Atlantic Coastal Cooperative Statistics Program

Proceedings of the Workshop on Percent Standard Error (PSE) of Recreational Fishing Data

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Final Report

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Acknowledgements

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Executive Summary

The ACCSP Percent Standard Error (PSE) project began in 2012 to establish standards for PSE in the use of recreational data that are applicable to the various management needs of state and federal stakeholders. Since 1994, ASMFC guidance supported the use of recreational estimates when PSE was less than or equal to 20%. In 2012, the Marine Recreational Information Program (MRIP) utilized a new weighted estimation method to re-estimate the catch from 2004 to 2011 to improve accuracy and more explicitly account for potential biases. Updated MRIP data queries noted that estimates with PSE values greater than 50% indicate a very imprecise estimate. Therefore ACCSP requested support from MRIP to investigate the influence of PSE on fisheries assessment and management and develop updated guidance on the use of catch estimates with variable precision.

The ACCSP PSE Steering Committee oversaw the development of a computational model to evaluate how different levels of PSE affect the stock assessment and management of fisheries. The management strategy evaluation (MSE) model was completed in January 2014. The ACCSP convened a workshop of fisheries stock assessment scientists and fishery managers in September 2014 to present the empirical model results and supporting presentations. These presentations included the current use of PSE in fisheries stock assessments, incorporating uncertainty in fisheries management from the National Standard One perspective, and the use of PSE in the Council process.

Workshop participants discussed a variety of perspectives from technical assessment to management decisions and supported the approach to evaluate PSE targets using the MSE simulation model. In this model there were 189 scenarios run at seven PSE levels, three life histories, three sizes of recreational fishery and three levels of fishing intensity. In general, model estimates are more reliable (unbiased) for input data with PSEs up to 40-60%. Higher values (>=60%) of recreational data precision were tolerated for species with a shorter life history and smaller recreational fishery component.

Roundtable discussions by regions (North Atlantic, Mid-Atlantic, and South Atlantic / Gulf of Mexico) suggest general agreement by all regions that data with a PSE of 40% or below provides for valid input to stock assessment models. Data with PSE values between 40% and 60% may be used with caution using sensitivity analysis or other methods to mitigate potential biases and allow for flexibility in the assessment process. Data with a PSE of 60% and above should only be used with extreme caution, and participants recognized the need for additional guidance on actions to mitigate management risks in high PSE situations.

The workshop improved the understanding of how recreational data precision impacts scientific uncertainty in stock assessments, and provided guidance for use of PSE in stock assessments. However, workshop participants did not reach consensus on a single target PSE that could be considered acceptable in all situations. Regarding management actions, participants identified common themes and recommendations for further exploration and development.

This report and workshop presentations are available on the ACCSP website at: http://www.accsp.org/recreational-fisheries?key=fisheries.

Project objectives and scope

The ACCSP Percent Standard Error (PSE) project aims to establish standards for PSE in the use of recreational data that are applicable to the various management needs of state and federal stakeholders. Previous 'targets' of percent standard error (PSE) for recreational data collection on the Atlantic and Gulf coasts were based on a workshop conducted by the Atlantic States Marine Fisheries Commission in 1994. Later, the ASMFC and ACCSP derived a general target of PSE <= 20% which has been the de facto standard ever since. Changes in fisheries management, dictated by both state and federal law, have required substantial changes in both commercial and recreational data collection. Commercial collection has moved to a universal trip level standard. Recreational data collection and estimation methodologies are evolving through the MRIP process. A new estimate calculation methodology was implemented in 2012 to improve accuracy of the catch and PSE estimates. Prior to 2012, precision was over-estimated (PSE was under-estimated). Since that time, the MRIP data queries note that PSE values greater than 50 indicate a very imprecise estimate. ACCSP requested support from MRIP to investigate the influence of PSE on fisheries assessment and management and develop updated guidance on the use of catch estimates with variable precision.

The PSE Steering Committee recommended the development of a computational model to evaluate how different levels of PSE affect the stock assessment and management of fisheries. Specifically, exploring a range of PSEs for recreational harvest estimates, the effect this uncertainty has on the estimation of important quantities from traditional stock assessment approaches (biomass estimates, exploitation rates, reference points), and how error in stock assessment estimates can impact the management of a stock. This modeling approach is called management strategy evaluation (MSE) and the selected contractor (Wiedenmann, 2012) had experience in the development and application of MSE models for testing harvest control rules used to determine the acceptable biological catch (ABC) in data-rich and –poor situations (Wilberg et al. 2011). The PSE adapted model was completed in January 2014 and the outputs and summary report were distributed to workshop participants as baseline information.

The goal of the workshop was to improve the understanding of how recreational data precision impacts scientific and management uncertainty, with the specific objective to develop informed consensus on target PSE values for use of data in stock assessments and fishery management. The intended audience included a blend of technical and management perspectives. Presentations were chosen to provide context of the current use of PSE in fisheries and support discussion and development of target PSE levels.

Marine Recreational Information Program (MRIP) Process & Perspective

Summary of Presentation by Gordon C. Colvin, ECS-Federal , Inc.

The Marine Recreational Information Program (MRIP) was established in 2008 with approval of its initial Implementation Plan (IP) by the MRIP Executive Steering Committee (ESC). The ESC is comprised of senior managers from NOAA Fisheries, partner organizations, and the Marine Fisheries Advisory Committee, and provides overall management of the program. Per the IP, MRIP's strategy has been to initially prioritize and focus efforts on developing, testing and approving or "certifying" survey methods that addressed the fundamental design findings and recommendations from the 2006 National Research

Council's "Review of Recreational Fisheries Survey methods". Following successful development of improved survey designs, the new methods would be implemented as appropriate, based on regional needs. As a final step, regions would identify additional requirements for expanded data collection to address improving the timeliness of production of catch estimates, increased precision of estimates, expanded survey coverage, and special needs for rare event and pulse fisheries, etc.

MRIP has made substantial progress in addressing the fundamental design recommendations for the Atlantic and Gulf coast surveys. In 2012, a new weighted estimation method was developed and utilized to re-estimate the catch from 2004 to 2011. In 2013, a new access point angler intercept survey design, which further addressed sources of potential bias in estimates of catch rate per trip, was completed and implemented. In 2014, pilot study work on development of a new mail effort survey design to replace the coastal household telephone survey was completed. Implementation of these improvements substantially completes the process of addressing the fundamental design recommendations of the National Research Council and pave the way for consideration of expanded data collection. Anticipating the need for regional decision making to select certified methods for implementation and to prioritize expanded data collection methods, the ESC conducted a workshop in 2013 to develop a recommended approach for regional implementation of MRIP. The workshop recommended that regional data collection partnerships, including ACCSP, be the primary vehicle for determining the best fit survey methodologies and to set priorities for enhanced data collection in each region. In 2012, ACCSP had updated its recreational data collection standards, including provisions that addressed the initial MRIP improvements. The 2012 standards also addressed certain of the supplemental data collection needs, including seasonal coverage, geographic coverage and timeliness. At that time, ACCSP considered updating standards for precision of recreational catch estimates but deferred adoption of a revised standard pending a more comprehensive assessment of cost and benefits associated with establishing a precision standard. Consideration of a precision standard at this workshop is consistent with both MRIP's current implementation status and MRIP's implementation strategy whereby regional partners assess supplemental data collection needs and priorities.

Review of Precision use in Stock Assessments

Summary of Presentation by Dr. Katie Drew, ASMFC

Members of the ACCSP Recreational Technical Committee reached out to science and management staff at the federal Councils, the Atlantic States Marine Fisheries Commission, and state wildlife and fisheries agencies to determine how MRIP PSEs are used in stock assessment and fisheries management at the federal, interstate, and state level.

The Committee found there is no consistent policy across management entities, and even within an agency, the use of PSEs is driven by the needs of a given species and its fishery. Many agencies do use PSEs both quantitatively and qualitatively to inform their assessments and/or management. In addition, there is interest in formalizing more rigorous guidelines for use of PSEs in management practice.

Relative Standard Error in Health Statistics

Summary of Presentation by Geoff White, ACCSP

In regards to standard error, published examples of industry-specific risk tolerance, or criteria for use of data in analysis are rare. However, a series of publications on health statistics reviewed the criteria for data suppression from 22 major data contributors performing surveys of human population in the United States. Data not meeting various criteria were either not reported or excluded from analysis. In the case of recreational fisheries, all of the data are reported, but developing guidance on measures of precision for use (or exclusion) supports the goals of the PSE workshop. Of the health data sources reviewed, many of those with criteria used an RSE >= 30% for data suppression, and some also included a sample size limitation, such as n < 50.

The Authors noted there was no national standard for deciding when RSE was too large, and supported flexibility of analysts to judge when the data was precise and stable enough for use in analyses. The Utah Health Department uses variable criteria for reporting survey data, where minimum criteria are used to measure gross changes over time, and recommend caution when data between 30-50% RSE. Strict criteria are to be used for policy decisions impacting many people, and measuring small changes over time and use RSE <30%. During the workshop, participants were asked to consider that the National Center for Health Statistics suggests minimum criteria to release or include data was a RSE of less than or equal to 30%.

Summary of Management Scenario Evaluation Model

Summary of Presentation by Dr. John Weidenmann, Rutgers University

Estimates of harvest in many recreational fisheries are often associated with a high degree of uncertainty. Accurate estimates of harvest in recreational fisheries are important for the effective assessment and management of species of recreational importance. For this study, a simulation model was developed to evaluate the effects of uncertainty in recreational harvest estimates on the assessment and management processes, and how these effects depend on the relative size of the recreational harvest for a stock. The model was run for three different species life histories ("fast", "medium", and "slow"), three sizes of the recreational fishery (with landings comprising 30, 60 and 90% of the total, on average), and varying levels of uncertainty in recreational landings estimates (PSEs of 20, 30, 40, 50, 60, 80, and 100%). Results of this work suggest that PSEs above 60 produce unreliable estimates of population status, such that inclusion of catch estimates with this level of uncertainty in an assessment may result in a biased estimate from the assessment, which may impact the management process for a stock. In general, model estimates are more reliable (unbiased) for PSEs below between 40% and 60%, with the specific upper limit dependent on the scenario being explored. Finally, the selection of a particular threshold PSE based on this study requires having clear objectives and specified levels of risk to effectively interpret the broad range of performance measures calculated.

It is difficult to characterize all potential sources of uncertainty that might influence stock assessment estimates. The work here focused on uncertainty in recreational estimates, while all other uncertain inputs assumed the same level of uncertainty across model scenarios. Other potential sources of uncertainty in assessment estimates include biased input data or incorrect model assumptions.

Incorporating all potential sources of error is not feasible in this type of modeling work, and the PSE thresholds identified in this work should be treated as optimistic. It is also important to emphasize that the PSE thresholds identified here were based on their effects on stock assessment estimates. This work did not explore the impact that uncertainty in recreational harvests and discards have on the interpretation of the success or failure of regulations (minimum size or bag limits and seasonal closures), as many states adjust regulations annually based on the estimated harvest relative to the target from the previous year.

Incorporating uncertainty in fisheries management – National Standard 1 perspective

Summary of Presentation by Wesley S. Patrick, NOAA Office of Sustainable Fisheries

Marine fisheries management is based on a system of target and limit reference points, which contain significant amounts of scientific and management uncertainty that fishery managers must address (see Table 1). In the United States, these target and limit reference points are based on the Annual Catch Limit (ACL) framework (Figure 1), which was mandated by the Magnuson-Stevens Fishery Conservation and Management Act in 2009 (MSA; 16 U.S.C. 1801 et al.). Within this ACL framework, scientific uncertainty is accounted for in the setting of the Acceptable Biological Catch (ABC), while management uncertainty is accounted for in the setting of the Annual Catch Target (ACT) (Methot et al. 2013).

The National Standard 1 guidelines, which operationalize the ACL mandates of the MSA, describe the process by which scientific and management uncertainty are accounted for within a science-management feedback loop (Figure 2). In general, this process begins with a Fishery Management Council developing an ABC risk policy that describes how conservative it wants to be in accounting for scientific uncertainty. The Fishery Management Council's Scientific and Statistical Committee (SSC) then uses the risk policy to construct an ABC control rule and specify the ABC for a stock. In most cases, the process results in an ABC that has a 30% to 45% probability of overfishing the stock (Carmichael and Fenske 2011). The maximum probability of overfishing allowed under the National Standard 1 guidelines (Federal Register 2009, Methot et al. 2013) is50%.

The process of accounting for management uncertainty is less formal and does not include an ACT risk policy, nor does it necessarily require that an ACT control rule be developed. This is likely because ACTs are not mandated by the MSA. However, several Fishery Management Councils recognize the importance of accounting for management uncertainty in preventing overfishing (Fisheries Forum 2012). The process used by Fishery Management Councils varies from region to region, but generally involves either reducing the ACL from the ABC, or setting an ACT below the ACL based on qualitative or semi-quantitative analyses. Some examples include:

- <u>The Western Pacific Fishery Management Council (WESPAC)</u> established a Social, Economic, Ecological, and Management (SEEM) working group comprised of social scientists, economists, WESPAC staff, and fisheries resource managers that uses a score-card system to identify region-specific considerations in specifying how ACTs can be reduced from ACLs. Currently, Hawaii's deep seven stock complex is the only fishery with sufficient information to support a SEEM analysis; it had an ACT that was set 6% below the ACL in the 2012-2013 fishing season. For all other stocks, the WESPAC reviews the SSC's ABC choice for each stock, and then recommends an ACL that takes management uncertainty into account.

- The Gulf of Mexico Fishery Management Council uses a decision table ACL/ACT control rule to account for management uncertainty. The decision table considers factors like the percentage of times ACL was exceeded in the past, uncertainty associated with recreational landings (e.g., MRIP PSE), and stock status. If the analysis suggests that management uncertainty is a concern, an ACT is specified, and the ACL is typically set equal to the ABC. When used, ACTs are typically set 15% to 20% below ACLs for non-catch share fisheries, and 0% to 5% below ACLs for catch-share fisheries. When a stock's ACL or ACT is divided into commercial and recreational sector allocations, the control rule is applied to each sector. For example, in 2012, the commercial greater amberjack ACT was set 15% below the ACL, whereas the recreational greater amberjack ACT was set 13% below the ACL. Both sectors had experienced harvest overages in recent years, but the magnitude of the overages in the different sectors warranted the use of different buffers.

- The South Atlantic Fishery Management Council specifies ACTs for many of the recreational fisheries it manages. These ACTs are based on MRIP PSE values. The degree of the ACT reduction from the ACL ranges between 0% and 50%, depending on the MRIP PSE value. The South Atlantic Council uses these ACTs for performance monitoring, rather than as soft or hard limits that would trigger an accountability measure (e.g., trip or bag-limit reduction, area closures, etc.).

- The Mid-Atlantic Fishery Management Council (MAFMC) relies on its Species Monitoring Committee to qualitatively determine if an ACT needs to be set for a fishery, and if so, by how much. For example, in 2013 the Species Monitoring Committee recommended to the MAFMC that the Atlantic mackerel fishery set an ACT that was 90% of the ACL to account for management uncertainty. All other stocks had ACTs set equal to the ACLs because actual harvests were historically less than the ACLs.

- The New England Fishery Management Council sets ACLs equal to the ABCs for most of the stocks it manages, because they are thought to have low levels of management uncertainty. Other New England stocks incorporate explicit buffers into their ACT-ACL specifications process for management uncertainty considerations. Some fisheries, like Atlantic herring and small-mesh multi-species fisheries, have an ACL that is 5% less than the ABC. Fisheries like monkfish and the Northeast skate complexes have ACTs that range between 13% and 25% less than the ACL.

In summary, the National Standard guidelines recommend that Fishery Management Councils account for scientific and management uncertainty through the use of the ACL framework. The process used to account for scientific uncertainty includes the specification of an ABC risk policy and ABC control rule, while the process for management uncertainty is less structured and varies from region to region.

Use of Precision in Council Process

Summary of presentation by Dr. Richard Seagraves, MAFMC

The reauthorization of the Magnuson-Stevens Fishery Conservation and Management Act (MSA) in 2006 included new requirements for ACLs and AMs and other provisions designed to prevent and end overfishing in US federally managed fisheries (16 U.S.C. §1853(a)(15)). As a result, NOAA's National Marine Fisheries Service (NMFS) revised guidance for implementing National Standard 1 (74 FR 3178; January 16, 2009; NS1 guidelines) which became effective February 17, 2009. To address the MSA requirements and the revised National Standard 1 guidance, the Mid-Atlantic Fishery Management Council (Council) implemented an Omnibus Amendment that specified mechanisms to set acceptable biological catch (ABC), annual catch limits (ACLs), and accountability measures (AMs) for Atlantic mackerel, butterfish, Atlantic bluefish, spiny dogfish, summer flounder, scup, black sea bass, Atlantic surfclam, ocean quahog, and tilefish

The Omnibus Amendment formalized the process of addressing scientific and management uncertainty when setting catch limits for the upcoming fishing year(s) and to establish a comprehensive system of accountability for catch (including both landings and discards) relative to those limits, for each of the managed resources subject to this requirement. Specifically, the Omnibus Amendment: (1) established ABC control rules, (2) established a Council risk policy, which is one variable needed for the ABC control rules, (3) established ACL(s), (4) established a system of comprehensive accountability, which addresses all components of the catch, (5) described the process by which the performance of the annual catch limit and comprehensive accountability system will be reviewed, and (6) described the process to modify the measures above in 1-5 in the future.

The Council worked with its Scientific and Statistical Committee (SSC) to develop an approach to derive ABC through a set of four levels, which is applied to each of the managed resources. The levels are based on the information available to assess the stock as well as other relevant information. In general, higher levels will contain assessments with greater detail and lower scientific uncertainty while lower levels have less robust assessments with higher associated scientific uncertainties. When a new stock assessment completes peer-review for any of the managed resources, the SSC is responsible for determining to which level the assessment belongs. Then the processes described within each level are used to calculate ABC. For the upper levels, this applies a distribution of the overfishing limit (OFL) and a probability of overfishing based on a Council risk policy. For the lowest level, alternative types of approaches must be applied to derive ABC. In the NS1 Guidelines response to comment 42 (74 FR 3191; January 16, 2009), it is stated, "The SSC must recommend an ABC to the Council after the Council advises the SSC what would be the acceptable probability that a catch equal to the ABC would result in overfishing. This risk policy is part of the required ABC control rule." As such, the Council adopted a formal risk policy which defines the Council's tolerance for overfishing for the managed resources.

A multi-level approach is used for setting an ABC for each Mid-Atlantic stock, based on the overall level of scientific uncertainty associated with its assessment. The stock assessment provides estimates of the maximum fishing mortality threshold (MFMT) and future biomass, the probability distributions of these estimates, the probability distribution of the overfishing limit (OFL; level of catch that would achieve MFMT given the current or future biomass), and a description of factors considered and methods used to estimate their distributions. The multi-level approach defines four levels of overall assessment uncertainty defined by characteristics of the stock assessment and determination by the SSC that the uncertainty in the probability distribution of OFL adequately represents best available science. The procedure used to determine ABCs is different in each level of the methods framework. The SSC determines to which level the assessment for a particular stock belongs when setting single or multi-year ABC specifications and a description of the justification for assignment to a level must be provided with the ABC recommendation. The ABC recommendations should be more precautionary as an assessment moves from level 1 to level 4. Recommendations for ABC may be made for up to 3 years for all of the managed resources except spiny dogfish which may be specified for up to 5 years. The rationale for assigning an assessment to a level will be reviewed each time an ABC determination is made.

The levels of stock assessments, their characteristics, and procedures for determining ABCs are defined as follows:

Level 1: Level 1 represents the highest level to which an assessment can be assigned. Assignment of a stock to this level implies that all important sources of uncertainty are fully and formally captured in the stock assessment model and the probability distribution of the OFL calculated within the assessment provides an adequate description of uncertainty of OFL. Accordingly, the OFL distribution will be estimated directly from the stock assessment. In addition, for a stock assessment to be assigned to Level 1, the SSC must determine that the OFL probability distribution represents best available science. Examples of attributes of the stock assessment that would lead to inclusion in Level 1 are: 1) assessment model structure and any treatment of the data prior to inclusion in the model includes appropriate and necessary details of the biology of the stock, the fisheries that exploit the stock, and the data collection methods; 2) estimation of stock status and reference points integrated in the same framework such that the OFL calculations promulgate all uncertainties (stock status and reference points) throughout estimation and forecasting; 3) assessment estimates relevant quantities including F_{MSY}[1], OFL, biomass reference points, stock status, and their respective uncertainties; and 4) substantial retrospective patterns in the estimates of fishing mortality (F), biomass (B), and recruitment (R) are present in the stock assessment estimates. The important part of Level 1 is that the precision estimated using a purely statistical routine will define the OFL probability distribution. Thus, all of the important sources of uncertainty are formally captured in the stock assessment model. When a Level 1 assessment is achieved, the assessment results are likely unbiased and fully consider uncertainty in the precision of estimates. Under Level 1, the ABC will be determined solely on the basis of an acceptable probability of overfishing (P*), determined by the Council's risk policy, and the probability distribution of the OFL.

