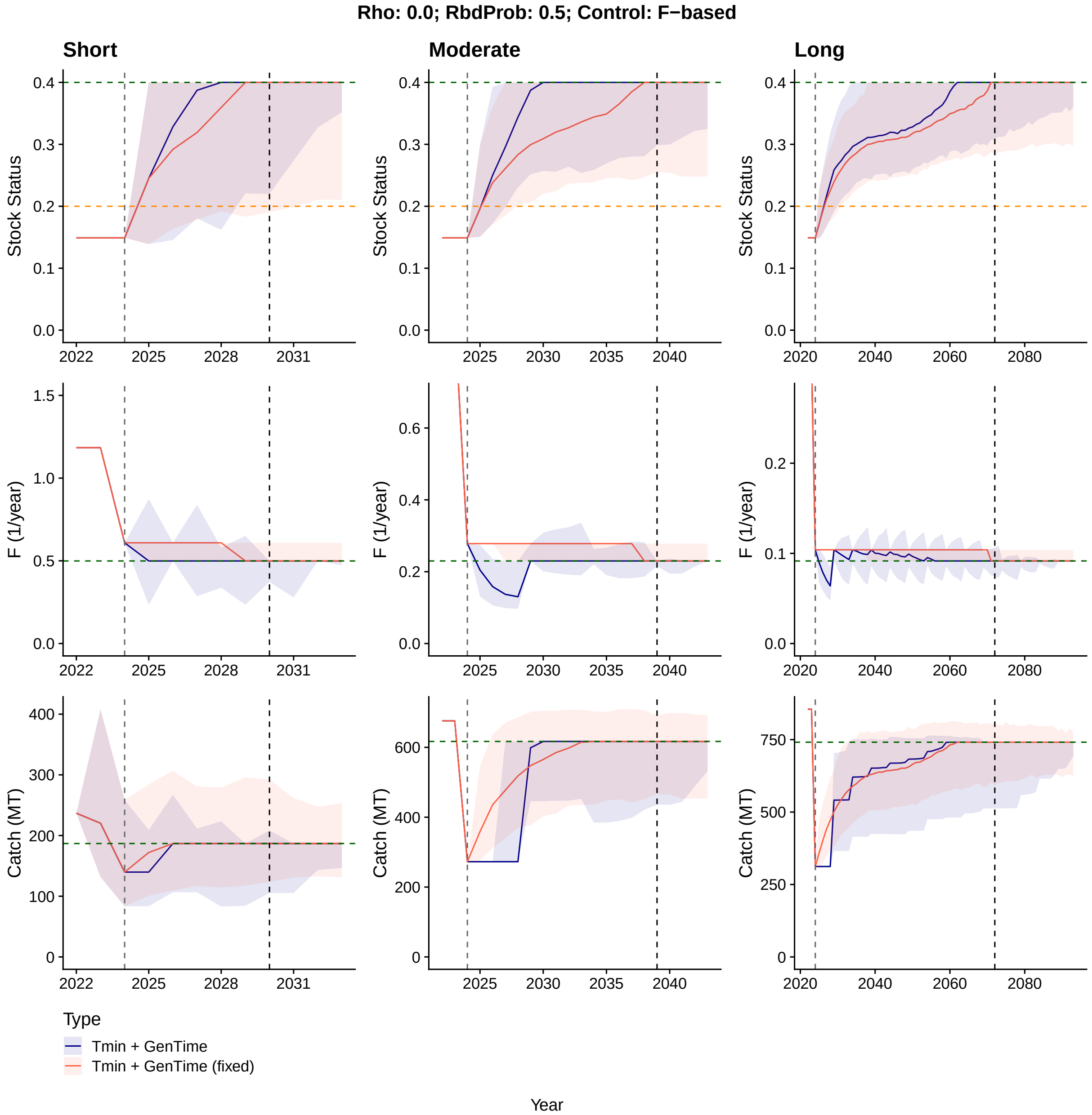

Figure 8: Rebuilding timelines (median of simulated stock trajectories) management based on fishing mortality (F) across rebuilding policies. Stock status (SSB/SSB_0; top row), fishing mortality (middle row) and catch (C; bottom row) across life histories (columns), for the base scenario without autocorrelation in recruitment (Rho = 0) and with a 50% rebuild probability to estimate T_{min}. Control-rule-based policies are shown in shades of red/orange and timeline-based policies are shown in shades of blue, with corresponding rebuilding targets shown by the dashed vertical line.

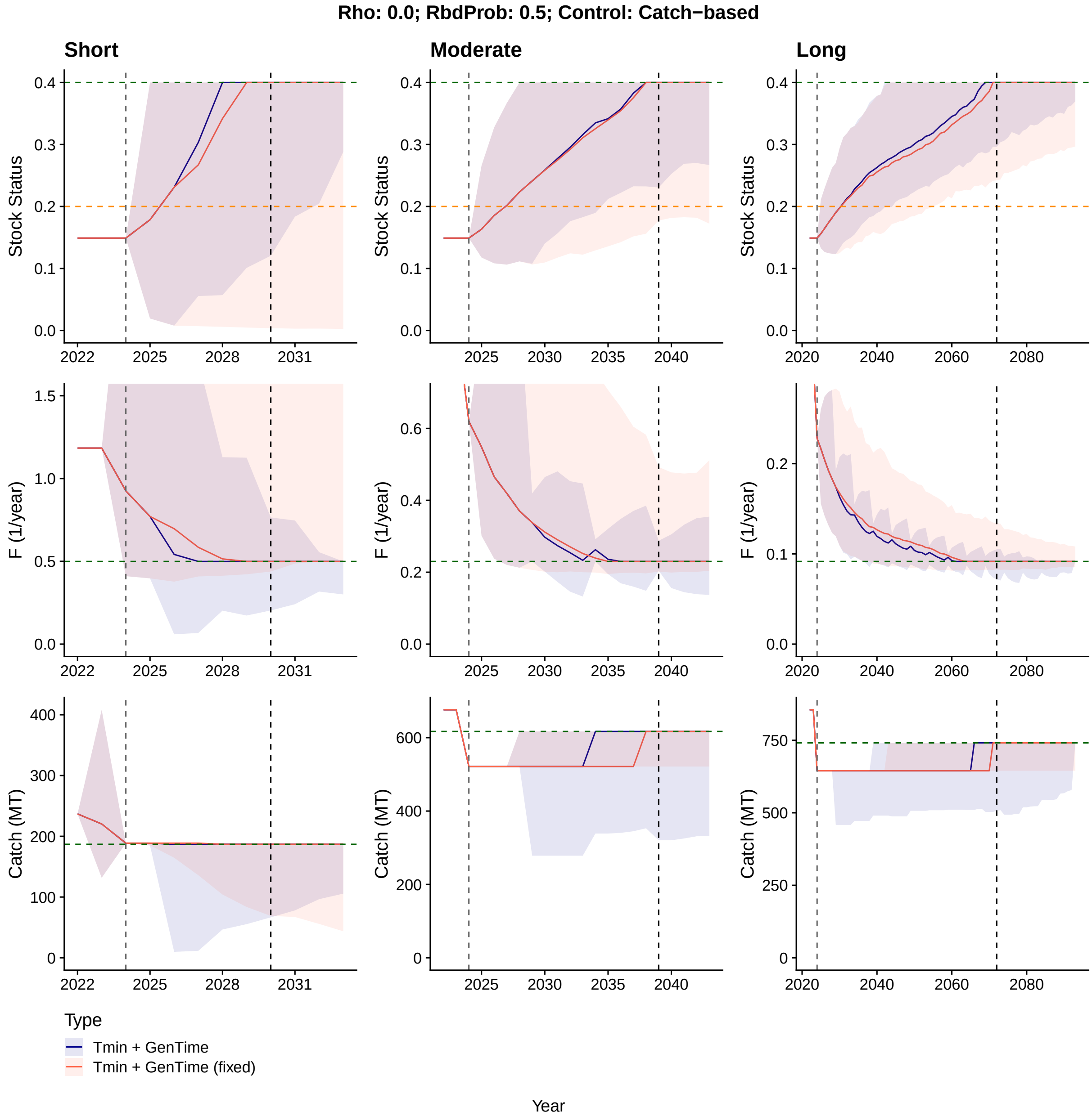

Figure 9: Rebuilding timelines (median of simulated stock trajectories) for management based on catch (C) across fixed (pure) rebuilding policies. Stock status (SSB/SSB_0; top row), fishing mortality (F; middle row) and catch (bottom row) across life histories (columns), for the base scenario without autocorrelation in recruitment (Rho = 0) and with a 50% rebuild probability to estimate T_{min}. Control-rule-based policies are shown in shades of red/orange and timeline-based policies are shown in shades of blue, with corresponding rebuilding targets shown by the dashed vertical line.

3.3 Catch stability

Control-rule-based policies and F-based management often led to large initial catch reductions but allowed for earlier increases in catch during the rebuilding period (Figures 10 & 11). Timeline-based policies, especially catch-based policies, showed more gradual initial reductions, but were more prone to subsequent large adjustments.

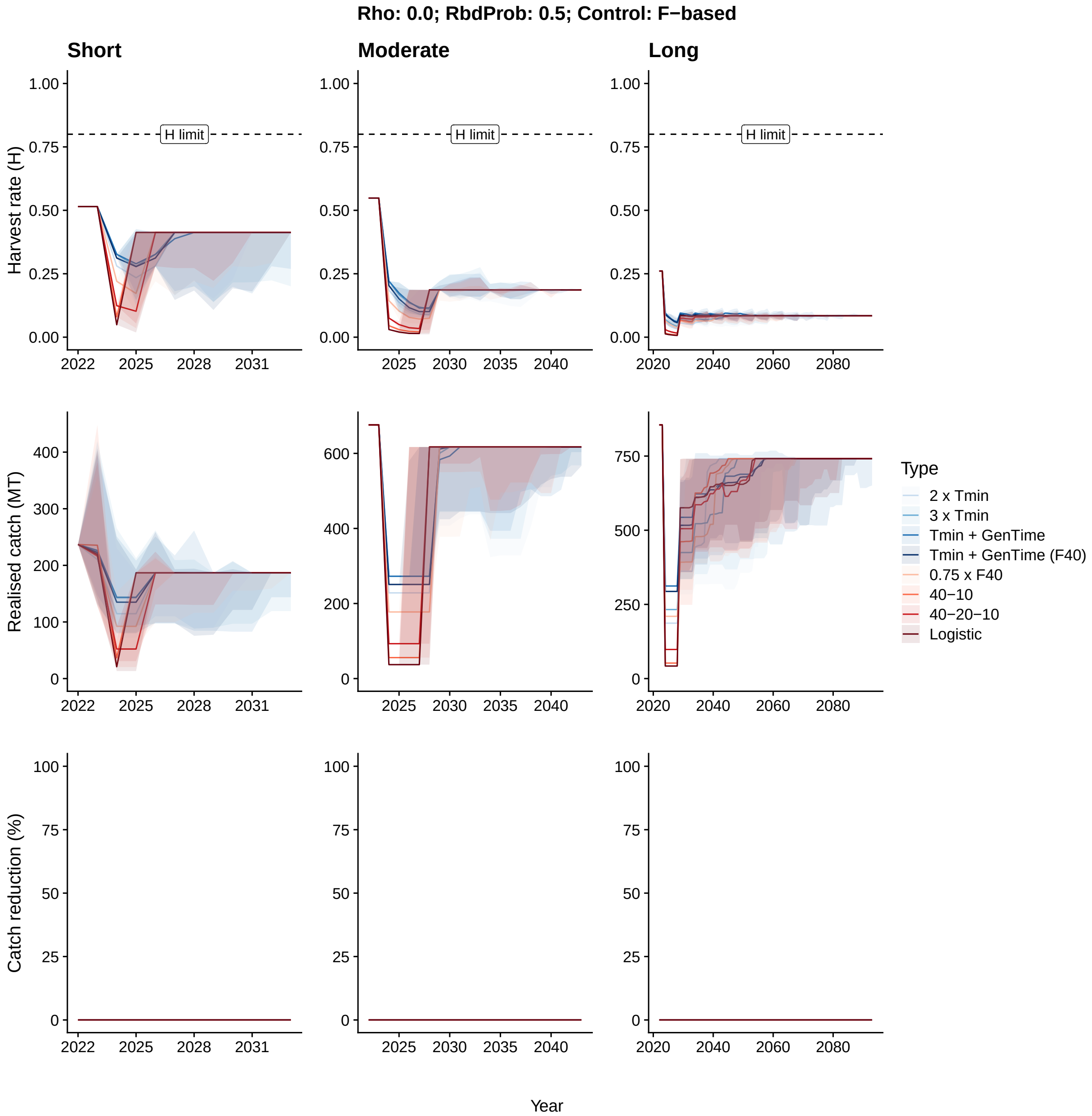

Figure 10: Trends in harvest rate, realised catch, and catch reductions (i.e., proportion of catch not able to be taken in simulations when the exploitation-rate limit was reached) for management based on fishing mortality and alternative rebuilding policies. Control-rule-based policies are shown in shades of red/orange and timeline-based policies are shown in shades of blue.

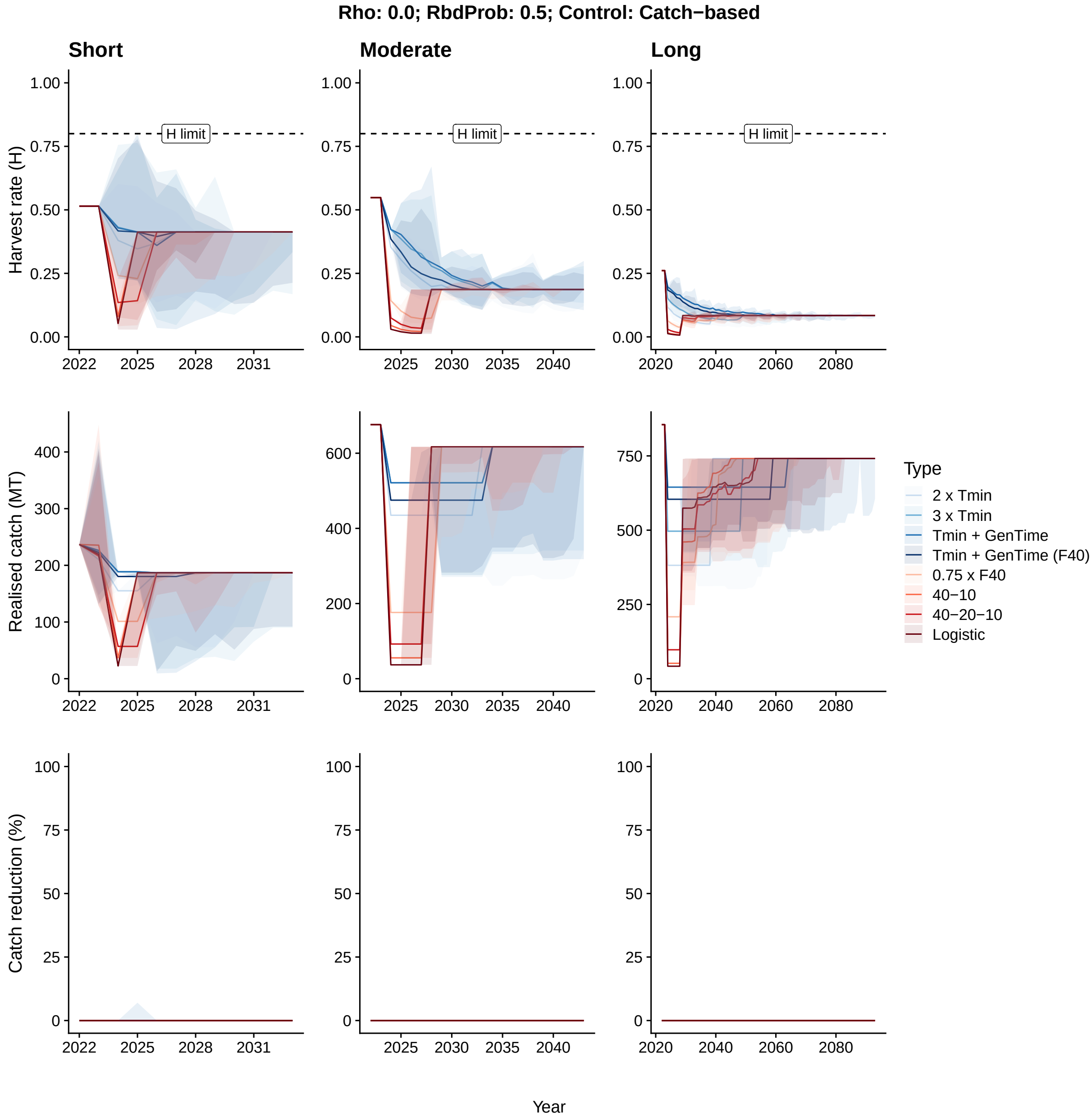

Figure 11: Trends in harvest rate, realised catch, and catch reductions (i.e., proportion of catch not able to be taken in simulations when the exploitation-rate limit was reached) for catch-based management and alternative rebuilding policies. Control-rule-based policies are shown in shades of red/orange and timeline-based policies are shown in shades of blue.

3.4 Risk

The risk of falling below the hard limit (10% SSB_0) was generally lower for control-rule-based policies compared to timeline-based policies (Figures 12 & 13). Although all stocks were initiated below the soft limit, only long timeline-based policies applied to the short life history led to any risk of breaching the hard limit under simulated conditions. In comparison, stocks managed using catch-based settings and timeline-based rules spent substantially longer below the soft limit during the rebuilding phase, owing to the higher catch and slower rebuilt rate applied for these policies.

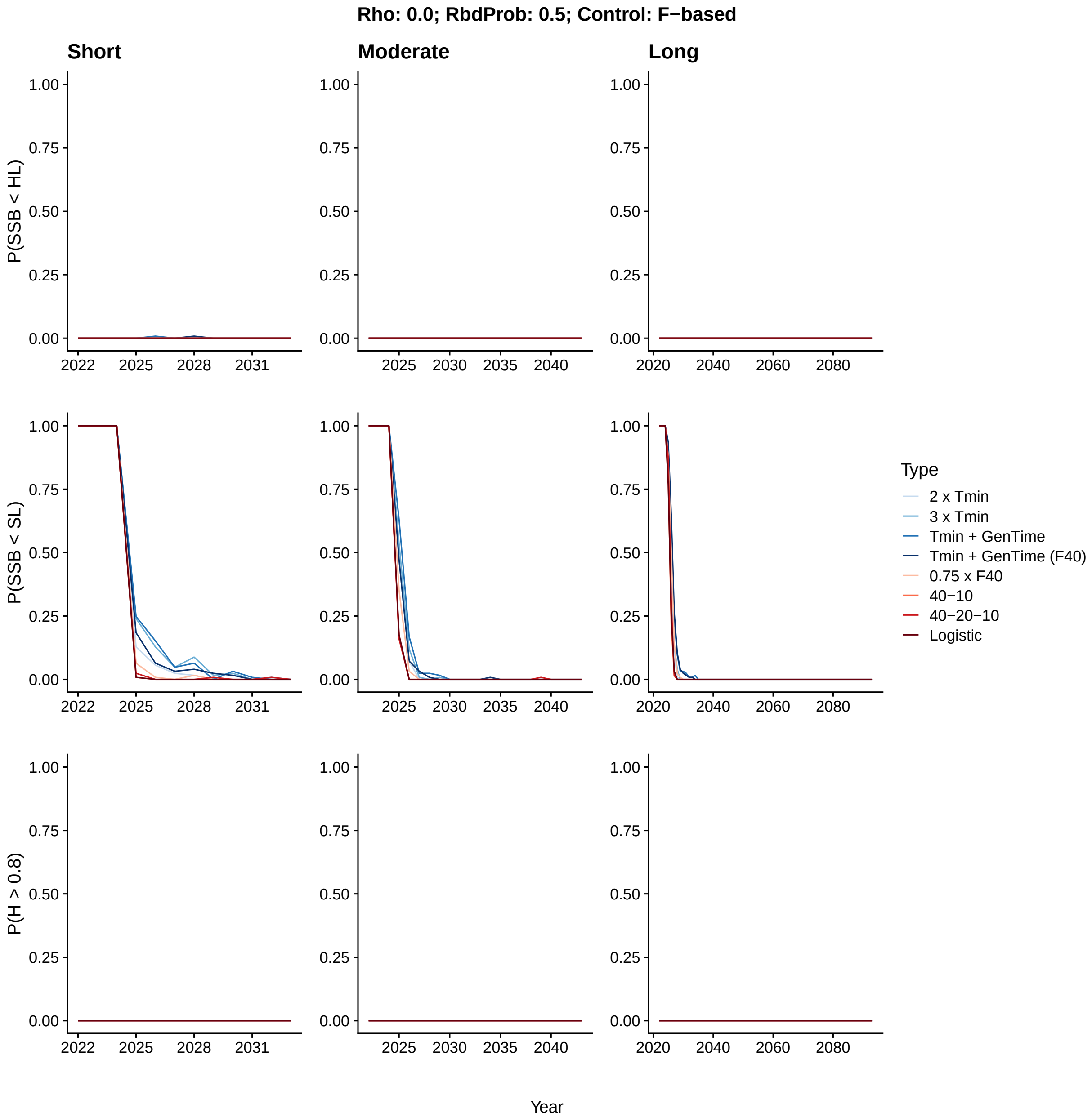

Figure 12: Simulated risk for management based on fishing mortality of falling below the hard limit (10% SSB_0) (top row), soft limit (20% SSB_0) (middle row), and proportion of simulated trajectories that breached the limit of an 80% exploitation rate (bottom row), across simulated life histories (columns), for the base scenario without autocorrelation in recruitment (Rho = 0) and with a 50% rebuild probability to estimate T_{min}.

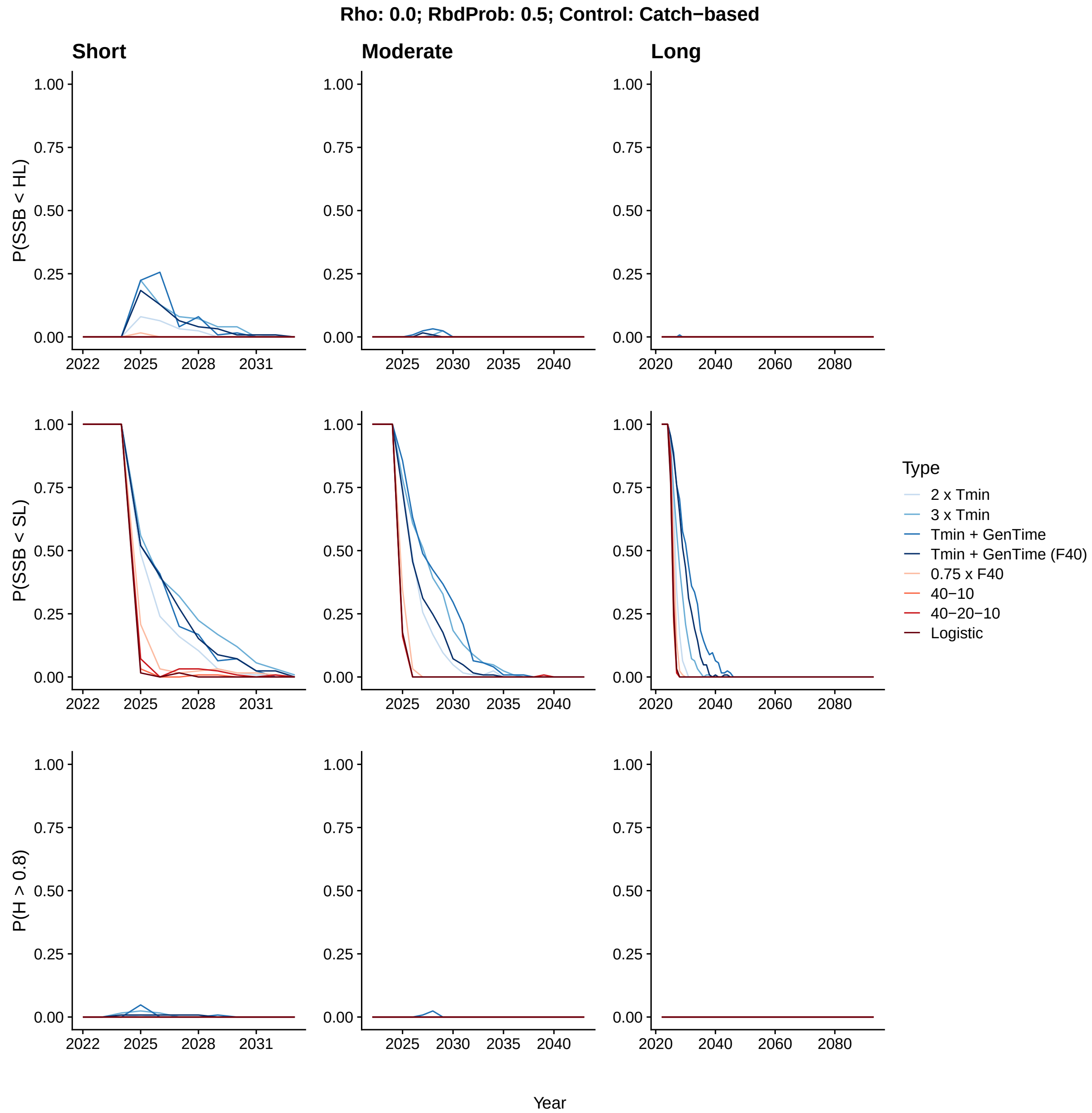

Figure 13: Simulated risk for catch-based management of falling below the hard limit (10% SSB_0) (top row), soft limit (20% SSB_0) (middle row), and proportion of simulated trajectories that breached the limit of an 80% exploitation rate (bottom row), across simulated life histories (columns), for the base scenario without autocorrelation in recruitment (Rho = 0) and with a 50% rebuild probability to estimate T_{min}.

3.5 Economic performance

There was no clear advantage in terms of NPV for control-rule- versus timeline-based policies at base settings for cost and CPUE hyperstability; all policies performed better than the current setting ($2 \times T_{min}$) in nearly half the simulations, and worse in the other half (Figures 14 & 15). The performance of each rule depended on the realised recruitment during the rebuild, with lower-than-expected recruitment leading to lower NPV for longer timelines as initial catch reductions were often insufficient to achieve a rebuild (Figure 16). When recruitment was average or better than expected, the lower initial reductions in catch were often sufficient to rebuild the stock, leading to higher NPV relative to policies that restricted initial catch.

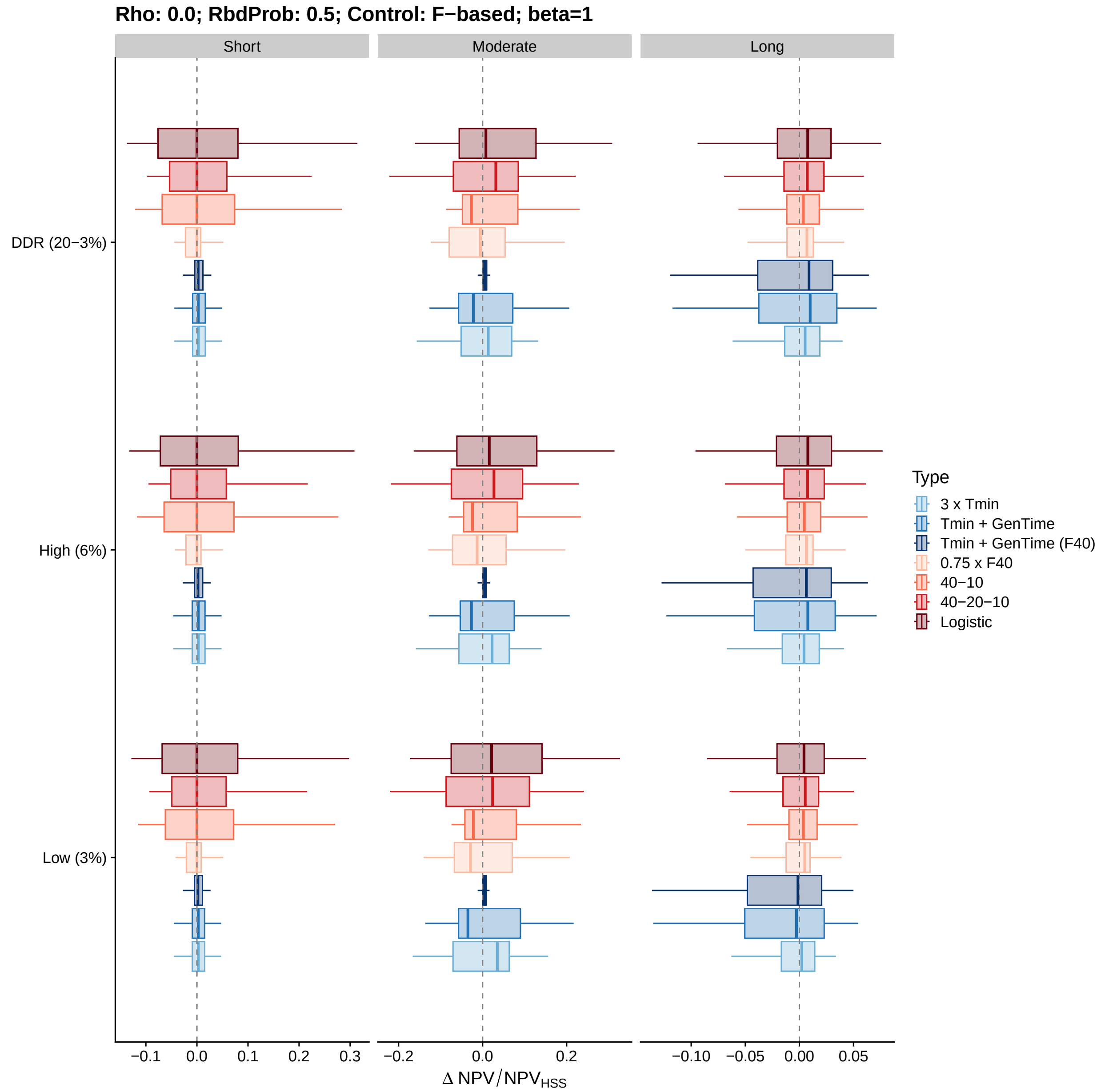

Figure 14: Relative difference in net present value (NPV) from the current policy (Harvest Strategy Standard (HSS), $2 \times T_{min}$) across life histories (columns) for management based on fishing mortality at base per-unit-effort cost (0.1) and no CPUE hyperstability, across alternative discount rates (rows; DDR: declining discount rate). Control-rule-based policies are shown in shades of red/orange and timeline-based policies are shown in shades of blue.

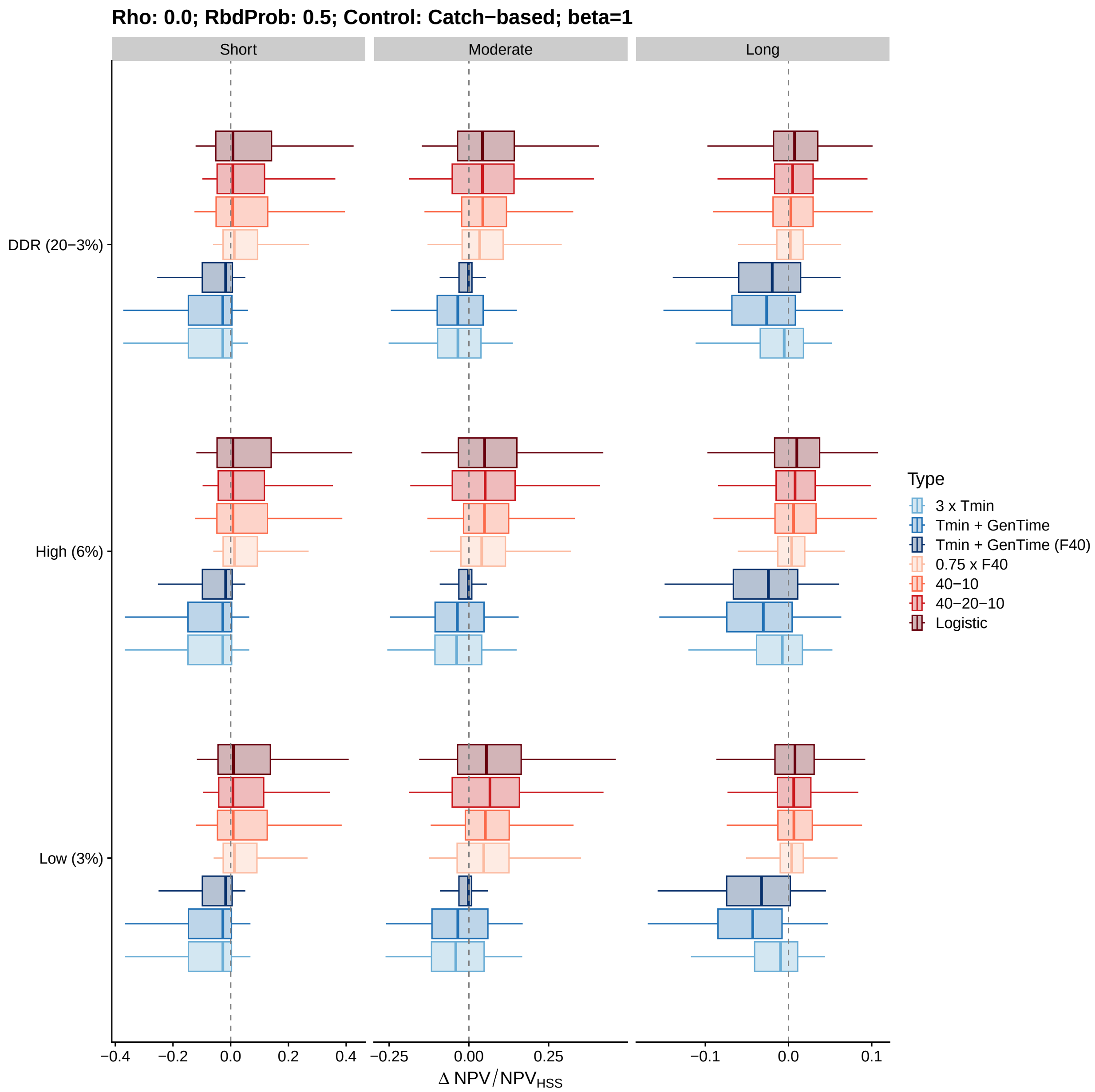

Figure 15: Relative difference in net present value (NPV) from the current policy (Harvest Strategy Standard (HSS), $2\times T_{min}$) across life histories (columns) for catch-based management at base per-unit-effort cost (0.1) and no CPUE hyperstability, across alternative discount rates (rows; DDR: declining discount rate). Control-rule-based policies are shown in shades of red/orange and timeline-based policies are shown in shades of blue.