Level 2: Level 2 indicates that an assessment has greater uncertainty than Level 1. Specifically, the estimation of the probability distribution of the OFL directly from the stock assessment model fails to include some important sources of uncertainty, necessitating expert judgment during the preparation of the stock assessment, and the OFL probability distribution is deemed best available science by the SSC. Examples of attributes of the stock assessment that would lead to inclusion in Level 2 are: 1)key features of the biology of the stock, the fisheries that exploit it, or the data collection methods are missing from

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[1] With justification, F_{MSY} may be replaced with an alternative maximum fishing mortality threshold to define the OFL.

[2] An updated description of the MAFMC ABC Control Rule framework can be found at: http://www.mafmc.org/s/2015-09-11-MAFMC-ABC.pdf.

the stock assessment; 2) assessment estimates relevant quantities, including reference points (which may be proxies) and stock status, together with their respective uncertainties, but the uncertainty is not fully promulgated through the model or some important sources may be lacking; 3) estimates of the precision of biomass, fishing mortality rates, and their respective reference points are provided in the stock assessment; and 4) accuracy of the MFMT and future biomass is estimated in the stock assessment by using *ad hoc* methods. In this level, ABC is determined by using the Council's risk policy, as with a Level 1 assessment, but with the OFL probability distribution based on the specified distribution in the stock assessment.

Level 3: Attributes of a stock assessment that would lead to inclusion in Level 3 are the same as Level 2, except that the assessment does not contain estimates of the probability distribution of the OFL or the probability distribution provided does not, in the opinion of the SSC, adequately reflect uncertainty in the OFL estimate. Assessments in this level are judged to over- or underestimate the accuracy of the OFL. The SSC can adjust the distribution of the OFL and develop an ABC recommendation by applying the Council's risk policy (see below) to the modified OFL probability distribution. The SSC developed a set of default levels of uncertainty in the OFL probability distribution for this level based on literature review and a continuing evaluation of ABC control rules. A control rule of 75 percent of F_{MSY} may be applied as a default if an OFL distribution cannot be developed.

Level 4: Stock assessments in Level 4 are deemed to have reliable estimates of trends in abundance and catch, but absolute abundance, fishing mortality rates, and reference points are suspect or absent. Additionally, there are limited circumstances that may not fit the standard approaches to specification of reference points and management measures set forth in these guidelines (i.e., ABC determination). In these circumstances, the SSC may propose alternative approaches for satisfying the NS1 requirements of the MSA than those set forth in the NS1 guidelines. In particular, stocks in this level do not have point estimates of the OFL or probability distributions of the OFL that are considered best available science. In most cases, stock assessments that fail peer review or are deemed highly uncertain by the SSC will be assigned to this level. Examples of potential attributes for inclusion in this category are: 1)assessment approach is missing essential features of the biology of the stock, characteristics of data collection, and the fisheries that exploit it; 2) stock status and reference points are estimated, but are not considered reliable; 3) assessment may estimate some relevant quantities including biomass, fishing mortality or relative abundance, but only trends are deemed reliable; 4) large retrospective patterns usually present; and 5) uncertainty may or may not be considered, but estimates of uncertainty are probably substantially underestimated. In this level, a simple control rule is used based on biomass and catch history and the Council's risk policy.

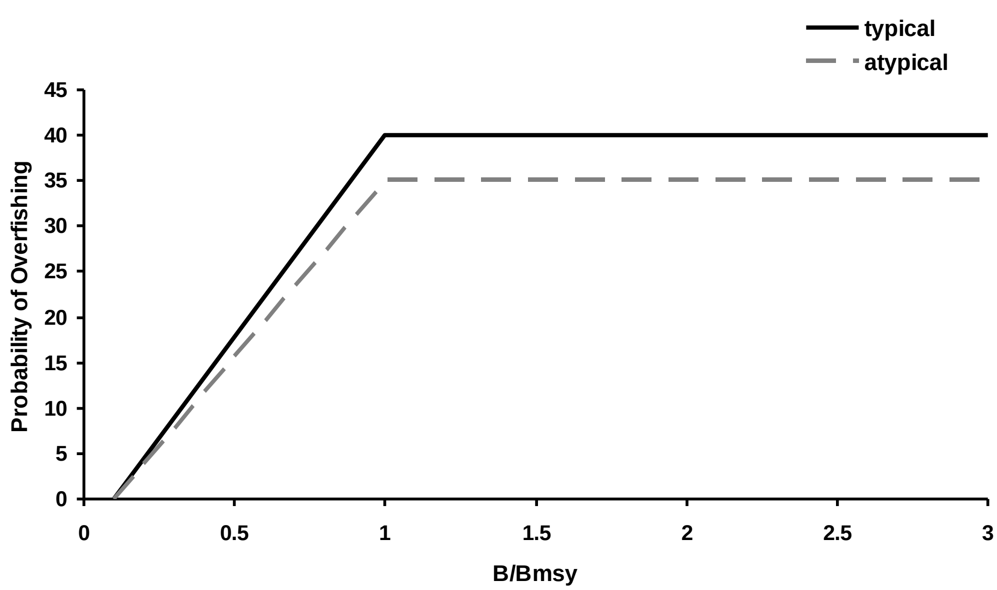
The SSC determines, based on the assessment level to which a stock is classified, the specifics of the control rule to specify ABC that would be expected to attain the probability of overfishing specified in the Council's risk policy. The SSC may deviate from the above control rule methods framework or level criteria and recommend an ABC that differs from the result of the ABC control rule calculation, but must provide justification for doing so.

Under this framework, a stock replenishment threshold defined as the ratio of $B/B_{MSY} = 0.10$, is utilized to ensure the stock does not reach low levels from which it cannot recover. The probability of overfishing will be 0 percent if the ratio of B/B_{MSY} is less than or equal to 0.10. Probability of overfishing increases linearly for stock defined as typical as the ratio of B/B_{MSY} increases, until the inflection point of

B/B_{MSY} = 1.0 is reached and a 40 percent probability of overfishing is utilized for ratios equal to or greater than 1.0. Probability of overfishing increases linearly for stock defined as atypical as the ratio of B/B_{MSY} increases, until the inflection point of B/B_{MSY} = 1.0 is reached and a 35 percent probability of overfishing is utilized for ratios equal to or greater than 1.0. The SSC will determine whether a stock is typical or atypical each time an ABC is recommended. Generally speaking, an atypical stock has a life history strategy that results in greater vulnerability to exploitation, and whose life history has not been fully addressed through the stock assessment and biological reference point development process.

In addition, for managed resources that are under rebuilding plans, the upper limit on the probability of exceeding $F_{REBUILD}$ is 50 percent unless modified to a lesser value (i.e., higher probability of not exceeding $F_{REBUILD}$) through a rebuilding plan amendment. In instances where the SSC derives a more restrictive ABC recommendation, based on the application of the ABC control rule methods framework and risk policy, than the ABC derived from the use of $F_{REBUILD}$ at the MAFMC-specified overfishing risk level, the SSC shall recommend to the MAFMC the lower of the ABC values.

Mid-Atlantic Council's Risk Policy



The primary question is how the precision of recreational catch estimates affects both the calculation of ABC and the invocation of accountability measures (i.e., if annual catch limits are exceeded). For species with stock assessments deemed by the SSC as level 1, uncertainty in recreational catch estimates is propagated forward in uncertainty in the catch projections (yield) at the overfishing limit (F_{msy} or proxy) . Given the current Council procedure for deriving ABC, greater uncertainty in catch will tend to decrease the precision of the OFL estimate and (all else equal), will result in a greater buffer between ABC and OFL (i.e., will result in lower allowable yields given the Council's tolerance for risk). The degree of this impact depends on the proportion of total catch from the recreational sector and the magnitude of the

CV of the OFL. However, currently the imprecise nature of recreational catch estimates has little to no impact on ABC calculations because none of the peer reviewed and accepted quantitative stock assessments for Mid-Atlantic species are classified as level 1. Consequently all ABC calculations are made following the procedures outlined for level 3 stock assessments where an assumed value for the precision of the OFL estimate is used to derive ABC. Thus, the statistical veracity of recreational catch estimates currently does not directly affect the calculation of ABC for Mid-Atlantic species (i.e., the CV assumed by the SSC dictates the size of the buffer between ABC and OFL). In the case of accountability measures, the Omnibus Amendment makes no distinction between catch overages derived from estimates of high or low precision. That is, all deviations from catch limits are treated equally irrespective of precision.

Workshop Summary

Throughout the workshop participants discussed a variety of perspectives from technical assessment to management decisions. Issues related to guidance on data precision ranged along the axis of slow to fast life history and northern to southern fisheries. However, all participants supported the approach to evaluate PSE targets using the MSE simulation model with known true values and a range of treatments tested. In this model there were 189 scenarios run at seven PSE levels, three life histories, three sizes of recreational fishery and three levels of fishing intensity. In general, model estimates are more reliable (unbiased) for input data with PSEs up to 40-60%. Generally, the MSE model results noted that higher values (>=60%) of recreational data precision were tolerated for species with a shorter life history and smaller recreational fishery component.

Roundtable discussions by regions (North Atlantic, Mid-Atlantic, and South Atlantic / Gulf of Mexico) suggest general agreement by all regions that data with a PSE of 40% or below provides for valid input to stock assessment models. Data with PSE values between 40% and 60% may be used with caution using sensitivity analysis or other methods to mitigate potential biases and allow for flexibility in the assessment process. Data with a PSE of 60% and above should only be used with extreme caution such as in cases where a smaller recreational fishery would minimize the effect of the more variable recreational catch estimates. However, participants recognized the need for additional guidance on actions to mitigate risks in high PSE situations.

Further, given the desire for flexibility and case by case risk evaluation, participants agreed that fisheries management approaches should match the precision of the data temporally and spatially. Put another way, fishing regulations should be set in ways that can be measured and distinguished at the precision of the data. Participants also agreed that more standardized methods to include measures of precision would be beneficial.

It became clear that the large number of factors affecting the success of a fisheries stock assessment and management program made it difficult to set a single threshold PSE to be applied in all situations. The group recognized that even in situations where input data had low PSE measures, that the assessment and regulations may not accomplish intended results due to other factors. Additional work will be required to clarify guidance on appropriate measures of precision for data use, including species life history, the geographical scope of the management action, or determination of conservation equivalency.

Guidance for use of PSE in fisheries stock assessments

There was significant progress during the workshop on guidance on PSE use in the stock assessment process. Participants noted that data and assessment reviews are likely to address outlier values within a wave or location using smoothing techniques. Also, assessment model parameters tended to provide for some adjustment or smoothing of data with higher PSE values. While no perfect threshold PSE value could be recommended, there was consensus to use ranges of data precision for guidance. In some cases, the regional round table discussions varied and noted a need for regional flexibility in the approach taken due to the length of the growth and fishing season and the life history of more temperate fishes.

Workshop attendees provided technical expertise and recommendations for use of data in assessments with PSE in three broad ranges. Most current assessment methods are capable of incorporating uncertainty in catch estimates through a statistical framework. However, few assessments use the empirical PSE values from MRIP; most use an ad-hoc CV chosen based on expert opinion. This approach was deemed valid for PSE less than or equal to 40%, and there are current processes to use data with PSE values in this range. Generally, the MSE model noted that PSE values below 40% did not provide significantly different assessment results and those data are appropriate for use in stock assessments. This was surprising to many participants, yet closely matches previous data caveats on the MRIP web queries urging caution when PSE >= 50%.

In situations where PSE falls between 40% and 60% workshop participants urged a cautious approach and suggested additional examination of the data and results by the assessment team to mitigate potential biases. For example, species life history and percentage of total catch from the recreational fishery may provide ancillary information to support the use of data with mid-range PSE values. Finally, the group suggested data with a PSE above 60% should only be used with extreme caution, or only in cases with a low percentage of recreational fishing. One suggested method to mitigate high PSE is to pool the analysis to larger temporal and spatial scales.

While these ranges of PSE were considered generally applicable, participants noted the need for additional input and suggested alignment of PSE target values to species life history and assessment geographical scale. Discussion of applying a standard precautionary buffer to data prior to the assessment was not supported. The group noted that stock assessment scientists should not incorporate precautionary approaches when PSE are high, as precision should be addressed by committees such as the Council Science and Statistical Committees through allowable biological catch (ABC) control rule or other stock assessment review committees.

Recommendations for use of PSE in management actions

Workshop objectives included discussion of how much management uncertainty may be affected by recreational data precision, and if possible, to develop guidance on what level of PSE is tolerable within the context of management uncertainty. The common themes on this topic supported the following recommendations:

- Management Scenario Evaluation (MSE) frameworks are a useful tool to evaluate data and management implications, especially for fisheries under quota management;
- A single threshold PSE value could not be recommended because the appropriate PSE value for a species and management situation depends on the assessment model used, species life history, stock status, and regulatory framework;
- Fisheries management actions should be aligned with the ability to measure the effect of those regulations on catch removals, and the conservation principle should be applied;
- The precision for management measures should be matched to the precision of the assessment. For example, if the assessment is performed as a coastal unit stock, and the coastal PSE is x%, then estimates of recreational catch should have x% or lower PSE to enact management measures at more detailed level (by time period, state, or mode) ;
- When management uncertainty is high (e.g. ability to control removals is low) then more precise criteria for data should be used;
- The risk of unnecessary restrictions on harvest regulations does not increase with increasing PSEs.

Recommendations for further development

Some unresolved concerns were raised during discussion. These items were recommended for an additional process to gather wider input from the Councils and Commissions. The following recommendations are grouped by subject area.

MSE Model

- Investigate why MSE model bias becomes stronger above PSE of 60%
- Investigate variable PSE, such as year to year changes, define average PSE, terminal year PSE variation, PSE scaled to evaluation periods (steady for 3 yrs then altered), and/or trending PSE over time
- Perform model runs with smaller sample sizes (< 50 vs 50-200) to create age compositions and evaluate if those results may impact recommendations on biological sampling.
- Evaluate if generalized life history parameters used in model would be appropriate for species-specific use by the regional Councils and Commissions
- Update MSE model to incorporate management uncertainty. Currently, removals are assumed to be equal to the quota, but the ability to monitor and enforce the quota is affected by the PSE, and actual removals may be more or less than the point value of the quota
- Update MSE model to incorporate alternative control rules such as quota setting processes

Fisheries Management

- Determine appropriate cautionary approaches to incorporate PSE in management. The MSE model was developed with all parameters known (without uncertainty). While this helps interpretation of the effects of PSE on model results, real applications are expected to have additional uncertainty suggesting a more precautionary level of PSE may be appropriate to support management actions

- Develop guidance for management actions or approaches to be explored in situations where PSE values are very high (e.g. in data poor situations how can high recreational PSE be mitigated?)
- Define implementation options that balance federal (SSC) accountability in setting ACTs with state and Commission flexibility in setting and measuring catch targets
- Clarify a vetting process to obtain confirmation or redirection on PSE workshop proceedings and model results from the Council SSCs and ASMFC Assessment Science Committee
- Evaluate management actions scaled to precision of the data (e.g. if PSE = 30%, then evaluate regulations to modify landings by greater than a 30% change)

Future Guidance

- Consider PSE workshop outcomes in the evaluation of optimized recreational survey sample size and timeliness
- Develop guidance on including PSE in assessment and management frameworks, including the use of different buffers for data rich and data poor situations.
- Evaluate the effect of current PSEs on management uncertainty in the short term
- Research the need for lower PSE criteria on quota managed or small scale fisheries
- Evaluate management measures that can be effective with input PSE values of 40-60%
- Evaluate PSE guidance for assessment of rare event species, or when PSE exceeds 60%
- Evaluate extreme cases of high PSE for managed species and identify alternative data collection and/or management approach

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Appendix A: Workshop Terms of Reference

TERMS OF REFERENCE

ACCSP-MRIP RECREATIONAL DATA PRECISION WORKSHOP

1. Evaluate and discuss the effects of PSE on stock assessment and fishery management performance measures, as explored in a simulation model "Evaluation of the Effects of Uncertainty in Recreational Harvest Estimates on Fisheries Assessment and Management". Quantify how much unidentified risk or conservation principle should be applied relative to simulation model results. Document relevant group discussion, action items, or recommendations.

2. Document the current use of sampling precision in fisheries and other industries, and evaluate situations where PSE requirements are more critical to effectively support stock assessment.

3. Describe the management framework and evaluate options for measuring and tracking landings overages, including when to trigger accountability measures.

4. Define the threshold(s) of input data precision above which scientific uncertainty negatively affects stock assessments and/or management uncertainty negatively affects management action.

5. Determine if a single PSE value can be identified as guidance for generalized application to recreational fisheries data. If not, evaluate under what circumstances should advice on PSE be subdivided (e.g. geographic scale (region/state/local), life history, size of recreational fishery)

6. Develop informed consensus on target PSE values for use with recreational fisheries data in stock assessments and management. Where necessary, provide boundaries on PSE levels based on a state/region's contribution to coastwide landings, species life history, fishery characteristics, or state, Commission, and Council fishery management.

7. Post Workshop: Develop a workshop proceedings document summarizing recommendations on the use of PSE in fisheries stock assessments and management on the Atlantic Coast.

Appendix B: Workshop Presenter Bios

Mr. Colvin has over 40 years of experience in natural resource and environmental management with state and federal government, including over 24 years of senior management experience as the Director of Marine Resources for the New York State Department of Environmental Conservation. Mr. Colvin has extensive experience in intra-state, inter-state, and state-federal management of marine fisheries and marine habitat conservation programs.

Dr. Katie Drew is a Senior Stock Assessment Scientist for the Atlantic States Marine Fisheries Commission. She conducts stock assessments on recreationally important species including striped bass, tautog, and weakfish, and serves on the ACCSP Recreational Technical Committee. Her other areas of research include data poor stocks and anadromous species. She has also developed and taught courses for the ASMFC's introductory and intermediate stock assessment science training programs.

Dr. Wesley Patrick has been a Senior Policy Analyst for NOAA Fisheries Office of Sustainable Fisheries, since 2007.   Wesley's primary duties over the last seven years have been related to the implementation of Annual Catch Limits (ACLs) in U.S. fisheries. Wesley was a member of the team that wrote the 2009 revisions of National Standard 1 Guidelines that implemented the ACL framework, and he is currently leading the team that is considering revising those guidelines to address recent stakeholder concerns on how the ACL framework has been implemented. Other items in Wesley's research portfolio include ecological risk assessments, data-poor stock assessment methods, management uncertainty, rebuilding overfished stocks, and ecosystem-based approaches to fisheries management.

Rich Seagraves is the Mid Atlantic Fishery Management Council staff's Senior Scientist. His primary duty is to act as the liaison with the Scientific and Statistical Committee and he is also responsible for the Research Set Aside Program and Protected Resource issues. A new project in his portfolio is the development of an Ecosystems Based Fishery Management Plan Advisory Document.

Dr. Wiedenmann is an Assistant Research Professor in the Department of Ecology, Evolution and Natural Resources at Rutgers University. He research is in fisheries biology, with a broad interested in understanding the population dynamics of exploited marine species. The core of his work aims to identify robust harvest policies to allow for the sustainable harvest and effective recovery of exploited populations. Harvest policies typically require 1) an estimate of population size, 2) a policy or "control rule" that determines how much should be harvested given the population size and management objectives, and 3) the fishing regulations set to achieve that target catch. Dr. Wiedenmann's research spans these areas, and utilizes a variety of statistical and simulation modeling approaches to address these issues.

Geoff White is the Data Team Leader at the Atlantic Coastal Cooperative Statistics Program. He staffs the ACCSP Recreational Technical Committee and supports projects related to recreational fishing. He also provides guidance for all data-related activities, including the development and operation of the Data Warehouse, data quality projects, and data communications.

Appendix C: Workshop Participants

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Appendix D: Evaluation of the Effects of Uncertainty in Recreational Harvest Estimates on Fisheries Assessment and Management. (Weidenmann, 2014)

Report begins on next page.

Evaluation of the Effects of Uncertainty in Recreational Harvest Estimates on Fisheries Assessment and Management

Final Report to the Atlantic Coastal Cooperative Statistics Program
January 20th, 2014

John Wiedenmann
Institute of Marine and Coastal Science
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EXECUTIVE SUMMARY

Estimates of harvest in many recreational fisheries are often associated with a high degree of uncertainty. Accurate estimates of harvest in recreational fisheries are important for the effective assessment and management of species of recreational importance. For this study, a simulation model was developed to evaluate the effects of uncertainty in recreational harvest estimates on the assessment and management processes, and how these effects depend on the relative size of the recreational harvest for a stock. The model was run for three different species life histories ("fast", "medium", and "slow"), three sizes of the recreational fishery (with landings comprising 30, 60 and 90% of the total, on average), and even levels of uncertainty in recreational landings estimates (PSEs of 0.2, 0.3, 0.4, 0.5, 0.6, 0.8, and 1.0). Results of this work suggest that PSEs above 0.6 produce unreliable estimates of population status, such that inclusion of catch estimates with this level of uncertainty in an assessment may result in a biased estimate from the assessment, which may impact the management process for a stock. In general, model estimates are more reliable (unbiased) for PSEs at or below between 0.4 and 0.6, with the specific upper limit dependent on the scenario being explored. Finally, the selection of a particular threshold PSE based on this study requires having clear objectives and specified levels of risk to effectively interpret the broad range of performance measures calculated.

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INTRODUCTION

Estimates of harvest in many recreational fisheries are often associated with a high degree of uncertainty. For many species, the uncertainty of harvest estimates from the Marine Recreational Information Program (MRIP) is high, with proportional standard errors (PSEs) sometimes in excess of 0.5. Accurate estimates of harvest in recreational fisheries are important for the effective assessment and management of species of recreational importance, and may be particularly important for populations where the recreational harvest comprises a sizeable fraction of the total harvest.

Estimates of total harvest from recreational fisheries are used in the assessment of stock status, which in turn informs the determination of the sustainable harvest for a stock. Error in harvest estimates from the recreational fishery can propagate throughout the assessment and management process, resulting in catch limits being set that are too conservative or too high. While uncertainty in recreational harvest estimates can have a large impact on the assessment and management of a stock, it remains unclear how much uncertainty is tolerable. That is, it is unknown if there is a threshold amount of uncertainty (measured as the PSE of the harvest), above which output from an assessment model is unreliable, and how this threshold may depend upon the size on recreational fishery for a particular stock.

For this study, a simulation model was developed to evaluate the effects of uncertainty in recreational harvest estimates on the assessment and management processes, and how these effects depend on the relative size of the recreational harvest for a stock. The model was developed to be flexible enough to explore a range of scenarios, and for the current report, the model was run for three different life histories (“fast”, “medium”, and “slow”), three sizes of the recreational fishery (with landings comprising 30, 60 and 90% of the total, on average), and seven levels of uncertainty in recreational landings estimates (PSEs of 0.2, 0.3, 0.4, 0.5, 0.6, 0.8, and 1.0).

METHODS

Overview of Model Structure

The simulation model was developed in AD Model Builder (Fournier, 2011), and contains three main components (Figure 1). The foundation of the simulation is the operating model, which determines the population dynamics of the stock and how data are generated. Data generated in the operating model are based on the "true" dynamics within the model with some specified amount of error. The operating model generates data on the recreational and commercial harvests, as well as a fishery-independent index of abundance. These data are then used in the assessment model to estimate stock status and biological reference points. The assessment model is a statistical catch-at-age (SCAA) model, and output from the assessment is used in the management model to determine the catch limit using a set harvest policy. The catch limit estimated in the management model is removed from the population, with some implementation error, and the simulation loop continues for a set number of years. This process is repeated many times for each model specification (e.g. amount of error in the data, relative size of the recreational fishery) to account for the variability in the data generation and population dynamics. At the end of each run, the performance of the model is measured for comparison across different model specifications (called scenarios).

Operating, Assessment and Management Models

The operating model used age-structured population dynamics with the equations governing these dynamics in Table 1 and variable definitions in Table 2. Equations used in the model are referenced by their number in Table 1, such that the numerical abundance-at-age is referred to as equation T1.1. Annual abundance of recruited ages was determined from the abundance of that cohort the previous year, decreased by continuous natural and fishing mortality (equation T1.1). Recruitment to the population followed the Beverton-Holt stock-recruit relationship, with bias-corrected lognormal stochasticity (equation T1.2). Parameters for the Beverton-Holt model were derived from the unfished spawning biomass, unfished recruitment, and the steepness parameter (equation T1.3), where steepness represents the fraction of unfished recruitment that results when the spawning biomass is reduced to 20% of the unfished level (Myers et al. 1999). Total spawning biomass in a given year was calculated by summing the product of the proportion mature, weight at age and abundance at age over all recruited age classes (equation T1.4). Weight at age was an allometric function of length at age, which followed a von Bertalanffy growth function (equations T1.5 and T1.6). The proportion mature at age was calculated using a logistic function (equation T1.7). Length, weight, and maturity at age were fixed for a given life history.

The model contains both commercial and recreational fisheries, with selectivity at age calculated using a logistic (saturating) function (equation T1.8). Because both natural (M) and fishing mortality (F) occurred continuously throughout the year, catch was calculated using the Baranov catch equation (Quinn and Deriso 1999; equation T1.9).

Discards were not considered in this model, so the catch for a fishery is equal to the landings. Thus the terms catch, harvest, and landings are used interchangeably throughout this report.

Each model run spans 58 years divided into two periods, denoted the initial and management periods (Figure 2). The initial and management periods cover 40 and 18 years, respectively. During the start of the initial period, the population is in the unfished state. Both recreational and commercial fisheries develop at this time, and a fixed pattern of total fishing mortality (F) is applied to the population. Example patterns in F during the initial period are shown in Figure 3, but all results shown herein are for the model run where F plateaus during the initial period. The intensity of fishing (e.g., light, moderate, or heavy exploitation) during this period determines the population abundance at the start of the management period. The total F in each year is allocated between the commercial and recreational fisheries so that the recreational landings are a fixed proportion of the total landings in each year (0.3, 0.6, and 0.9; herein called the recreational ratio), on average.

At the end of the initial period (year 40) the population is first assessed using data generated during the initial period. The data are generated starting in year 10 of the initial period, representing close to 30 years of data when the population is first assessed. This length of time was selected as it approximates the length of time that recreational landings data have been collected along the eastern U.S. There is a 1-year lag between the data and the assessment, such that for an assessment that is done in year 40, data from years 10 through 39 are used. The data that are generated annually are the catch from each fishery (both total and at-age) and a fishery-independent survey-derived index of abundance (both total and at-age). These data are generated based on the true value and some observation error (equations T1.10 - T1.13). The amount of observation error is fixed across years in the creation of data from the commercial fishery (PSE = 0.1) and the survey (0.25), with PSEs of 0.2, 0.3, 0.4, 0.5, 0.6, 0.8 and 1.0 explored for the recreational fishery (Figure 4). For a given PSE, the standard deviation in the data-generating model is calculated with $\sigma = (\log(\text{PSE} + 1)^2)^{0.5}$. To generate abundance at age data, a multinomial distribution was used, which requires specifying the number of samples to be drawn to generate the random values. Larger values result in the random sample being closer to the true value. For the commercial and survey data, samples sizes of 200 were used. For the recreational fishery, the sample size decreased with increasing PSE. The assumption here is that as PSEs increase, the error in classifying the age structure also increases. Within both the operating and assessment models, sample sizes of 200, 185, 170, 155, 140, 130, and 120 with corresponding PSEs of 0.2, 0.3, 0.4, 0.5, 0.6, 0.8 and 1.0, respectively.

The time series of catch and survey data are input into the SCAA model to estimate the abundance at age and fishery-specific exploitation rates in each year. The specific parameters estimated in the SCAA are the initial abundance at age (in year 10), recruitments and fishing mortality rates (across years), fishery selectivity parameters, and the survey catchability. Parameters are estimated using a maximum likelihood approach and the objective function shown in Table 3. All other required SCAA inputs (i.e., natural mortality, and maturity and weight at age; Table 2) are set to the true values specified in the operating model (Bence et al. 1993; Wilberg and Bence 2006). The SCAA model also estimates the spawning potential ratio (SPR) – based reference points (NEFSC 2002). The limit fishing mortality rate that defines overfishing (F_{lim}) depends on the assumed level of steepness for the species life history, as Punt et al. (2008) have shown a direct relationship between steepness and the SPR that produces MSY. Thus, different SPR% values were selected as the proxies for F_{MSY} for the different life histories (Table 2.). Estimates of F_{lim} are used to define overfishing in the model, and therefore calculate the overfishing limit, or OFL (the catch at F_{lim}). The target fishing mortality rate (F_{targ}) is set at an SPR% above the limit value (Table 2), and is used to estimate the ABC (which is set as the target catch). The spawning biomass reference point and MSY-proxy are calculated by multiplying the SPR and yield-per-recruit (YPR) from fishing at F_{lim}, respectively, by the mean estimate of recruitment over the time series. Because most of the inputs are fixed at the true values, the SPR-based reference points vary across assessments based on the estimated selectivities in each fishery and the estimated mean recruitment. Due to the 1-year lag in the data collection and stock assessment, the OFL and ABC that are calculated are based on a 1-year projection of population biomass. This projection uses the terminal estimates of abundance at age and fishing mortality, and the mean recruitment to predict abundance in the current year to calculate the OFL and the ABC.

The estimated ABC is divided between the recreational and commercial fisheries (based on a specified recreational ratio), and there is sector-specific amount of implementation error (CV = 0.1 for the commercial fishery and 0.2 for the recreational fishery), such that the actual catch fluctuates around the target across years. The ABC is fixed for 2 years, as this time period represents the interval between assessments. Every 2 years the population is re-assessed (using new data that are collected) and the target catch is updated. Note the model contains a fixed-F control rule, with the $F_{\mathrm{targ}} < F_{\mathrm{lim}}$. The management model does not adjust F_{targ} if the population is estimated to be overfished (i.e., there is no specific management response for rebuilding).

Based on the error in the assessment estimates in a given year and the uncertainty in recruitment dynamics, it is possible for the ABC to exceed to the total exploitable biomass in a given year. In such cases, the actual catch is set to 60% of the exploitable biomass, thus preventing the fishery from removing all individuals in a given year.

Performance Measures

At the end of each 58-year period, a range of performance measures is calculated to determine the effects of uncertainty in recreational estimates on the assessment and management of the population. Performance measures can be grouped into 2 categories; those that summarize the status of the population and the fishery, and those that summarize the accuracy of the assessment model (Table 4). Performance measures that summarize population / fishery status were calculated using the true values over the management period. For example, the ratio of spawning biomass to the MSY reference point (S_{MSY}) was calculated as the mean spawning biomass over the management period (years 41 – 58) relative to S_{MSY}. Other performance measures are calculated as the proportion of years when something occurs during the management period. For example, the proportion of years when overfishing occurs is calculated by determining the frequency of years in which the total fishing mortality ($F_{tot} = F_{com} + F_{rec}$) exceeds F_{lim}.

For performance measures summarizing assessment accuracy (Table 4), the relative error (RE) in each assessment-estimated quantity in the terminal year (biomass, recruitment, harvest rates, OFL) is calculated as

$$RE = \frac{estimated - true}{estimated} \times 100$$

Since there are 10 assessments that are conducted in the management period, there are 10 estimates of RE of a particular model estimate. For the purposes of summarizing assessment accuracy over the years for a single model run, the median of the relative error (MRE) is calculated (Wilberg and Bence, 2006). If the MRE of a quantity (such as biomass) equals 0, it means that half of the terminal assessment estimates are above and half are below the true value. Herein, the term unbiased is used to indicate MREs that are near 0. In addition to the MRE, the median of the *absolute* relative error (MARE) is also calculated. Estimates of MARE measure the width of the distribution of the REs. For example, an MARE of 20 indicates that half of the estimates are within ± 20% of the true value, while half are in excess of ± 20%. MRE an MARE were used in place of the mean relative error or the root mean square error to reduce the influence of extreme values of RE (Wilberg and Bence, 2006).

Parameterization and Model Runs

The model was run for three different life histories, which are labeled 'slow', 'medium' and 'fast'. The slow life history has slow growth, late maturation, and low productivity. In contrast, the fast life history has rapid growth, early maturation, and high productivity. The medium life history is between the slow and fast life histories. Rather than use parameters from real species, a number of generalizations were made across life histories. Both steepness and the growth rates increased going from the slow to the fast life history, while age at maturity and recruitment to the population and fisheries decreased going from the slow to the fast life history. Unfished recruitment (R_0) and the parameters controlling the length-weight relationship were identical for each stock.

Running the Model

The model was run for 3 life histories (slow, medium, and fast), three recreational fisheries comprising 30, 60, and 90% of the total landings (herein the term recreational ratio is used to denote the size of the fishery, with a value 0.3 = 30%), and 7 levels of uncertainty in recreational landings (PSEs = 0.2, 0.3, 0.4, 0.5, 0.6, 0.8, and 1.0). For these scenarios, all other parameters (e.g., PSE of the commercial catch and survey index) were fixed. For each of these scenarios, 1,000 model iterations were conducted. The fishing mortality during the initial period was also varied for a given scenario, such that maximum level of F shown in Figure 3 was set to 0.5, 1.0, and 2.0 x F_{lim}. This resulted in the population being lightly, moderately, and heavily exploited at the start of the management period. Thus, 1/3 of the 1,000 model iterations represented the light-, moderate-, and heavy exploitation scenarios. As a result, 189 different scenarios were run (3 x 3 x 3 x 7), with ~ 333 model runs for each scenario.

In addition to the scenarios run above, a sensitivity run was conducted to explore the effects of model uncertainty. For this run, natural mortality was allowed to vary across years (around the true mean) in the operating model, but it was fixed across years at the mean value shown in Table 2 in the assessment model (similar to the approach of Deroba and Schueller, 2013). This scenario exploring an incorrect model assumption was run for the medium life history that was moderately exploited.

Results

Performance measures were summarized primarily using boxplots for each scenario, with the bold horizontal line representing the median of the performance measure and box representing the interquartile range. In addition, contour plots were used to summarize the interactions between the recreational ratio and the PSE of the catch estimates across scenarios. Plots were qualitatively examined for trends across scenarios (c.f. Deroba and Schueller, 2013).

In Figures 5- 7, the RE in spawning biomass estimates is shown across scenarios for the entire time period (initial + management period; based on output from the final stock assessment conducted in year 58) for the fast, medium, and slow life histories, respectively. From these figures, a number of patterns appear. First, the range of RE in biomass estimates (based on the 95% confidence intervals) remains relatively constant for much of the time series, but expands as towards the end of the time period. Thus, the uncertainty in estimates increases approaching the most recent year. Second, as the PSE increases, the median biomass estimate becomes biased over all years, with the estimates being above the true value. For the largest PSEs, the median estimates of spawning biomass RE are as large, or larger than the upper 95% confidence interval for the lowest PSEs (Figures 5-7).

Estimates of spawning biomass RE shown in in Figures 5-7 are for the entire time series from a single output stock assessment. However, the most important estimates from an assessment are in the final (terminal) year, as these estimates have management implications. Terminal assessment estimates determine the target catch in subsequent years, and also determine if the population is currently overfished and / or experiencing overfishing. In such cases, costly measures may need to be taken to reduce fishing mortality and rebuild the stock. Therefore, many of the performance measures calculated are based on the RE in terminal estimates from repeated assessments of many important quantities. Both the median RE (MRE) and median of the absolute RE (MARE) are calculated using terminal estimates of spawning biomass (Figures 8 - 13), recruitment (Figures 14 - 19), recreational fishing mortality (Figures 20 - 25), total fishing mortality (Figures 26 - 31), and the OFL (Figures 32 - 37). In addition, the proportion of years when the terminal estimates of spawning biomass and the OFL were within ± 20% of the true value was also calculated (Figure 38 – 43). Terminal assessment estimates of total fishing mortality are also used to determine the frequency of overfishing false negatives (when overfishing occurs in the terminal year but is not identified by the assessment; Figures 44 - 46) and false positives (when the assessment incorrectly estimates that overfishing occurred; Figures 47 – 49). These figures are boxplots showing the range of the estimates for the performance measures over the iterations for a single model scenario. The median values for each scenario (the bold horizontal line within each box) are also listed in Tables 5 – 7. All plots shown are for the base model run where natural mortality is fixed on both the operating and assessment models. Results from the sensitivity run where natural mortality varies in the operating model but is assumed fixed in the assessment model, are summarized in Tables 8 and 9.

Due to the large number scenarios explored, a detailed description of the dynamics of each Figure is impractical. Therefore, only broad patterns of assessment accuracy are described here. For a given life history, exploitation history, and recreational ratio, as the PSE increases, the MRE in spawning biomass (Figure 8 -10) and recruitment (Figures 14 - 16) becomes positively biased, with terminal assessment estimates being generally higher than the true value. The effect of this positive bias is that the fishing mortality rates are underestimated (negative bias; Figure 20-22 and 26-28) and the OFL is overestimated (Figures 32 – 34).

There appears to be a threshold PSE, above which the estimates go from unbiased (median of the MRE estimates near 0) to biased, but the specific PSE where this occurs is dependent upon the life history, exploitation history, and size of the recreational fishery. For biomass and recruitment estimates, biased estimates occur for PSEs of 0.6 and above for nearly all scenarios, but in some cases estimates become biased for PSEs as low as 0.4. In general, this threshold PSE decreases going from the heavy to the light exploitation cases. That is, assessment estimates are generally more robust for higher PSEs for the heavily exploited population. In addition, higher PSE thresholds (between 0.5 and 0.6) generally occur when the recreational fishery is small (30% of total landings). The threshold level decreases for the larger recreational fisheries, but there appears to be a saturating effect, as the differences between the larger recreational fisheries (60 and 90% of the total) are generally small.

Estimates of the OFL, in contrast, show more instances of positive bias at lower PSEs. Across life histories, bias in the OFL estimates increases going from the light exploitation to the heavy exploitation scenarios (Figures 32 – 34). In fact, for the heavy exploitation case, the OFL estimates exhibit positive bias for all PSEs. Similar to the biomass and recruitment estimates, there appears to be a threshold effect where the magnitude of the bias (i.e., the size of the deviation from 0) increases rapidly at or above PSEs of 0.5.

The MRE performance measures help identify directional bias in estimates from the stock assessment, but they do not characterize the overall variability in the estimates well. For example, there can be two distributions for the MRE in biomass that are centered at 0, but with very different levels of variability in the estimates (i.e., the box and whiskers of the boxplot span a larger range of values). In both cases, estimates have an equal chance of being above or below the true value, but with increased variability, more extreme levels of error are possible. Therefore, it is important to evaluate the magnitude of the variability, and this magnitude is captured by the median of the absolute value of the relative error (MARE). For example, if the median of the distribution of MARE in biomass estimates is 0.2, it means half of the estimates are within ± 20% of the true value, and half are outside ± 20%. A similar performance measure also calculated is the proportion of years when an estimate is within ± 20% of the true value.

For biomass, recruitment, and the OFL, estimates of the MARE show similar patterns to the estimates of the MRE, with the magnitude of error increasing for PSEs typically above 0.5 (Figures 11-13, 17-19, 35-37). For biomass and the OFL, the MARE is similar across life histories, whereas for recruitment, it is lower for the fast life history.

It is perhaps easiest to identify the threshold PSE values by looking at the proportion of years when estimates of biomass are within ± 20% of the true value (Figures 38 – 43). From these Figures it becomes clear when the assessment estimates begin to fall outside of this range. For biomass estimates, at lower PSEs the baseline level is around 0.7, 0.8, and between 0.7 and 0.9 for the fast, medium and slow life histories respectively. These values rapidly decline at PSEs at or above 0.5, with terminal biomass estimates being within ± 20% of the true value in as few as 10 – 20% of assessments in extreme cases. For the OFL, baseline proportions are 0.4, 0.6, and between 0.5 and 0.7 for the fast, medium and slow life histories, respectively, and rapidly decline at PSEs at or above 0.5. While the proportion of years when estimates are within ± 20% varied across life histories (with the fast life history having estimates within this range less frequently), the PSE thresholds are consistent across life histories for a given recreational ratio and exploitation history.