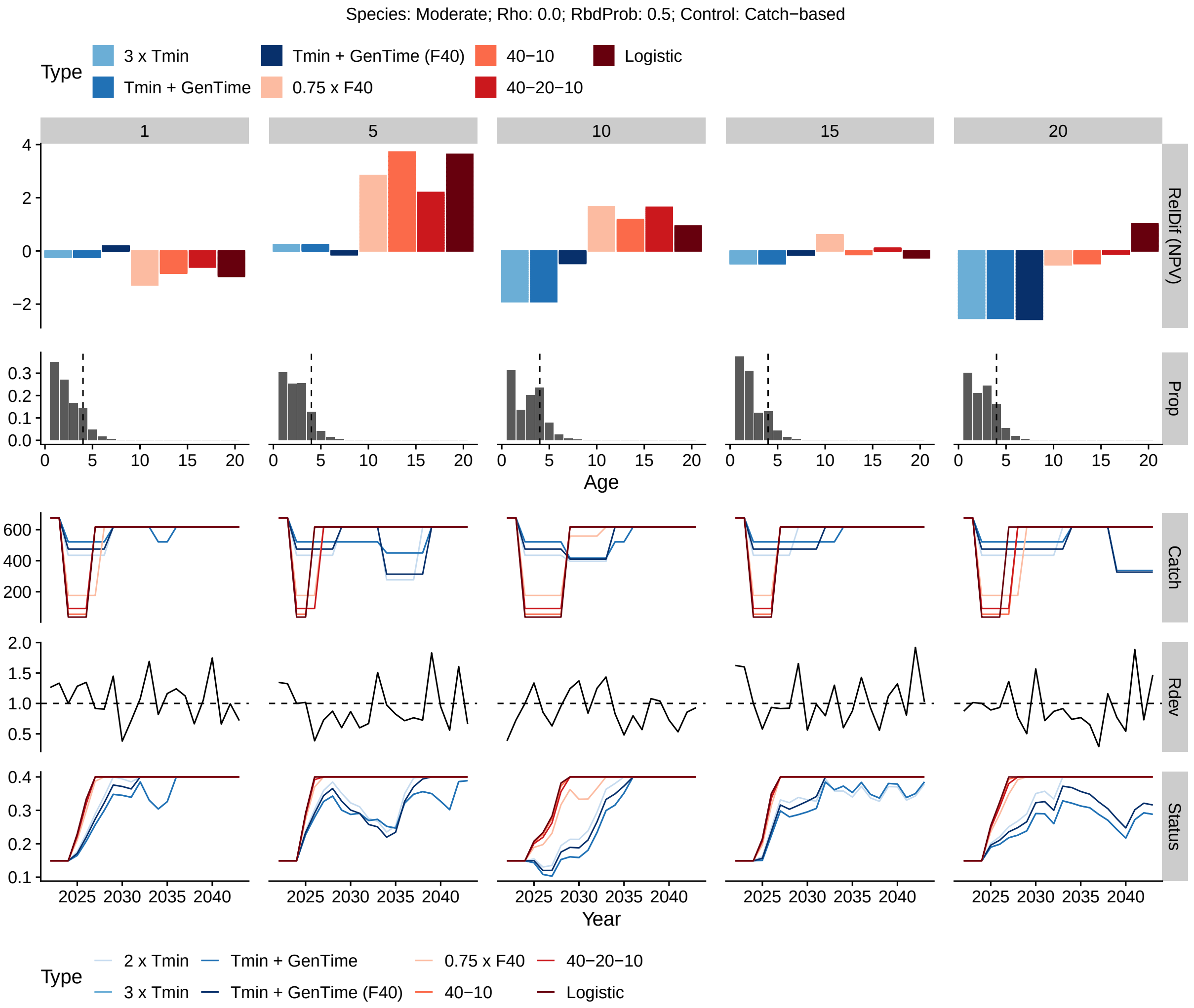

Figure 16: Relative difference in net present value (NPV) from the current policy ($2 \times T_{min}$; top row), proportion of age distribution (second row), catch (third row), recruitment deviations (Rdev; fourth row) and stock status (bottom row), for randomly drawn simulation trajectories (columns) for catch-based management at base per-unit-effort cost (0.1) and no CPUE hyperstability. Control-rule-based policies are shown in shades of red/orange and timeline-based policies are shown in shades of blue.

The NPV results were highly sensitive to the relationship between CPUE and biomass, and to the per-unit-effort cost. In the case of hyperstability of CPUE (or low per-unit-effort cost), longer rebuilding timelines achieved higher NPV than the current policy or control-rule-based policies (Figures 17 & 18). Conversely, with hyper-depleted CPUE or high per-unit-effort cost, longer timelines were associated with lower NPV (Figures 19 & 20). These differences were due to the development of profits and costs over time under different levels of hyperstability or unit effort cost (Figures 21 & 22).

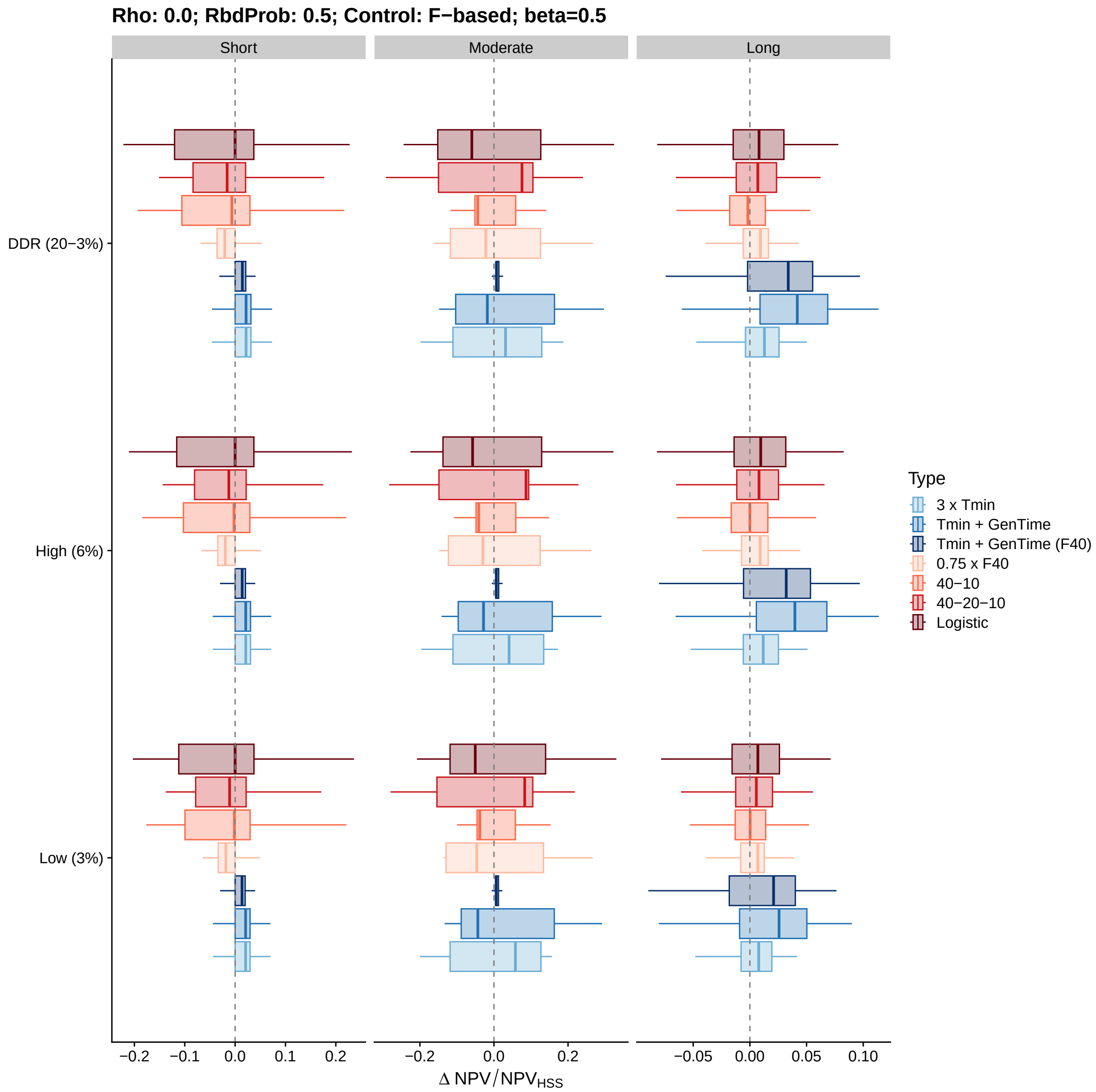

Figure 17: Relative difference in net present value (NPV) from the current policy (Harvest Strategy Standard (HSS), $2\times T_{min}$) across life histories (columns) for management based on fishing mortality at base per-unit-effort cost (0.1) and hyperstable CPUE, across alternative discount rates (rows; DDR: declining discount rate). Control-rule-based policies are shown in shades of red/orange and timeline-based policies are shown in shades of blue.

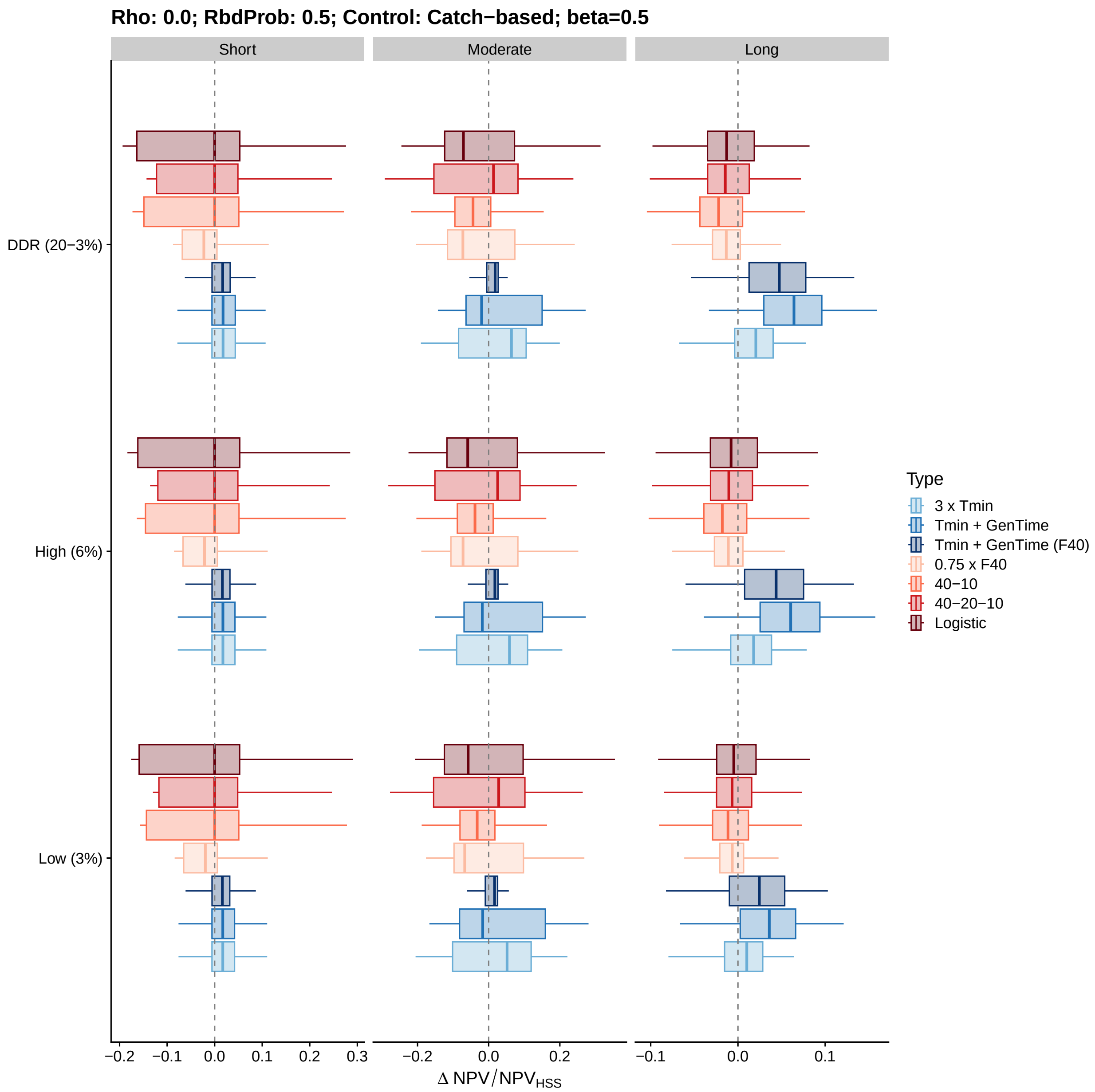

Figure 18: Relative difference in net present value (NPV) from the current policy (Harvest Strategy Standard (HSS), $2 \times T_{min}$) across life histories (columns) for catch-based management at base per-unit-effort cost (0.1) and hyperstable CPUE, across alternative discount rates (rows; DDR: declining discount rate). Control-rule-based policies are shown in shades of red/orange and timeline-based policies are shown in shades of blue.

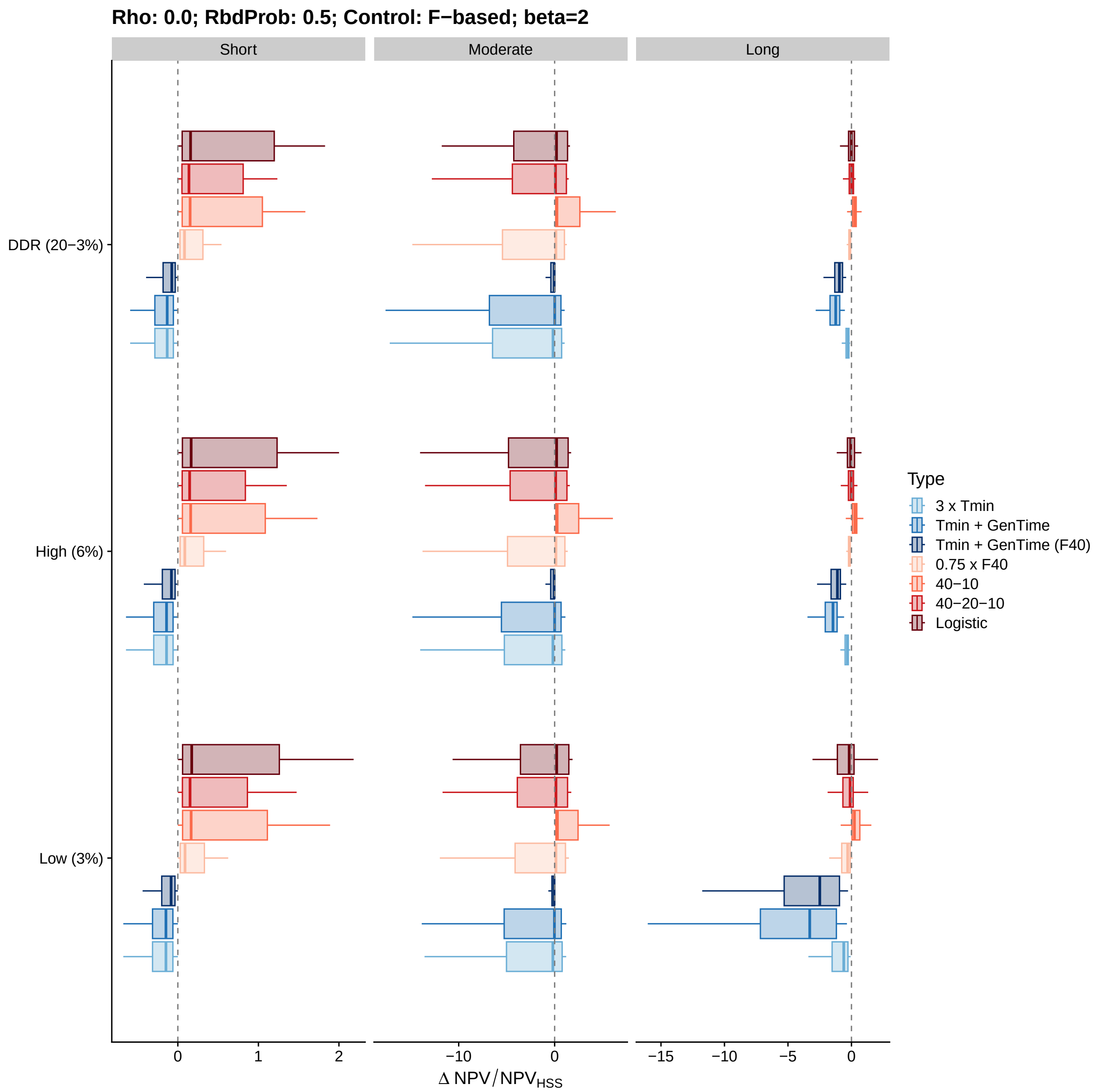

Figure 19: Relative difference in net present value (NPV) from the current policy (Harvest Strategy Standard (HSS), $2 \times T_{min}$) across life histories (columns) for management based on fishing mortality at base per-unit-effort cost (0.1) and hyper-depleted CPUE, across alternative discount rates (rows; DDR: declining discount rate). Control-rule-based policies are shown in shades of red/orange and timeline-based policies are shown in shades of blue.

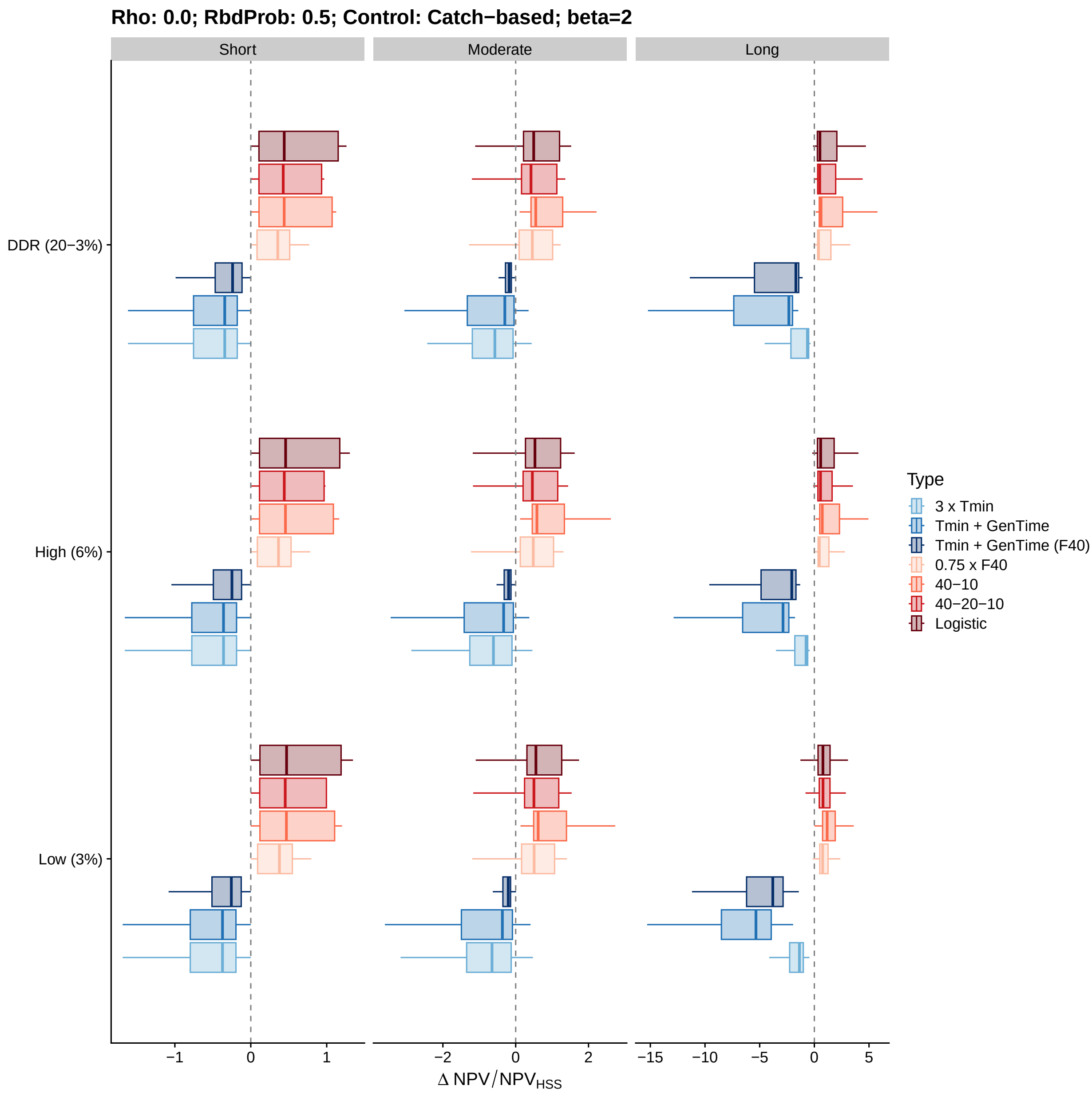

Figure 20: Relative difference in net present value (NPV) from the current policy (Harvest Strategy Standard (HSS), $2 \times T_{min}$) across life histories (columns) for catch-based management at base per-unit-effort cost (0.1) and hyper-depleted CPUE, across alternative discount rates (rows; DDR: declining discount rate). Control-rule-based policies are shown in shades of red/orange and timeline-based policies are shown in shades of blue.

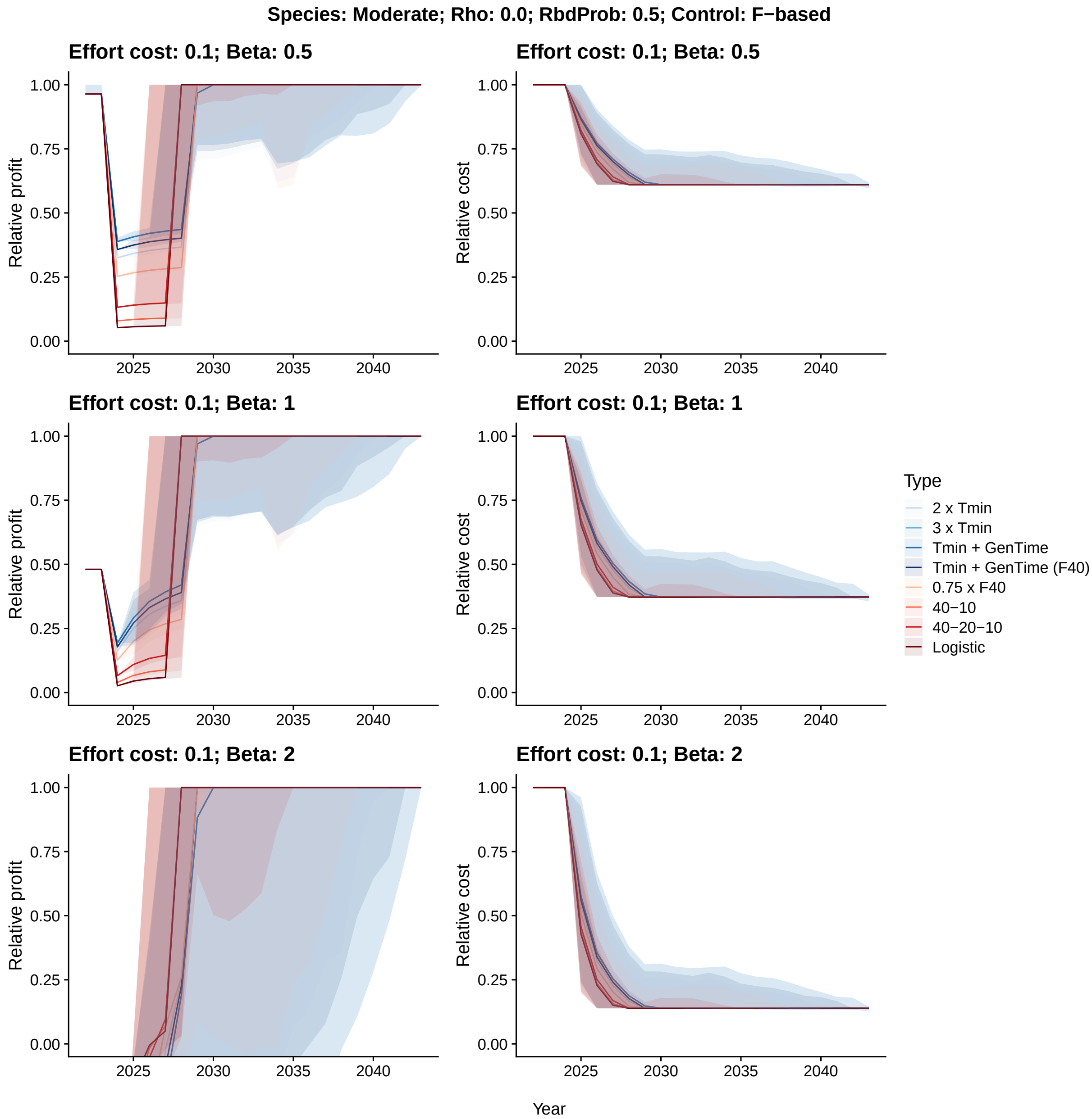

Figure 21: Relative profit and cost for management based on fishing mortality at base per-unit-effort cost (0.1) and across assumptions of catch-per-unit-effort (CPUE) hyperstability (Beta), illustrated for the moderate life history. Control-rule-based policies are shown in shades of red/orange and timeline-based policies are shown in shades of blue.

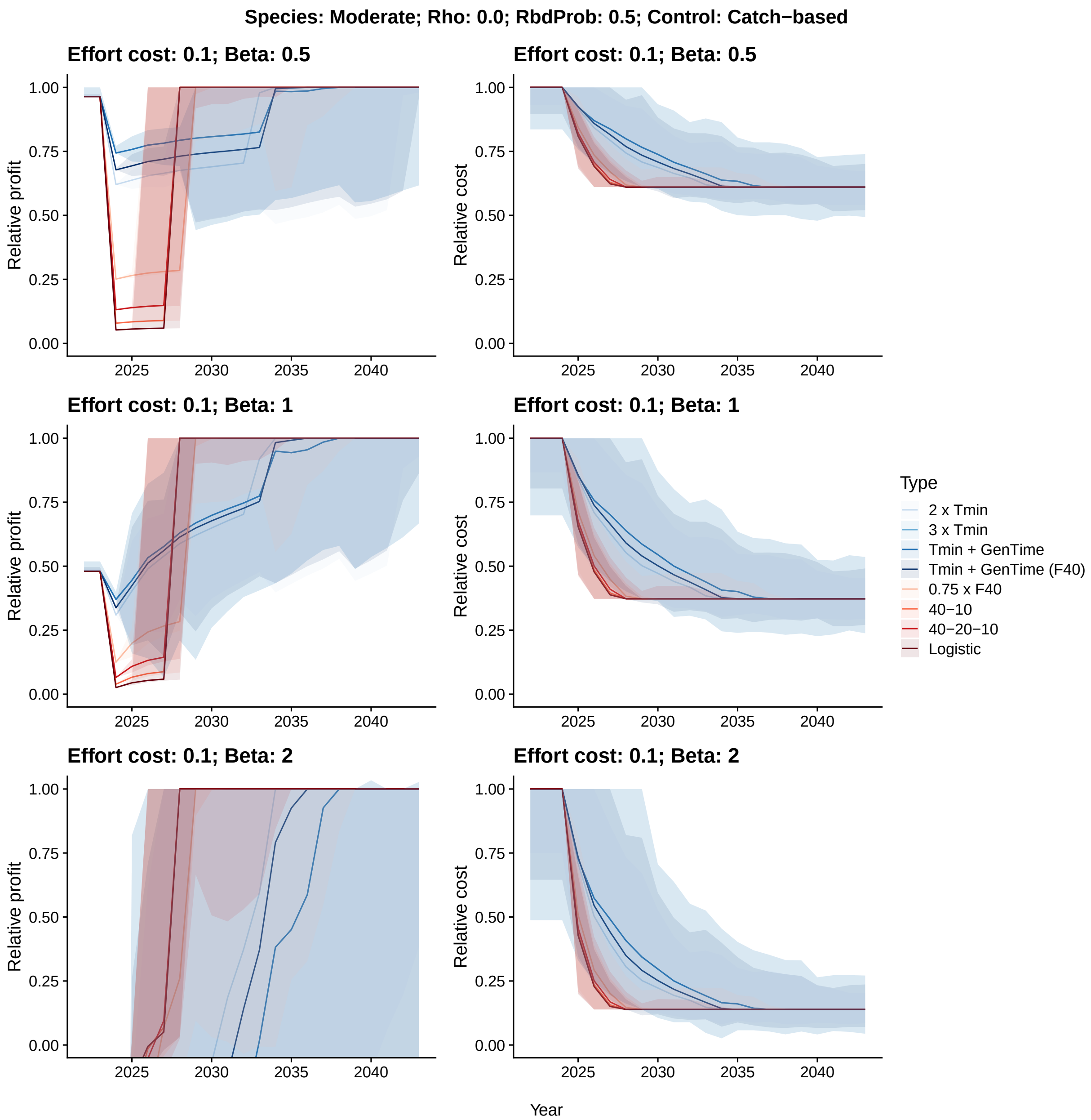

Figure 22: Relative profit and cost for catch-based management at base per-unit-effort cost (0.1) and across assumptions of catch-per-unit-effort (CPUE) hyperstability (Beta), illustrated for the moderate life history. Control-rule-based policies are shown in shades of red/orange and timeline-based policies are shown in shades of blue.

3.6 Sensitivity analyses

Increasing the rebuilding probability threshold from 50 to 70% resulted in longer rebuilding times for all policies, but did not significantly change their relative performance (Appendix B). Introducing recruitment autocorrelation increased the variability in rebuilding outcomes, and emphasised the necessity to adjust settings during rebuilding policies, especially for long-lived species (Appendix C).

3.7 Tarakihi case study

The simplified tarakihi model had a T_{min} of nine years, and a generation time of 16 years without fishing, and 12 years with fishing.

The tarakihi case study largely corroborated the findings from the simulations: as expected, longer rebuilding timelines increased estimated rebuilding times and risk of the stock dropping below the hard limit (Figures 23 & 24). (It is noted here that for the tarakihi simulations, no intermediate adjustments were made, so these risks reflect fixed settings during the rebuilding period and, therefore, overestimate risk.) The relative performance of different policies was sensitive to assumptions about cost structure and CPUE hyperstability (Figure 25).