Assessment estimates of total fishing mortality and the overfishing level (F_{lim}) are used to determine if overfishing is occurring. Incorrectly declaring that a stock is experiencing overfishing when it is not (a false positive) can have a negative impact on the fishery as unnecessary penalties may imposed. Alternatively, not identifying overfishing (a false negative) can have a negative impact on the population, as unsustainable harvest rates are not reduced. The proportion of years with overfishing false negatives and false positives were calculated across scenarios and are shown Figures 44 – 49. Generally, the rate of false positives is consistent across PSEs (between 10 – 20% of the time). In contrast, false negatives increase with increasing PSEs from a baseline occurrence in 10% of the years for lower PSEs, to as high as 40% for the highest PSEs (Figures 44-46).

Error in the assessment process will impact the population and fishery though estimates of the catch limit (or ABC) that is set each year. With increasing PSEs, the estimates of OFL from the assessment became higher than the true value, resulting in the population biomass being lower for runs with higher PSEs relative to lower PSEs (Figures 50 – 52). The magnitude of these differences can be very large, and depends on the exploitation history. For example, for the medium life history that was moderately exploited, the spawning biomass ranged from about 10% above S_{MSY} for a PSE of 0.2 to about 30% below S_{MSY} for a PSE of 1.0.

Similarly, the rate of population growth (or decline) was impacted by the PSE. Because the target catch is set at a fishing mortality rate near F_{lim}, the biomass of should trend towards S_{MSY}, so the change in biomass over the time period depends on the biomass before the management model was initiated. Thus, a decline, no change, and an increase in biomass are expected for the lightly, moderately, and heavily exploited populations, respectively. Increasing PSEs affect the magnitude of the change in biomass, with greater declines in the light exploitation scenario, and less increases in the heavy exploitation scenario (Figures 53 – 55). Interestingly, there is little to no effect on the amount of yield for a given scenario across PSEs. While the biomass is lower for higher PSEs, the positive bias in the OFL results in catches being similar or slightly higher at higher PSEs for the fast and medium life histories (Figures 56 – 57), and much higher for the largest PSEs for the slow life history (Figure 58). Running the model for a longer time period would likely alter these trends, as continued decreases in biomass would ultimately result in lower yields to the fishery, on average.

Inflated OFL estimates can result in increased instances of overfishing, and increased risk of the population becoming (or remaining) overfished. Figures 59 – 64 show the probability of the population being overfished, and the probability that overfishing occurs (calculated as the proportion of years over the management period where each event occurs). Increasing the PSE results in increased probabilities of being overfished and experiencing overfishing. For the fast life history, the population can become overfished for all exploitation histories explored (Figure 59). For the medium and slow life histories, the population generally only becomes overfished for the light and moderate exploitation scenarios when PSEs are 0.8 or higher (Figures 60 and 61). Across life histories, instances of overfishing occur for all exploitation scenarios. The probability of overfishing begins to exceed 0.5 (where overfishing is more likely to occur than not) at PSEs of 0.6 and above (Figures 62-64).

The final performance measure calculated is the probability that the ABC exceeds the available biomass in a given year (Figure 65 – 67). Such an occurrence could result from an erroneous assessment, a very low recruitment event, or both. This occurred very infrequently for the medium and slow life histories (Figures 66 and 67). For the fast life history under certain scenarios, the ABC exceeded the population biomass between 5 and 20% of the time, with more frequent occurrence resulting from the highest PSEs.

For the performance measures described thus far, the boxplots are split across exploitation histories and life histories. While this separation is useful for identifying patterns across these scenarios, it obscures the relationship between the PSE and the recreational ratio for a given performance measure. To make this relationship more clear for a subset of the performance measures, contour plots were crated by combing the data across all exploitation history scenarios, and the median value was selected for each PSE / recreational ratio combination. From these plots the threshold effect is apparent, as the MRE and MARE of biomass and recruitment rapidly become more extreme (contour lines closer together) at PSEs between 0.5 and 0.6 for a given sized recreational fishery (Figures 68 – 70). Similar patterns result for the MRE and MARE in estimates of fishing mortality and the OFL. (Figures 71 – 73).

For a given PSE, the interaction with the recreational ratio can be identified by looking at the slope of the contour line across the recreational ratios. A downward slope for the MRE / MARE estimates shown indicates that values become more extreme as the size of the fishery increases (for a given PSE), an increasing slope indicates values become less extreme, and no slope indicates that that size of the fishery does not at that PSE for a particular performance measure. In general, for the MRE / MARE in biomass and recruitment, values become more extreme going from a recreational ratio of 0.3 to 0.6. This trend levels off above a recreational ratio of 0.6, indicating the size of the recreational fishery has an effect up to this point. In some cases at the highest PSEs, the lines slope upward, indicating performance measures become less extreme for the largest fishery. This pattern exists for both the MRE and MARE of the OFL, but only for the

MRE of fishing mortality estimates, which has downward sloping contour lines for all recreational ratios (Figure 71 - 73). For the plots showing the proportion of years with estimates of biomass and the OFL within ± 20% (Figures 74 - 76) the interpretation of trends in the contour lines is similar, although in these instances "more extreme" values indicate that model estimation becomes worse, with fewer estimates (and thus a lower proportion) within this range. For these measures, the effect of the recreational fishery is most apparent at smaller ratios. Patterns are opposite for the overfishing false negative and false positive performance measures. Overfishing false negative occurrence is influenced at smaller recreational ratios (between 0.3 and 0.6), but not higher ratios. In contrast, false positives are not affected by lower ratios, but increase rapidly between 0.6 and 0.9 (Figure 74 – 76).

Error in assessments estimates in this simulation study result from uncertainty in the survey and catch data (i.e. data uncertainty). Another important source of uncertainty is model uncertainty, where specific assumptions made in the assessment model about the underlying population dynamics are incorrect. In base scenarios explored in this simulation model, all assessment inputs (excluding the survey and catch data) were fixed at the true values used in the population dynamics model (Table 2). Estimates of natural mortality, maturity-, and weight-at-age used in the stock assessment were set at the values used in the operating model (Table 2). Thus, the assessment estimates in this model may exhibit less bias for a given PSE than may occur in cases when erroneous assumptions are made in the stock assessment. A sensitivity run was conducted where the true natural mortality rate fluctuates annually (around the mean value in Table 2 but with no trend), but the assessment assumes a fixed value across years. This sensitivity run was conducted for the medium life history that experienced moderate exploitation. Output from this run is shown in Table 8, and a comparison of select performance measures with the base model (where natural mortality is fixed over time) is shown in Table 9. Many of the performance measures show similar values at PSEs at or below 0.6. For higher PSEs, the estimates from the sensitivity run are more extreme. An exception to this trend across PSEs is for the probability of overfishing, which increases rapidly above PSEs of 0.3.

Conclusions

The results of this work can be used to help determine threshold levels of uncertainty in recreational harvest estimates. It is clear from these model runs that assessment estimates become biased for PSEs at or above 0.6 across all scenarios explored. Furthermore, the amount of bias increases greatly for PSEs of 0.8 and 1.0. Thus, using PSEs of this magnitude will likely have a large impact on the assessment accuracy and management of a stock. While such high PSEs are ill advised, the question remains as to how much uncertainty is tolerable for the assessment and management of a population.

In general, assessment estimates were unbiased below PSEs between 0.4 and 0.6, with the particular threshold level depending upon the specific scenario (life history, exploitation, history, and recreational ratio). Threshold PSE values were typically higher for heavily exploited populations relative to lightly exploited populations. However, care is needed in trying to select a particular PSE threshold based on exploitation history, as an accurate determination of population status from a stock assessment is required to do so. In other words, trying to select a threshold amount of data uncertainty for an assessment based on exploitation history requires that the exploitation history can be accurately classified, which typically requires a reliable assessment (which may not be available in such cases). Threshold PSE levels tended to decrease between recreational ratios of 0.3 and 0.6, but were relatively consistent above a ratio of 0.6. Therefore, similar threshold may be selected for moderate and large recreational fisheries.

Determining a specific threshold level of uncertainty in landings estimates will depend on the specific objectives that managers are trying to achieve, and how much risk managers are willing to accept. For example, for the fast life history that is moderately exploited with a recreational ratio of 0.9 (Figure 8), estimates of biomass become biased at a PSE of 0.5, but the amount of bias for this PSE is small relative to PSEs of 0.6 and higher. Managers who want to avoid bias altogether may therefore set a threshold PSE of 0.5, whereas managers who are willing to accept a small amount of bias may opt for a threshold of 0.6.

As another example of using specific objectives to determine the threshold PSE, the revised Magnuson Act aims to prevent overfishing, and this has been interpreted to mean that the probability of overfishing is below 0.5. Many Fisheries Management Councils have adopted policies to achieve lower probabilities of overfishing, such as 0.4. To achieve a particular probability of overfishing, the output shown in Figures 62 – 64 can be used to inform this decision. However, the probability of overfishing calculated here is specific to the harvest policy used (fishing at an $F_{\text{targ}} < F_{\text{lim}}$) in this analysis. Higher probabilities would result for less conservative harvest policies, and vice-versa.

It is important to emphasize that the model results presented are based only on runs with data uncertainty. In other words, error in the assessment estimates results only from error in the catch and survey data, as all other inputs to the assessment model are fixed at the true values used in the operating model (e.g., weight and maturity at age). It is likely that model error (i.e., incorrect assumptions in the assessment) will also impact the assessment estimates. A sensitivity run was conducted to explore model error, where natural mortality varied annually around the mean (with no trend), but was assumed fixed across years in the assessment. The effect of this model error was small at lower PSEs, but became more pronounced at higher PSEs (Table 9). However, it is likely different types of model error will impact estimates differently. Exploration of alternative sources of model error is warranted, and a possible example is to include time-varying selectivity in the recreational fishery that is ignored in the assessment.

The assessment process in the model was automated, with the output from the assessment treated as the best available estimates and used in the management process. In the model, there are no checks and balances throughout this process, which might otherwise identify erroneous data or model estimates. For example, certain estimates of catch may be thrown out or modified during the Data Workshop. The assessment model may also be modified by an assessment scientist, by adjusting likelihood weights, for example, if initial runs produce questionable estimates. Including such checks is not feasible in such a model, but it is important to acknowledge that the error in assessment estimates might get reduced in an actual assessment through various approaches. Also, an assessment might be rejected in the review process, which would mean results could not be used for management purposes. In such cases data-poor methods might be relied upon, but such methods require "reliable" catch estimates such that error in recreational landings might have a larger effect of management of the stock (c.f., Wiedenmann et al. 2013).

This work only explored the uncertainty in annual, coastwide harvest estimates on the assessment process, and ignored the implications of PSEs at smaller spatial scales. While the coastwide landings estimates for a stock may have a low PSE, estimates for particular states for the stock in a give year may be considerably higher. State-specific data are often used to set regulations in the recreational fishery for a given stock, and large amounts of uncertainty can impact the effectiveness of the state-specific regulations, which can potentially impact the larger population. Such an analysis was beyond the scope of this work, but has potentially important implications in the management of some recreational fisheries.

In summary, the results of this work suggest that PSEs above 0.6 produce unreliable estimates of population status, such that inclusion of catch estimates with this level of uncertainty in an assessment may result in a biased estimate from the assessment, which may impact the management process for a stock. In general, model estimates are more reliable (unbiased) for PSEs at or below between 0.4 and 0.6, with the specific upper limit dependent on the scenario being explored. Finally, the selection of a particular threshold PSE based on this study requires having clear objectives and specified levels of risk to effectively interpret the broad range of perform measures calculated.

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Table 1. Equations characterizing the age-structure population and fishing dynamics in the operating model (see Quinn and DeRiso 1999 for more details on age-structured dynamics).

	Equation	Description
	Population dynamics	
1	$N(a,t)=\begin{cases} R(t) & a=a_R \\ N(a-1,t-1)e^{-Z(a-1,t-1)} & a_R<a<a_{\max} \\ N(a-1,t-1)e^{-Z(a-1,t-1)}+N(a,t-1)e^{-Z(a,t-1)} & a=a_{\max} \end{cases}$	Numerical abundance at age
2	$R(t)=\dfrac{S(t-a_R)}{\alpha+\beta S(t-a_R)}e^{\theta_R-0.5\sigma_R^2}$ $\alpha=\dfrac{S_0\left(1-h\right)}{4hR_0} \qquad \beta=\dfrac{5h-1}{4hR_0}$	Stock-recruit relationship
3	$S(t)=\sum_{a=a_R}^{a_{\max}} m(a)w(a)N(a,t)$	Spawning biomass
4	$Z(a,t)=M+\sum_f s(a,f)F(t,f)$	Total mortality
	Life history	
5	$L(a)=L_\infty\left(1-e^{-k(a-a_0)}\right)$	Length at age
6	$w(a)=bL(a)^c$	Weight at length
7	$m(a)=\dfrac{1}{1+e^{-\left(\frac{a-m_{50\%}}{m_{slope}}\right)}}$	Maturity at age
	Fishing dynamics	
8	$s(a,f)=\dfrac{1}{1+e^{-\left(\frac{a-s_{50\%}(f)}{s_{slope}(f)}\right)}}$	Selectivity at age in fishery *f* (or in the survey, denoted $s(a,v)$)
9	$C(a,t,f)=\dfrac{s(a,f)F(t,f)}{Z(t,a)}w(a)N(a,t)\left(1-e^{-Z(a,t)}\right)$ $C(t,f)=\sum_a C(a,t,f)$ $C(t)=\sum_f C(t,f)$	Total catch

Data-generating dynamics

10	$C_{obs}(t,f) = C(t,f)e^{\varepsilon(t,f)-0.5\sigma^2(f)}$ $\varepsilon(t,f) \sim N(0,\sigma^2(f))$	Observed catch
11	$I(a,t,v) = q(v)s(a,v)N(a,t)$ $I(t,v) = \sum_a I(a,t,v)$	True index of abundance
12	$I_{obs}(t,v) = I(t,v)e^{\varepsilon(t,v)-0.5\sigma^2(v)}$ $\varepsilon(t,v) \sim N(0,\sigma^2(v))$	Observed index of abundance
13	$\mathbf{p}_{obs}(t,f) = \frac{1}{n(f)}\mathbf{\Theta}(t,f)$ $\mathbf{\Theta}(t,f) \sim Multinomial\big(n(f),\mathbf{p}(t,f)\big)$ $\mathbf{p}(t,f) = \frac{1}{C(t,f)}\big(C(a=1,t,f),...,C(a_{\max},t,f)\big)$	Observed vector of proportion-at-age in fishery *f*

Table 2. Parameter values for the slow, medium, and fast life histories for the simulation. Important quantities derived from these parameters used in the analyses are also listed.

Parameter	Description	Life History Slow	Medium	Fast
Specified				
a_r	Age at recruitment (to population)	3	1	1
a_{max}	Maximum age	15	10	7
M	Natural mortality rate	0.12	0.2	0.4
R_0	Virgin recruitment	$1x10^6$	$1x10^6$	$1x10^6$
h	Steepness	0.45	0.65	0.85
a_0	Age at length=0	0	0	0
L_∞	Maximum length	105	90	50
k	Growth rate	0.15	0.25	0.35
b_1	L-W scalar	$2.98x10^{-7}$	3.0×10^{-6}	3.0×10^{-6}
b_2	L-W exponent	3	3	3
m_{50}	Age at 50% maturity	4	2.5	1.25
m_{slope}	Slope of maturity function	1	0.5	0.25
s_{50}	Age at 50% selectivity (commercial, recreational, survey)	5.5, 5.5, 3.5	3.25, 3.25, 1.75	2, 2, 1
δ	Slope of selectivity function	0.5	0.5	0.5
SPR_{lim}	Limit SPR % that defines overfishing	0.45	0.4	0.35
SPR_{targ}	Target SPR% used to set the ABC	0.5	0.45	0.4
Derived				
S_{MSY}	Spawning biomass that produces *MSY*	4,032,260	1,326,560	94,127
S_{targ}	Spawning biomass when fishing at F_{lim}	4,663,130	1,216,650	91,635
F_{MSY}	Fishing mortality that produces *MSY*	0.07	0.2	0.54
F_{lim}	Fishing mortality that defines overfishing	0.08	0.22	0.56
MSY	Maximum sustainable yield	284,565	201,599	28,870
F_{lim} / M	Ratio of F_{lim} to M	0.8	1.1	1.4

Table 3. The negative log-likelihood function used to estimate the parameters in the statistical catch-at-age (SCAA) model.

1	$L=\sum_f \ell_C(f)+\sum_f \ell_{p_C}(f)$ $+\sum_f \ell_I(v)+\sum_v \ell_{p_I}(v)$	Objective function
2	$\ell_C(f)=0.5n(f)\log(\sigma^2_{est}(f))+\frac{1}{2\sigma^2_{est}(f)}\sum_t\left(\log(C_{obs}(t,f)-\log(C_{est}(t,f))\right)$	Fishery catch
3	$\ell_I(v)=0.5n(v)\log(\sigma^2_{est}(v))+\frac{1}{2\sigma^2_{est}(v)}\sum_t\left(\log(I_{obs}(t,v)-\log(I_{est}(t,v))\right)$	Survey index
4	$\ell_{p_C}(f)=-g(f)\sum_t\sum_a p_{obs}(a,t,f)\log(p_{est}(a,t,f))$	Fishery proportion-at-age
5	$\ell_{p_C}(v)=-g(v)\sum_t\sum_a p_{obs}(a,t,v)\log(p_{est}(a,t,v))$	Survey proportion-at-age

Table 4. Performance measures calculated for each model iteration for each scenario. MRE and MARE refer to the median relative error and median absolute relative error in terminal estimates from each stock assessment. Measures in the Population and Fishery Dynamics category are calculated using the final 18 years of the model run. Measures in the Assessment Estimates category are calculated comparing terminal assessments from 10 assessments to the true value in that year.

Category	Performance Measure
Population and Fishery Dynamics	Mean spawning biomass ratio (S / S_{MSY})
	Proportional change in biomass (ΔS)
	Mean catch / MSY
	Proportion of years when the population is overfished
	Proportion of years with overfishing occurring
	Proportion of years when the ABC > exploitable biomass
Assessment Estimates	MRE / MARE in terminal S estimates
	MRE / MARE in terminal R estimates
	MRE / MARE in terminal OFL estimates
	MRE / MARE in terminal F_{rec} estimates
	MRE / MARE in terminal F_{tot} estimates
	Proportion of years when overfishing not identified (false negative)
	Proportion of years when overfishing incorrectly declared (false positive)
	Proportion of years with S estimates within ± 20% of the true value
	Proportion of years with OFL estimates within ± 20% of the true value

Table 5. Median estimates of performance measures across iterations for each model scenario explored for the fast life history.

Exploitation Level	Landings Ratio (Rec : Total)	PSE	Spawning Biomass MRE	Spawning Biomass MARE	Recruitment MRE	Recruitment MARE	OFL MRE	OFL MARE	F_{rec} MRE	F_{rec} MARE	F_{tot} MRE	F_{tot} MARE	Years (prop.) when overfishing wrongly declared	Years (prop.) when overfishing not identified
	0.3	0.2	-2.63	7.33	0.39	7.87	4.91	12.14	4.28	11.35	4.37	9.31	0.10	0.10
	0.6	0.2	-2.11	6.88	0.92	6.99	6.38	11.95	3.77	10.79	3.01	10.34	0.10	0.10
	0.9	0.2	-1.01	7.47	0.25	8.41	5.97	13.43	3.17	10.87	3.32	10.42	0.10	0.10
	0.3	0.3	-1.69	6.79	0.87	7.09	6.40	11.78	2.36	12.09	2.25	10.26	0.10	0.10
	0.6	0.3	-1.53	6.62	1.10	7.86	7.03	12.85	2.21	11.85	3.30	9.67	0.10	0.10
	0.9	0.3	0.43	6.93	1.49	7.69	7.99	14.90	2.69	11.65	2.73	11.26	0.10	0.10
	0.3	0.4	-0.02	6.17	2.37	7.09	10.77	14.08	1.65	13.84	3.00	9.21	0.10	0.10
	0.6	0.4	0.83	6.35	3.90	8.37	10.49	15.06	-0.87	14.97	0.15	11.58	0.10	0.10
	0.9	0.4	3.04	7.47	4.79	9.93	12.53	17.57	2.77	13.37	2.56	13.37	0.10	0.10
Light	0.3	0.5	1.20	6.90	3.77	8.40	9.90	14.25	3.07	14.32	3.77	10.26	0.10	0.10
	0.6	0.5	3.30	6.55	8.08	9.95	17.14	18.03	-3.26	16.01	-0.20	11.86	0.10	0.10
	0.9	0.5	5.60	7.65	6.73	10.66	15.29	17.98	-1.41	14.95	-0.22	14.11	0.10	0.10
	0.3	0.6	3.31	6.46	6.54	9.06	18.06	18.31	-3.63	16.66	0.04	8.90	0.10	0.10
	0.6	0.6	8.71	9.19	10.03	11.48	23.11	23.11	-3.32	16.73	-3.18	11.47	0.10	0.15
	0.9	0.6	9.33	9.50	9.05	10.56	21.94	22.49	-3.03	17.19	-2.82	15.52	0.10	0.10
	0.3	0.8	15.67	15.15	18.81	18.88	40.68	40.68	-12.45	22.19	-8.14	12.60	0.00	0.20
	0.6	0.8	18.26	16.90	22.35	22.35	43.48	43.48	-14.79	21.70	-13.48	16.93	0.10	0.20
	0.9	0.8	20.38	14.40	20.05	20.05	43.52	43.52	-12.04	19.65	-12.32	18.73	0.10	0.20
	0.3	1	32.17	26.28	30.83	30.83	69.63	69.63	-20.06	26.24	-19.16	19.33	0.00	0.20
	0.6	1	38.35	30.18	34.44	34.44	69.28	69.28	-22.77	27.19	-22.02	23.08	0.00	0.30
	0.9	1	33.48	22.86	29.49	29.49	62.66	62.66	-19.40	22.42	-18.98	21.65	0.10	0.20
	0.3	0.2	-1.77	7.21	0.32	6.64	16.25	16.76	2.20	10.56	4.06	10.61	0.10	0.10
	0.6	0.2	-2.85	6.90	1.62	7.31	19.34	20.27	2.95	11.52	4.99	12.05	0.10	0.10
	0.9	0.2	-0.87	7.15	1.57	7.52	20.64	21.26	2.90	10.96	2.94	11.02	0.10	0.10
	0.3	0.3	-0.16	6.66	1.70	7.60	17.75	18.40	3.72	13.87	4.34	11.18	0.10	0.10
	0.6	0.3	0.35	7.72	1.23	8.81	18.78	19.99	4.58	12.70	6.18	11.49	0.10	0.10
	0.9	0.3	-0.12	7.11	2.38	8.08	20.23	21.41	5.01	11.93	4.74	12.41	0.10	0.10
	0.3	0.4	0.32	7.23	2.86	7.15	20.16	20.20	2.02	12.70	5.09	10.38	0.10	0.10
	0.6	0.4	1.64	6.82	4.99	8.38	23.02	23.34	0.67	13.28	1.78	11.21	0.10	0.10
	0.9	0.4	0.90	7.07	3.18	8.28	24.62	24.68	3.15	15.54	3.23	14.56	0.10	0.10
	0.3	0.5	1.36	6.10	4.77	7.62	23.37	23.64	2.99	14.70	2.40	8.89	0.10	0.10
Moderate	0.6	0.5	4.01	7.27	8.13	11.33	27.39	27.39	1.89	15.00	2.11	11.00	0.10	0.10
	0.9	0.5	3.50	7.88	5.23	10.75	20.57	21.83	2.65	15.44	3.24	14.32	0.10	0.10
	0.3	0.6	3.89	9.23	9.31	10.03	32.73	32.73	-4.27	16.87	-1.36	9.97	0.10	0.10
	0.6	0.6	8.22	8.24	9.21	11.53	30.85	30.85	-2.43	15.37	0.54	12.00	0.10	0.10
	0.9	0.6	6.94	7.70	7.38	11.13	30.47	30.47	-1.09	15.11	0.18	14.19	0.10	0.10
	0.3	0.8	14.95	14.50	18.47	18.47	53.34	53.34	-10.76	20.84	-6.47	11.49	0.00	0.10
	0.6	0.8	16.91	13.76	16.94	17.00	52.19	52.19	-9.58	20.08	-8.16	15.35	0.05	0.20
	0.9	0.8	14.25	10.61	12.23	12.98	42.05	42.05	-7.72	19.44	-6.26	18.03	0.10	0.20
	0.3	1	26.27	21.99	28.19	28.19	72.88	72.88	-17.87	24.35	-13.77	15.19	0.00	0.20
	0.6	1	30.40	19.75	26.91	26.91	68.27	68.27	-12.49	22.01	-12.05	18.46	0.00	0.20
	0.9	1	22.61	12.21	15.15	15.50	48.43	48.43	-7.09	21.56	-6.00	19.65	0.10	0.20
	0.3	0.2	-0.88	6.13	-0.33	7.22	-5.57	11.93	3.89	10.55	5.26	8.99	0.10	0.00
	0.6	0.2	-1.31	6.22	-0.15	7.30	-3.46	11.63	2.90	10.60	3.12	9.04	0.10	0.05
	0.9	0.2	-0.55	6.64	-0.39	8.09	-1.86	12.67	1.53	8.14	1.86	8.37	0.10	0.10
	0.3	0.3	-0.30	6.45	-0.24	7.33	-3.77	10.66	3.75	11.27	4.25	7.86	0.10	0.05
	0.6	0.3	-0.95	6.90	0.99	7.41	-2.56	12.52	2.23	11.97	3.94	9.79	0.10	0.10
	0.9	0.3	-1.09	6.66	1.75	7.91	1.83	13.06	-0.80	10.33	-0.31	10.15	0.10	0.10
	0.3	0.4	0.11	6.18	1.11	8.01	-2.26	10.48	1.05	12.52	2.47	8.57	0.10	0.10
	0.6	0.4	0.99	6.40	2.25	7.94	0.01	12.19	1.41	12.70	1.84	10.48	0.10	0.10
Heavy	0.9	0.4	0.18	7.38	5.42	9.60	5.21	14.06	1.28	13.66	0.35	12.79	0.10	0.10
	0.3	0.5	2.43	7.34	2.25	7.95	0.15	11.92	-1.61	13.95	1.07	8.57	0.10	0.10
	0.6	0.5	3.47	7.74	4.96	9.15	4.20	13.51	-3.48	15.11	-0.76	11.81	0.10	0.10
	0.9	0.5	0.61	8.69	7.75	10.68	6.17	15.09	-2.31	14.23	-2.03	13.64	0.10	0.10
	0.3	0.6	6.50	7.05	5.91	9.10	4.72	12.18	-3.00	16.20	0.01	8.76	0.10	0.10
	0.6	0.6	5.24	10.06	11.21	12.34	10.57	16.44	-2.42	15.59	-2.21	12.23	0.10	0.10
	0.9	0.6	3.57	11.42	11.85	13.68	15.93	19.65	-4.65	16.26	-4.36	15.55	0.10	0.10
	0.3	0.8	14.56	15.67	18.72	18.78	27.25	27.25	-15.10	21.70	-12.26	14.36	0.00	0.20
	0.6	0.8	13.22	18.26	24.41	24.41	36.04	36.04	-14.82	23.27	-14.90	17.96	0.00	0.20
	0.9	0.8	7.04	20.38	25.97	25.97	40.47	40.47	-11.96	17.53	-10.37	17.01	0.10	0.20
	0.3	1	22.10	32.17	36.81	36.81	62.82	62.82	-22.77	27.64	-21.73	22.15	0.00	0.20
	0.6	1	19.80	38.35	44.54	44.54	71.93	71.93	-21.95	27.84	-24.55	25.45	0.00	0.30
	0.9	1	11.20	33.48	37.92	37.92	61.83	61.83	-19.07	23.35	-18.73	22.48	0.00	0.20

Table 5 continued.

Exploitation Level	Landings Ratio (Rec : Total)	PSE	Years (prop.) with S est. within ± 20%	Years (prop.) with OFL est. within ± 20%	Years (prop.) with overfishing	Years (prop.) when overfished	Years (prop.) ABC above biomass	C / MSY	S / S_{MSY}	ΔS
	0.3	0.2	0.70	0.50	0.28	0.00	0.00	1.03	1.19	-0.40
	0.6	0.2	0.80	0.40	0.33	0.00	0.00	1.04	1.18	-0.42
	0.9	0.2	0.70	0.40	0.39	0.11	0.06	1.04	1.14	-0.46
	0.3	0.3	0.70	0.50	0.33	0.00	0.00	1.05	1.18	-0.42
	0.6	0.3	0.70	0.40	0.33	0.00	0.00	1.04	1.18	-0.41
	0.9	0.3	0.70	0.40	0.39	0.11	0.06	1.04	1.11	-0.44
	0.3	0.4	0.70	0.40	0.33	0.00	0.00	1.06	1.18	-0.44
	0.6	0.4	0.70	0.40	0.39	0.00	0.00	1.05	1.16	-0.49
	0.9	0.4	0.70	0.35	0.44	0.11	0.06	1.03	1.10	-0.51
Light	0.3	0.5	0.70	0.40	0.39	0.00	0.00	1.04	1.12	-0.49
	0.6	0.5	0.70	0.30	0.44	0.03	0.00	1.06	1.11	-0.48
	0.9	0.5	0.70	0.30	0.44	0.17	0.06	1.05	1.03	-0.52
	0.3	0.6	0.70	0.40	0.44	0.00	0.00	1.07	1.15	-0.51
	0.6	0.6	0.60	0.30	0.56	0.06	0.03	1.07	1.06	-0.54
	0.9	0.6	0.60	0.30	0.50	0.17	0.11	1.02	0.95	-0.54
	0.3	0.8	0.50	0.20	0.67	0.17	0.06	1.06	0.94	-0.59
	0.6	0.8	0.50	0.20	0.67	0.17	0.11	1.08	0.92	-0.63
	0.9	0.8	0.50	0.20	0.64	0.28	0.17	1.05	0.87	-0.64
	0.3	1	0.40	0.20	0.83	0.28	0.17	1.05	0.77	-0.70
	0.6	1	0.30	0.20	0.83	0.28	0.17	1.07	0.79	-0.66
	0.9	1	0.40	0.20	0.78	0.39	0.22	1.05	0.76	-0.72
	0.3	0.2	0.70	0.40	0.33	0.00	0.00	0.94	1.06	0.08
	0.6	0.2	0.70	0.40	0.33	0.00	0.00	0.94	1.07	0.09
	0.9	0.2	0.70	0.30	0.33	0.06	0.06	0.96	1.04	-0.07
	0.3	0.3	0.70	0.30	0.36	0.00	0.00	0.95	1.06	0.00
	0.6	0.3	0.70	0.30	0.39	0.00	0.00	0.94	1.04	-0.01
	0.9	0.3	0.70	0.30	0.39	0.11	0.06	0.93	0.99	0.00
	0.3	0.4	0.70	0.40	0.44	0.00	0.00	0.95	1.04	-0.02
	0.6	0.4	0.70	0.30	0.44	0.00	0.00	0.95	1.01	-0.01
	0.9	0.4	0.70	0.30	0.39	0.11	0.06	0.93	1.01	-0.10
	0.3	0.5	0.70	0.30	0.44	0.00	0.00	0.94	1.03	0.07
Moderate	0.6	0.5	0.70	0.30	0.50	0.06	0.00	0.96	1.00	-0.08
	0.9	0.5	0.70	0.30	0.44	0.11	0.06	0.97	1.01	-0.05
	0.3	0.6	0.70	0.30	0.44	0.06	0.00	0.95	0.97	0.05
	0.6	0.6	0.70	0.30	0.56	0.11	0.00	0.94	0.93	-0.13
	0.9	0.6	0.70	0.30	0.50	0.17	0.06	0.94	0.93	-0.12
	0.3	0.8	0.60	0.20	0.67	0.17	0.06	0.96	0.83	-0.25
	0.6	0.8	0.50	0.20	0.67	0.17	0.06	0.94	0.82	-0.25
	0.9	0.8	0.60	0.20	0.67	0.28	0.11	0.95	0.78	-0.33
	0.3	1	0.40	0.20	0.78	0.28	0.17	0.94	0.70	-0.35
	0.6	1	0.50	0.20	0.81	0.28	0.11	0.96	0.74	-0.36
	0.9	1	0.50	0.20	0.67	0.33	0.17	0.93	0.70	-0.36
	0.3	0.2	0.70	0.40	0.33	0.11	0.00	0.88	1.00	1.46
	0.6	0.2	0.70	0.40	0.33	0.11	0.00	0.82	0.97	1.33
	0.9	0.2	0.70	0.40	0.39	0.17	0.06	0.83	0.94	1.39
	0.3	0.3	0.70	0.40	0.33	0.11	0.00	0.82	0.94	1.45
	0.6	0.3	0.70	0.40	0.33	0.11	0.00	0.83	0.96	1.41
	0.9	0.3	0.70	0.40	0.39	0.17	0.06	0.83	0.93	1.15
	0.3	0.4	0.70	0.40	0.39	0.11	0.00	0.83	0.96	1.55
	0.6	0.4	0.70	0.40	0.39	0.11	0.00	0.84	0.94	1.48
Heavy	0.9	0.4	0.70	0.40	0.39	0.17	0.06	0.82	0.92	1.38
	0.3	0.5	0.70	0.40	0.44	0.11	0.00	0.83	0.92	1.25
	0.6	0.5	0.70	0.40	0.44	0.17	0.00	0.85	0.92	1.16
	0.9	0.5	0.60	0.30	0.39	0.17	0.06	0.83	0.93	1.38
	0.3	0.6	0.70	0.40	0.50	0.17	0.00	0.85	0.88	1.22
	0.6	0.6	0.60	0.30	0.47	0.17	0.00	0.85	0.89	1.28
	0.9	0.6	0.60	0.30	0.44	0.17	0.06	0.85	0.87	1.16
	0.3	0.8	0.50	0.30	0.67	0.22	0.06	0.86	0.79	0.92
	0.6	0.8	0.50	0.30	0.61	0.22	0.06	0.85	0.78	0.85
	0.9	0.8	0.40	0.20	0.50	0.28	0.11	0.82	0.78	0.92
	0.3	1	0.30	0.20	0.72	0.28	0.11	0.84	0.69	0.64
	0.6	1	0.20	0.20	0.67	0.28	0.06	0.87	0.74	0.65
	0.9	1	0.30	0.20	0.53	0.28	0.11	0.85	0.77	0.64

Table 6. Median estimates of performance measures across iterations for each model scenario explored for the medium life history.

Exploitation Level	Landings Ratio (Rec : Total)	PSE	Spawning Biomass MRE	Spawning Biomass MARE	Recruitment MRE	Recruitment MARE	OFL MRE	OFL MARE	F_{rec} MRE	F_{rec} MARE	F_{tot} MRE	F_{tot} MARE	Years (prop.) when overfishing wrongly declared	Years (prop.) when overfishing not identified
	0.3	0.2	-2.14	8.08	-0.49	11.88	1.04	9.36	0.57	9.41	2.63	8.75	0.10	0.10
	0.6	0.2	-0.94	6.44	-0.48	12.04	1.70	8.80	1.20	9.51	1.38	9.14	0.10	0.10
	0.9	0.2	-2.81	7.91	0.32	11.84	2.13	9.94	-0.86	10.57	-0.79	10.61	0.10	0.10
	0.3	0.3	-0.43	6.83	-1.77	12.07	2.39	8.07	-0.38	13.12	-0.31	8.80	0.10	0.10
	0.6	0.3	-0.70	7.28	-1.24	12.67	4.16	9.77	0.04	11.21	-0.19	8.85	0.10	0.10
	0.9	0.3	-0.91	7.93	0.12	10.42	4.10	9.04	1.49	9.91	0.98	9.94	0.10	0.10
	0.3	0.4	0.65	6.88	-0.59	11.94	4.01	9.33	-1.55	13.22	0.12	8.10	0.10	0.10
	0.6	0.4	2.24	6.94	3.64	12.67	5.82	9.91	-2.88	13.32	-2.13	11.23	0.10	0.10
	0.9	0.4	2.07	8.53	1.62	12.88	5.60	11.40	-1.01	13.42	-0.61	12.76	0.20	0.10
Light	0.3	0.5	2.14	7.35	1.24	11.16	4.66	9.15	0.95	14.65	1.37	9.48	0.10	0.10
	0.6	0.5	6.27	8.51	6.98	13.00	9.27	10.98	-4.59	16.87	-3.64	12.02	0.10	0.10
	0.9	0.5	6.51	9.39	7.11	13.58	10.49	12.41	-4.62	14.07	-4.15	13.98	0.20	0.10
	0.3	0.6	4.68	7.67	3.90	13.25	9.54	11.35	-5.24	16.67	-4.05	9.93	0.10	0.10
	0.6	0.6	11.93	12.17	11.43	15.13	16.76	17.39	-6.61	16.19	-6.97	12.51	0.10	0.20
	0.9	0.6	12.33	12.65	12.88	17.00	14.98	16.12	-8.49	16.35	-7.46	15.22	0.10	0.20
	0.3	0.8	18.31	17.96	18.58	20.28	27.92	27.92	-14.62	23.78	-12.40	13.80	0.10	0.20
	0.6	0.8	25.19	23.60	28.16	28.34	37.69	37.69	-21.49	24.13	-19.10	19.80	0.10	0.30
	0.9	0.8	6.15	26.48	30.57	30.97	40.16	40.16	-20.21	22.73	-20.08	22.65	0.10	0.30
	0.3	1	41.17	36.73	36.14	36.14	56.23	56.23	-27.63	30.52	-26.04	26.04	0.00	0.30
	0.6	1	50.68	46.32	48.30	48.30	73.93	73.93	-32.42	34.37	-32.25	32.50	0.00	0.30
	0.9	1	49.88	50.76	46.70	46.70	67.88	67.88	-33.40	34.01	-32.52	32.82	0.00	0.30
	0.3	0.2	-1.32	7.69	-4.16	10.19	8.96	10.42	-0.45	9.32	0.31	8.57	0.10	0.10
	0.6	0.2	-0.87	7.59	-0.98	11.84	8.18	11.04	0.32	11.17	1.77	9.97	0.10	0.10
	0.9	0.2	-0.01	7.93	1.10	11.60	9.78	12.65	-0.11	10.56	0.37	10.50	0.10	0.10
	0.3	0.3	0.62	7.12	-1.76	10.50	7.71	9.93	-0.04	12.04	2.11	9.67	0.10	0.10
	0.6	0.3	1.69	7.44	-0.25	11.31	9.50	10.79	1.15	11.18	1.66	9.98	0.10	0.10
	0.9	0.3	0.41	8.46	0.95	10.92	10.82	12.07	0.16	11.68	0.46	11.61	0.10	0.10
	0.3	0.4	2.07	7.69	-1.82	13.40	11.28	12.28	-0.03	12.33	1.66	8.46	0.10	0.10
	0.6	0.4	2.20	7.06	3.18	11.59	12.97	13.81	-1.79	13.56	-1.33	10.72	0.10	0.10
	0.9	0.4	2.59	7.45	1.80	11.90	12.97	14.16	-2.64	13.63	-2.28	12.74	0.10	0.10
	0.3	0.5	1.13	6.94	2.68	13.00	12.36	13.13	0.38	14.45	1.03	8.05	0.10	0.10
Moderate	0.6	0.5	4.70	7.57	7.20	13.80	16.55	16.72	-2.93	12.87	-1.77	9.89	0.10	0.10
	0.9	0.5	6.91	7.98	6.34	14.73	14.30	14.84	-3.67	15.25	-2.73	13.90	0.10	0.10
	0.3	0.6	4.70	9.06	5.57	13.65	19.64	19.64	-7.13	16.58	-3.41	10.25	0.10	0.10
	0.6	0.6	11.45	9.83	9.18	14.14	20.43	20.43	-6.30	15.66	-4.49	11.42	0.10	0.20
	0.9	0.6	10.31	10.06	10.86	15.11	20.47	20.47	-8.90	17.82	-7.98	16.64	0.10	0.20
	0.3	0.8	17.87	16.49	18.30	19.25	34.80	34.80	-12.88	20.22	-11.38	13.14	0.00	0.20
	0.6	0.8	23.60	20.09	24.09	24.09	39.89	39.89	-17.36	22.29	-15.79	17.89	0.10	0.20
	0.9	0.8	26.60	16.61	19.79	20.75	33.58	33.59	-16.84	23.34	-16.25	21.55	0.10	0.20
	0.3	1	36.66	28.93	30.45	30.45	54.76	54.76	-24.31	28.25	-20.56	20.88	0.00	0.30
	0.6	1	46.10	32.37	34.35	34.62	60.23	60.23	-25.12	28.29	-23.32	24.13	0.00	0.30
	0.9	1	40.93	24.47	29.06	29.06	45.97	45.97	-20.73	27.73	-21.08	26.51	0.10	0.30
	0.3	0.2	-0.10	8.43	-0.97	12.04	-3.08	9.44	2.99	10.74	2.53	9.71	0.10	0.10
	0.6	0.2	-1.14	7.95	-1.47	12.05	-2.62	10.29	1.03	10.00	1.86	9.21	0.10	0.10
	0.9	0.2	0.17	6.35	-4.40	13.84	-4.46	7.91	3.15	8.87	3.70	8.48	0.10	0.10
	0.3	0.3	0.25	7.74	-3.94	12.50	-1.73	9.05	0.59	11.35	1.49	8.59	0.10	0.10
	0.6	0.3	-0.13	7.25	-0.63	11.29	-1.86	10.06	1.21	10.61	1.52	9.10	0.10	0.10
	0.9	0.3	0.54	6.75	1.46	12.26	-3.07	8.82	1.81	10.71	2.51	10.15	0.10	0.10
	0.3	0.4	0.03	7.00	-1.18	12.63	-0.52	9.26	-0.46	14.09	0.35	8.31	0.10	0.10
	0.6	0.4	1.91	8.24	4.04	13.23	2.13	11.02	-2.58	14.17	-1.98	11.45	0.10	0.10
Heavy	0.9	0.4	1.66	6.87	1.86	11.66	-0.41	8.84	0.26	11.40	-0.47	10.69	0.10	0.10
	0.3	0.5	2.76	7.99	1.34	13.06	1.79	8.83	-4.47	13.58	-1.42	8.79	0.10	0.10
	0.6	0.5	4.16	8.70	5.60	14.00	5.64	10.62	-7.84	14.33	-5.79	11.57	0.10	0.10
	0.9	0.5	2.25	7.38	5.52	15.32	0.69	8.99	0.02	12.90	0.69	12.50	0.15	0.10
	0.3	0.6	7.14	8.45	4.68	13.55	3.38	9.89	-5.57	16.98	-2.99	9.51	0.10	0.10
	0.6	0.6	8.45	13.15	11.03	16.93	10.54	15.17	-7.37	16.53	-6.65	12.81	0.10	0.20
	0.9	0.6	8.27	8.67	7.09	14.41	2.92	11.57	-3.07	15.04	-1.85	13.70	0.10	0.10
	0.3	0.8	16.51	18.31	19.31	21.63	23.08	23.08	-19.15	23.38	-13.19	15.06	0.00	0.20
	0.6	0.8	20.11	25.19	27.72	27.85	35.03	35.03	-20.70	25.03	-21.10	22.23	0.00	0.20
	0.9	0.8	16.16	8.34	13.97	18.07	4.96	10.00	-2.80	20.23	-2.27	19.35	0.20	0.10
	0.3	1	28.96	41.17	41.38	41.38	60.64	60.64	-29.33	31.47	-27.39	27.48	0.00	0.30
	0.6	1	32.38	50.68	51.31	51.31	73.37	73.37	-30.47	31.76	-29.99	30.75	0.00	0.30
	0.9	1	24.50	8.46	14.23	17.53	5.73	10.03	-7.24	23.62	-6.64	21.57	0.20	0.10