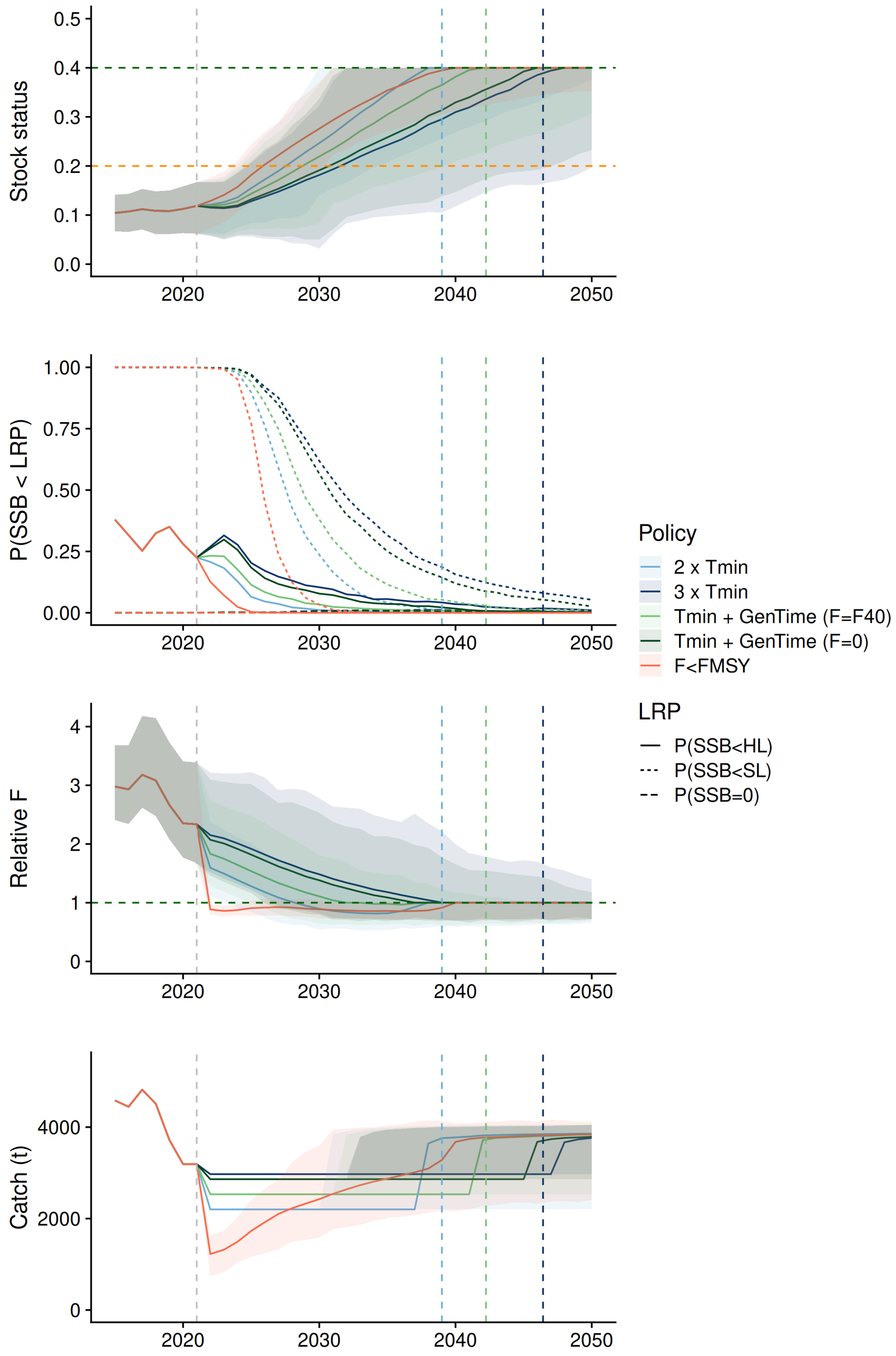

Figure 23: Rebuilding timelines across rebuilding policies for the tarakihi case study. Stock status (SSB/SSB_0; top row), probability of the stock exceeding limit reference points (second row), fishing mortality (third row) and catch (C; bottom row). $F<F_{MSY}$ shows a policy of maintaining F below F_{MSY} for comparison with timeline based strategies.

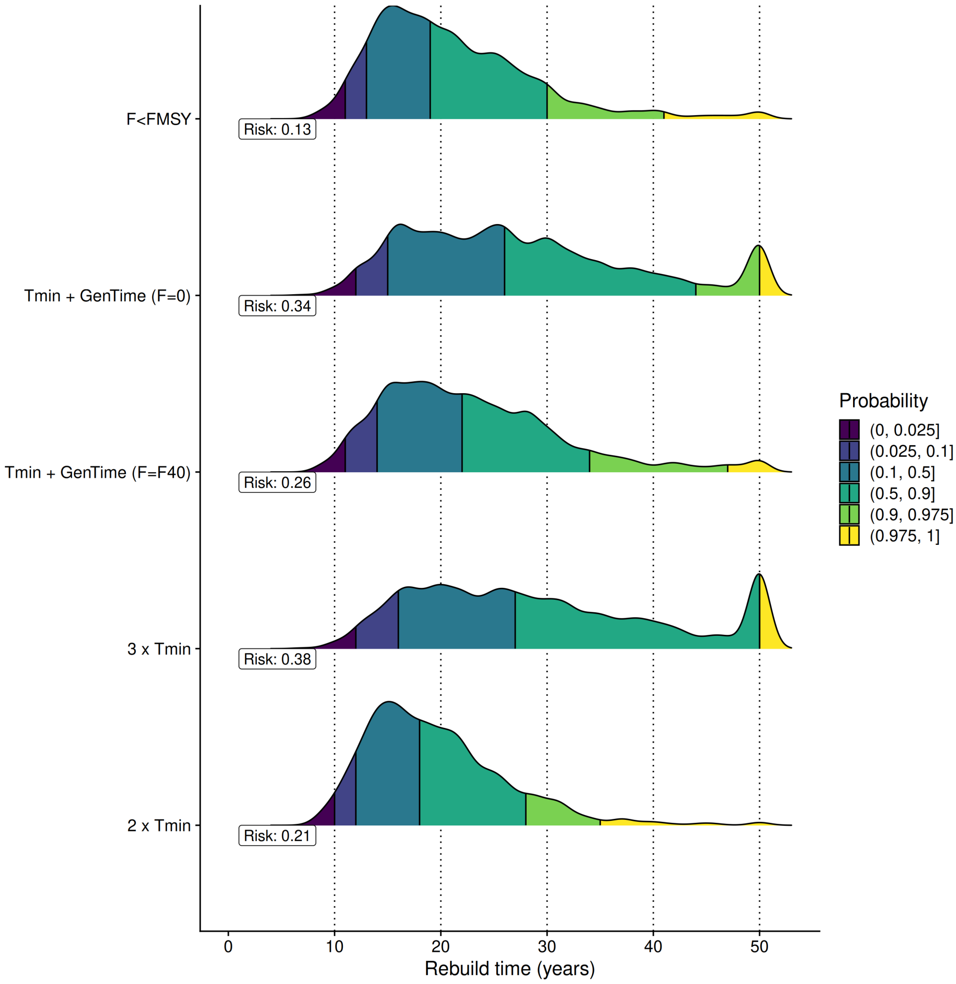

Figure 24: Rebuilding time distributions for alternative rebuilding timelines (policies) for tarakihi, and corresponding risk (probability that stock status falls below the hard limit during the evaluation period of 40 years).

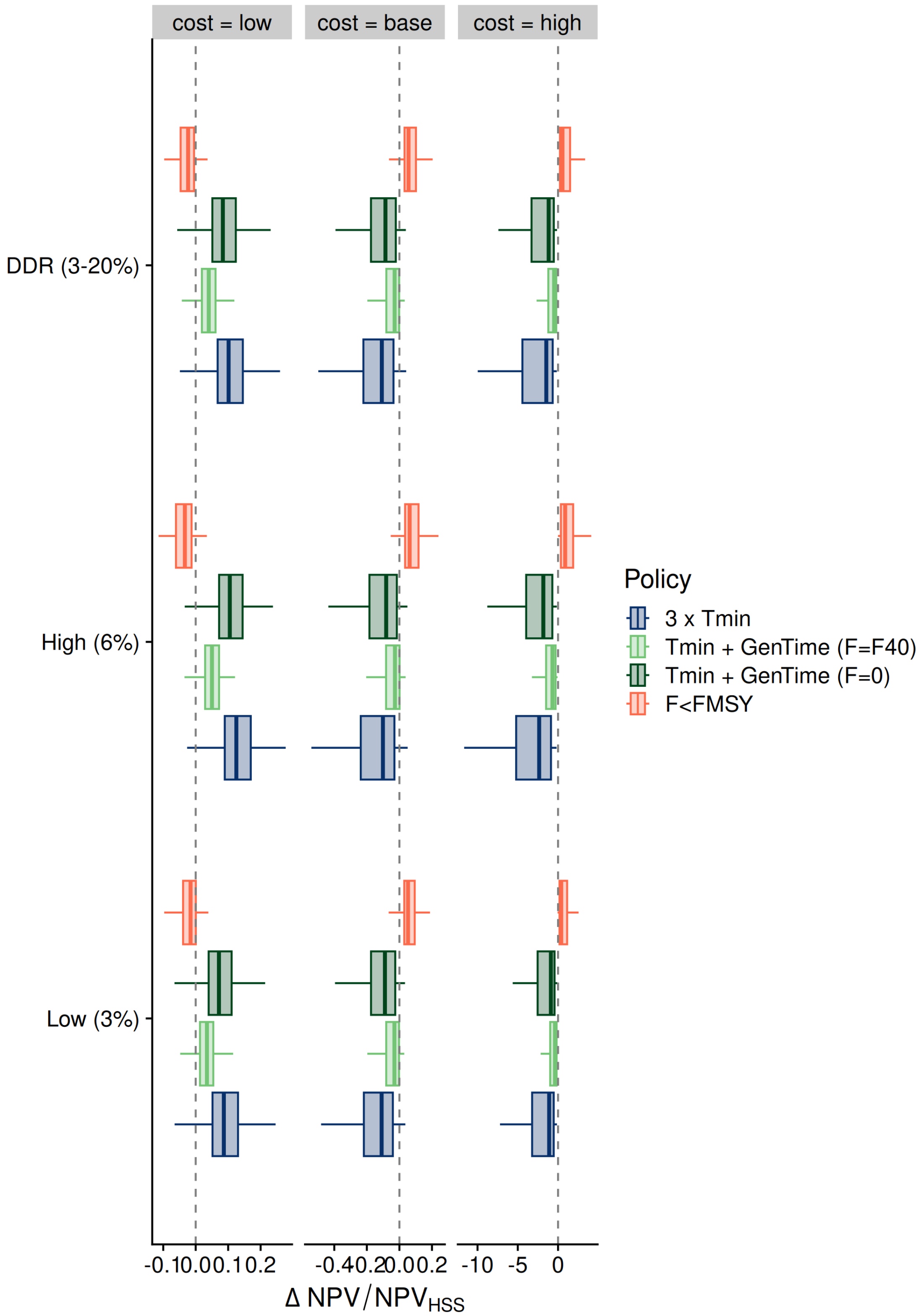

Figure 25: Relative difference in net present value (NPV) from the current policy (Harvest Strategy Standard (HSS), $2 \times T_{min}$) for tarakihi simulations for alternative parameter values for the base per-unit-effort cost and with no CPUE hyperstability, for alternative discount rates (DDR: Declining discount rate).

4. DISCUSSION

Our evaluation of alternative rebuilding strategies built on a considerable body of research about stock rebuilding (Worm et al. 2009, Murawski 2010, Hilborn et al. 2012, Neubauer et al. 2013). Nevertheless, relatively few studies have explicitly evaluated the relative merit of alternative rebuilding policies, and compared the risk and economic implications of alternative policies across species or life histories (but see Hilborn et al. 2012, Wetzel & Punt 2016).

It is self-evident that life history characteristics, especially stock productivity, and environmental conditions need to be considered when designing rebuilding plans and associated timelines. Our simulations across different life histories highlight the importance of customising rebuilding policies to species-specific traits. Long-lived species exhibited more stable rebuilding trajectories but required long timeframes to achieve target biomass levels. In contrast, short-lived species with high natural mortality and productivity showed faster rebuilding potential; however, they also had higher sensitivity of rebuilding timelines to recruitment variability, with resulting uncertainty about the feasibility of specific rebuilding timelines. For species with short lifespans (e.g., flatfish or similar species) that are subject to notable fluctuations due to environmental factors, responsive control rules may perform better than specific rebuilding timelines. For longer-lived species, however, considerations of stock productivity and long-term risk become most important, and environmental variability can be addressed during the rebuild by adjusting catch or fishing mortality.

For timeline-based policies, the concept of T_{min} is central to most rebuilding policies; it is the basis for the present rebuilding policy required under the New Zealand's Harvest Strategy Standard (HSS; Ministry of Fisheries 2008), which requires rebuilding within T_{min} to $2 \times T_{min}$ as a default. T_{min} encapsulates stock productivity (how fast a stock can rebuild from the estimated level of depletion), and a strategy of minimal risk (i.e., no fishing). Nevertheless, it is important to acknowledge that even at T_{min}, the risk of failing to rebuild, or for stocks to decline further is not zero: for any stock existing in a naturally-fluctuating environment, there is a non-zero risk of decline even in the absence of fishing. With any fishing, the risk of falling into an undesirable state (e.g., a state where recruitment is impaired) increases from the baseline set by T_{min}. Any multiple of T_{min} is, therefore, a reflection of risk tolerance, in contrast to a fundamental biological property (i.e., while T_{min} is a property that is solely determined by biology, the multiple applied to T_{min} is not). Any timeframe beyond T_{min} is, therefore, a policy decision that reflects a level of risk above the baseline risk. To the extent that this risk can be characterised by estimated recruitment variability, it can be simulated and quantified to evaluate alternative rebuilding timelines (e.g., simulated risk as a function of timelines defined in terms of multiples of T_{min}).

Most international rebuilding frameworks (e.g., Fisheries and Oceans Canada 2019) acknowledge the difficulty in estimating T_{min} for data-limited stocks (which is likely to constitute the majority of stocks). Even for data-rich stocks, the definition of T_{min} is open to some interpretation: if recent recruitment was strong, and used in projections to determine T_{min}, then the estimated T_{min} and derived rebuilding timelines will be short, effectively assuming that robust recruitment will persist over the course of the rebuilding timeframe. It may be most appropriate to set expected recruitment to average recruitment for the purpose of defining rebuilding timelines so as to avoid timelines that are biased short (or long) due to assumptions of strong (or low) recruitment. In addition to alternative definitions, key productivity parameters are often fixed, based on limited information in stock assessments, essentially leading to an *a priori* fixed T_{min}. Therefore, unless the assessment incorporates uncertainty for all parameters relevant to T_{min} (i.e., natural mortality, growth, steepness and shape of the stock recruitment relationship), T_{min} can be largely determined by expert input rather than by available data.

In addition to uncertainties about the most-adequate method to derive rebuilding timeframes based on stock productivity (via T_{min}), in the absence of a population model for a given stock, alternative measures of stock productivity need to be used to derive biologically-relevant rebuilding timelines. Generation time is often used as a proxy for productivity to guide rebuilding timeframes. Nevertheless, there are a number of definitions of generation time, each with different requirements for data and assumptions (Patrick & Cope 2014, Staerk et al. 2019), some of which may be poorly related to productivity (Patrick & Cope 2014). At minimum, all generation time estimates require estimates of natural mortality and fecundity schedules (similar to integrated stock assessment or other demographic models). These parameters are poorly understood for many species, yet the choice of assumption about these parameters will inevitably determine estimates of generation time and associated rebuilding timeframes. It is noted that if there is insufficient information to calculate T_{min}, which requires a population dynamics model from which projections can be made, there will also be insufficient information to determine management actions (reductions in catch or F) to rebuild stocks using solely timeframes based on generation time. In other words, generation time on its own is not a substitute for policies based on T_{min} or multiples thereof.

Our analysis of different generation time metrics showed that the choice between unfished (F = 0) and fished (F_{40}) conditions can impact rebuilding timelines, especially for long-lived species. That is, the use of generation time calculated under fished conditions resulted in shorter rebuilding timeframes. Although there is no clear guideline about the most adequate method for calculating generation time in a fisheries context, the fished generation time can be understood as the time to rebuild the population age structure and mean fecundity to fishery target levels during recovery, a process that is typically slower than T_{min} alone (Walters et al. 2008). This definition of generation time may, therefore, have a stronger basis as a biologically-motivated timeframe in a fisheries context. Nevertheless, as both metrics are systematically higher than T_{min}, policies based on T_{min} plus a form of generation time will typically be longer than those based on $2 \times T_{min}$.

Regardless of the specific implementation, rebuilding plans in general may not adequately account for the inherent variability in fish population dynamics or the economic realities of fisheries, because not all uncertainties are accounted for (National Research Council 2014). Climate-induced reductions in inherent stock productivity, for example, can substantially prolong required rebuilding timeframes (Neubauer et al. 2013, Britten et al. 2017), but are difficult to account for *a priori*. In this case, intermediate adjustment to catch or F settings are necessary to adjust fishing mortality, and ensure a stock can meet rebuilding timelines.

4.1 Timeline versus control rule policies

The results consistently showed that more conventional control-rule-based policies (i.e., not linked to rebuilding timelines) often led to shorter rebuilding times than timeline-based approaches with associated risk reduction. Nevertheless, this outcome is due to large initial reductions in catch at the simulated initial depletion levels. The reduced risk and marked initial reductions largely reflect the design of most control rules, including control rules used here, to maintain a stock near the target biomass and avoid biomass limits. While control rule-based policies respond dynamically to changes in stock status (assuming status is regularly assessed), and lower the risk that a stock will reach a depleted state, for already depleted stocks most conventional control rules approach a minimum risk (i.e., T_{min}) strategy of no fishing.

In contrast to control rules, timeline-based policies may be either relatively conservative or relatively strong at the outset to meet their target rebuilding timeline, depending on the recruitment trajectory during rebuilding. Our study concurs with findings by Wetzel & Punt (2016) that, on average, the difference between fixed catch settings and intermediate updates of catch settings during the rebuilding phase is relatively small; however, intermediate monitoring and adjustments reduce the variability in rebuilding timelines when recruitment is below expectations and, therefore, mitigates risk. It is, therefore, worthwhile monitoring stock trends during rebuilding for signs that recruitment is below expectations. In addition, with adequate monitoring and potentially prescribed management procedures to adjust catch for under-performing stocks, longer rebuilding policies could be considered suitable; in general, the expected rebuilding timeline under intermediate adjustments is shorter than the period used to set the timeline, because catch will be adjusted downward for under-performing stocks. Although a longer timeline with continuous (or periodic) review of rebuilding performance contains a risk of further reductions during the rebuilding period, this approach may lead to an acceptable level of overall risk while requiring smaller initial reductions in catch than a shorter timeline with no review and equivalent risk.

4.2 Economic considerations

The incorporation of economic factors in our evaluation provided a way to integrate over the cost of initial catch reductions and the benefits of returning to target levels. The results demonstrate that the relative economic merit of rebuilding policies is strongly influenced by cost structures and the relationship between stock abundance and catch rates (CPUE hyperstability). Control rule policies generally outperformed timeline-based policies when recruitment is below expectations. This finding largely underscores the value of continuous adjustments in fishing mortality during rebuilding. Future research could evaluate and optimise rebuilding strategies to minimise risk and optimise economic performance by finding the most appropriate adjustment strategy. Larkin et al. (2006) showed that under low discount rates, an optimal strategy is to briefly introduce substantial reductions in fishing mortality, and to gradually rebuild catch thereafter, similar to the constant F strategy in our simulations. Nevertheless, the results from Larkin et al. (2006) were obtained using assumptions of constant recruitment, and did not consider risk. To be biologically-relevant, a formal evaluation of rebuilding timelines and strategies needs to first consider risk to be biologically-releant, and be able to optimise for economic benefit if alternative strategies with alternative economic outcomes show equivalent risk.

4.3 Conclusions

There are no rebuilding timelines or policies that can be defined as most suitable under all circumstances—all approaches reflect a level of risk that can and should be quantified based on best available data. We suggest that specific rebuilding plans could be designed to minimise risk by specifying, and simulation testing, adjustment policies during the rebuilding timelines. This approach may lead to equivalent or lower risk for longer postulated rebuilding timeframes. For example, a rebuilding timeline of $3 \times T_{min}$ with a suitable adjustment policy may have an equivalent risk to a timeline based on $2 \times T_{min}$ with no adjustments. This approach may require more frequent monitoring and management interventions, which can be resource intensive. Nevertheless, a carefully-designed rebuilding strategy implementing hybrid policies that combine advantageous elements of timeline-based (lower initial catch reduction) and control rule-based strategies (lower risk through dynamic updates of F) may offer a pragmatic solution to provide near-optimal outcomes in terms of both reduced risk and potential economic impacts.

ACKNOWLEDGMENTS

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APPENDIX A: SIMULATION MODEL

For the simulation-estimation experiments, we developed a simple age-structured population model. The operating model to simulate data was developed in *R* (R Core Team 2021) and *Stan* (Carpenter et al. 2017) to allow efficient simulation.

A.1 Parameter definitions

Table A-1: Definitions for the terms used in the age-structured model.

Notation	Description
a	Index for ages.
A	Maximum age.
t	Index for years.
T	Index for the last year.
$N_{a,t}$	Abundance of fish of age a in year t.
H_t	Exploitation rate for year t.
Y_t	Yield (i.e., catch in weight) in year t.
$\tilde{N}_a$	Abundance of fish of age a at unexploited equilibrium.
R_0	Recruitment at unexploited equilibrium.
R_t	Recruitment in year t.
σ_R^2	Variance of recruitment deviations.
M	Instantaneous rate of natural mortality.
h	Steepness parameter.
l_a	Mean length at age a .
L_∞, κ, a_0	von Bertalanffy parameters.
ζ	Brody coefficient (i.e., $\zeta = e^{-\kappa}$).
SSB_t	Spawning stock biomass in year t.
SSB_0	Spawning stock biomass at unexploited equilibrium.
W_a	Mean weight at age a.
ω_1, ω_2	Length-weight relationship parameters.
S_a	Selectivity at age a.
a_{50}, v	Selectivity parameters.
Mat_a	Maturity at age a.
a_{Mat}	Age at 100% maturity.
VB_t	Vulnerable biomass in year t.
VB_0	Vulnerable biomass at unexploited equilibrium.
φ	Proportion of females.
I_t	Abundance index in year t.
q	Catchability coefficient.
$\hat{P}_{a\|t}$	Model-estimated age-composition proportion of age a in year t.

A.2 Age-structured dynamics

The age-structured dynamics of the population are defined as:

$$N_{a,t} = \begin{cases} R_t, & \text{for } a = 1, \\ N_{a-1,t-1} \cdot (1 - S_{a-1} \cdot H_{t-1}) \cdot e^{-M}, & \text{for } 1 < a < A, \\ N_{a-1,t-1} \cdot (1 - S_{a-1} \cdot H_{t-1}) \cdot e^{-M} + N_{a,t-1} \cdot (1 - S_a \cdot H_{t-1}) \cdot e^{-M}, & \text{for } a = A, \end{cases} \quad \text{(A-1)}$$

where $N_{a,t}$ is the abundance of fish of age a at the beginning of year t, R_t is the recruitment at age 1 in year t, S_a is the time-invariant age-dependent selectivity, H_t is the exploitation rate ($0 \leq H_t \leq 1$) in year t, A is the maximum age which is the plus group, and M is the instantaneous rate of natural mortality.

The initial population (i.e., $N_{a,1}$) was assumed to be at unexploited equilibrium:

$$\tilde{N}_a = \begin{cases} R_0, & \text{for } a = 1, \\ \tilde{N}_{a-1} \cdot e^{-M}, & \text{for } 1 < a < A, \\ \dfrac{\tilde{N}_{a-1} \cdot e^{-M}}{1 - e^{-M}}, & \text{for } a = A, \end{cases} \tag{A-2}$$

where $\tilde{N}_a$ is the abundance of fish of age a at unexploited equilibrium, R_0 is the recruitment at age 1 at unexploited equilibrium, M is the instantaneous rate of natural mortality, and A is the maximum age which is the plus group.

A.3 Stock-recruitment relationship

The Beverton-Holt stock-recruitment function, reparameterised in terms of the steepness parameter h (Mace & Doonan 1988), was used to model the annual recruitment at age 1 R_t:

$$R_{t+1} = \frac{4 \cdot h \cdot R_0 \cdot SSB_t}{(1-h) \cdot SSB_0 + (5 \cdot h - 1) \cdot SSB_t} \cdot e^{\varepsilon_{t+1} - 0.5 \cdot \sigma_R^2}, \tag{A-3}$$

where SSB_t is the spawning stock biomass in year t, SSB_0 is the spawning stock biomass at unexploited equilibrium, ε_t are the annual recruitment deviations, which are normally distributed with mean 0 and variance σ_R^2, R_0 is the recruitment at age 1 at unexploited equilibrium, and the subtracted term $-0.5 \cdot \sigma_R^2$ is the bias correction term.

A.4 Length-at-age distribution of the catch

For simplicity, the length-at-age distribution of the catch $G_{j|a}$ was assumed to be the same as the length-at-age distribution of the population (i.e., there is no length-dependent selectivity):

$$G_{j|a} = \begin{cases} \int_0^{\bar{L}_j + r/2} f(L|l_a, \sigma_a^2) dL, & \text{for } j = 1, \\ \int_{\bar{L}_i - r/2}^{\bar{L}_j + r/2} f(L|l_a, \sigma_a^2) dL, & \text{for } 1 < j < J, \\ 1 - \int_0^{\bar{L}_j - r/2} f(L|l_a, \sigma_a^2) dL, & \text{for } j = J, \end{cases} \tag{A-4}$$

where r is the length bin width, $\bar{L}_j$ is the midpoint of the length bin j, l_a is the mean length-at-age, σ_a is the standard deviation of the length-at-age distribution, $f(L|l_a, \sigma_a^2)$ is the normal density of the random variable L with mean l_a and variance σ_a^2, and J is the last length bin.

The mean length-at-age, l_a, was modelled with the von Bertalanffy function:

$$l_a = L_\infty \cdot [1 - e^{-\kappa \cdot (a - a0)}], \tag{A-5}$$

where L_∞ is the asymptotic length, κ is the growth rate, and a_0 is the theoretical age at length 0.

The standard deviation of the length-at-age distribution σ_a was modelled with the function, which was adopted from the MULTIFAN-CL model (Fournier et al. 1990, Fournier et al. 1998):

$$\sigma_a = \lambda_1 \cdot e^{\lambda_2 \cdot \left[-1+2\cdot\left(\frac{1-\zeta^{a-1}}{1-\zeta^{A-1}}\right)\right]}, \tag{A-6}$$

where λ_1 determines the scale of the standard deviations, λ_2 determines the length-dependent increase in the standard deviations, and ζ is the Brody growth coefficient (i.e., $\zeta = e^{-\kappa}$).

A.5 Length-weight relationship

The mean weight-at-age, W_a, was modelled with the length-weight relationship function:

$$W_a = \omega_1 \cdot \mu_a^{\omega_2}, \tag{A-7}$$

where ω_1 and ω_2 are the two parameters which determine the allometric curve.

A.6 Maturity

The sexual maturity-at-age Mat_a was assumed to follow a knife-edged function (Punt et al. 1995):

$$Mat_a = \begin{cases} 0 & \text{if } a < a_{Mat}, \\ 1 & \text{if } a \geq a_{Mat}, \end{cases} \tag{A-8}$$

where a_{Mat} is the age at 100% maturity.

A.7 Selectivity

Selectivity was assumed to be knife-edge at the age of maturity, except for the short life history.

A.8 Biomass quantities

The spawning stock biomass SSB_t and its unexploited value at equilibrium SSB_0 are:

$$SSB_t = \varphi \cdot \sum_{a=1}^{A} N_{a,t} \cdot W_a \cdot Mat_a; \quad SSB_0 = \varphi \cdot \sum_{a=1}^{A} \tilde{N}_a \cdot W_a \cdot Mat_a, \tag{A-9}$$

where φ is the proportion of females in the stock.

Similarly, the vulnerable (or exploitable) biomass VB_t and its unexploited equilibrium value VB_0 are:

$$VB_t = \sum_{a=1}^{A} N_{a,t} \cdot W_a \cdot S_a; \quad VB_0 = \sum_{a=1}^{A} \tilde{N}_a \cdot W_a \cdot S_a. \tag{A-10}$$

A.9 Exploitation rate

We assumed the catch data Y_t had no error, thus treating the exploitation rates H_t as derived quantities:

$$H_t = Y_t / VB_t. \tag{A-11}$$

A.10 Catch-at-age

Based on the exploitation rate H_t, population abundance $N_{a,t}$, and age-dependent selectivity S_a, the model estimated catch-at-age $\hat{C}_{a,t}$ as:

$$\hat{C}_{a,t} = N_{a,t} \cdot S_a \cdot H_t.$$

APPENDIX B: SIMULATIONS WITH REBUILDING PROBABILITY THRESHOLD OF 70%

The following plots are in the same order as plots in the main text, using a 50% rebuild probability to allow for comparisons.

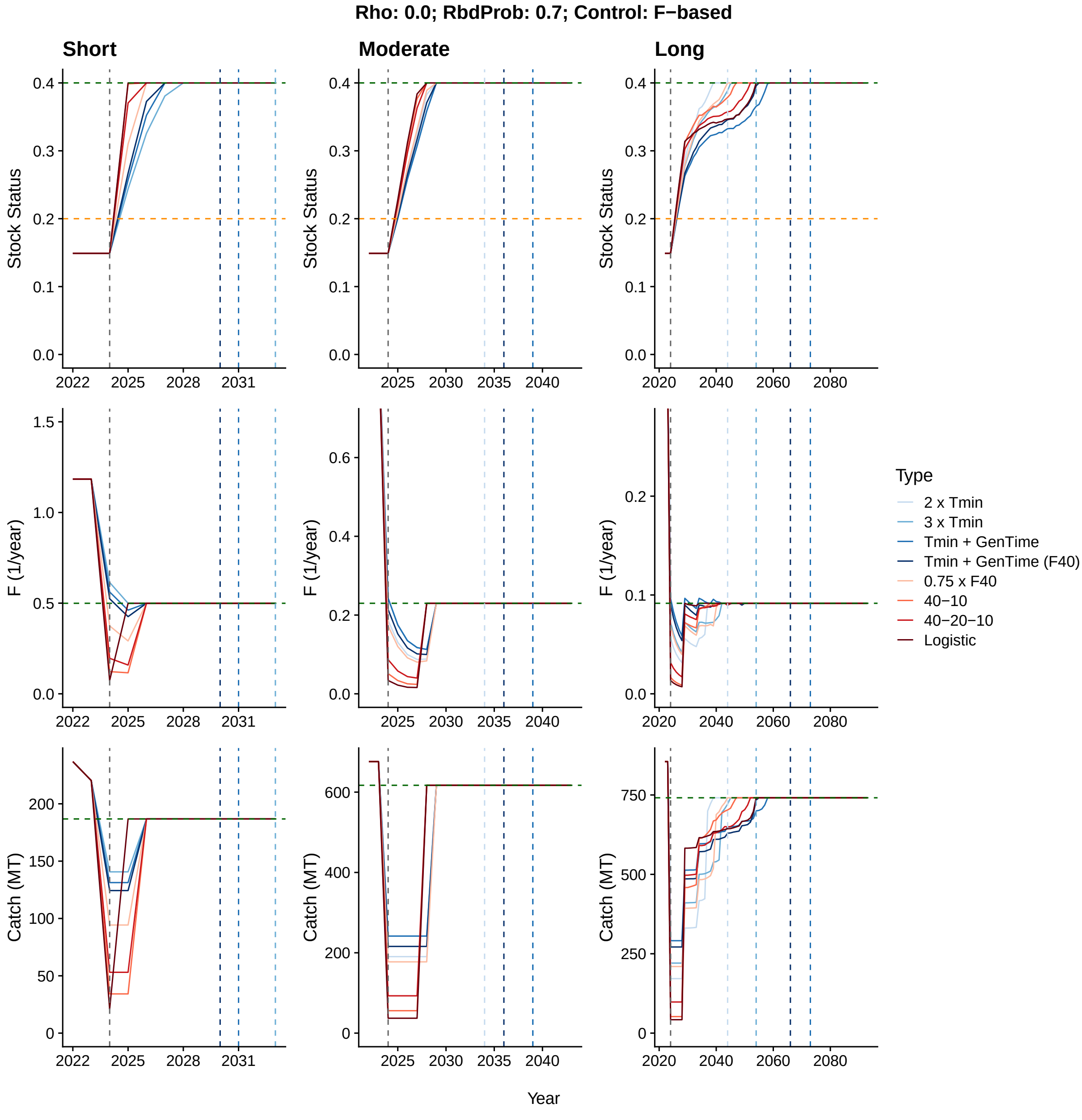

Figure B-1: Rebuilding timelines (median of simulated stock trajectories) for management based on fishing mortality across rebuilding policies. Stock status (SSB/SSB_0; top row), fishing mortality (F; middle row) and catch (C; bottom row) across life histories (columns), for the base scenario without autocorrelation in recruitment (Rho = 0) and with a 70% rebuild probability to estimate T_{min}. Control-rule-based policies are shown in shades of red/orange, and timeline-based policies are shown in shades of blue, with corresponding rebuilding targets shown by dashed vertical lines of the corresponding colour.

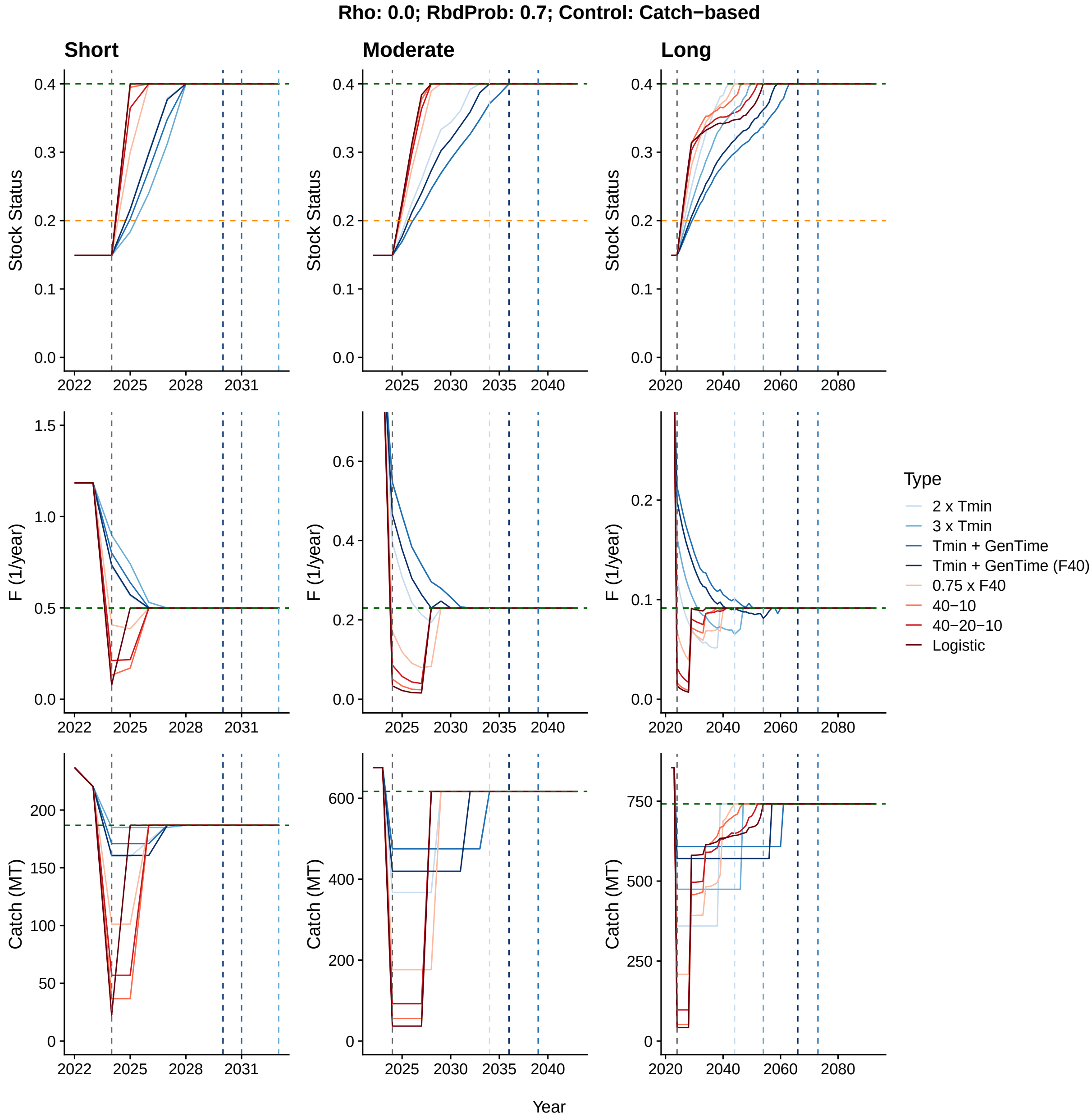

Figure B-2: Rebuilding timelines (median of simulated stock trajectories) for catch-based management across rebuilding policies. Stock status (SSB/SSB$_0$; top row), fishing mortality (F; middle row) and catch (C; bottom row) across life histories (columns), for the base scenario without autocorrelation in recruitment (Rho = 0) and with a 70% rebuild probability to estimate T$_{min}$. Control-rule-based policies are shown in shades of red/orange, and timeline-based policies are shown in shades of blue, with corresponding rebuilding targets shown by dashed vertical lines of the corresponding colour.

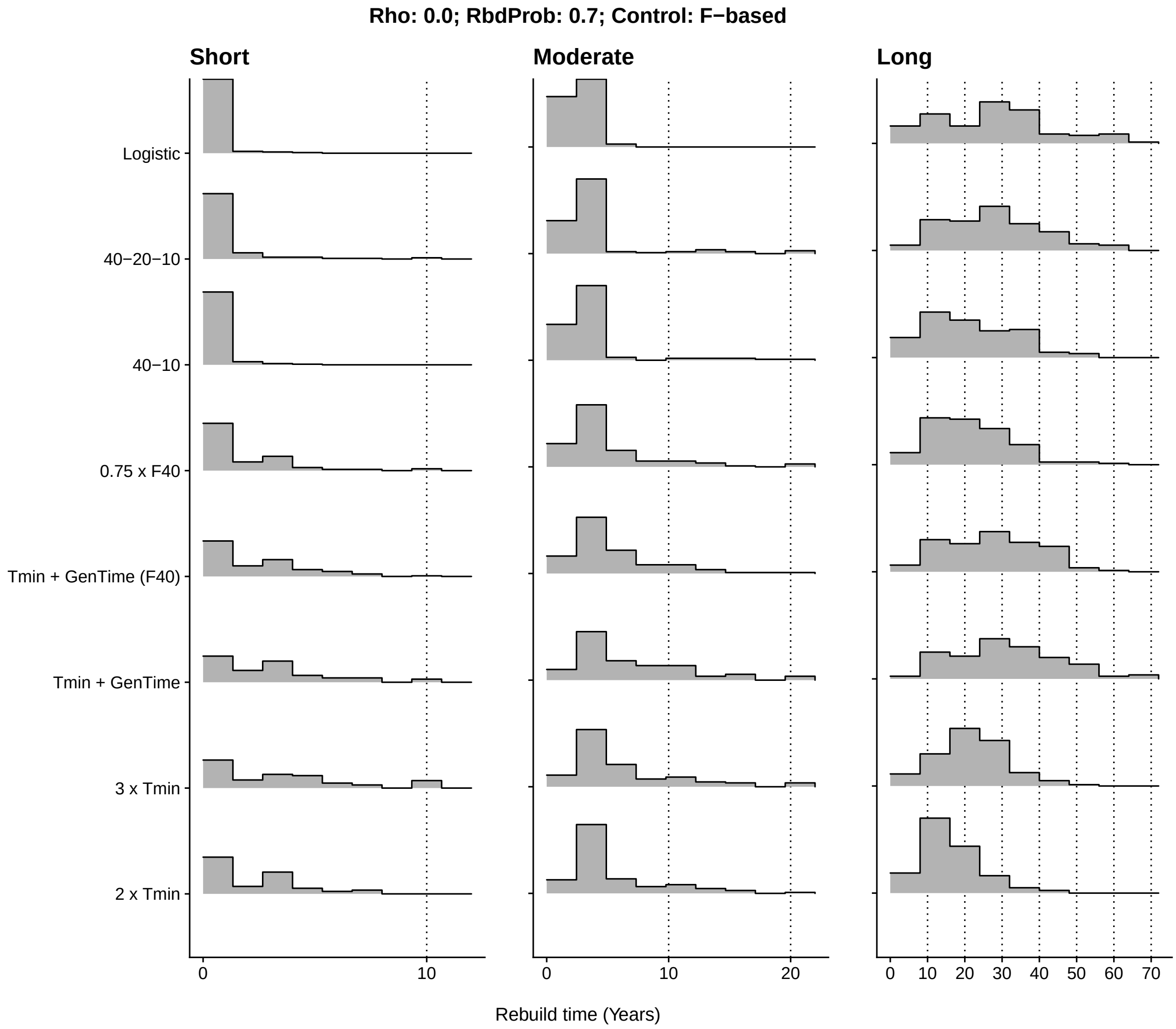

Figure B-3: Rebuilding time distribution (in years) for management based on fishing mortality (F) across rebuilding policies using a 70% rebuild probability to estimate T_{min}.

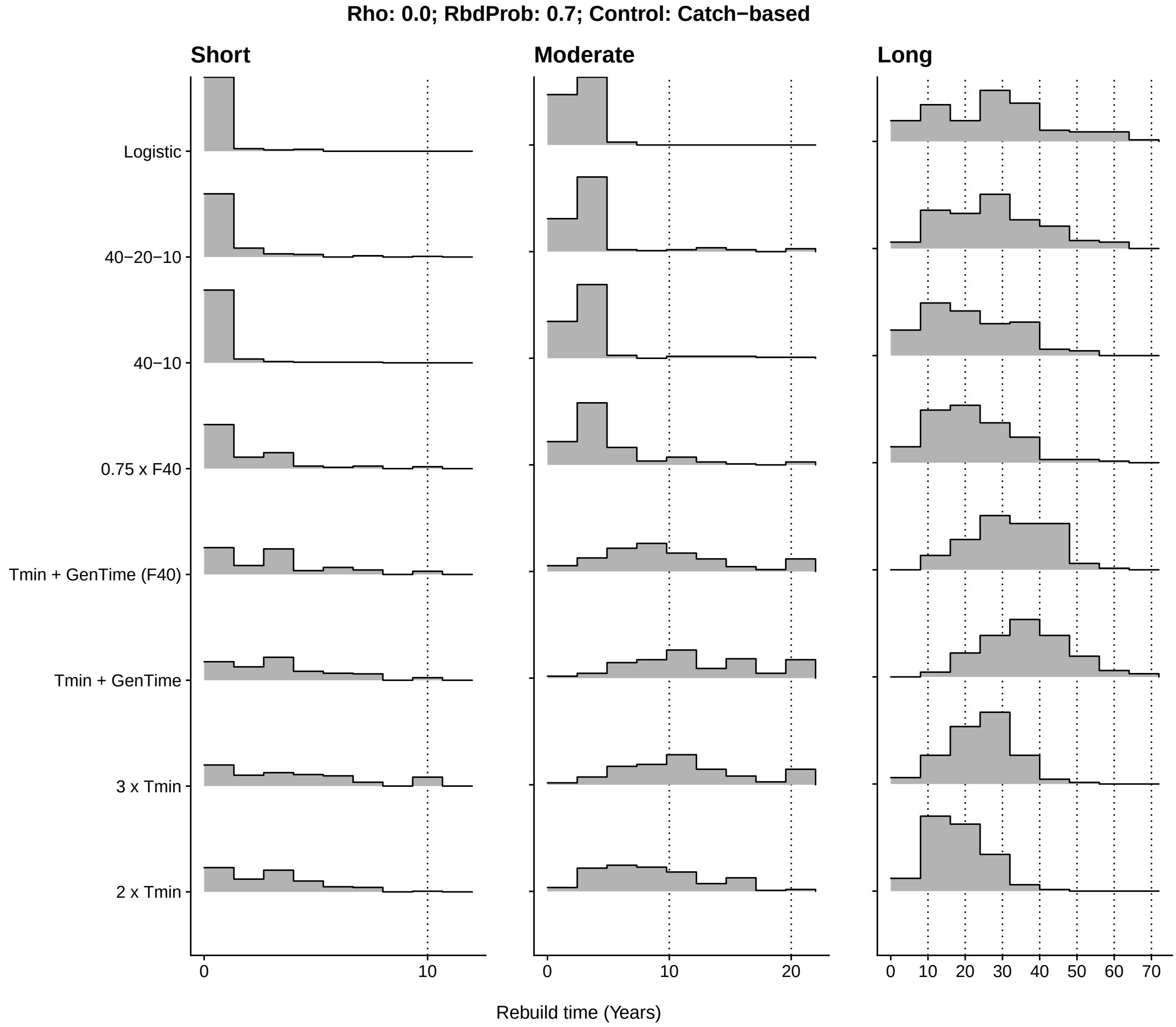

Figure B-4: Rebuilding time distribution (in years) for catch-based management across rebuilding policies using a 70% rebuild probability to estimate T_{min}.

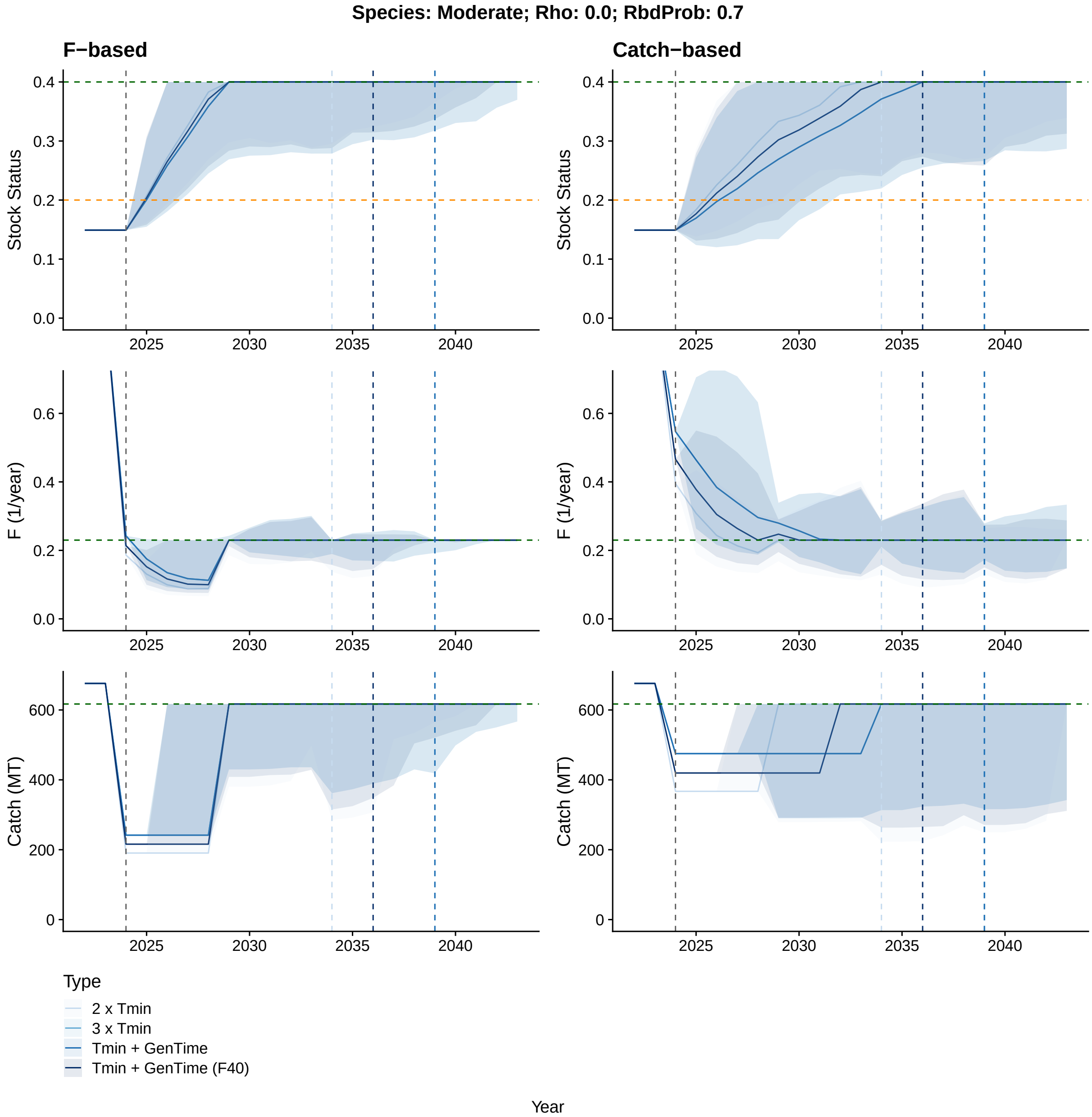

Figure B-5: Difference between management based on fishing mortality (F) and on catch (C) illustrated for the moderate life history. Comparison of timeline-based rebuilding policies, with corresponding rebuilding targets shown by dashed vertical lines of the corresponding shading using a 70% rebuild probability to estimate T_{min}.

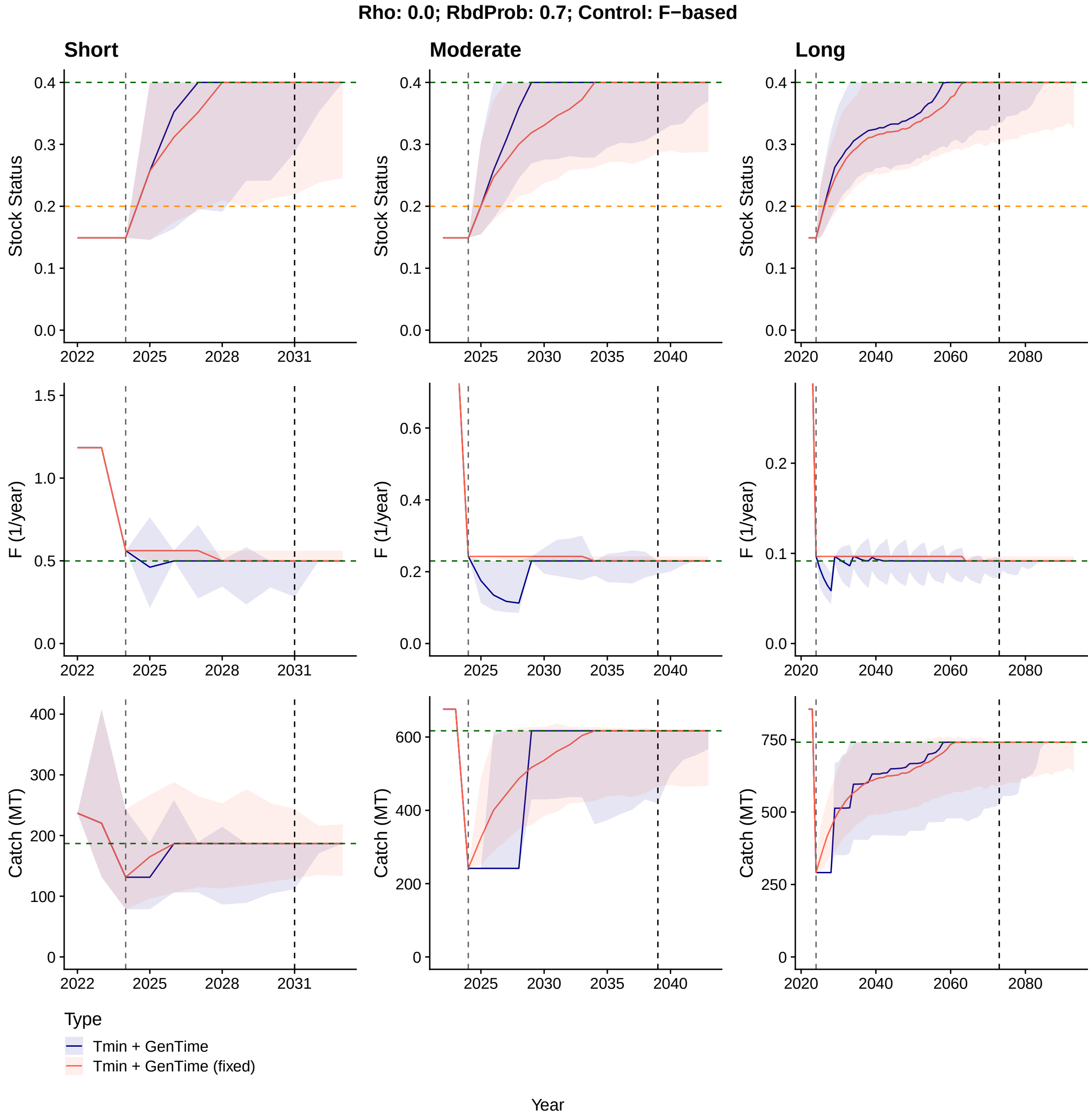

Figure B-6: Rebuilding timelines for management based on fishing mortality across rebuilding policies. Stock status (SSB/SSB_0; top row), fishing mortality (F; middle row) and catch (C; bottom row) across life histories (columns), for the base scenario without autocorrelation in recruitment (Rho = 0) and with a 70% rebuild probability to estimate T_{min}. Control-rule-based policies are shown in shades of red/orange and timeline-based policies are shown in shades of blue, with corresponding rebuilding targets shown by dashed vertical lines of the corresponding colour.

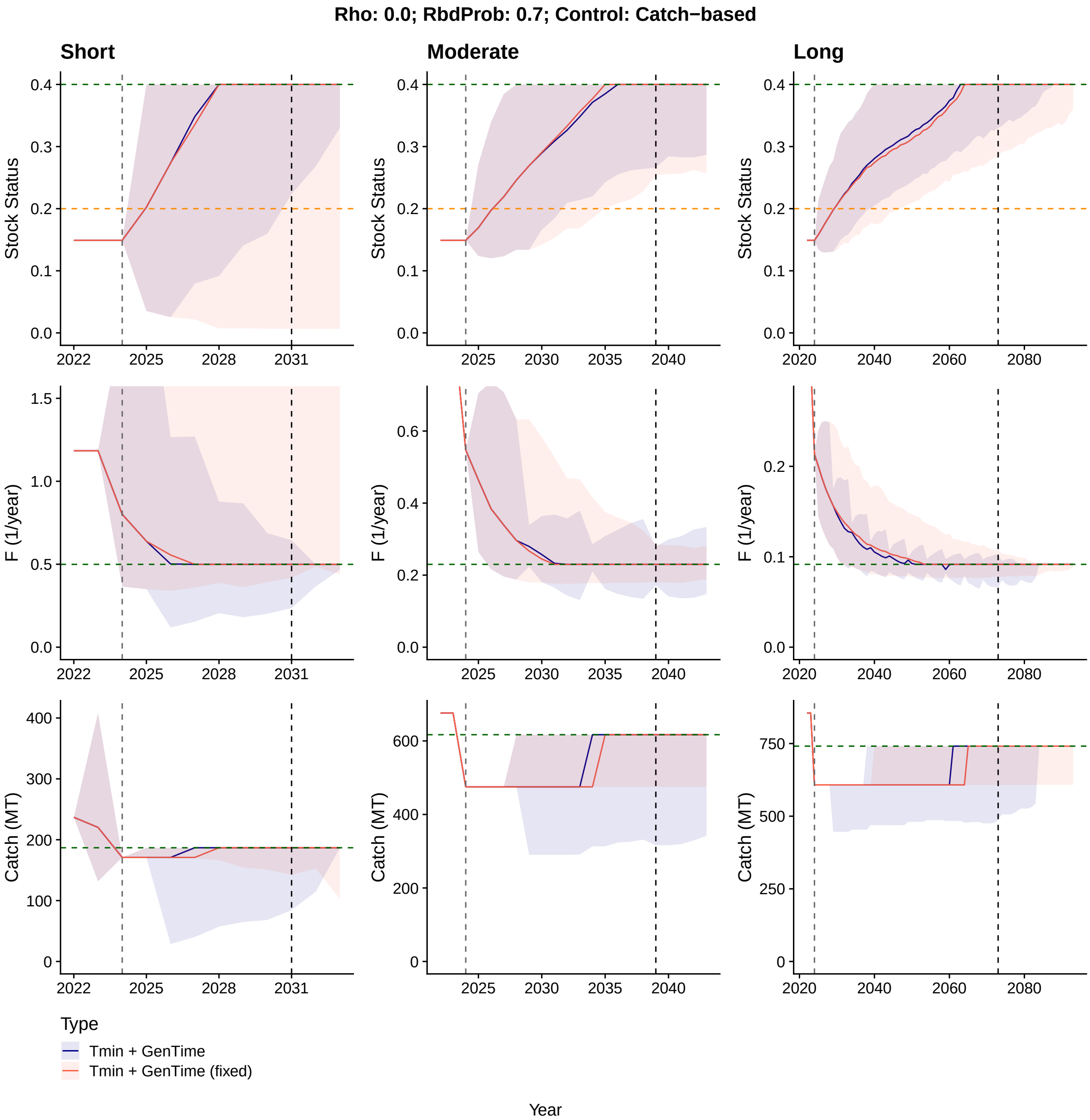

Figure B-7: Rebuilding timelines for catch-based management across rebuilding policies. Stock status (SSB/SSB_0; top row), fishing mortality (F; middle row) and catch (C; bottom row) across life histories (columns), for the base scenario without autocorrelation in recruitment (Rho = 0) and with a 70% rebuild probability to estimate T_{min}. Control-rule-based policies are shown in shades of red/orange and timeline-based policies are shown in shades of blue, with corresponding rebuilding targets shown by dashed vertical lines of the corresponding colour.

B.1 Catch stability

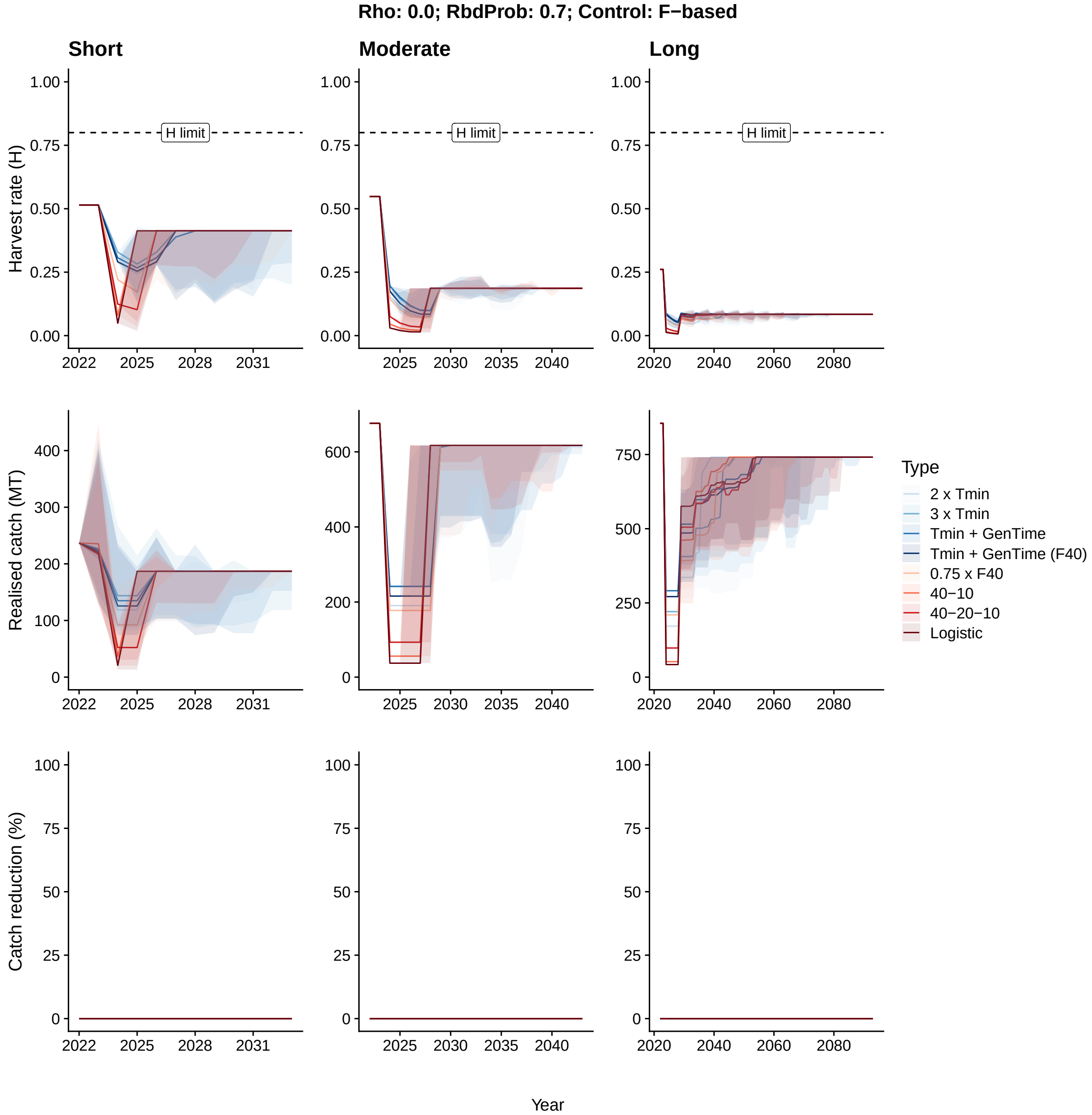

Figure B-8: Trends in harvest rate, realised catch, and catch reductions (i.e., proportion of catch not able to be taken in simulations when the exploitation-rate limit was reached) for management based on fishing mortality and alternative rebuilding policies using a 70% rebuild probability to estimate T_{min}. Control-rule-based policies are shown in shades of red/orange and timeline-based policies are shown in shades of blue.

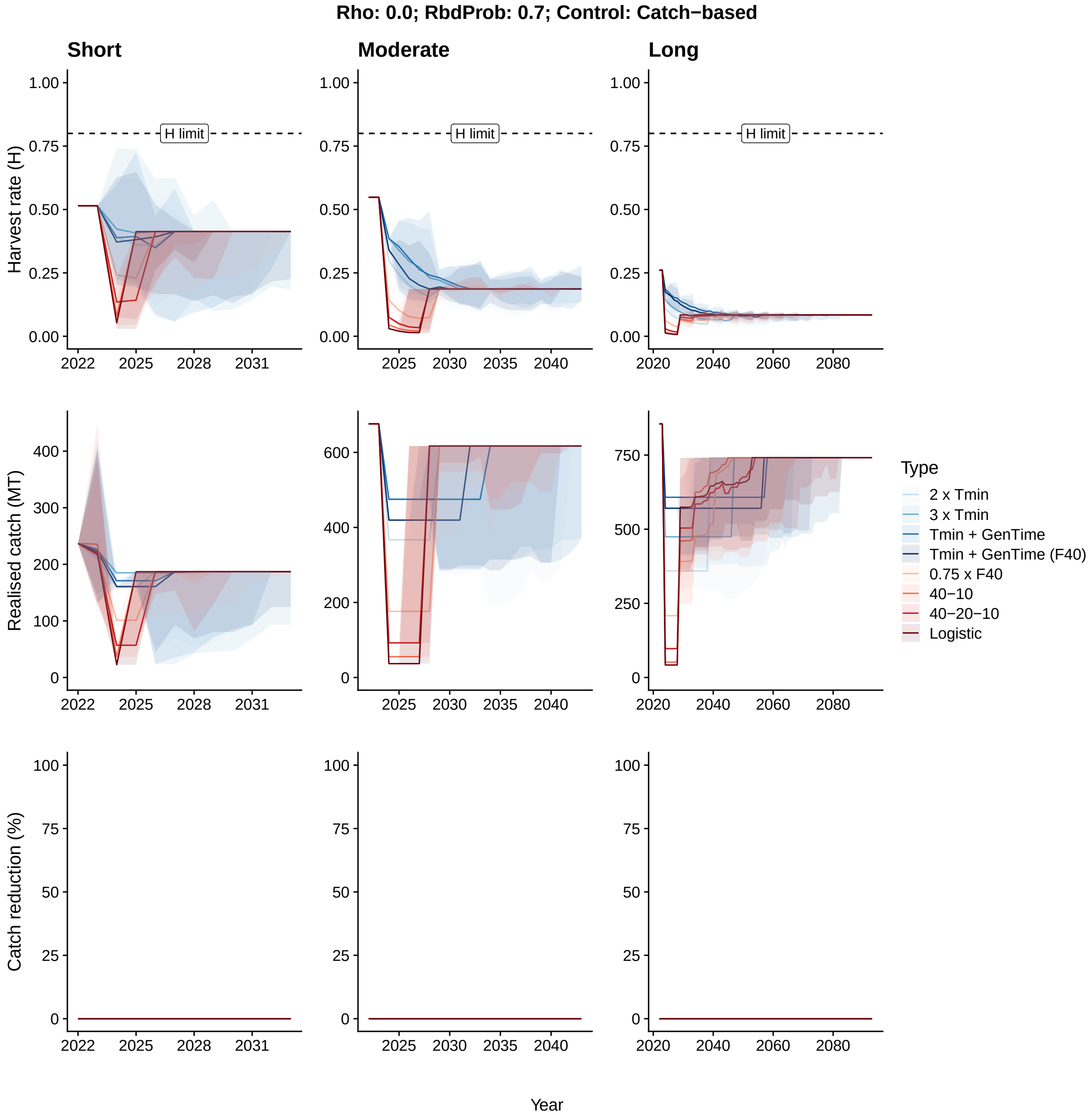

Figure B-9: Trends in harvest rate, realised catch, and catch reductions (i.e., proportion of catch not able to be taken in simulations when the exploitation-rate limit was reached) for catch-based management and alternative rebuilding policies using a 70% rebuild probability to estimate T_{min}. Control-rule-based policies are shown in shades of red/orange and timeline-based policies are shown in shades of blue.