Table 6 continued.

Exploitation Level	Landings Ratio (Rec : Total)	PSE	Years (prop.) with S est. within ± 20%	Years (prop.) with OFL est. within ± 20%	Years (prop.) with overfishing	Years (prop.) when overfished	Years (prop.) ABC above biomass	C / MSY	S / S_{MSY}	ΔS
	0.3	0.2	0.80	0.70	0.22	0.00	0.00	1.20	1.40	-0.40
	0.6	0.2	0.80	0.70	0.22	0.00	0.00	1.21	1.38	-0.45
	0.9	0.2	0.80	0.70	0.22	0.00	0.00	1.22	1.44	-0.45
	0.3	0.3	0.80	0.70	0.25	0.00	0.00	1.22	1.39	-0.43
	0.6	0.3	0.80	0.70	0.25	0.00	0.00	1.22	1.38	-0.43
	0.9	0.3	0.80	0.70	0.28	0.00	0.00	1.21	1.40	-0.45
	0.3	0.4	0.80	0.70	0.28	0.00	0.00	1.23	1.39	-0.44
	0.6	0.4	0.80	0.60	0.33	0.00	0.00	1.23	1.34	-0.48
	0.9	0.4	0.70	0.60	0.28	0.00	0.00	1.24	1.40	-0.47
Light	0.3	0.5	0.80	0.70	0.33	0.00	0.00	1.21	1.33	-0.46
	0.6	0.5	0.70	0.60	0.39	0.00	0.00	1.26	1.30	-0.49
	0.9	0.5	0.70	0.50	0.33	0.00	0.00	1.24	1.39	-0.50
	0.3	0.6	0.75	0.60	0.33	0.00	0.00	1.25	1.35	-0.47
	0.6	0.6	0.60	0.50	0.44	0.00	0.00	1.28	1.30	-0.53
	0.9	0.6	0.60	0.50	0.36	0.00	0.00	1.23	1.36	-0.50
	0.3	0.8	0.50	0.30	0.61	0.00	0.00	1.30	1.18	-0.56
	0.6	0.8	0.40	0.30	0.67	0.00	0.00	1.33	1.11	-0.62
	0.9	0.8	0.40	0.20	0.39	0.00	0.00	1.28	1.39	-0.53
	0.3	1	0.30	0.10	0.83	0.11	0.00	1.31	0.91	-0.71
	0.6	1	0.20	0.10	0.89	0.28	0.00	1.33	0.82	-0.74
	0.9	1	0.20	0.10	0.90	0.29	0.00	1.29	0.80	-0.78
	0.3	0.2	0.80	0.60	0.17	0.00	0.00	0.94	1.12	0.06
	0.6	0.2	0.80	0.60	0.22	0.00	0.00	0.96	1.10	0.07
	0.9	0.2	0.80	0.60	0.25	0.00	0.00	0.97	1.13	0.03
	0.3	0.3	0.80	0.60	0.22	0.00	0.00	0.97	1.10	0.02
	0.6	0.3	0.80	0.60	0.28	0.00	0.00	0.95	1.10	-0.02
	0.9	0.3	0.80	0.60	0.28	0.00	0.00	0.94	1.09	0.00
	0.3	0.4	0.80	0.60	0.22	0.00	0.00	0.96	1.10	0.01
	0.6	0.4	0.80	0.60	0.28	0.00	0.00	0.97	1.07	-0.01
	0.9	0.4	0.70	0.60	0.33	0.00	0.00	0.96	1.09	-0.03
	0.3	0.5	0.80	0.60	0.28	0.00	0.00	0.96	1.09	0.02
Moderate	0.6	0.5	0.80	0.50	0.33	0.00	0.00	0.99	1.06	-0.04
	0.9	0.5	0.70	0.50	0.33	0.00	0.00	0.99	1.09	-0.02
	0.3	0.6	0.70	0.50	0.33	0.00	0.00	0.96	1.04	0.00
	0.6	0.6	0.70	0.40	0.44	0.00	0.00	0.97	1.01	-0.11
	0.9	0.6	0.70	0.40	0.44	0.00	0.00	1.01	1.01	-0.11
	0.3	0.8	0.50	0.30	0.61	0.00	0.00	1.02	0.94	-0.20
	0.6	0.8	0.50	0.20	0.67	0.00	0.00	1.03	0.88	-0.24
	0.9	0.8	0.50	0.30	0.67	0.00	0.00	1.03	0.86	-0.29
	0.3	1	0.30	0.10	0.83	0.00	0.00	1.02	0.78	-0.39
	0.6	1	0.30	0.10	0.89	0.22	0.00	1.01	0.68	-0.48
	0.9	1	0.40	0.20	0.83	0.22	0.00	1.00	0.70	-0.48
	0.3	0.2	0.80	0.60	0.22	0.17	0.00	0.65	0.76	1.96
	0.6	0.2	0.80	0.60	0.22	0.22	0.00	0.60	0.72	1.91
	0.9	0.2	0.80	0.60	0.22	0.22	0.00	0.61	0.72	2.07
	0.3	0.3	0.80	0.60	0.17	0.22	0.00	0.60	0.73	1.98
	0.6	0.3	0.75	0.60	0.22	0.22	0.00	0.60	0.71	1.99
	0.9	0.3	0.80	0.70	0.28	0.22	0.00	0.62	0.72	1.95
	0.3	0.4	0.80	0.60	0.22	0.22	0.00	0.59	0.72	2.03
	0.6	0.4	0.70	0.60	0.28	0.22	0.00	0.61	0.70	1.96
Heavy	0.9	0.4	0.80	0.60	0.28	0.22	0.00	0.61	0.71	1.90
	0.3	0.5	0.70	0.60	0.28	0.22	0.00	0.61	0.69	1.87
	0.6	0.5	0.70	0.60	0.33	0.22	0.00	0.61	0.70	1.81
	0.9	0.5	0.70	0.60	0.28	0.22	0.00	0.60	0.71	1.87
	0.3	0.6	0.70	0.60	0.33	0.22	0.00	0.63	0.69	1.79
	0.6	0.6	0.60	0.50	0.39	0.22	0.00	0.63	0.68	1.72
	0.9	0.6	0.70	0.50	0.39	0.22	0.00	0.63	0.70	1.77
	0.3	0.8	0.50	0.40	0.56	0.28	0.00	0.65	0.63	1.44
	0.6	0.8	0.40	0.30	0.61	0.33	0.00	0.64	0.60	1.37
	0.9	0.8	0.60	0.50	0.50	0.28	0.00	0.63	0.63	1.33
	0.3	1	0.20	0.10	0.78	0.44	0.00	0.63	0.55	1.01
	0.6	1	0.20	0.10	0.72	0.44	0.00	0.65	0.54	0.94
	0.9	1	0.60	0.50	0.61	0.39	0.00	0.65	0.58	1.10

Table 7. Median estimates of performance measures across iterations for each model scenario explored for the slow life history.

Exploitation Level	Landings Ratio (Rec : Total)	PSE	Spawning Biomass MRE	Spawning Biomass MARE	Recruitment MRE	Recruitment MARE	OFL MRE	OFL MARE	F_{rec} MRE	F_{rec} MARE	F_{tot} MRE	F_{tot} MARE	Years (prop.) when overfishing wrongly declared	Years (prop.) when overfishing not identified
	0.3	0.2	0.05	8.88	-1.27	11.19	11.69	12.87	-1.02	10.78	-1.69	8.75	0.00	0.20
	0.6	0.2	1.50	7.89	-0.76	11.22	11.90	12.58	-0.11	9.83	-0.16	9.27	0.00	0.10
	0.9	0.2	1.16	9.56	0.77	11.86	13.33	14.00	-2.68	10.85	-2.29	10.72	0.00	0.20
	0.3	0.3	2.81	8.93	1.05	11.59	13.79	14.05	-3.51	13.25	-2.47	10.37	0.00	0.20
	0.6	0.3	2.54	8.99	2.41	11.49	14.61	14.91	-4.51	13.00	-3.65	10.89	0.05	0.20
	0.9	0.3	4.82	8.26	2.15	12.53	13.04	13.54	-2.72	10.65	-3.11	10.14	0.10	0.20
	0.3	0.4	1.91	8.56	1.75	11.71	16.09	16.32	-5.47	14.36	-3.53	9.52	0.00	0.20
	0.6	0.4	4.43	9.86	3.14	13.54	14.91	15.20	-5.92	14.15	-4.85	11.78	0.10	0.20
	0.9	0.4	9.50	10.95	7.13	15.65	16.38	16.86	-3.89	13.46	-4.32	13.40	0.10	0.20
Light	0.3	0.5	3.79	8.51	2.08	11.35	13.77	14.44	-2.25	14.99	-0.44	9.88	0.10	0.20
	0.6	0.5	8.65	10.21	5.30	12.16	18.90	19.09	-8.82	16.19	-6.88	13.28	0.10	0.20
	0.9	0.5	12.04	12.40	6.69	14.20	21.30	21.30	-9.41	14.98	-9.04	14.52	0.10	0.20
	0.3	0.6	7.25	9.45	3.94	11.92	18.69	18.69	-6.40	16.47	-5.09	10.02	0.10	0.30
	0.6	0.6	13.93	13.85	11.69	16.29	25.92	25.92	-7.74	16.67	-8.81	13.68	0.10	0.30
	0.9	0.6	19.18	17.50	17.25	19.75	28.20	28.20	-12.56	17.78	-11.91	16.78	0.10	0.30
	0.3	0.8	21.96	22.53	24.13	25.01	37.25	37.25	-17.88	24.78	-15.83	17.36	0.00	0.40
	0.6	0.8	34.67	32.62	35.32	35.32	47.88	47.88	-24.84	26.27	-23.52	23.74	0.00	0.40
	0.9	0.8	41.40	39.27	40.94	40.94	53.71	53.71	-28.86	30.19	-28.60	29.64	0.00	0.40
	0.3	1	51.15	48.37	50.19	50.19	69.50	69.50	-35.02	35.44	-30.76	30.76	0.00	0.50
	0.6	1	65.28	67.74	69.12	69.12	88.57	88.57	-42.01	42.42	-40.77	40.77	0.00	0.50
	0.9	1	67.23	68.77	73.25	73.25	89.05	89.05	-43.83	44.30	-42.82	42.92	0.00	0.40
	0.3	0.2	1.32	7.91	-1.06	8.98	20.23	20.23	-4.17	10.31	-1.98	8.63	0.00	0.20
	0.6	0.2	1.12	8.38	0.10	10.73	17.60	17.60	-1.73	10.59	0.09	9.48	0.00	0.10
	0.9	0.2	2.57	7.94	1.43	10.54	19.16	19.16	-1.76	10.48	-1.59	10.03	0.00	0.15
	0.3	0.3	2.59	7.88	1.30	10.96	19.33	19.33	-2.61	10.94	-2.45	9.04	0.00	0.10
	0.6	0.3	4.01	7.65	1.33	10.67	19.20	19.20	-2.47	10.90	-0.86	9.68	0.00	0.20
	0.9	0.3	3.70	8.07	2.23	10.01	21.28	21.28	-3.70	12.65	-2.92	12.51	0.10	0.20
	0.3	0.4	4.47	7.53	0.76	10.46	20.41	20.41	-2.48	11.57	-1.54	8.25	0.00	0.20
	0.6	0.4	4.70	8.96	2.27	10.42	23.20	23.20	-4.54	14.15	-3.97	11.55	0.10	0.20
	0.9	0.4	5.53	10.08	6.62	12.47	23.41	23.46	-6.64	14.81	-6.11	13.83	0.10	0.20
	0.3	0.5	2.91	7.58	4.82	11.12	22.06	22.06	-3.52	13.96	-2.36	9.07	0.10	0.20
Moderate	0.6	0.5	8.17	9.10	8.67	13.93	26.56	26.56	-7.52	14.22	-6.29	11.62	0.10	0.20
	0.9	0.5	10.33	9.55	9.25	14.60	26.75	26.75	-7.91	15.73	-7.55	15.11	0.10	0.20
	0.3	0.6	6.61	10.53	7.22	13.87	29.16	29.16	-10.27	18.27	-6.41	10.48	0.00	0.30
	0.6	0.6	13.42	13.76	15.06	16.79	34.20	34.20	-12.85	18.04	-10.57	14.47	0.10	0.30
	0.9	0.6	16.73	16.68	16.21	18.87	38.02	38.02	-15.37	20.90	-14.76	19.44	0.10	0.30
	0.3	0.8	22.07	24.10	25.37	25.51	49.16	49.16	-17.14	22.02	-16.35	16.99	0.00	0.40
	0.6	0.8	32.61	33.44	34.57	34.57	58.57	58.57	-27.02	27.78	-24.85	25.39	0.00	0.40
	0.9	0.8	39.28	33.74	37.54	37.54	60.52	60.52	-26.36	28.93	-25.97	28.54	0.00	0.40
	0.3	1	48.02	47.11	52.67	52.67	78.04	78.04	-33.77	35.65	-30.52	30.52	0.00	0.50
	0.6	1	67.73	59.69	64.53	64.53	93.42	93.42	-37.79	38.39	-36.40	36.51	0.00	0.50
	0.9	1	68.61	52.29	57.12	57.12	80.48	80.48	-34.67	35.57	-34.53	35.16	0.00	0.50
	0.3	0.2	2.01	10.44	-1.39	12.21	8.93	12.04	-0.98	13.04	0.06	10.78	0.00	0.20
	0.6	0.2	-0.03	10.44	-0.65	12.73	9.39	12.96	-1.51	12.00	-0.48	11.59	0.00	0.20
	0.9	0.2	1.43	10.04	0.09	12.44	8.88	12.32	-1.05	11.45	-0.75	11.02	0.00	0.10
	0.3	0.3	2.91	10.46	0.54	12.50	12.01	14.62	-2.73	11.85	-3.29	11.03	0.00	0.20
	0.6	0.3	2.58	10.45	1.27	13.08	10.41	12.58	-2.96	13.37	-1.78	12.26	0.00	0.20
	0.9	0.3	2.43	12.33	4.17	13.73	13.14	15.52	-5.35	13.77	-5.37	12.58	0.10	0.20
	0.3	0.4	1.96	9.67	2.96	12.96	10.57	13.28	-2.81	14.39	-2.63	11.21	0.00	0.20
	0.6	0.4	4.90	11.02	4.61	14.28	12.70	14.74	-6.71	16.38	-4.57	14.08	0.10	0.20
Heavy	0.9	0.4	4.85	12.78	7.65	14.71	17.14	18.46	-6.91	15.10	-7.36	14.44	0.10	0.20
	0.3	0.5	4.33	10.21	3.35	13.47	11.75	13.31	-5.44	14.65	-2.72	11.21	0.00	0.20
	0.6	0.5	7.03	11.42	5.52	13.26	17.16	17.40	-10.33	16.18	-7.87	13.86	0.10	0.20
	0.9	0.5	8.12	13.23	10.91	16.30	19.98	20.05	-10.72	16.64	-10.58	15.87	0.10	0.20
	0.3	0.6	8.85	11.02	3.92	14.14	16.09	16.70	-6.61	18.88	-4.04	11.85	0.00	0.20
	0.6	0.6	13.48	15.86	12.26	18.25	22.47	22.70	-9.00	17.45	-9.14	14.16	0.10	0.25
	0.9	0.6	16.48	20.78	17.28	20.52	28.06	28.06	-14.82	20.66	-14.74	20.78	0.10	0.30
	0.3	0.8	24.15	21.96	21.16	23.95	32.14	32.14	-18.93	23.98	-16.09	16.90	0.00	0.30
	0.6	0.8	33.45	34.67	32.73	32.73	45.86	45.86	-24.85	28.05	-24.12	24.69	0.00	0.40
	0.9	0.8	33.70	41.40	41.37	41.37	53.76	53.76	-26.53	28.55	-27.19	27.89	0.00	0.30
	0.3	1	47.17	51.15	52.91	52.91	67.83	67.83	-35.00	36.88	-31.22	31.27	0.00	0.40
	0.6	1	59.72	65.28	67.03	67.03	84.59	84.59	-39.58	39.71	-37.79	38.11	0.00	0.40
	0.9	1	52.42	67.23	69.51	69.51	81.28	81.28	-40.36	40.36	-40.50	40.50	0.00	0.40

Table 7 continued.