B.2 Risk

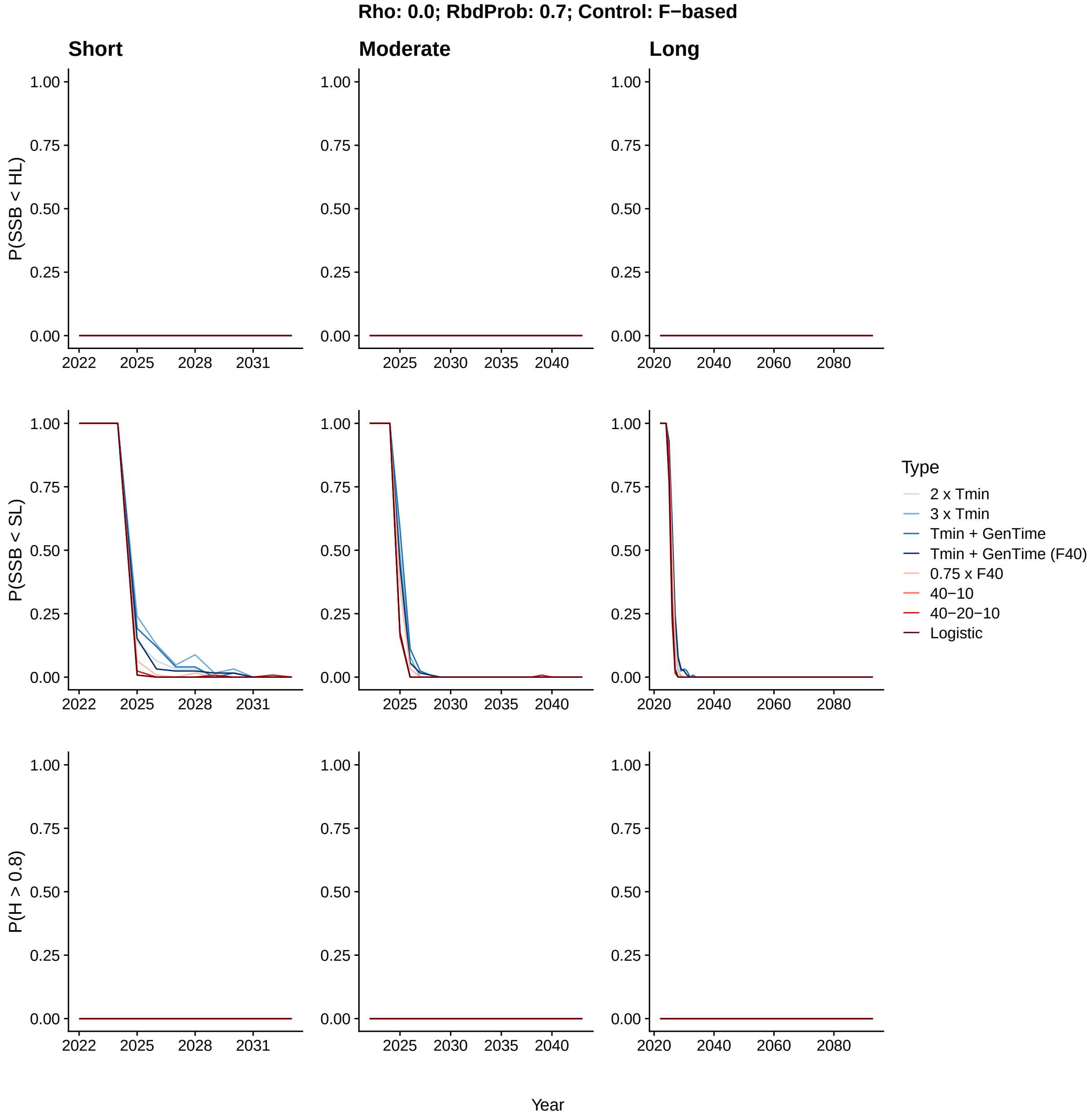

Figure B-10: Simulated risk for management based on fishing mortality of falling below the hard limit (10% SSB_0) (top row), soft limit (20% SSB_0) (middle row) and proportion of simulated trajectories that breached the limit of an 80% exploitation rate (bottom row), across simulated life histories (columns), for the base scenario without autocorrelation in recruitment (Rho = 0) and with a 70% rebuild probability to estimate T_{min}.

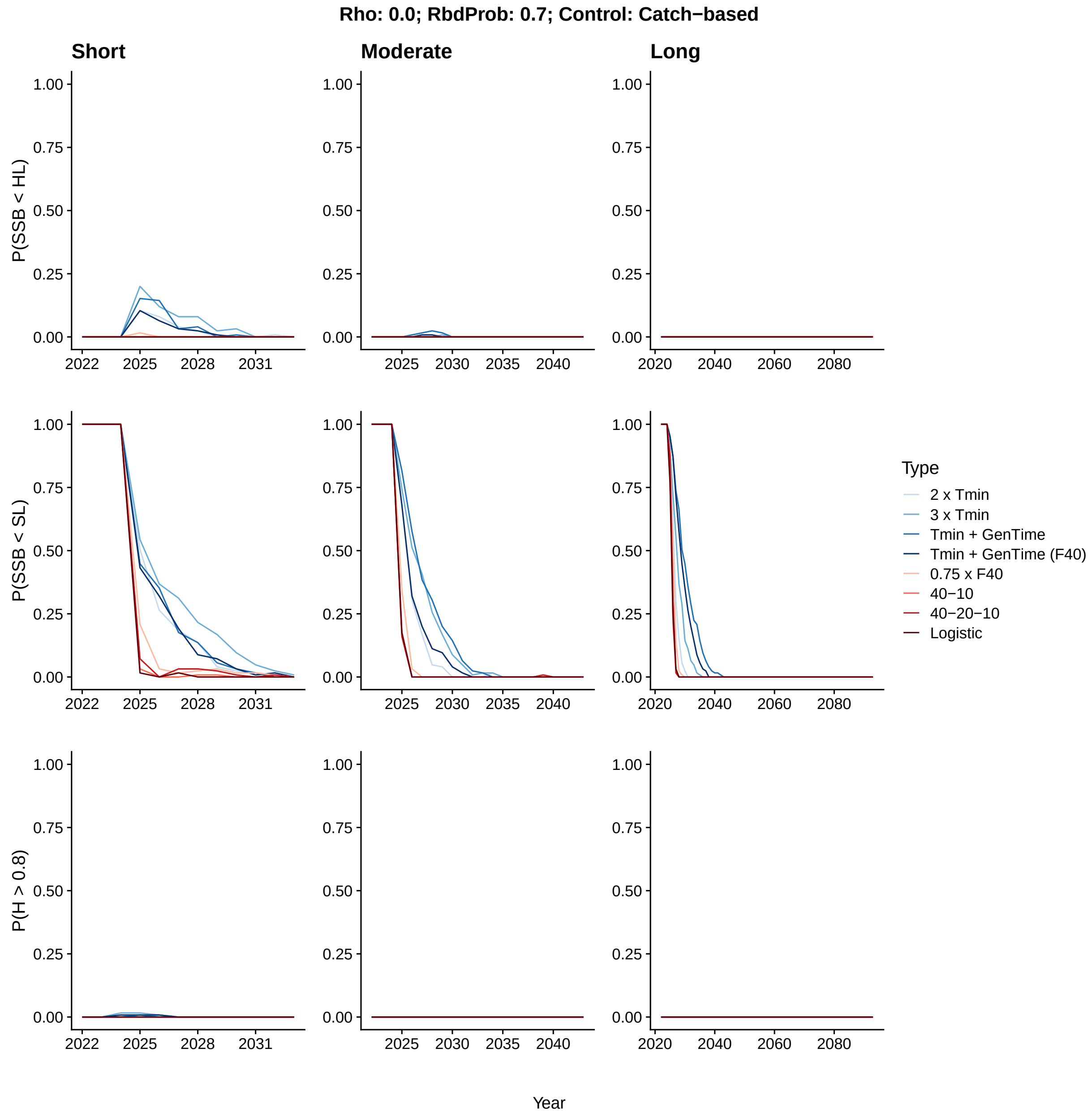

Figure B-11: Simulated risk for catch-based management of falling below the hard limit (10% SSB_0) (top row), soft limit (20% SSB_0) (middle row) and proportion of simulated trajectories that breached the limit of an 80% exploitation rate (bottom row), across simulated life histories (columns), for the base scenario without autocorrelation in recruitment (Rho = 0) and with a 70% rebuild probability to estimate T_{min}.

B.3 Economic performance

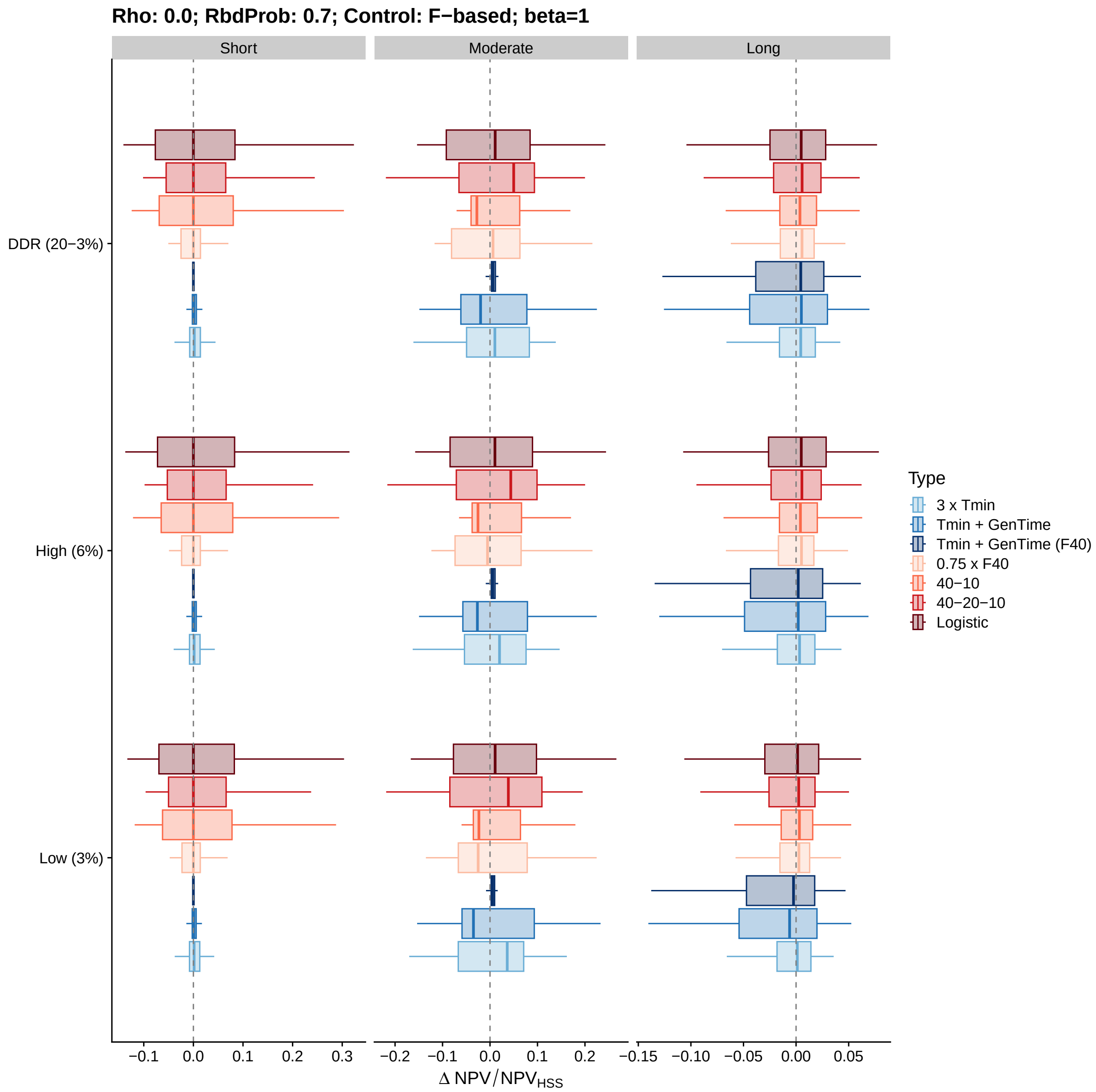

Figure B-12: Relative difference in net present value (NPV) from the current policy (Harvest Strategy Standard (HSS), $2\times T_{min}$) across life histories for management based on fishing mortality at base per-unit-effort cost (0.1) and no catch-per-unit-effort (CPUE) hyperstability, across alternative discount rates (rows; DDR: declining discount rate), using a 70% rebuild probability to estimate T_{min}. Control-rule-based policies are shown in shades of red/orange and timeline-based policies are shown in shades of blue.

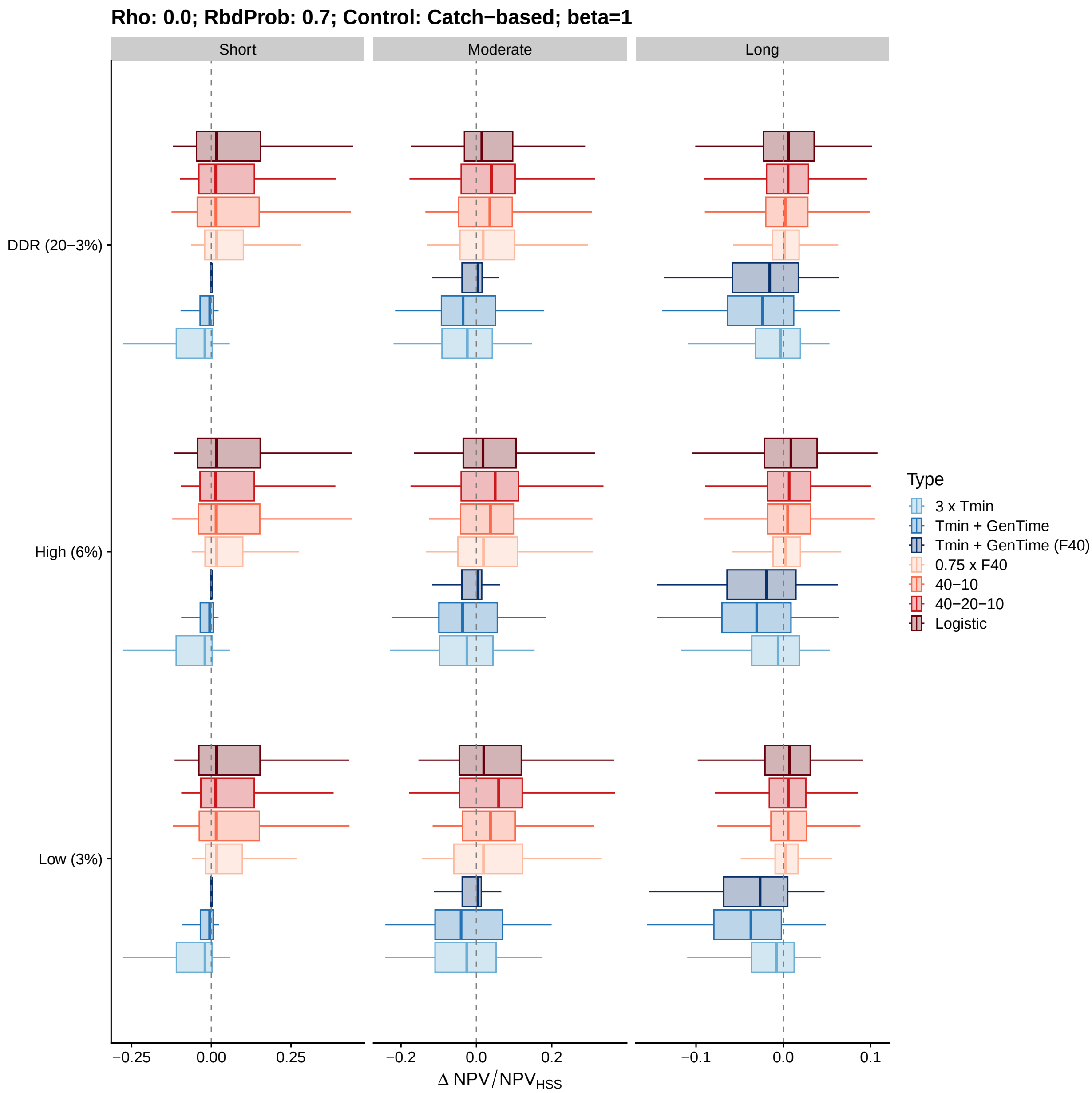

Figure B-13: Relative difference in net present value (NPV) from the current policy (Harvest Strategy Standard (HSS), $2\times T_{min}$) across life histories for catch-based management at base per-unit-effort cost (0.1) and no catch-per-unit-effort (CPUE) hyperstability, across alternative discount rates (rows; DDR: declining discount rate), using a 70% rebuild probability to estimate T_{min}. Control-rule-based policies are shown in shades of red/orange and timeline-based policies are shown in shades of blue.

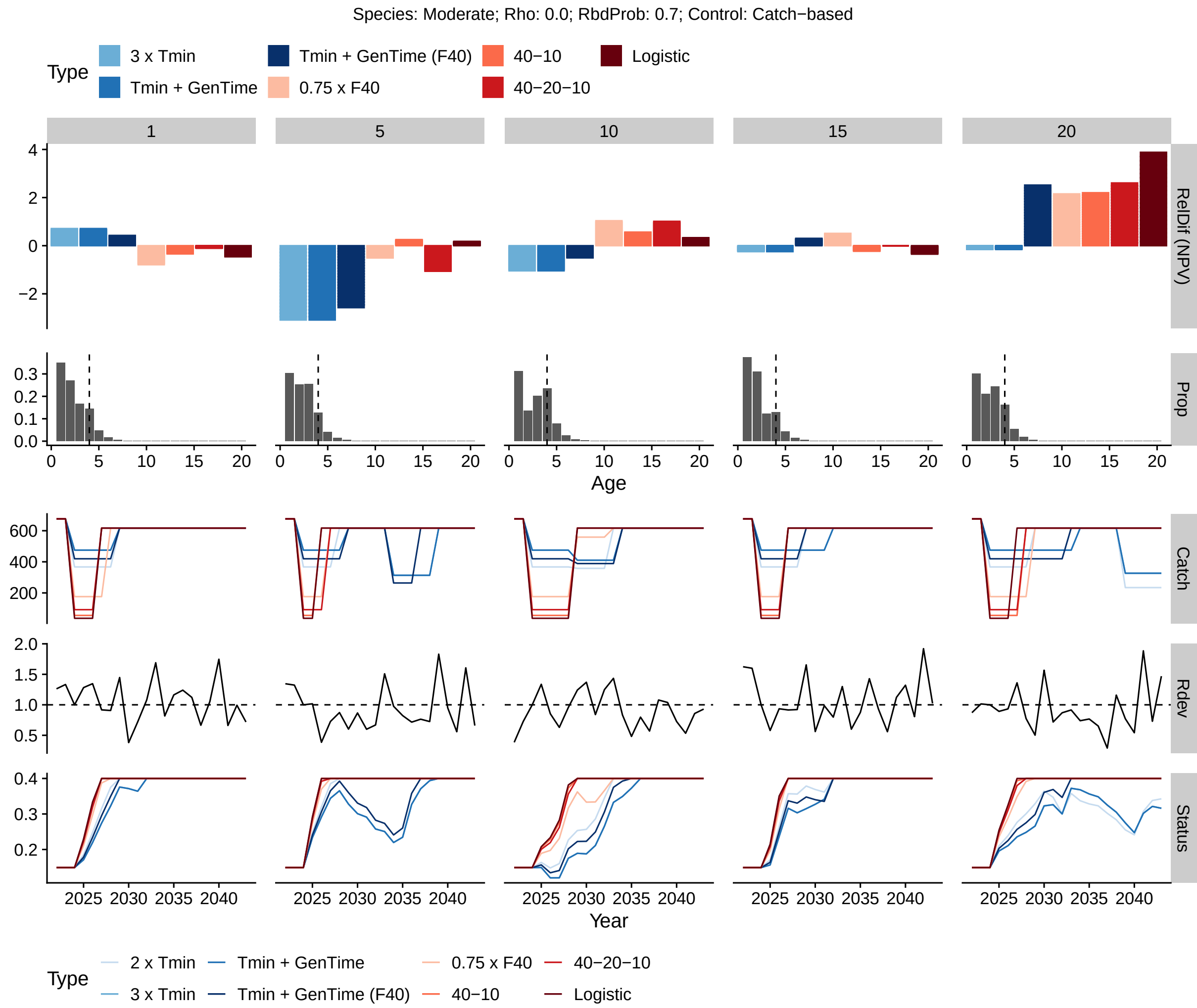

Figure B-14: Relative difference in net present value (NPV) from the current policy (2×T_{min}; top row), proportion of age distribution (second row), catch (third row), recruitment deviations (Rdev; fourth row) and stock status (bottom row), for randomly-drawn simulation trajectories (columns) for catch-based management at base per-unit-effort cost (0.1) and no catch-per-unit-effort (CPUE) hyperstability, across alternative discount rates (rows; DDR: declining discount rate), using a 70% rebuild probability to estimate T_{min}. Control-rule-based policies are shown in shades of red/orange and timeline-based policies are shown in shades of blue.

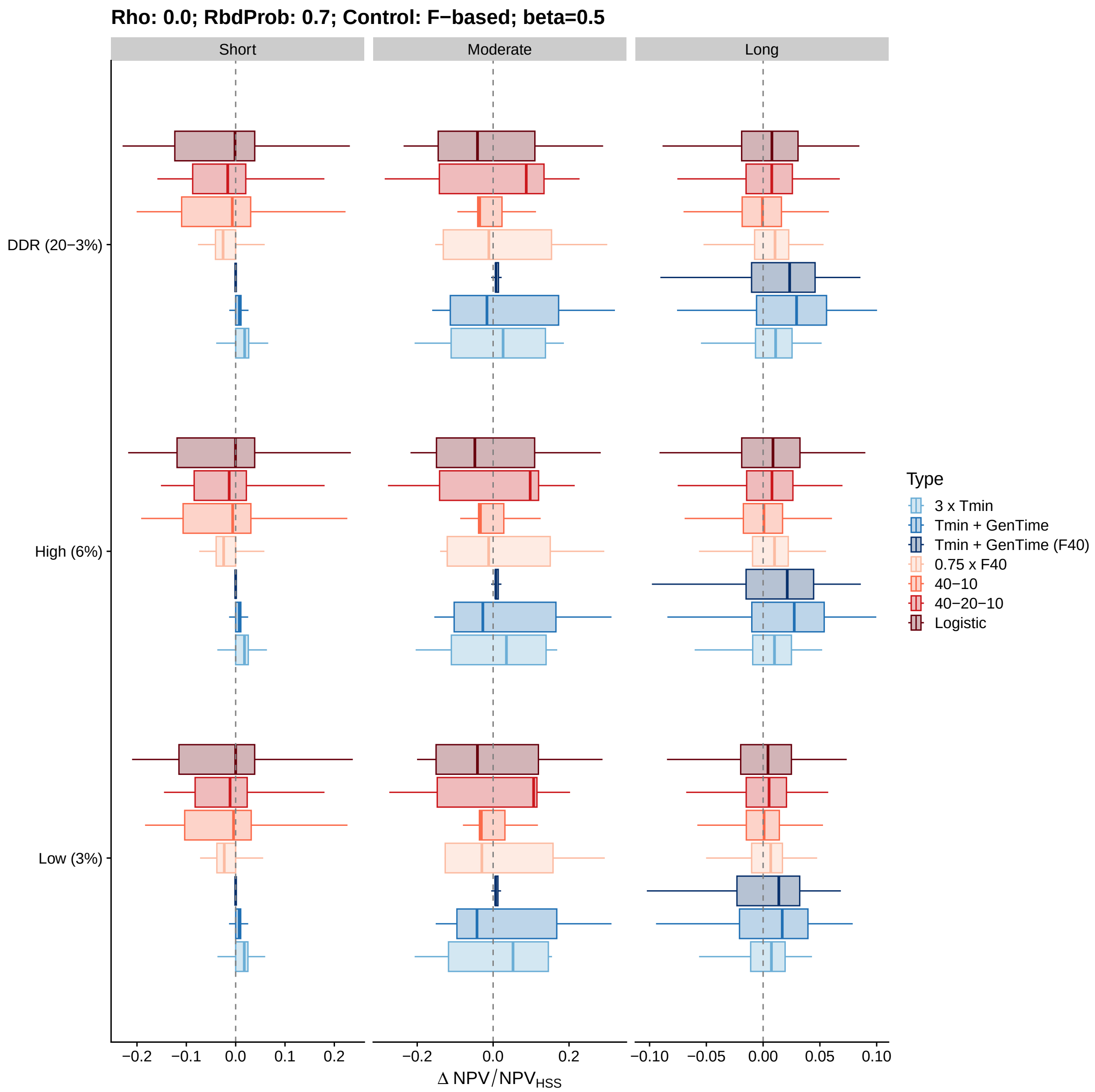

Figure B-15: Relative difference in net present value (NPV) from the current policy (Harvest Strategy Standard (HSS), $2 \times T_{min}$) across life histories for management based on fishing mortality at base per-unit-effort cost (0.1) and hyperstable catch-per-unit-effort (CPUE), across alternative discount rates (rows; DDR: declining discount rate), using a 70% rebuild probability to estimate T_{min}. Control-rule-based policies are shown in shades of red/orange and timeline-based policies are shown in shades of blue.

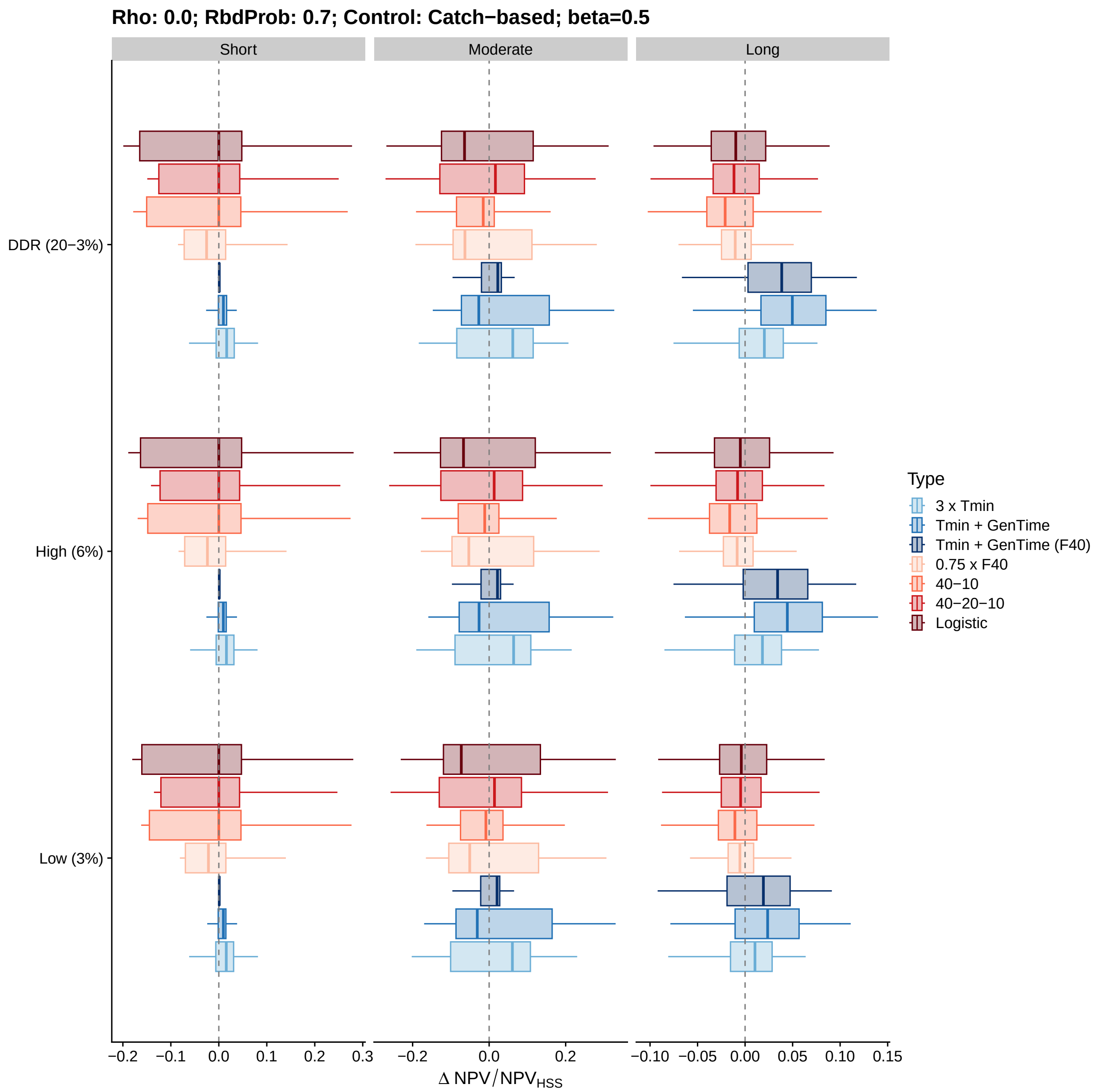

Figure B-16: Relative difference in net present value (NPV) from the current policy (Harvest Strategy Standard (HSS), $2\times T_{min}$) across life histories for catch-based management at base per-unit-effort cost (0.1) and hyperstable catch-per-unit-effort (CPUE), across alternative discount rates (rows; DDR: declining discount rate), using a 70% rebuild probability to estimate T_{min}. Control-rule-based policies are shown in shades of red/orange and timeline-based policies are shown in shades of blue.

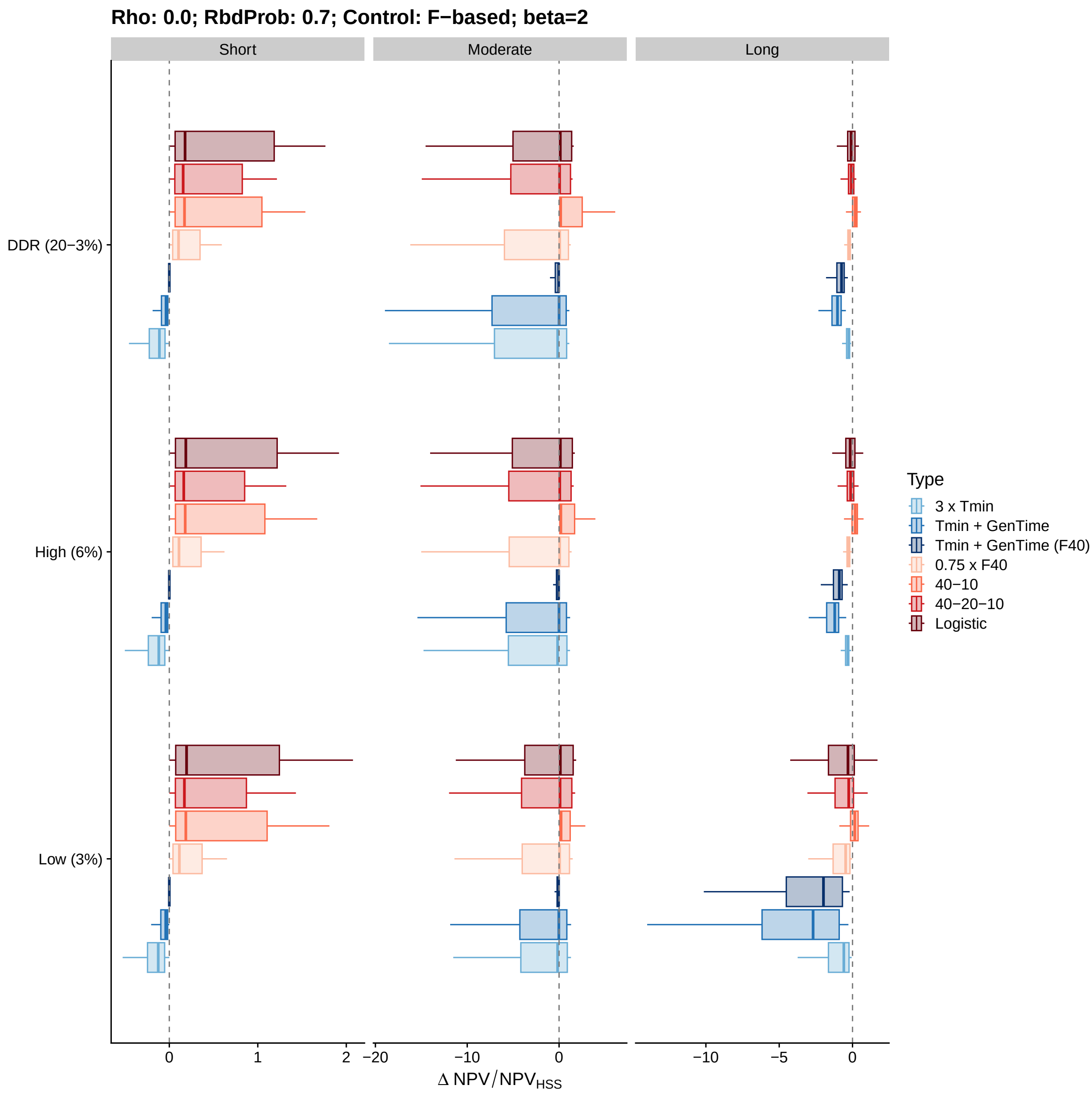

Figure B-17: Relative difference in net present value (NPV) from the current policy (Harvest Strategy Standard (HSS), $2 \times T_{min}$) across life histories for management based on fishing mortality at base per-unit-effort cost (0.1) and hyper-depleted catch-per-unit-effort (CPUE), across alternative discount rates (rows; DDR: declining discount rate), using a 70% rebuild probability to estimate T_{min}. Control-rule-based policies are shown in shades of red/orange and timeline-based policies are shown in shades of blue.

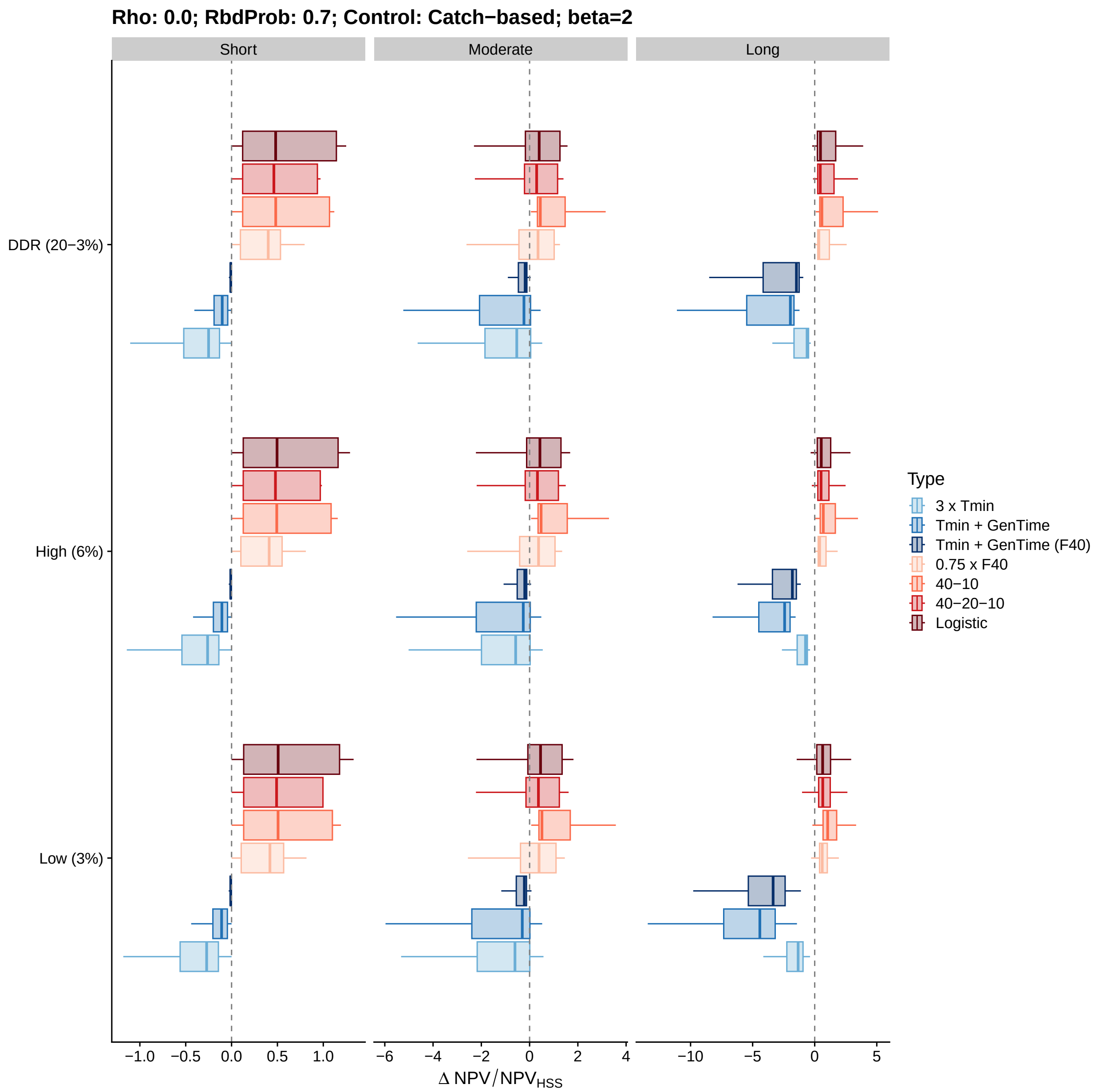

Figure B-18: Relative difference in net present value (NPV) from the current policy (Harvest Strategy Standard (HSS), $2 \times T_{min}$) across life histories for catch-based management at base per-unit-effort cost (0.1) and hyper-depleted catch-per-unit-effort (CPUE), across alternative discount rates (rows; DDR: declining discount rate), using a 70% rebuild probability to estimate T_{min}. Control-rule-based policies are shown in shades of red/orange and timeline-based policies are shown in shades of blue.

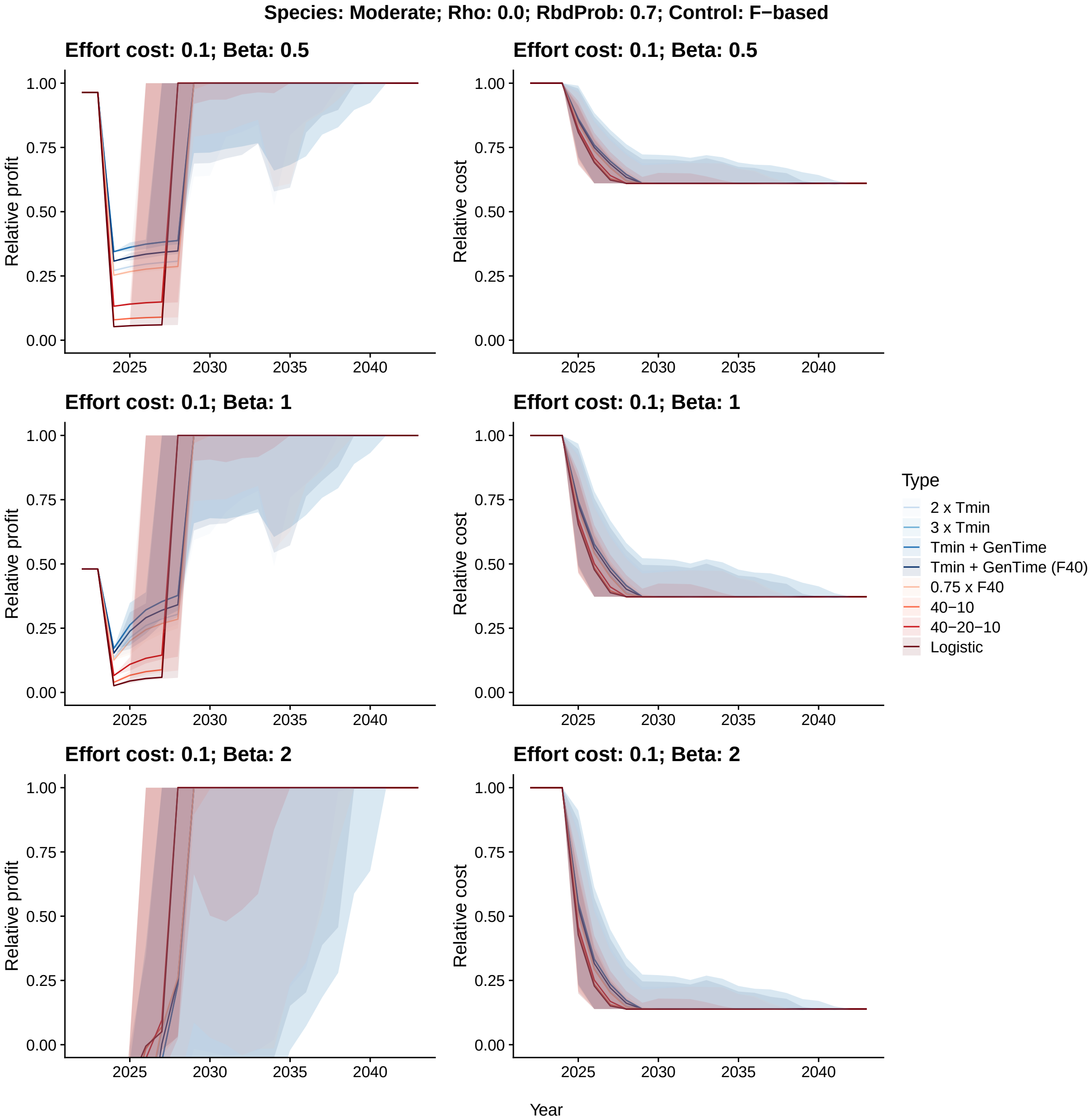

Figure B-19: Relative profit and cost for management based on fishing mortality at base per-unit-effort cost (0.1) and across assumptions of catch-per-unit-effort (CPUE) hyperstability (Beta), illustrated for the moderate life history using a 70% rebuild probability to estimate T_{min}. Control-rule-based policies are shown in shades of red/orange and timeline-based policies are shown in shades of blue.

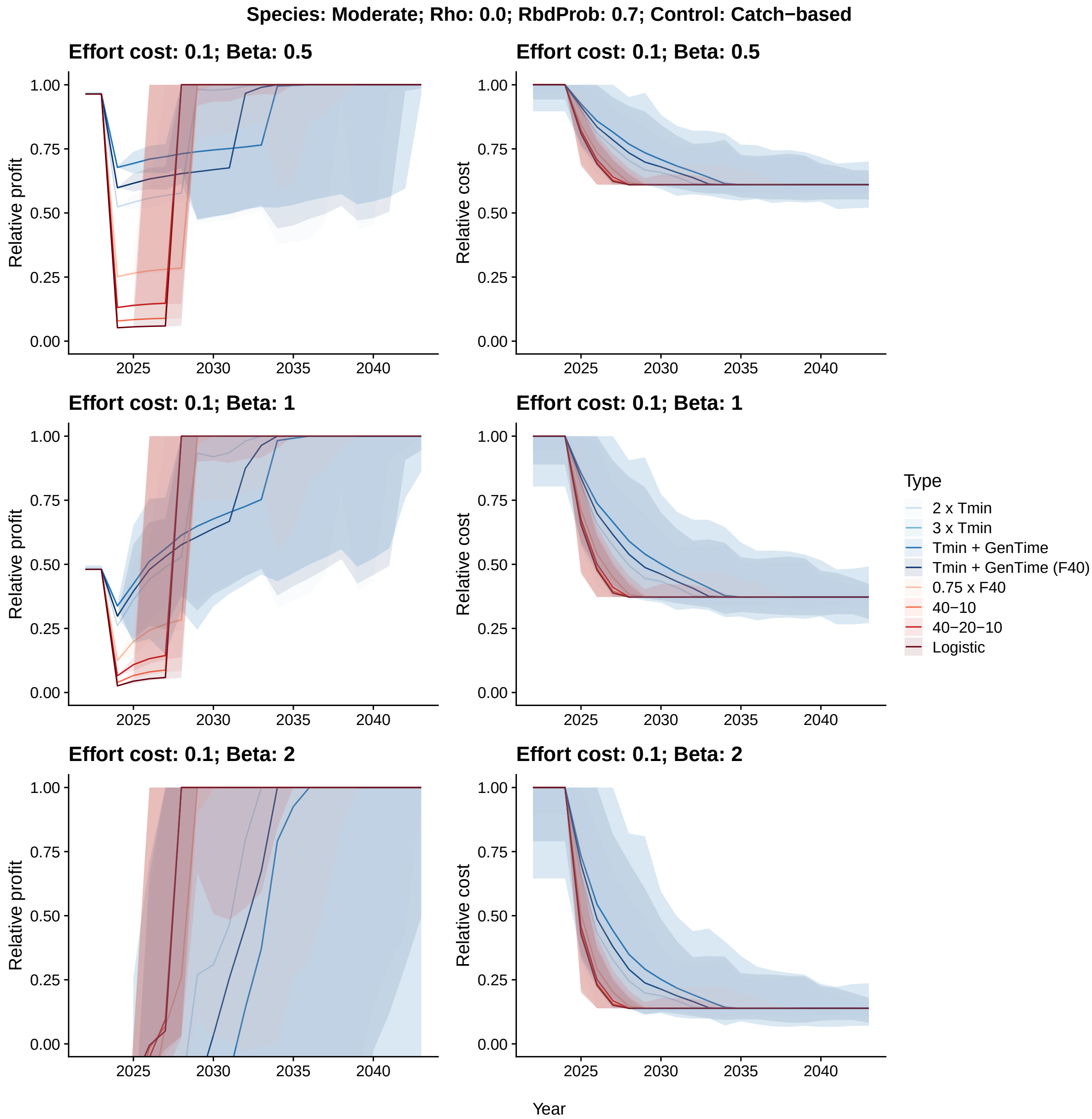

Figure B-20: Relative profit and cost for catch-based management at base per-unit-effort cost (0.1) and across assumptions of catch-per-unit-effort (CPUE) hyperstability (Beta), illustrated for the moderate life history using a 70% rebuild probability to estimate T_{min}. Control-rule-based policies are shown in shades of red/orange and timeline-based policies are shown in shades of blue.

APPENDIX C: SIMULATIONS WITH AUTOCORRELATED RECRUITMENT

The following plots follow the same order as those in the main text, using a 50% rebuild probability to allow for comparisons.

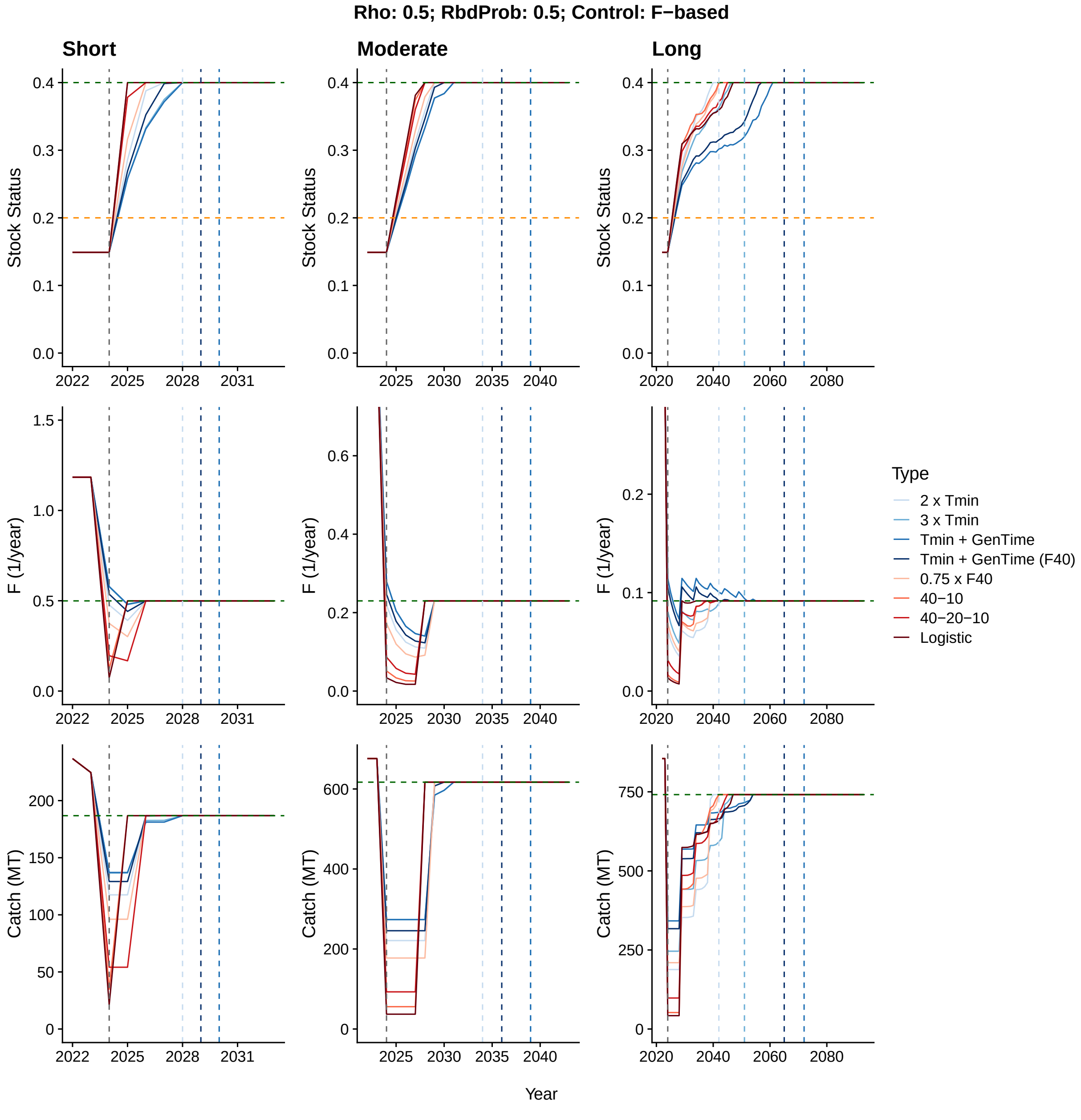

Figure C-1: Rebuilding timelines for management based on fishing mortality across rebuilding policies. Stock status (SSB/SSB_0; top row), fishing mortality (F; middle row) and catch (C; bottom row) across life histories (columns), for the scenario with autocorrelation in recruitment (Rho = 0.5) and with a 50% rebuild probability to estimate T_{min}. Control-rule-based policies are shown in shades of red/orange and timeline-based policies are shown in shades of blue, with corresponding rebuilding targets shown by dashed vertical lines of the corresponding colour.

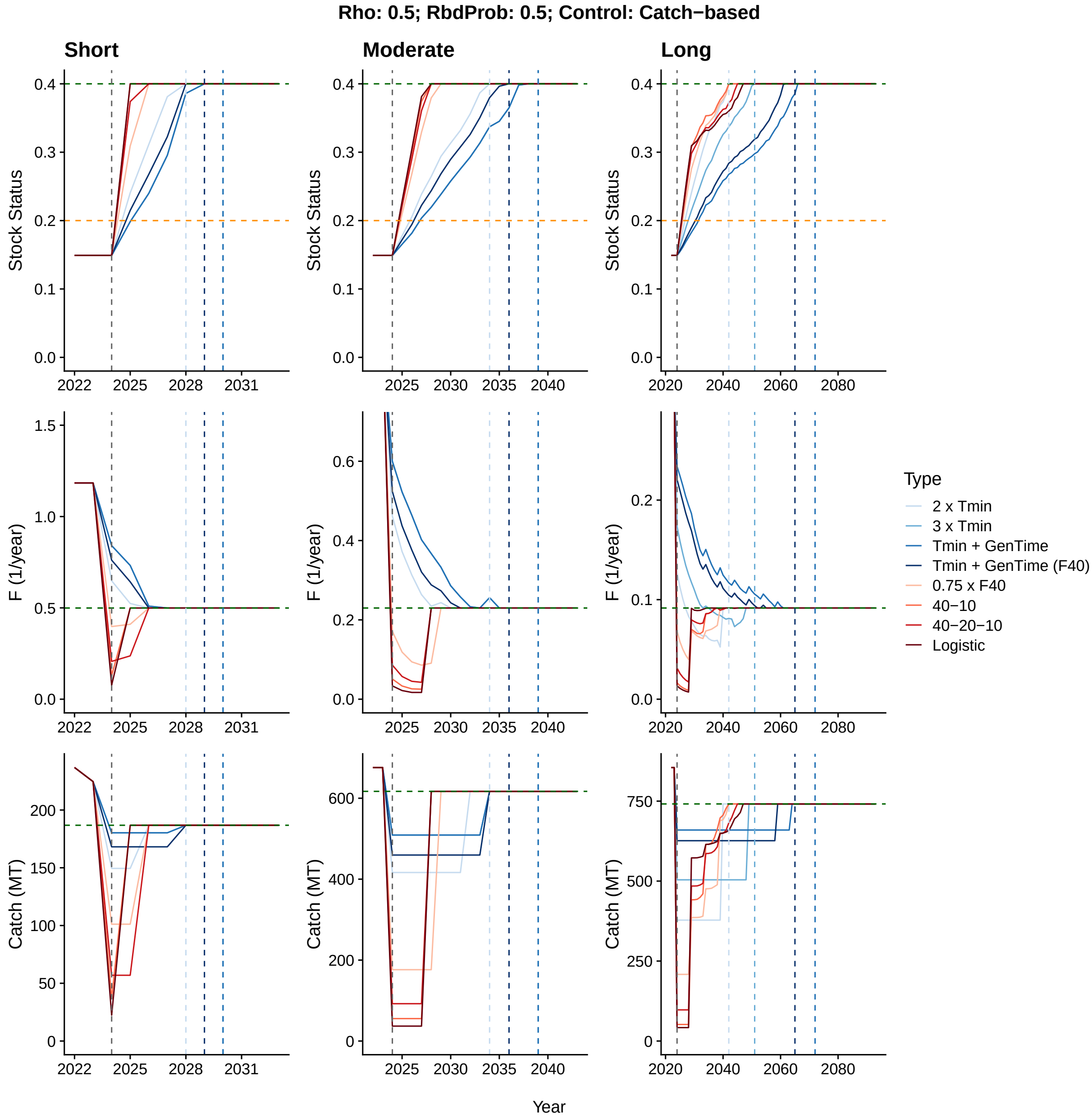

Figure C-2: Rebuilding timelines for catch-based management across rebuilding policies. Stock status (SSB/SSB_0; top row), fishing mortality (F; middle row) and catch (C; bottom row) across life histories (columns), for the scenario with autocorrelation in recruitment (Rho = 0.5) and with a 50% rebuild probability to estimate T_{min}. Control-rule-based policies are shown in shades of red/orange and timeline-based policies are shown in shades of blue, with corresponding rebuilding targets shown by dashed vertical lines of the corresponding colour.

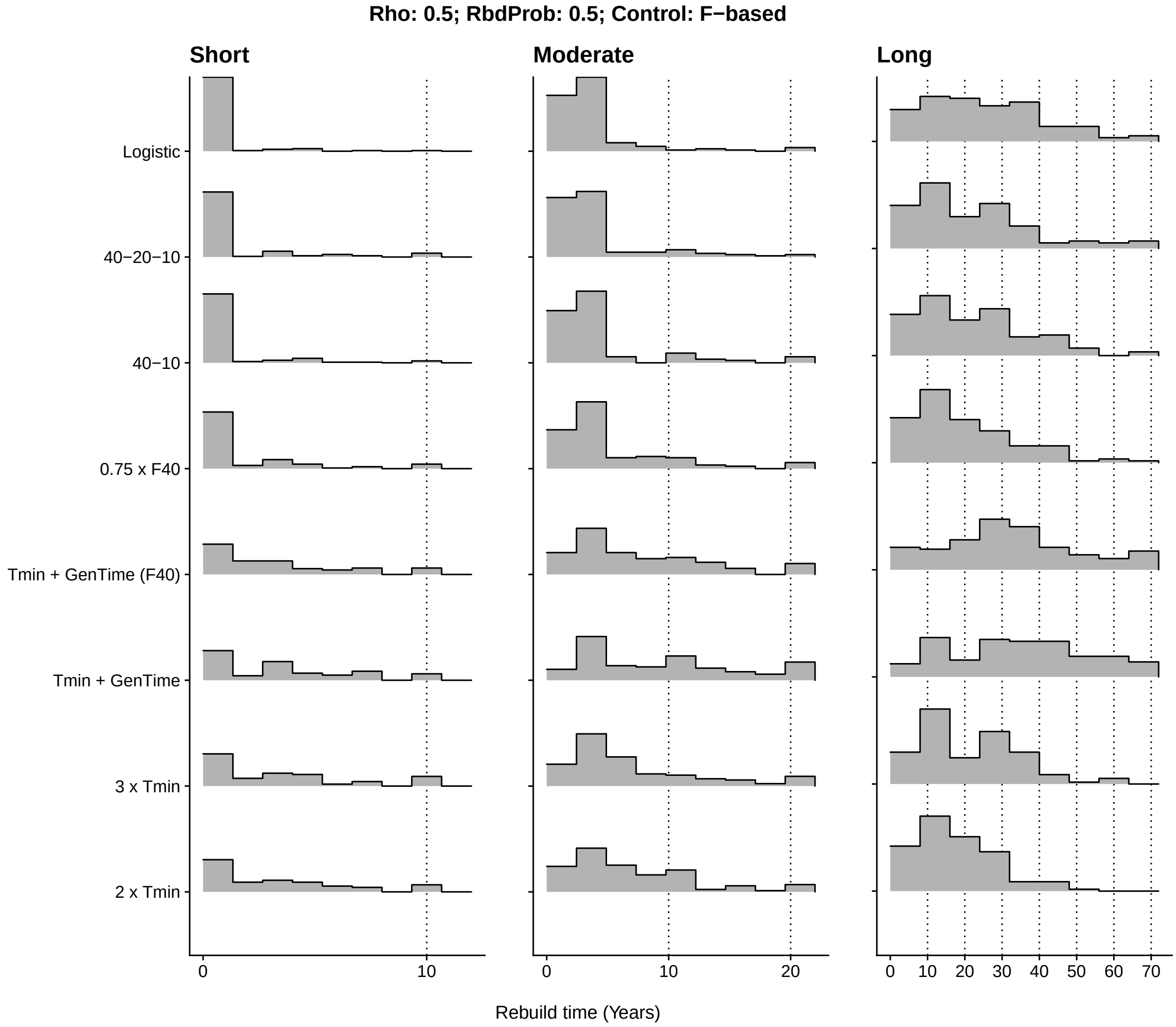

Figure C-3: Rebuilding time distribution (in years) for management based on fishing mortality (F) across rebuilding policies.

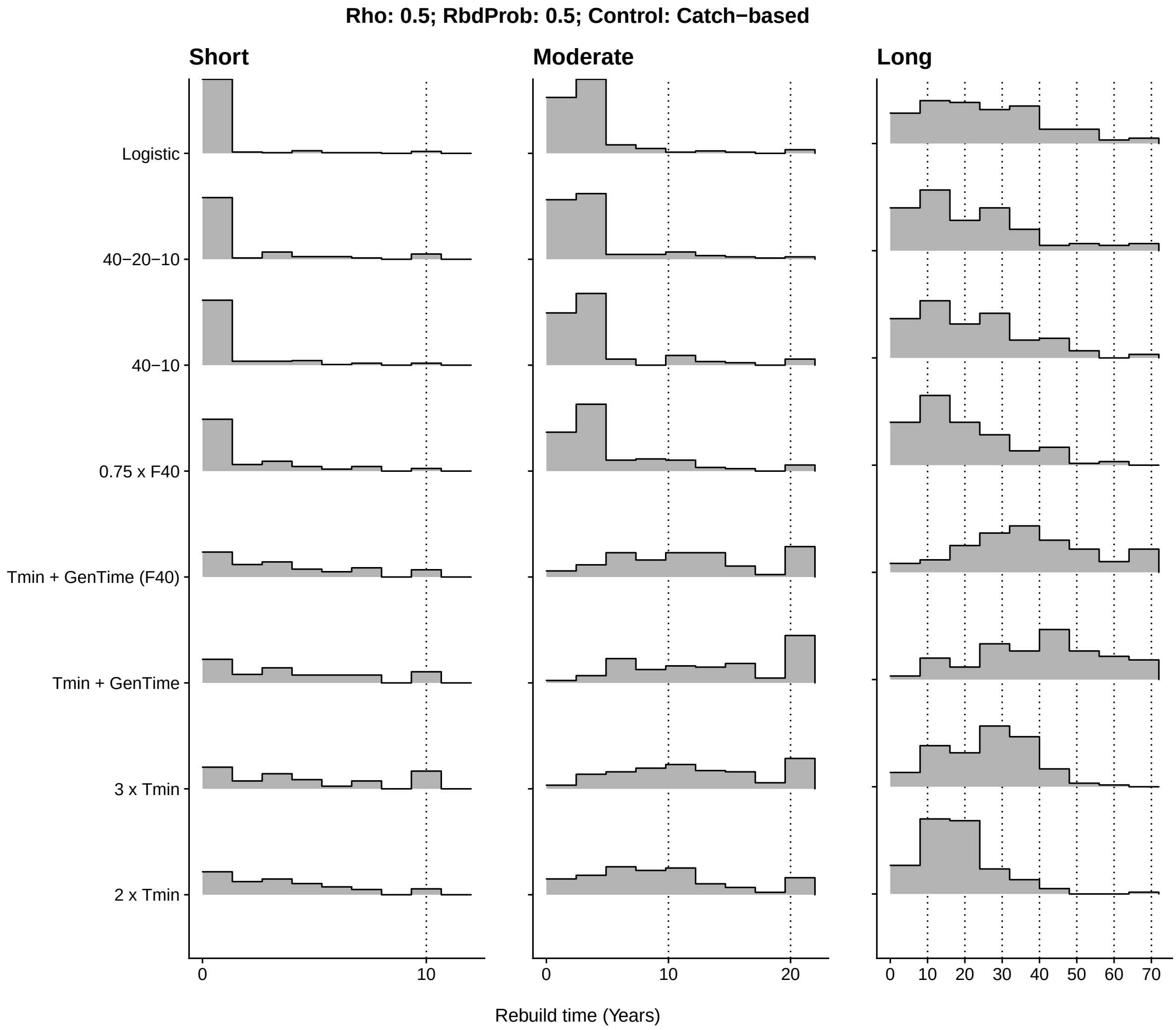

Figure C-4: Rebuilding time distribution (in years) for catch-based management across rebuilding policies.

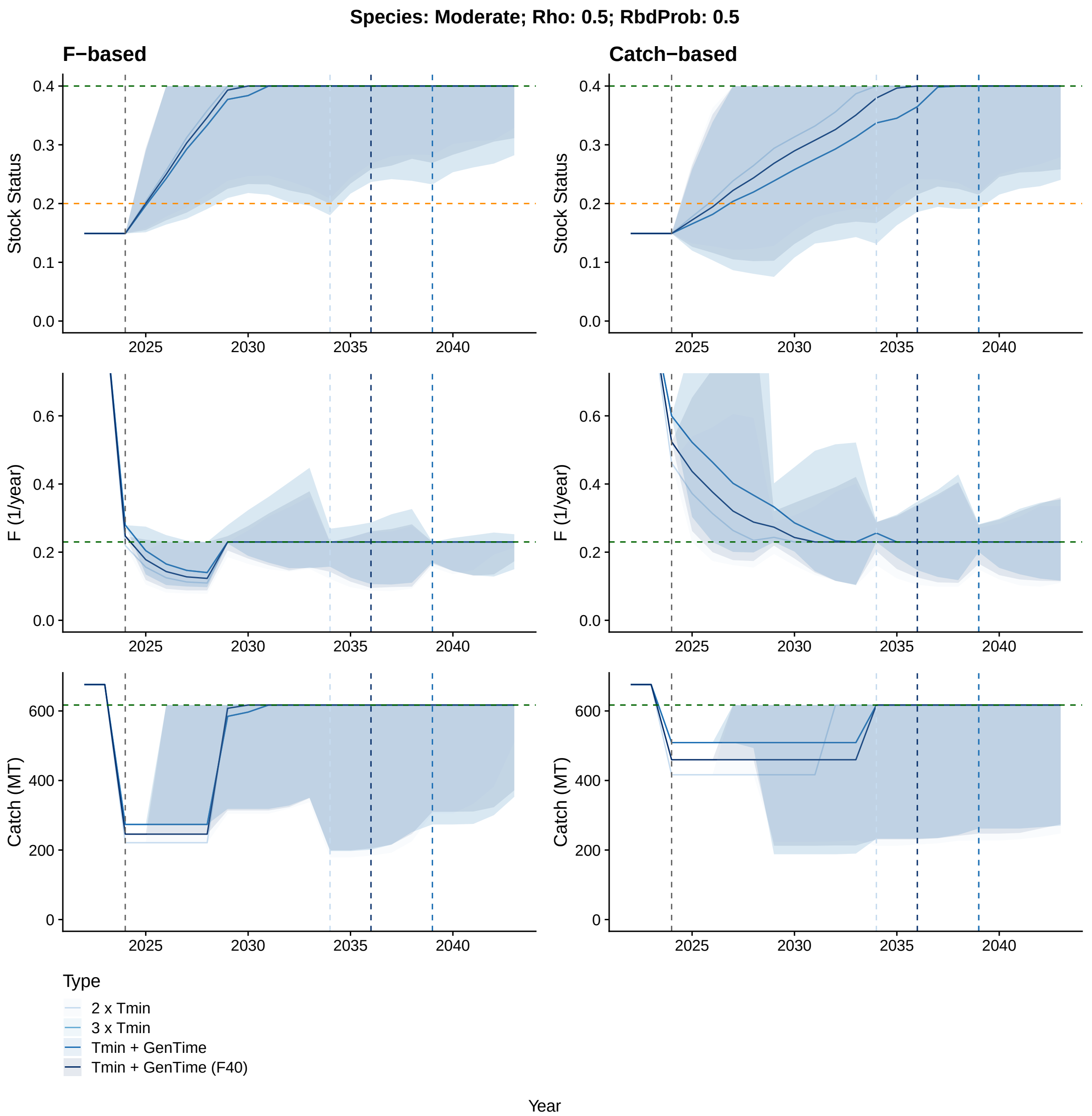

Figure C-5: Difference between management based on fishing mortality (F) and on catch (C) illustrated for the moderate life history, comparing timeline-based rebuilding policies, with corresponding rebuilding targets shown by dashed vertical lines of the corresponding shading.