Exploitation Level	Landings Ratio (Rec : Total)	PSE	Years (prop.) with S est. within ± 20%	Years (prop.) with OFL est. within ± 20%	Years (prop.) with overfishing	Years (prop.) when overfished	Years (prop.) ABC above biomass	C / MSY	S / S_{MSY}	ΔS
Light	0.3	0.2	0.90	0.70	0.22	0.00	0.00	1.47	1.63	-0.34
	0.6	0.2	0.90	0.70	0.22	0.00	0.00	1.49	1.63	-0.35
	0.9	0.2	0.80	0.60	0.33	0.00	0.00	1.49	1.65	-0.34
	0.3	0.3	0.80	0.70	0.28	0.00	0.00	1.49	1.62	-0.34
	0.6	0.3	0.80	0.60	0.33	0.00	0.00	1.50	1.61	-0.35
	0.9	0.3	0.80	0.60	0.33	0.00	0.00	1.50	1.59	-0.36
	0.3	0.4	0.80	0.60	0.33	0.00	0.00	1.49	1.63	-0.36
	0.6	0.4	0.80	0.60	0.33	0.00	0.00	1.50	1.60	-0.36
	0.9	0.4	0.70	0.60	0.39	0.00	0.00	1.56	1.58	-0.37
	0.3	0.5	0.80	0.70	0.28	0.00	0.00	1.48	1.59	-0.37
	0.6	0.5	0.70	0.50	0.44	0.00	0.00	1.55	1.59	-0.39
	0.9	0.5	0.70	0.50	0.44	0.00	0.00	1.60	1.57	-0.40
	0.3	0.6	0.80	0.50	0.39	0.00	0.00	1.52	1.61	-0.35
	0.6	0.6	0.60	0.40	0.56	0.00	0.00	1.59	1.59	-0.39
	0.9	0.6	0.50	0.30	0.50	0.00	0.00	1.62	1.48	-0.44
	0.3	0.8	0.40	0.20	0.67	0.00	0.00	1.67	1.50	-0.43
	0.6	0.8	0.30	0.20	0.78	0.00	0.00	1.81	1.46	-0.49
	0.9	0.8	0.20	0.10	0.78	0.00	0.00	1.80	1.40	-0.53
	0.3	1	0.20	0.10	0.89	0.00	0.00	1.89	1.28	-0.58
	0.6	1	0.10	0.00	0.94	0.00	0.00	1.95	1.19	-0.64
	0.9	1	0.10	0.00	0.89	0.00	0.00	1.96	1.23	-0.62
Moderate	0.3	0.2	0.90	0.50	0.22	0.00	0.00	1.14	1.30	-0.16
	0.6	0.2	0.90	0.55	0.22	0.00	0.00	1.18	1.31	-0.16
	0.9	0.2	0.90	0.50	0.28	0.00	0.00	1.17	1.31	-0.14
	0.3	0.3	0.90	0.50	0.22	0.00	0.00	1.17	1.31	-0.18
	0.6	0.3	0.90	0.50	0.28	0.00	0.00	1.19	1.29	-0.19
	0.9	0.3	0.80	0.45	0.28	0.00	0.00	1.17	1.30	-0.18
	0.3	0.4	0.90	0.50	0.25	0.00	0.00	1.18	1.29	-0.17
	0.6	0.4	0.90	0.40	0.33	0.00	0.00	1.20	1.29	-0.19
	0.9	0.4	0.80	0.40	0.39	0.00	0.00	1.19	1.28	-0.19
	0.3	0.5	0.90	0.40	0.28	0.00	0.00	1.16	1.29	-0.16
	0.6	0.5	0.80	0.30	0.39	0.00	0.00	1.23	1.27	-0.18
	0.9	0.5	0.70	0.40	0.39	0.00	0.00	1.23	1.28	-0.18
	0.3	0.6	0.80	0.30	0.44	0.00	0.00	1.17	1.26	-0.19
	0.6	0.6	0.60	0.20	0.50	0.00	0.00	1.24	1.24	-0.24
	0.9	0.6	0.50	0.20	0.56	0.00	0.00	1.27	1.24	-0.25
	0.3	0.8	0.40	0.10	0.72	0.00	0.00	1.30	1.19	-0.28
	0.6	0.8	0.30	0.10	0.78	0.00	0.00	1.37	1.12	-0.36
	0.9	0.8	0.30	0.10	0.72	0.00	0.00	1.43	1.11	-0.40
	0.3	1	0.10	0.00	0.89	0.00	0.00	1.46	1.03	-0.45
	0.6	1	0.10	0.00	0.94	0.00	0.00	1.54	0.95	-0.51
	0.9	1	0.10	0.10	0.89	0.00	0.00	1.53	0.93	-0.53
Heavy	0.3	0.2	0.70	0.70	0.28	0.00	0.00	0.62	0.71	0.50
	0.6	0.2	0.70	0.60	0.33	0.00	0.00	0.59	0.67	0.46
	0.9	0.2	0.70	0.65	0.33	0.00	0.00	0.59	0.67	0.45
	0.3	0.3	0.70	0.60	0.33	0.00	0.00	0.60	0.68	0.45
	0.6	0.3	0.70	0.60	0.33	0.00	0.00	0.59	0.67	0.45
	0.9	0.3	0.60	0.60	0.39	0.00	0.00	0.61	0.68	0.44
	0.3	0.4	0.70	0.60	0.31	0.00	0.00	0.59	0.68	0.48
	0.6	0.4	0.70	0.60	0.39	0.00	0.00	0.61	0.68	0.42
	0.9	0.4	0.60	0.50	0.47	0.00	0.00	0.62	0.67	0.41
	0.3	0.5	0.70	0.60	0.36	0.00	0.00	0.61	0.68	0.44
	0.6	0.5	0.70	0.50	0.44	0.00	0.00	0.62	0.67	0.41
	0.9	0.5	0.60	0.50	0.50	0.00	0.00	0.61	0.66	0.41
	0.3	0.6	0.70	0.50	0.39	0.00	0.00	0.62	0.66	0.40
	0.6	0.6	0.60	0.40	0.50	0.00	0.00	0.64	0.65	0.36
	0.9	0.6	0.50	0.30	0.61	0.00	0.00	0.66	0.65	0.32
	0.3	0.8	0.40	0.30	0.67	0.00	0.00	0.67	0.62	0.24
	0.6	0.8	0.30	0.20	0.78	0.06	0.00	0.70	0.58	0.13
	0.9	0.8	0.20	0.20	0.78	0.06	0.00	0.70	0.59	0.11
	0.3	1	0.15	0.10	0.89	0.31	0.00	0.73	0.54	-0.01
	0.6	1	0.10	0.10	0.94	0.39	0.00	0.77	0.52	-0.12
	0.9	1	0.10	0.10	0.89	0.33	0.00	0.76	0.54	-0.05

Table 8. Median estimates of performance measures across iterations for the sensitivity run where natural mortality varies across years, but is assumed fixed in the assessment model. The sensitivity run was conducted for medium life history that is moderately exploited.

Exploitation Level	Landings Ratio (Rec : Total)	PSE	Spawning Biomass MRE	Spawning Biomass MARE	Recruitment MRE	Recruitment MARE	OFL MRE	OFL MARE	F_{rec} MRE	F_{rec} MARE	F_{tot} MRE	F_{tot} MARE	Years (prop.) when overfishing wrongly declared	Years (prop.) when overfishing not identified
	0.3	0.2	-0.69	7.85	-0.06	12.04	1.38	9.05	2.27	11.24	1.30	9.98	0.10	0.10
	0.6	0.2	0.12	7.45	-1.37	11.11	2.95	9.81	0.73	10.40	0.29	9.43	0.10	0.10
	0.9	0.2	0.58	8.72	0.54	11.52	3.10	10.10	-0.24	11.13	-0.27	10.50	0.10	0.10
	0.3	0.3	-0.44	7.27	-0.65	13.14	2.61	8.77	1.86	14.04	2.59	9.73	0.10	0.10
	0.6	0.3	2.31	7.01	2.93	12.98	5.09	9.73	-2.42	12.70	-0.79	10.02	0.10	0.10
	0.9	0.3	2.34	8.91	2.75	12.93	5.64	11.35	1.19	13.63	0.86	12.96	0.10	0.10
	0.3	0.4	4.39	7.69	5.09	14.31	8.67	11.01	-3.43	15.65	-2.20	8.72	0.10	0.10
	0.6	0.4	12.60	12.89	12.10	15.99	17.53	17.97	-12.46	18.17	-9.96	14.02	0.10	0.20
	0.9	0.4	11.31	11.90	13.96	17.10	18.61	18.76	-12.03	16.85	-11.55	16.38	0.10	0.20
	0.3	0.5	2.88	8.08	3.20	12.37	5.23	10.40	-2.88	14.61	-1.38	9.74	0.10	0.10
Moderate	0.6	0.5	5.08	8.45	7.90	15.55	8.91	11.52	-2.98	16.03	-3.16	11.44	0.10	0.10
	0.9	0.5	7.36	9.97	9.14	14.78	11.88	13.66	-5.34	16.38	-4.82	15.25	0.10	0.10
	0.3	0.6	5.74	8.44	6.02	13.68	9.61	12.08	-5.53	17.18	-3.42	10.11	0.10	0.10
	0.6	0.6	11.21	12.14	13.51	16.10	17.80	18.20	-11.16	17.38	-10.05	13.66	0.10	0.20
	0.9	0.6	11.37	12.89	11.65	15.87	19.79	20.71	-9.75	17.06	-9.06	16.55	0.10	0.20
	0.3	0.8	20.25	20.25	18.64	19.60	28.81	28.81	-14.24	21.11	-13.00	14.91	0.10	0.20
	0.6	0.8	26.33	26.33	31.75	31.75	39.21	39.21	-21.64	25.47	-20.78	21.72	0.10	0.30
	0.9	0.8	25.69	25.69	30.06	30.42	37.42	37.42	-21.81	25.26	-21.54	24.83	0.10	0.20
	0.3	1	38.66	38.66	41.78	41.78	61.84	61.84	-28.90	31.31	-26.25	26.25	0.00	0.30
	0.6	1	47.85	47.85	49.67	49.67	74.33	74.33	-30.63	32.77	-30.87	30.93	0.00	0.30
	0.9	1	38.97	38.97	44.75	44.75	66.08	66.08	-29.73	31.24	-29.47	29.81	0.10	0.30

Exploitation Level	Landings Ratio (Rec : Total)	PSE	Years (prop.) with S est. within ± 20%	Years (prop.) with OFL est. within ± 20%	Years (prop.) with overfishing	Years (prop.) when overfished	Years (prop.) ABC above biomass	C / MSY	S / S_{MSY}	ΔS
	0.30	0.20	0.80	0.70	0.17	0.00	0.00	0.95	1.10	0.06
	0.60	0.20	0.80	0.70	0.25	0.00	0.00	0.95	1.13	-0.01
	0.90	0.20	0.80	0.60	0.28	0.00	0.00	0.95	1.12	0.02
	0.30	0.30	0.80	0.70	0.22	0.00	0.00	0.96	1.13	0.03
	0.60	0.30	0.80	0.60	0.28	0.00	0.00	0.96	1.11	-0.02
	0.90	0.30	0.70	0.60	0.33	0.00	0.00	0.98	1.08	-0.01
	0.30	0.40	0.80	0.60	0.33	0.00	0.00	0.99	1.06	0.02
	0.60	0.40	0.60	0.50	0.44	0.00	0.00	0.99	1.00	-0.15
	0.90	0.40	0.60	0.40	0.44	0.00	0.00	1.00	1.03	-0.11
	0.30	0.50	0.80	0.60	0.28	0.00	0.00	0.99	1.11	0.00
Moderate	0.60	0.50	0.70	0.60	0.33	0.00	0.00	0.96	1.05	-0.07
	0.90	0.50	0.70	0.50	0.39	0.00	0.00	0.96	1.03	-0.08
	0.30	0.60	0.70	0.60	0.39	0.00	0.00	0.99	1.05	-0.09
	0.60	0.60	0.60	0.50	0.44	0.00	0.00	1.01	1.02	-0.14
	0.90	0.60	0.60	0.40	0.44	0.00	0.00	1.00	1.01	-0.11
	0.30	0.80	0.50	0.30	0.61	0.00	0.00	1.02	0.94	-0.18
	0.60	0.80	0.40	0.20	0.67	0.00	0.00	1.03	0.87	-0.30
	0.90	0.80	0.40	0.30	0.61	0.00	0.00	1.03	0.87	-0.32
	0.30	1.00	0.20	0.10	0.83	0.11	0.00	1.05	0.78	-0.42
	0.60	1.00	0.10	0.10	0.83	0.17	0.00	1.04	0.71	-0.47
	0.90	1.00	0.20	0.10	0.72	0.22	0.00	1.01	0.72	-0.51

Table 9. Comparison of some performance measures from the sensitivity run (where M varies annually but is assumed fixed in the assessment) and the base model run (where M does not vary).

Exploitation Level	Landings Ratio (Rec : Total)	PSE	OFL MARE	OFL MARE	OFL MRE	OFL MRE	Years (prop.) with S est. within ± 20%	Years (prop.) with S est. within ± 20%	Years (prop.) with OFL est. within ± 20%	Years (prop.) with OFL est. within ± 20%	Years (prop.) with overfishing	Years (prop.) with overfishing
			Base	Varying M	Base	Varying M	Base	Varying M	Base	Varying M	Base	Varying M
	0.30	0.20	10.42	9.05	10.19	1.38	0.80	0.80	0.60	0.70	0.17	0.17
	0.60	0.20	11.04	9.81	11.84	2.95	0.80	0.80	0.60	0.70	0.22	0.25
	0.90	0.20	12.65	10.10	11.60	3.10	0.80	0.80	0.60	0.60	0.22	0.28
	0.30	0.30	9.93	8.77	10.50	2.61	0.80	0.80	0.60	0.70	0.22	0.22
	0.60	0.30	10.79	9.73	11.31	5.09	0.80	0.80	0.60	0.60	0.22	0.28
	0.90	0.30	12.07	11.35	10.92	5.64	0.80	0.70	0.60	0.60	0.22	0.33
	0.30	0.40	12.28	11.01	13.40	8.67	0.80	0.80	0.60	0.60	0.22	0.33
	0.60	0.40	13.81	17.97	11.59	17.53	0.80	0.60	0.60	0.50	0.22	0.44
	0.90	0.40	14.16	18.76	11.90	18.61	0.70	0.60	0.60	0.40	0.22	0.44
	0.30	0.50	13.13	10.40	13.00	5.23	0.80	0.80	0.60	0.60	0.22	0.28
Moderate	0.60	0.50	16.72	11.52	13.80	8.91	0.80	0.70	0.50	0.60	0.22	0.33
	0.90	0.50	14.84	13.66	14.73	11.88	0.70	0.70	0.50	0.50	0.22	0.39
	0.30	0.60	19.64	12.08	13.65	9.61	0.70	0.70	0.50	0.60	0.22	0.39
	0.60	0.60	20.43	18.20	14.14	17.80	0.70	0.60	0.40	0.50	0.22	0.44
	0.90	0.60	20.47	20.71	15.11	19.79	0.70	0.60	0.40	0.40	0.22	0.44
	0.30	0.80	34.80	28.81	19.25	28.81	0.50	0.50	0.30	0.30	0.28	0.61
	0.60	0.80	39.89	39.21	24.09	39.21	0.50	0.40	0.20	0.20	0.33	0.67
	0.90	0.80	33.59	37.42	20.75	37.42	0.50	0.40	0.30	0.30	0.28	0.61
	0.30	1.00	54.76	61.84	30.45	61.84	0.30	0.20	0.10	0.10	0.44	0.83
	0.60	1.00	60.23	74.33	34.62	74.33	0.30	0.10	0.10	0.10	0.44	0.83
	0.90	1.00	45.97	66.08	29.06	66.08	0.40	0.20	0.20	0.10	0.39	0.72

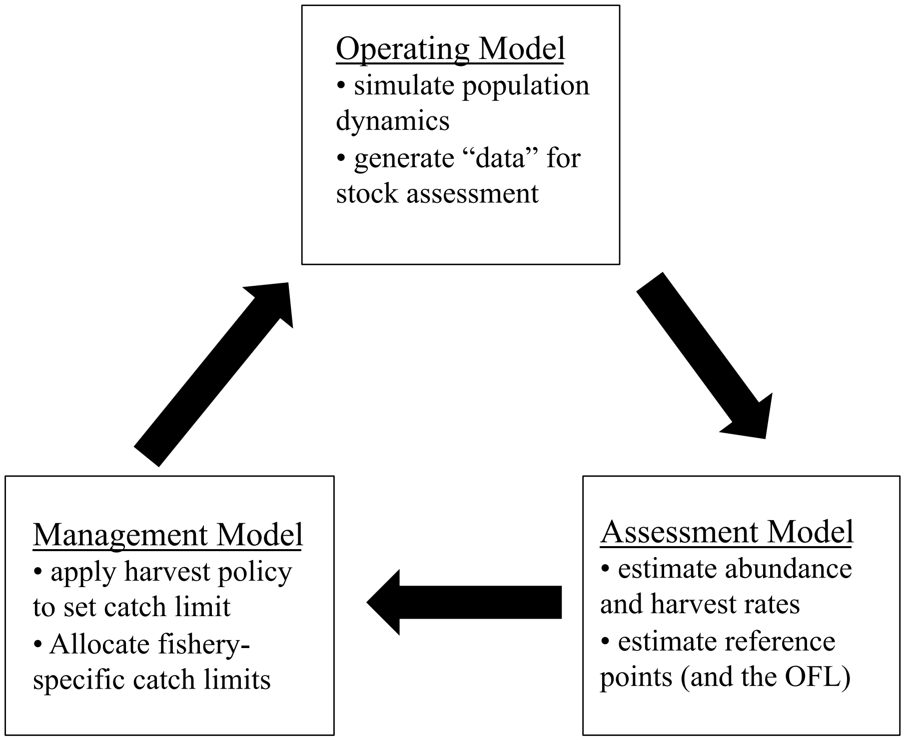

Figure 1. The individual model components linked together in the simulation. This loop is repeated over a set number of years for each run, and a total of 1,000 runs are conducted for each scenario of the simulation.

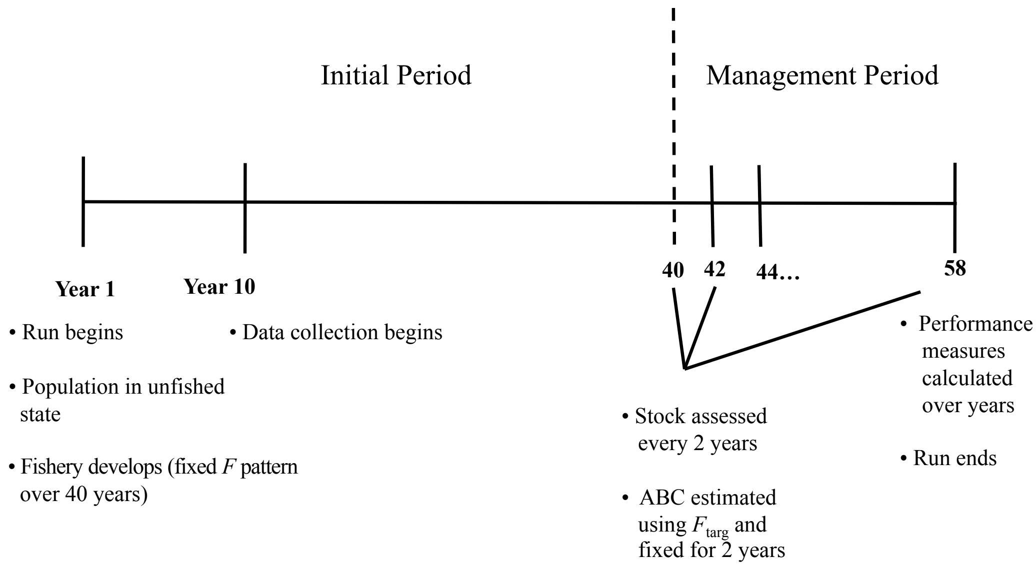

Figure 2. Timeline of the dynamics in the simulation model.