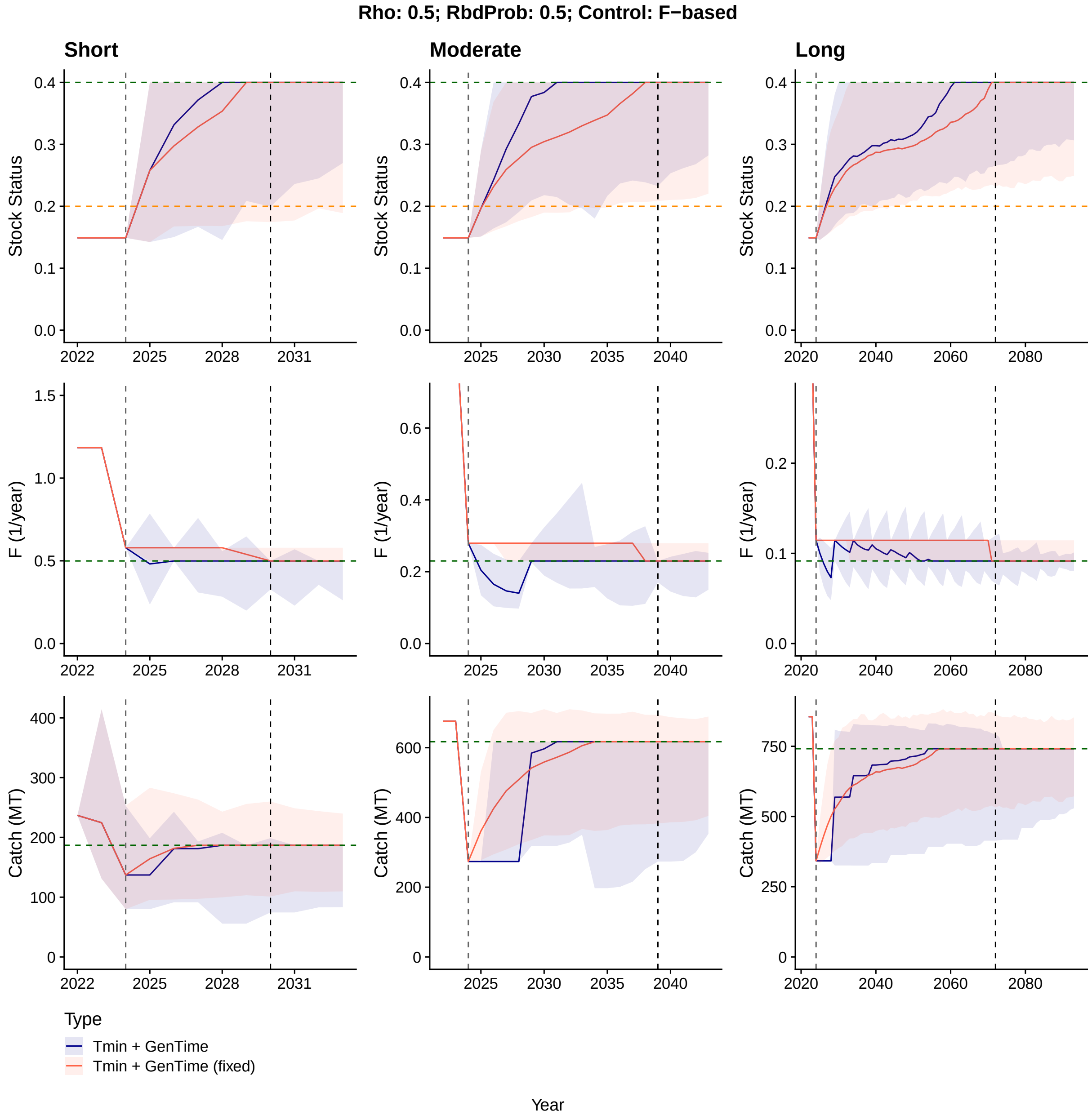

Figure C-6: Rebuilding timelines (median of simulated stock trajectories) for management based on fishing mortality across rebuilding policies. Stock status (SSB/SSB_0; top row), fishing mortality (F; middle row) and catch (C; bottom row) across life histories (columns), for the scenario with autocorrelation in recruitment (Rho = 0.5) and with a 50% rebuild probability to estimate T_{min}. Control-rule-based policies are shown in shades of red/orange and timeline-based policies are shown in shades of blue, with corresponding rebuilding targets shown by dashed vertical lines of the corresponding colour.

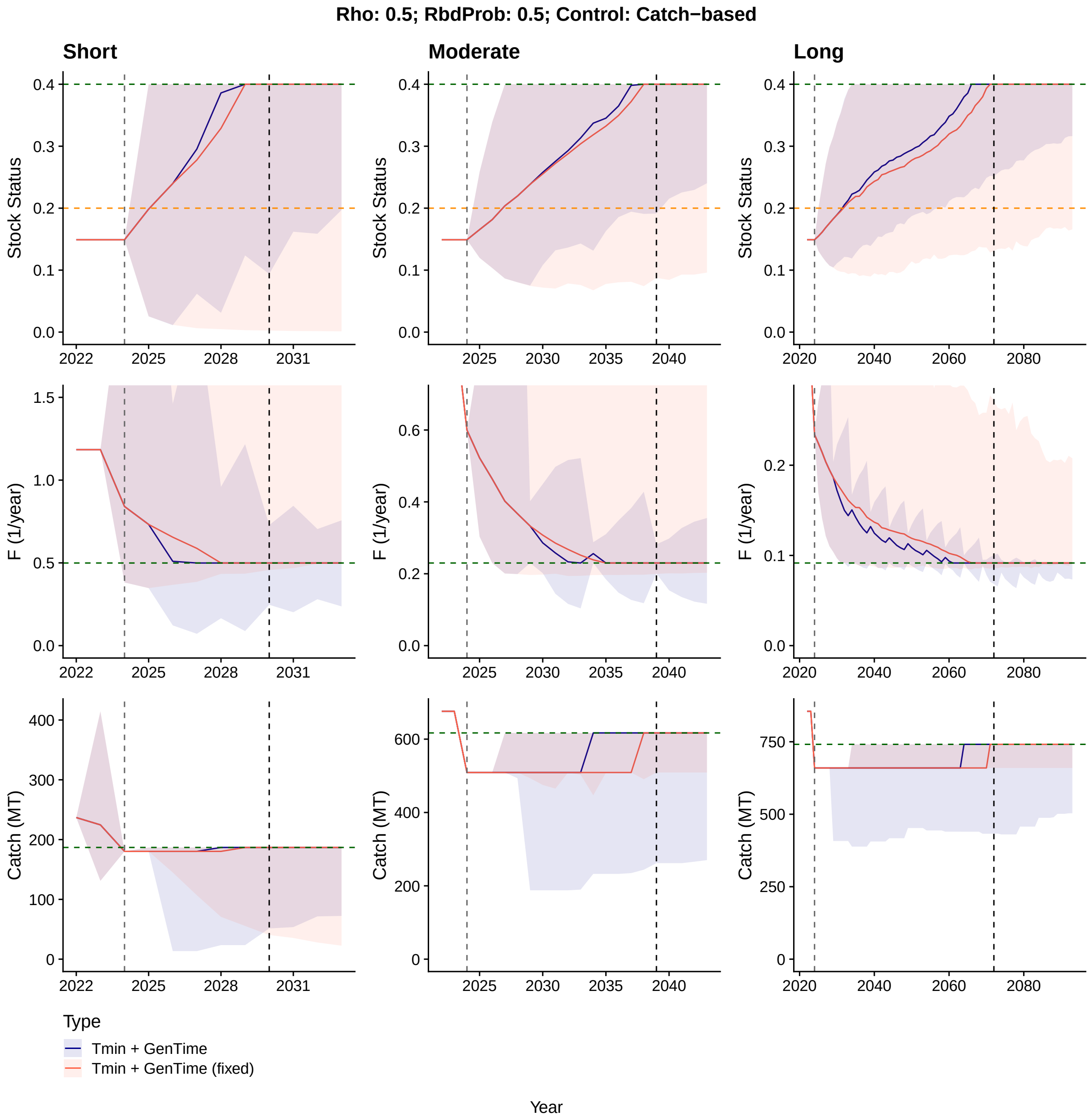

Figure C-7: Rebuilding timelines (median of simulated stock trajectories) for catch-based management across fixed (pure) rebuilding policies. Stock status (SSB/SSB_0; top row), fishing mortality (F; middle row) and catch (C; bottom row) across life histories (columns), for the scenario with autocorrelation in recruitment (Rho = 0.5) and with a 50% rebuild probability to estimate T_{min}. Control-rule-based policies are shown in shades of red/orange and timeline-based policies are shown in shades of blue, with corresponding rebuilding targets shown by dashed vertical lines of the corresponding colour.

C.1 Catch stability

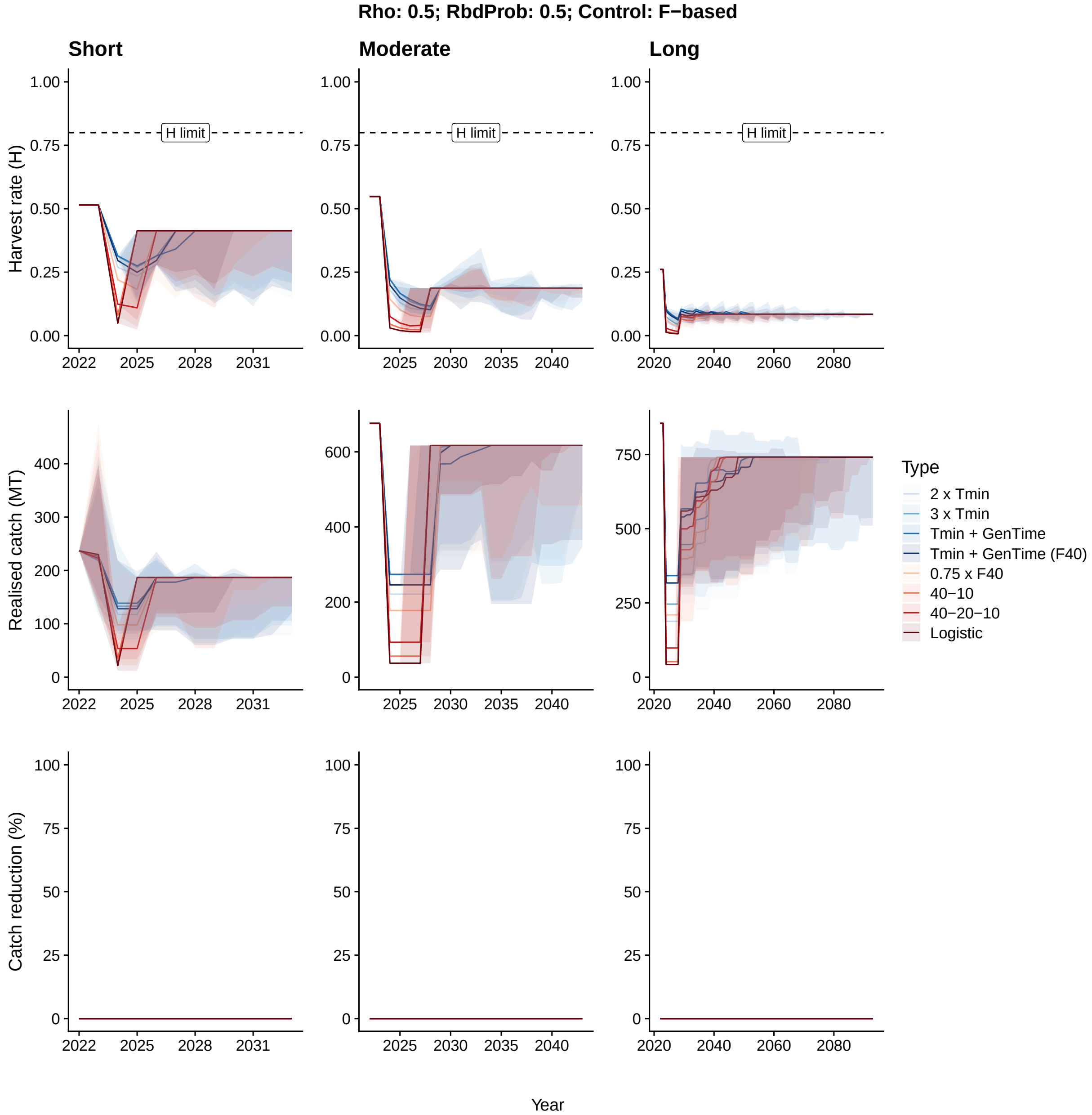

Figure C-8: Trends in harvest rate, realised catch, and catch reductions (i.e., proportion of catch not able to be taken in simulations when the exploitation-rate limit was reached) for management based on fishing mortality and alternative rebuilding policies. Control-rule-based policies are shown in shades of red/orange and timeline-based policies are shown in shades of blue.

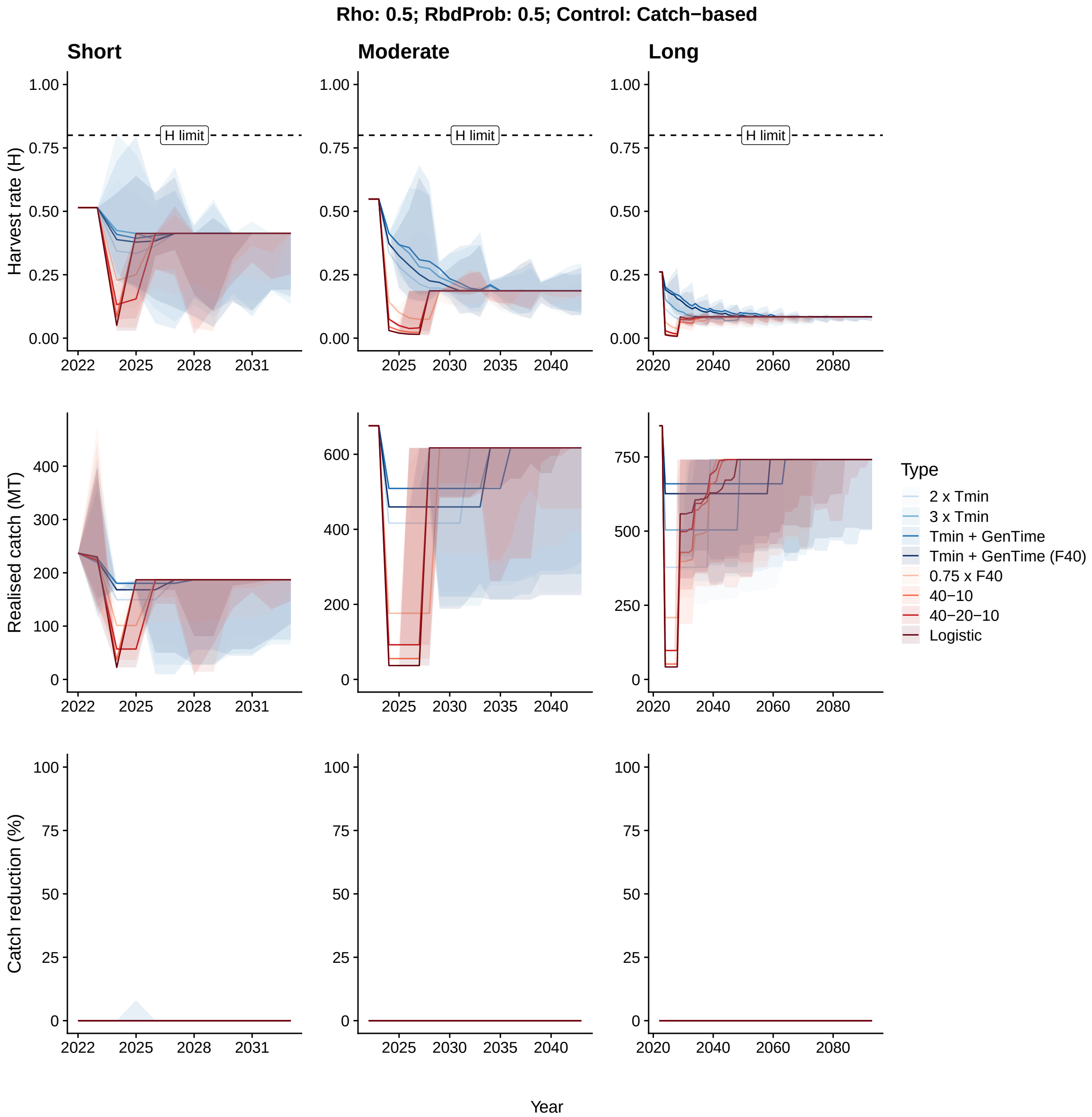

Figure C-9: Trends in harvest rate, realised catch, and catch reductions (i.e., proportion of catch not able to be taken in simulations when the exploitation-rate limit was reached) for catch-based management and alternative rebuilding policies. Control-rule-based policies are shown in shades of red/orange and timeline-based policies are shown in shades of blue.

C.2 Risk

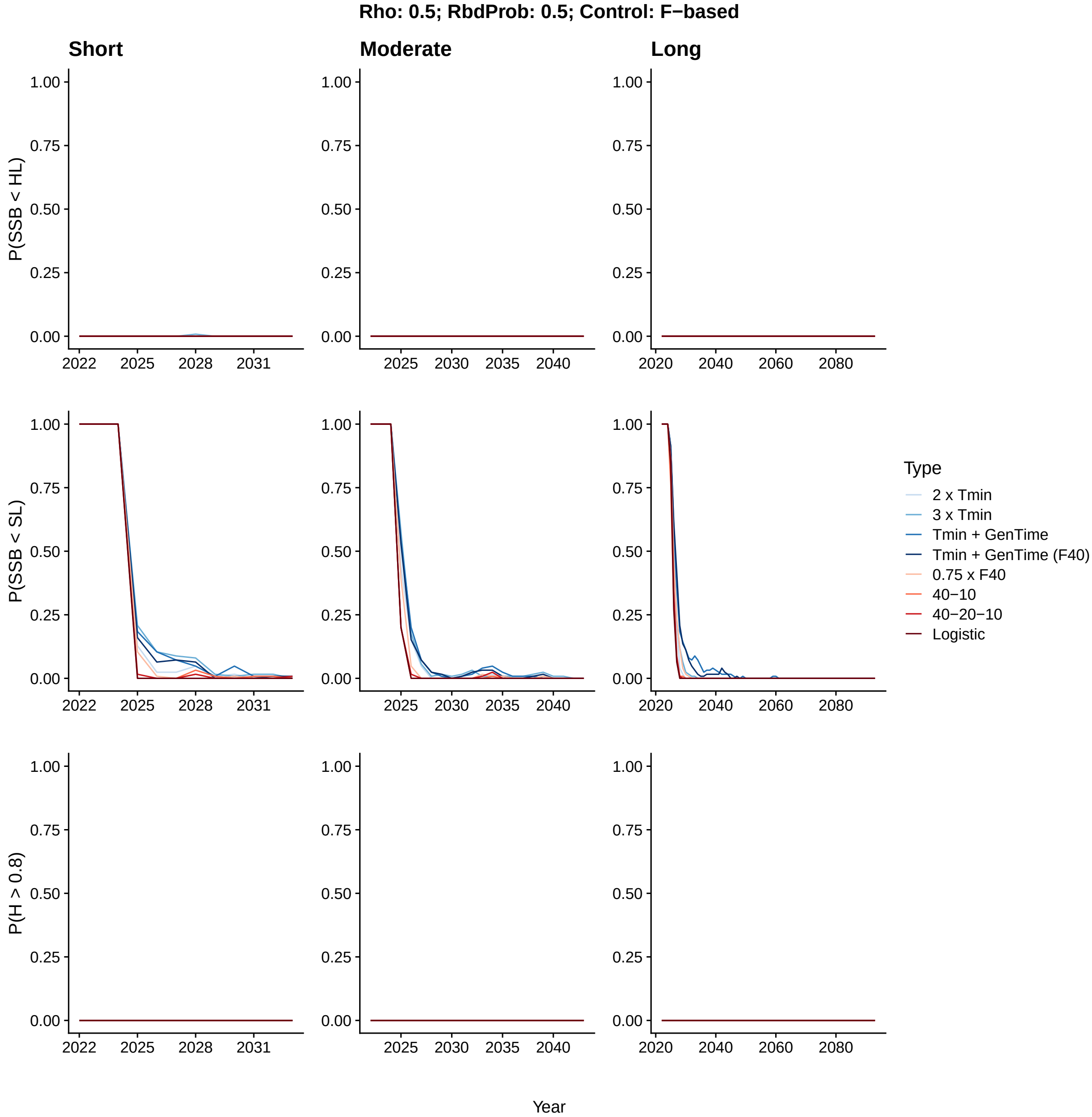

Figure C-10: Simulated risk for fishing mortality based management of falling below the hard limit (10% SSB_0) (top row), soft limit (20% SSB_0) (middle row) and proportion of simulated trajectories that breached the limit of an 80% exploitation rate, across simulated life histories (columns), for the scenario with autocorrelation in recruitment (Rho=0.5) and with a 50% rebuild probability to estimate T_{min}.

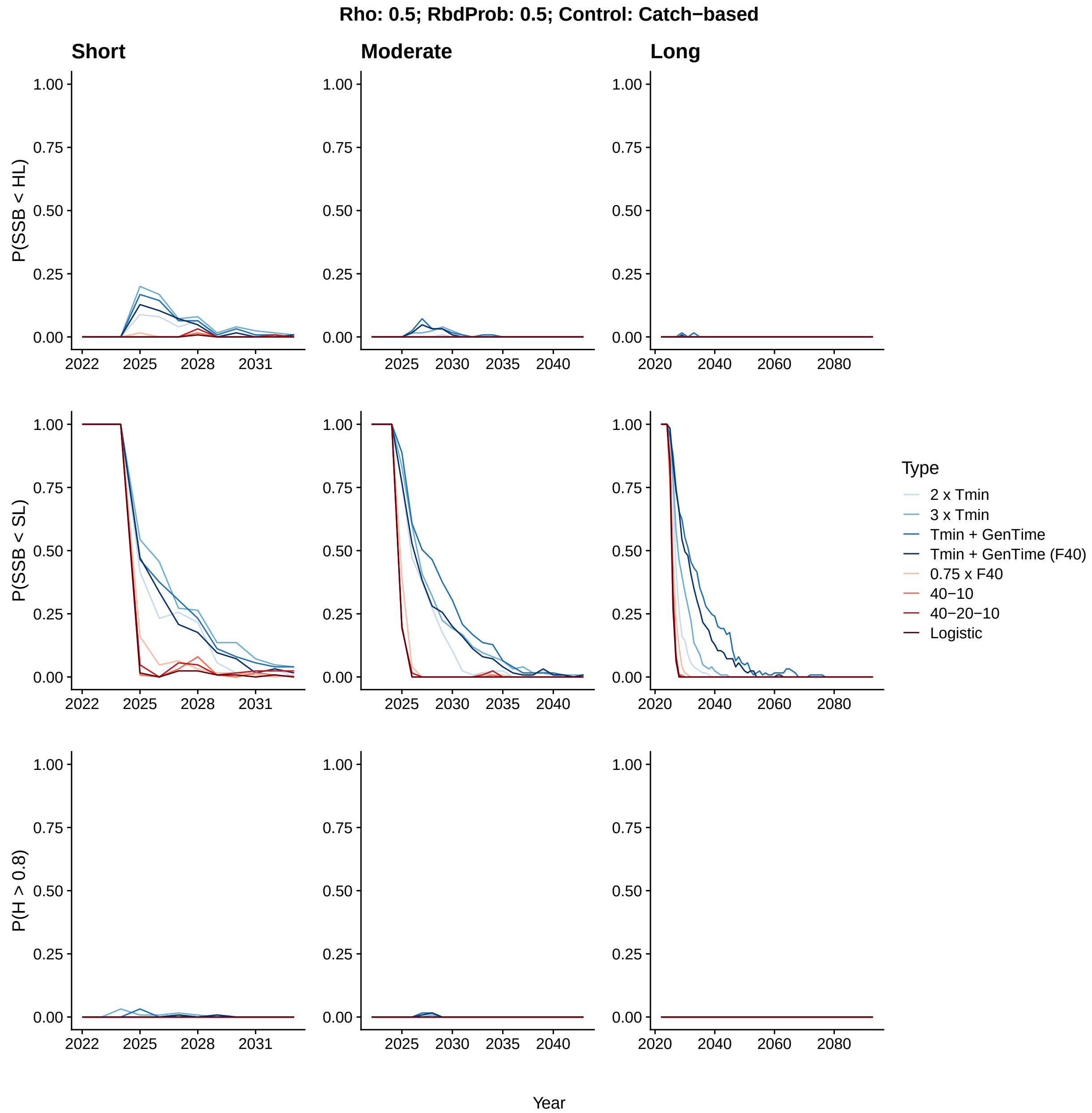

Figure C-11: Simulated risk for catch-based management of falling below the hard limit (10% SSB_0) (top row), soft limit (20% SSB_0) (middle row) and proportion of simulated trajectories that breached the limit of an 80% exploitation rate, across simulated life histories (columns), for the scenario with autocorrelation in recruitment (Rho = 0.5) and with a 50% rebuild probability to estimate T_{min}.

C.3 Economic performance

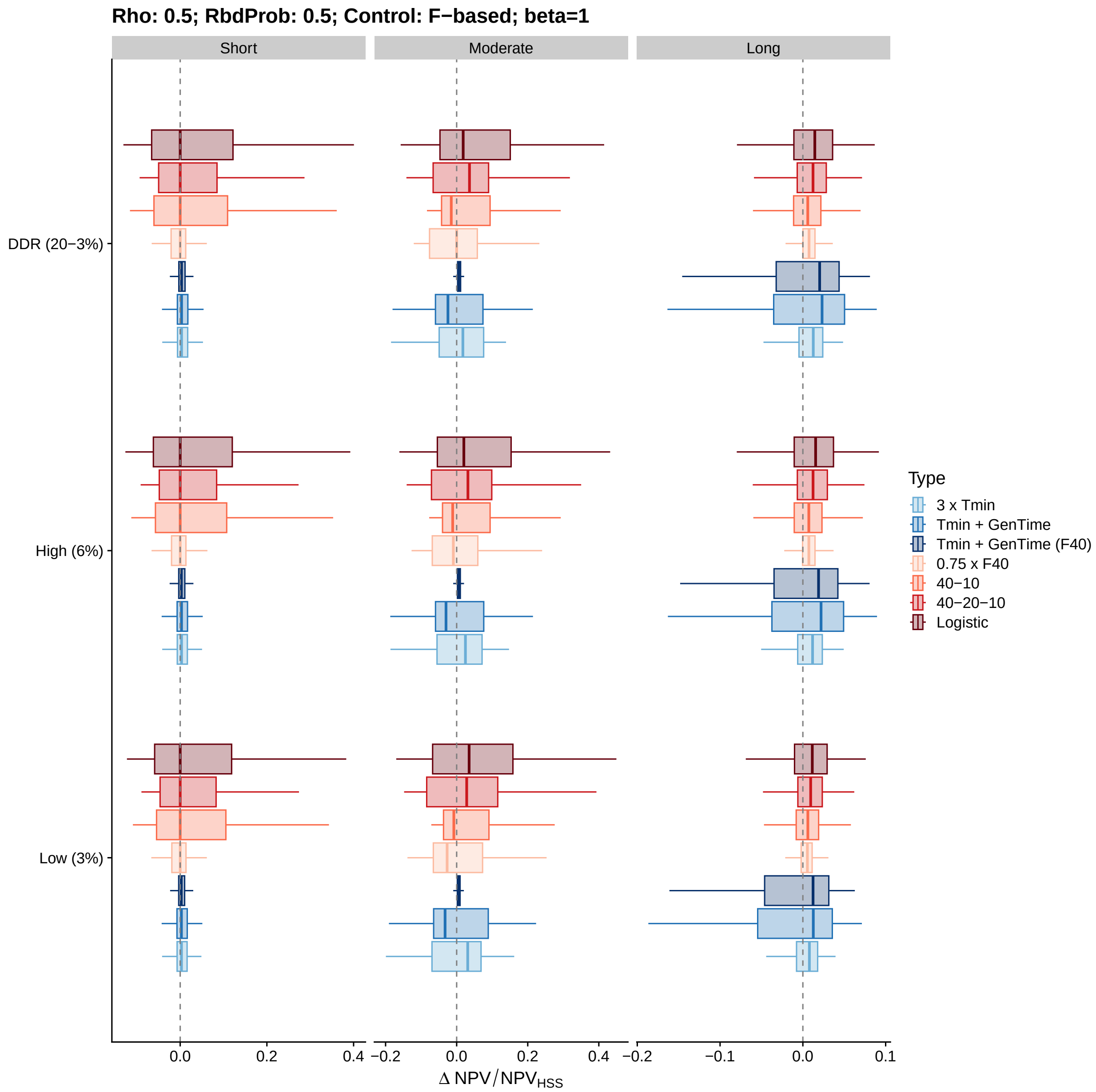

Figure C-12: Relative difference in net present value (NPV) from the current policy (Harvest Strategy Standard (HSS), $2\times T_{min}$) across life histories for management based on fishing mortality at base per-unit-effort cost (0.1) and no catch-per-unit-effort (CPUE) hyperstability, across alternative discount rates (rows; DDR: declining discount rate), for the scenario with autocorrelation in recruitment (Rho = 0.5) and with a 50% rebuild probability to estimate T_{min}. Control-rule-based policies are shown in shades of red/orange and timeline-based policies are shown in shades of blue.

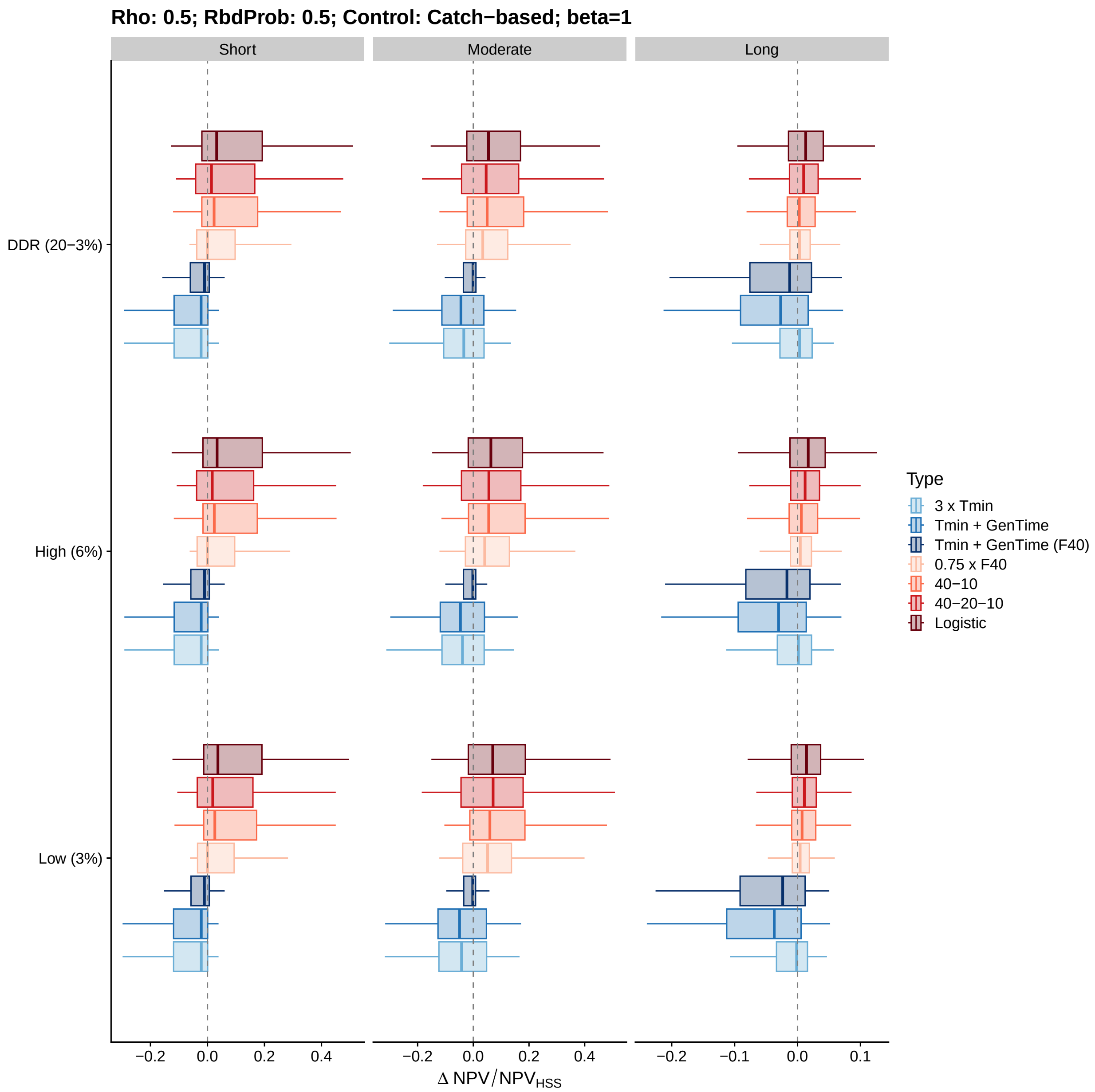

Figure C-13: Relative difference in net present value (NPV) from the current policy (Harvest Strategy Standard (HSS), $2 \times T_{min}$) across life histories for catch-based management at base per-unit-effort cost (0.1) and no catch-per-unit-effort (CPUE) hyperstability, across alternative discount rates (rows; DDR: declining discount rate), for the scenario with autocorrelation in recruitment (Rho = 0.5) and with a 50% rebuild probability to estimate T_{min}. Control-rule-based policies are shown in shades of red/orange and timeline-based policies are shown in shades of blue.

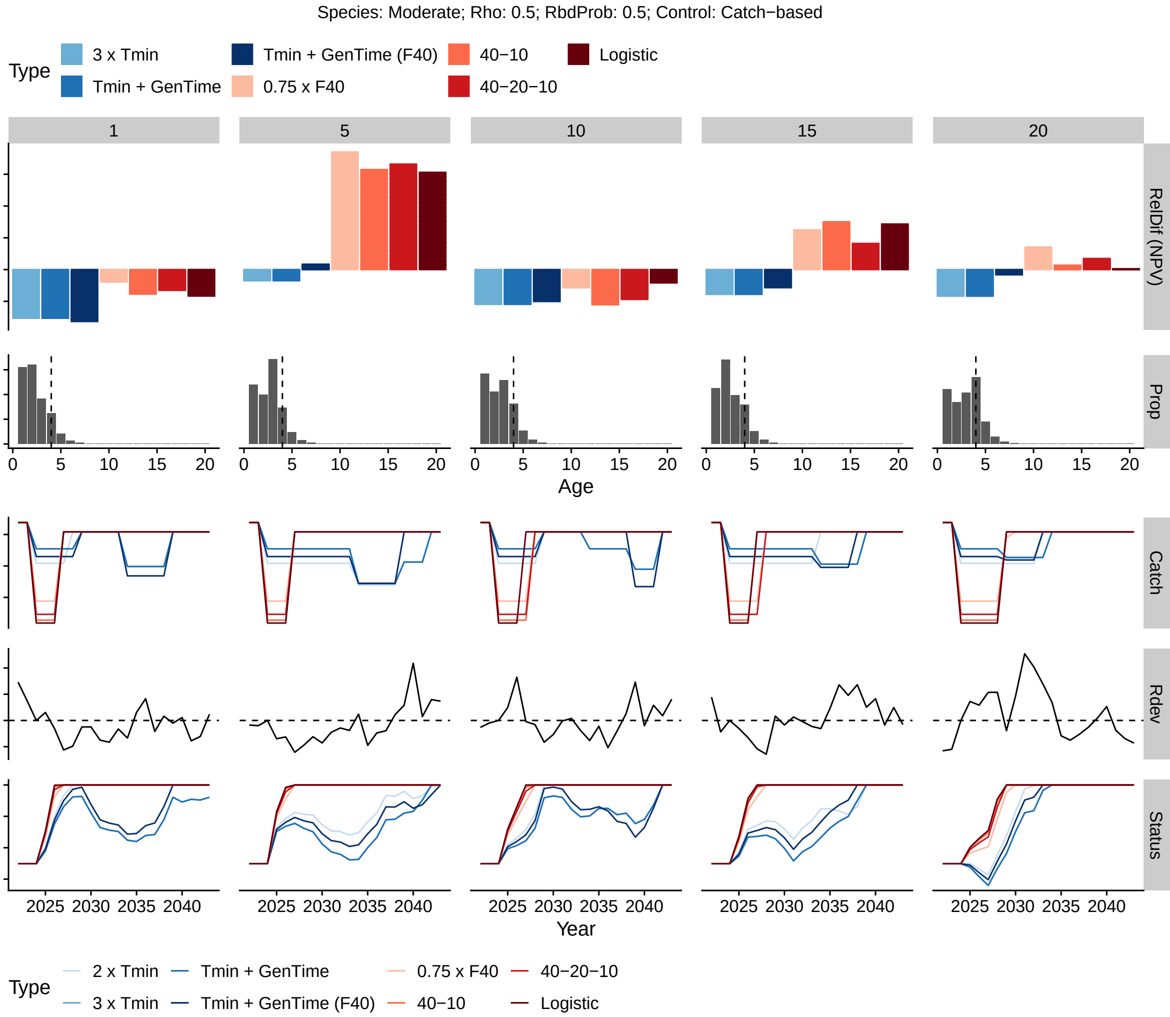

Figure C-14: Relative difference in net present value (NPV) from the current policy (2×T_{min}; top row), age distribution (second row), catch (third row), recruitment deviations (Rdev; fourth row) and stock status (bottom row), for randomly-drawn simulation trajectories (columns) for catch-based management at base per-unit-effort cost (0.1) and no catch-per-unit-effort (CPUE) hyperstability, across alternative discount rates (rows; DDR: declining discount rate), for the scenario with autocorrelation in recruitment (Rho = 0.5) and with a 50% rebuild probability to estimate T_{min}. Control-rule-based policies are shown in shades of red/orange and timeline-based policies are shown in shades of blue.

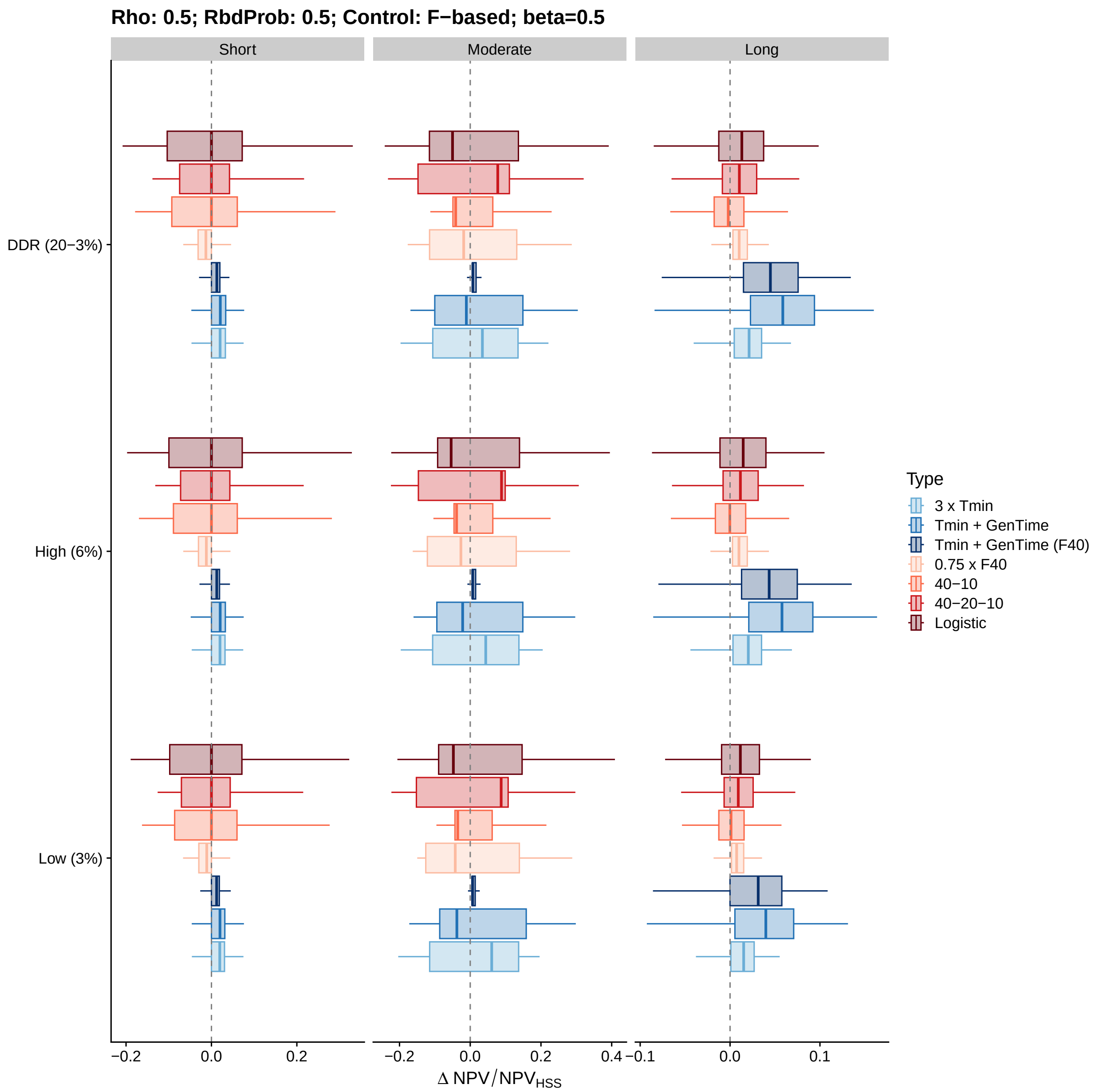

Figure C-15: Relative difference in net present value (NPV) from the current policy (Harvest Strategy Standard (HSS), $2 \times T_{min}$) across life histories for management based on fishing mortality at base per-unit-effort cost (0.1) and hyperstable catch-per-unit-effort (CPUE), across alternative discount rates (rows; DDR: declining discount rate), for the scenario with autocorrelation in recruitment (Rho = 0.5) and with a 50% rebuild probability to estimate T_{min}. Control-rule-based policies are shown in shades of red/orange and timeline-based policies are shown in shades of blue.

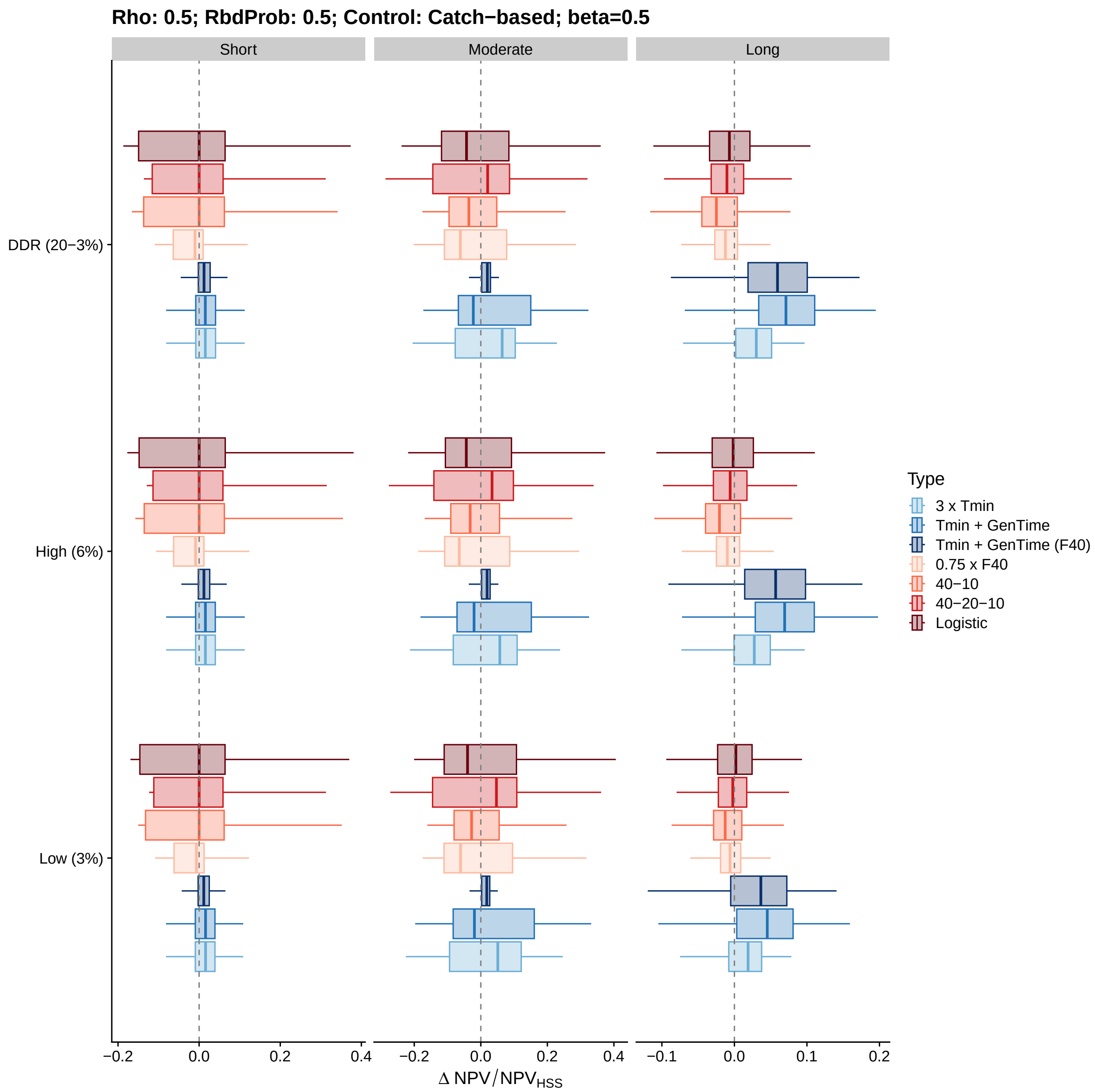

Figure C-16: Relative difference in net present value (NPV) from the current policy (Harvest Strategy Standard (HSS), $2 \times T_{min}$) across life histories for catch-based management at base per-unit-effort cost (0.1) and hyperstable catch-per-unit-effort (CPUE), across alternative discount rates (rows; DDR: declining discount rate), for the scenario with autocorrelation in recruitment (Rho = 0.5) and with a 50% rebuild probability to estimate T_{min}. Control-rule-based policies are shown in shades of red/orange and timeline-based policies are shown in shades of blue.

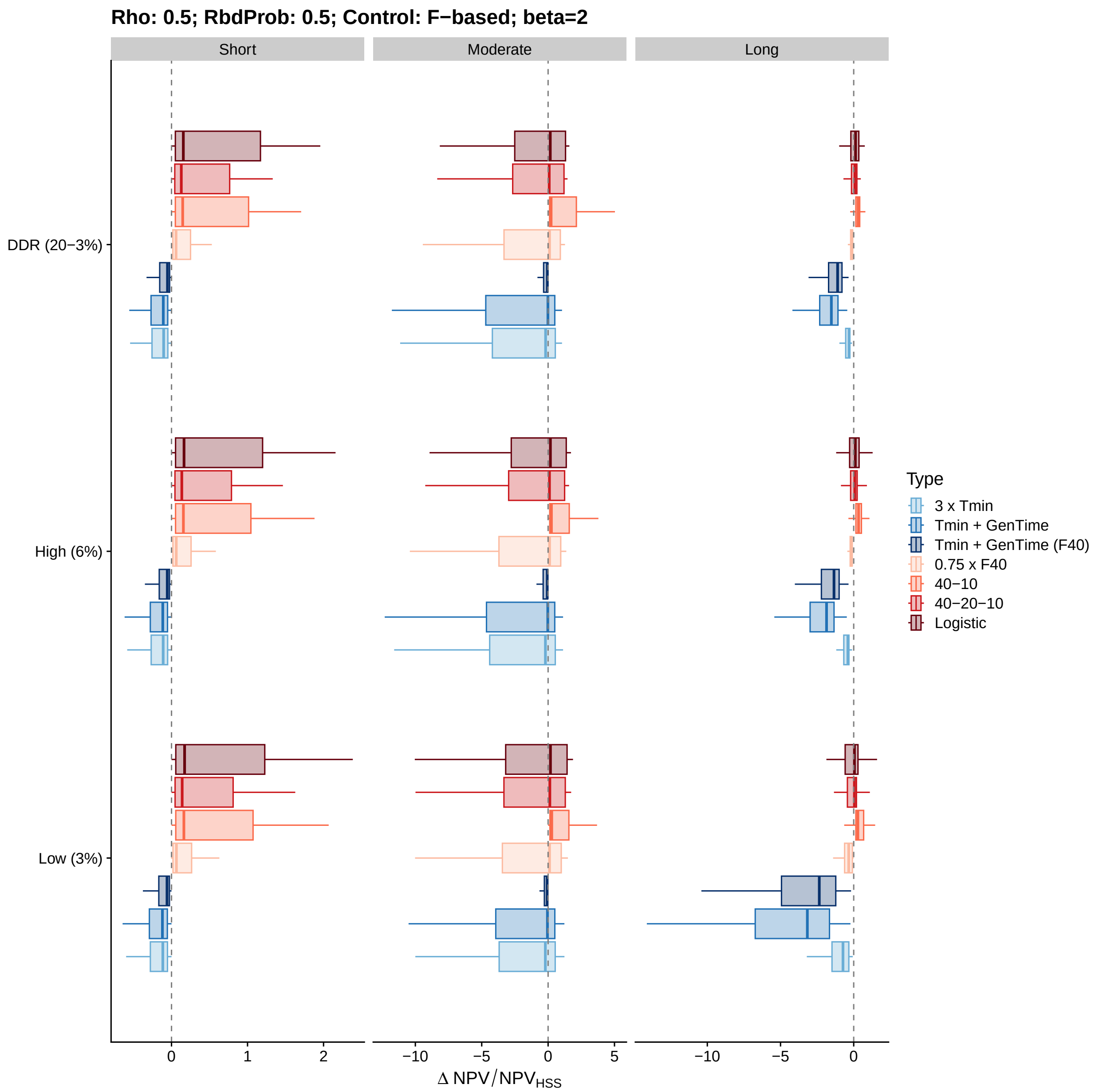

Figure C-17: Relative difference in net present value (NPV) from the current policy (Harvest Strategy Standard (HSS), $2 \times T_{min}$) across life histories for management based on fishing mortality at base per-unit-effort cost (0.1) and hyper-depleted catch-per-unit-effort (CPUE), across alternative discount rates (rows; DDR: declining discount rate), for the scenario with autocorrelation in recruitment (Rho = 0.5) and with a 50% rebuild probability to estimate T_{min}. Control-rule-based policies are shown in shades of red/orange and timeline-based policies are shown in shades of blue.

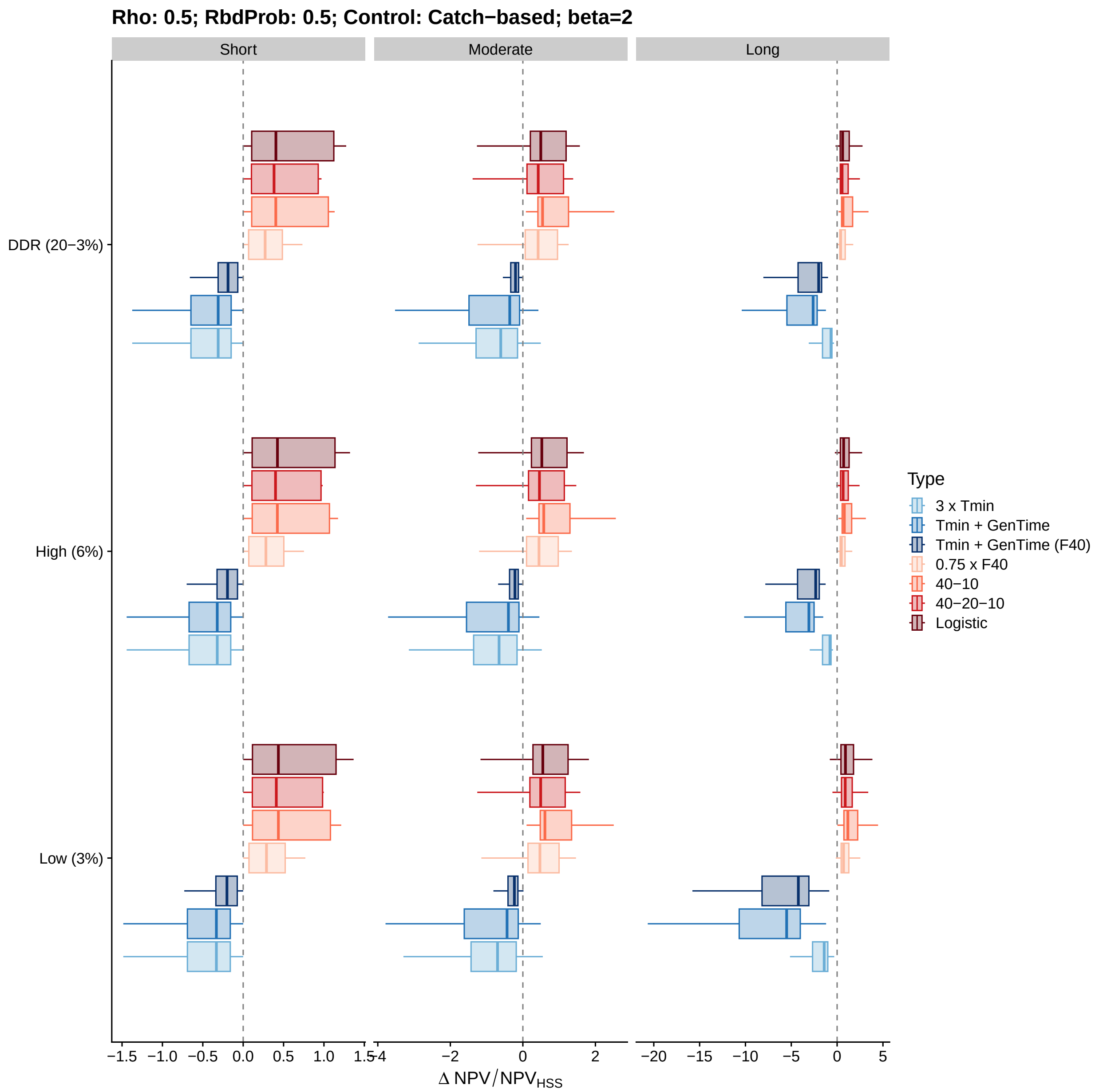

Figure C-18: Relative difference in net present value (NPV) from the current policy (Harvest Strategy Standard (HSS), $2 \times T_{min}$) across life histories for catch-based management at base per-unit-effort cost (0.1) and hyper-depleted catch-per-unit-effort (CPUE), across alternative discount rates (rows; DDR: declining discount rate), for the scenario with autocorrelation in recruitment (Rho = 0.5) and with a 50% rebuild probability to estimate T_{min}. Control-rule-based policies are shown in shades of red/orange and timeline-based policies are shown in shades of blue.

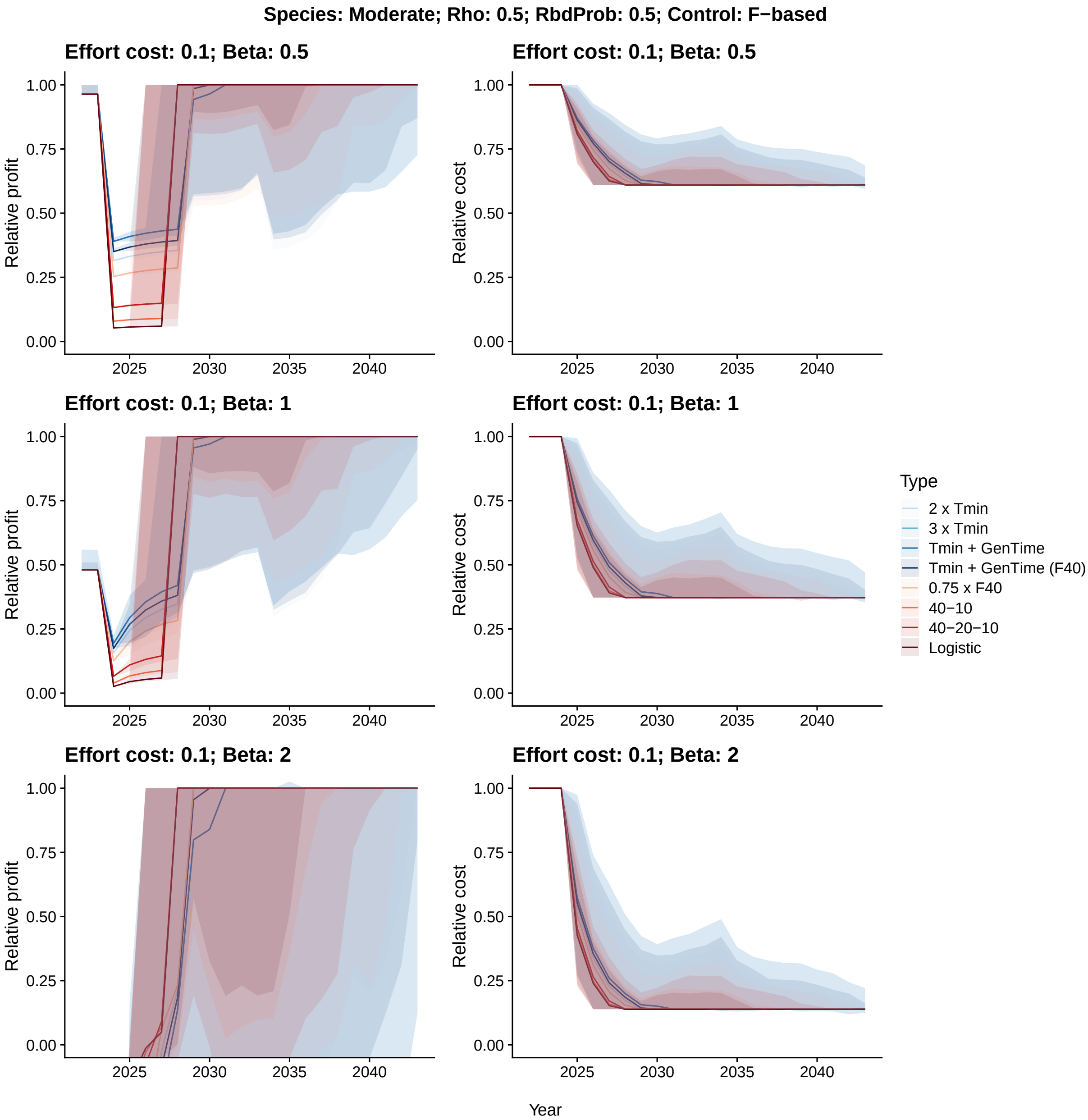

Figure C-19: Relative profit and cost for management based on fishing mortality at base per-unit-effort cost (0.1) and across assumptions of catch-per-unit-effort (CPUE) hyperstability (beta), illustrated for the moderate life history, for the scenario with autocorrelation in recruitment (Rho = 0.5) and with a 50% rebuild probability to estimate T_{min}. Control-rule-based policies are shown in shades of red/orange and timeline-based policies are shown in shades of blue.

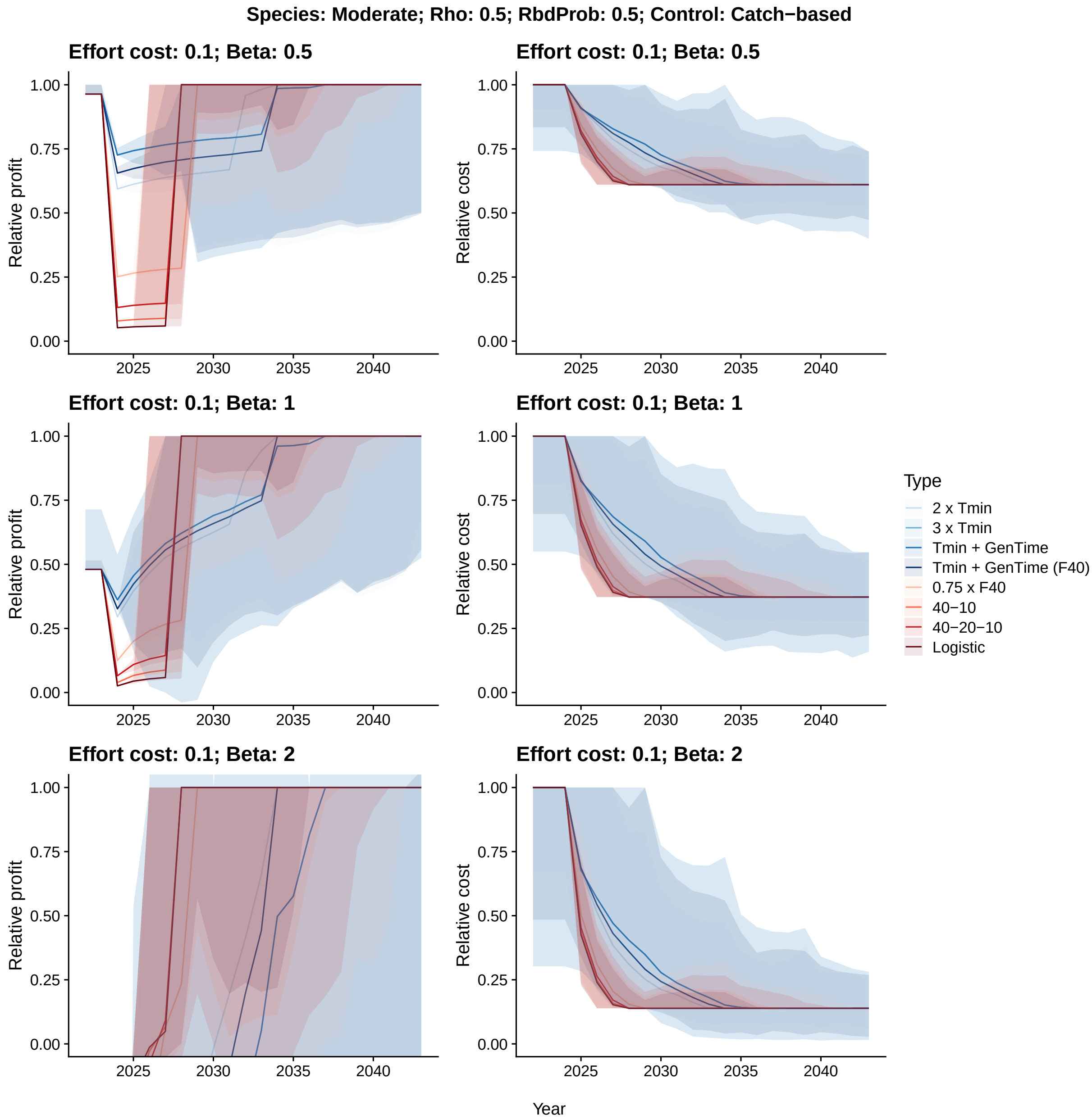

Figure C-20: Relative profit and cost for catch-based management at base per-unit-effort cost (0.1) and across assumptions of catch-per-unit-effort (CPUE) hyperstability (beta), illustrated for the moderate life history, for the scenario with autocorrelation in recruitment (Rho = 0.5) and with a 50% rebuild probability to estimate T_{min}. Control-rule-based policies are shown in shades of red/orange and timeline-based policies are shown in shades of blue.