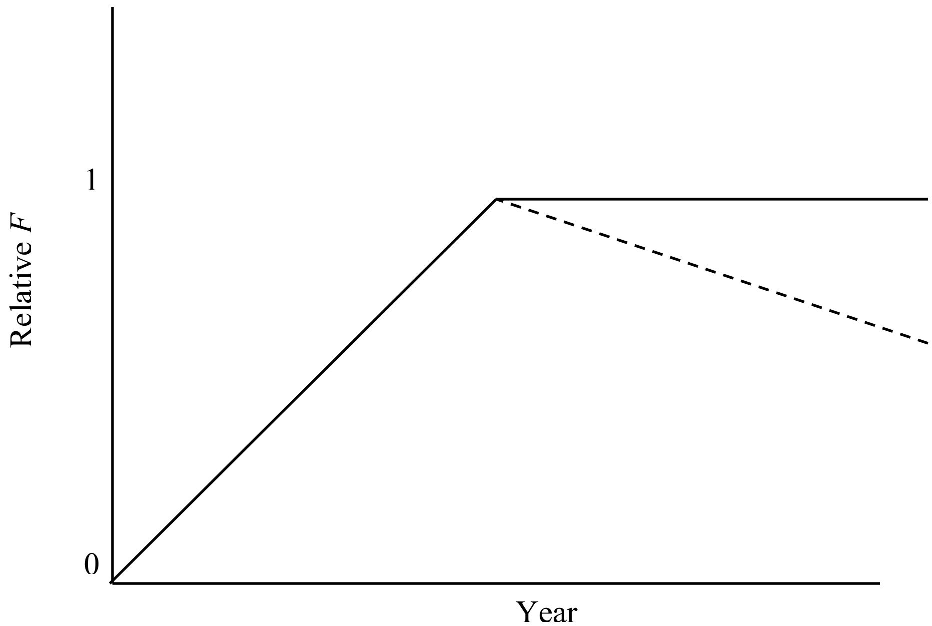

Figure 3. Example patterns of relative total fishing mortality (commercial + recreational) during the initial period. The fishery-specific estimates of F are estimated in the model and are dependent upon the exploitation scenario and the relative size of the recreational fishery. The maximum total fishing mortality in the initial period was set at 0.5, 1.0 and 2.0 x F_{MSY} for the light, moderate and heavy exploitation scenarios, respectively. Results are shown for the model with fishing mortality plateauing.

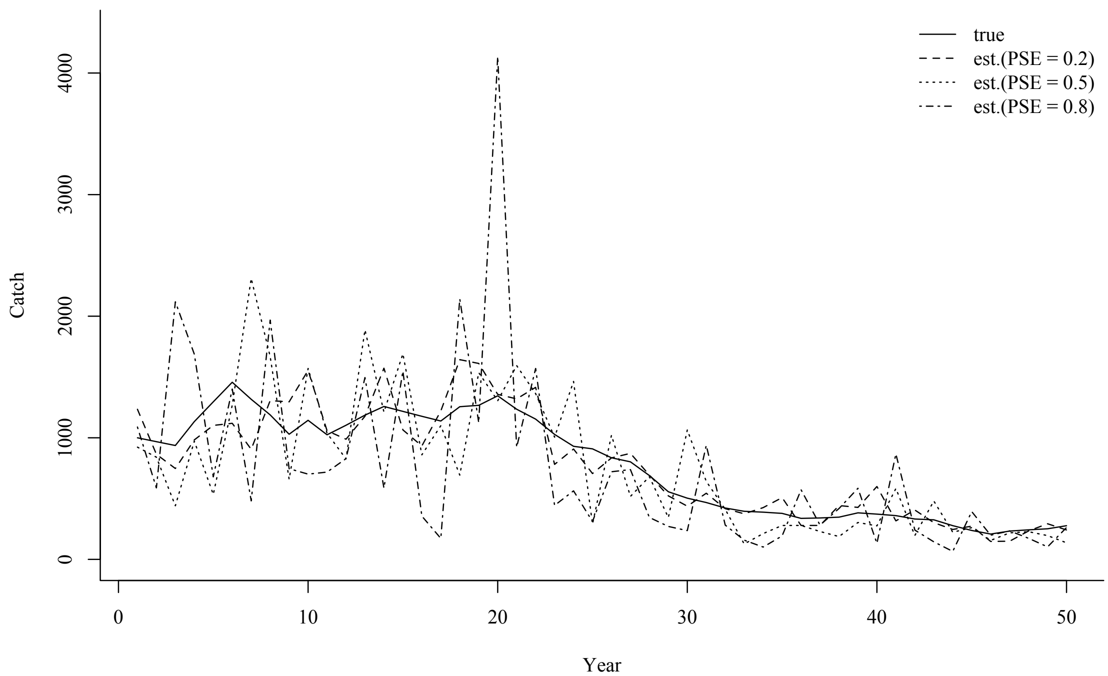

Figure 4. An example time series of true and observed catch levels for a single run of the simulation illustrating the effects of the proportional standard error (PSE) on the estimated values

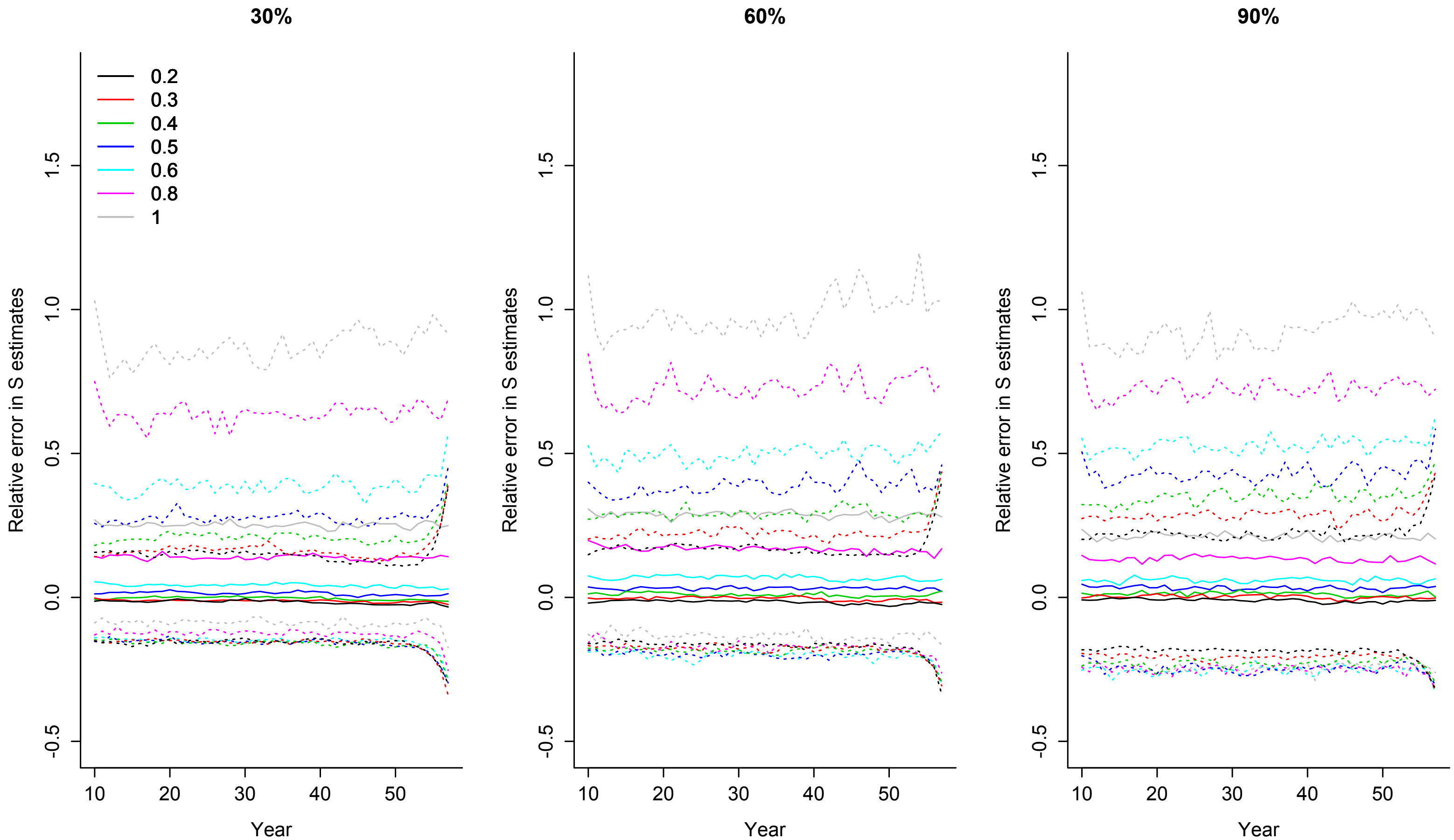

Figure 5. Time series of estimates of relative spawning biomass (estimated value / true value) for different sized recreational fisheries (30, 60, and 90% of total landings) for the fast life history. Colored lines denote the different PSE runs, with solid lines representing the median value across model iterations, and dashed lines representing the 95% confidence intervals.

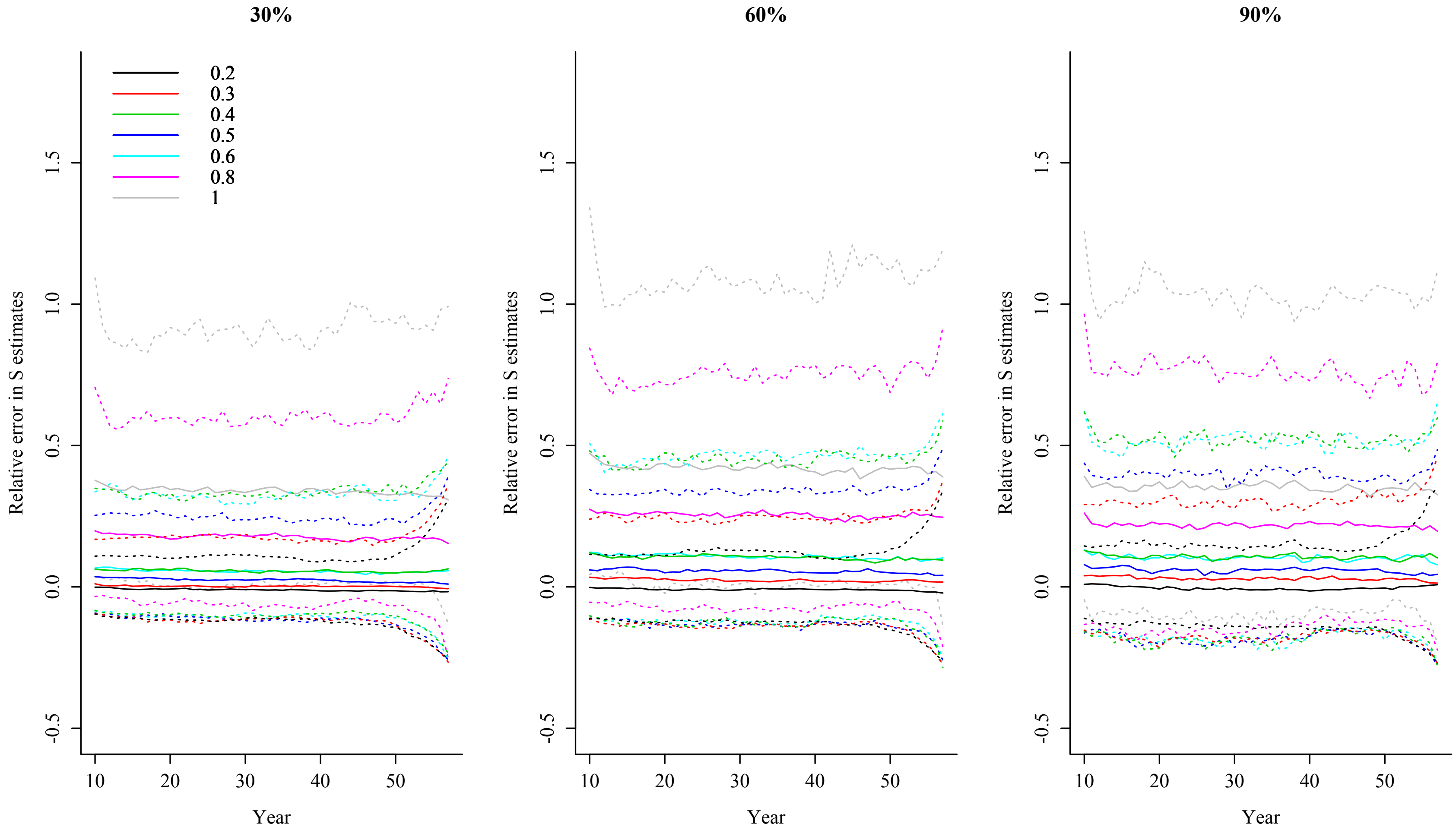

Figure 6. Similar to Figure 5, but for the medium life history.

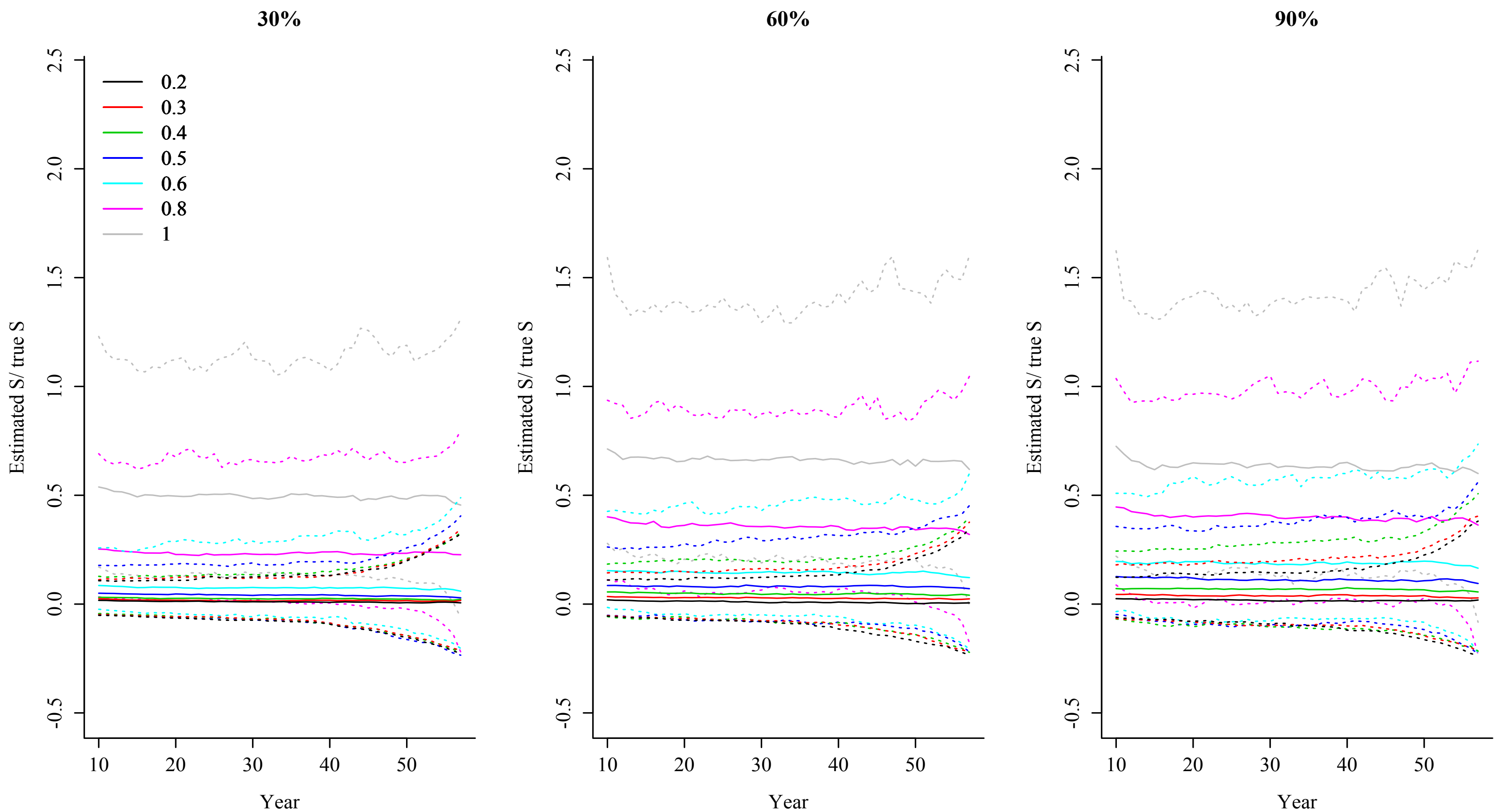

Figure 7. Similar to Figure 5, but for the slow life history.

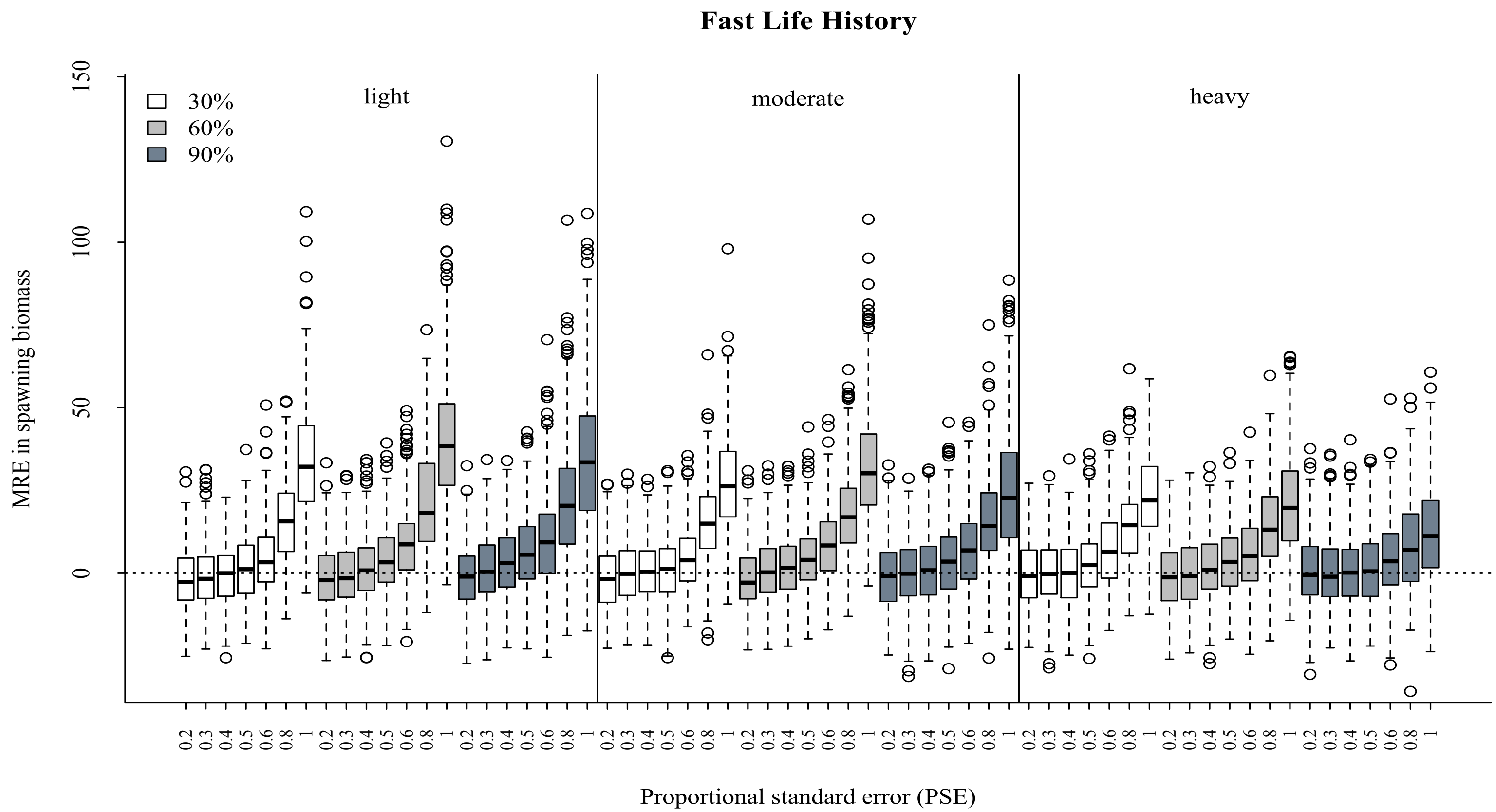

Figure 8. Boxplot of the median relative error (MRE) in terminal estimates of spawning biomass as a function of the proportional standard error (PSE) in recreational catch estimates across model runs for each scenario for the fast life history. Model runs for different exploitation scenarios are separated by the solid vertical lines, while runs for the different sized recreational fisheries (where the recreational fishery comprises 30, 60 and 90% of the total landings) are separated by color. Each box represent the interquartile

range on the estimates, with the median being the horizontal line within each box. The whiskers are ± 1.5 x the interquartile range, and the circles are observations outside the whiskers. The dashed line at 0 is added as a reference, with values below indicating the MRE is below the true value, and vice-versa.

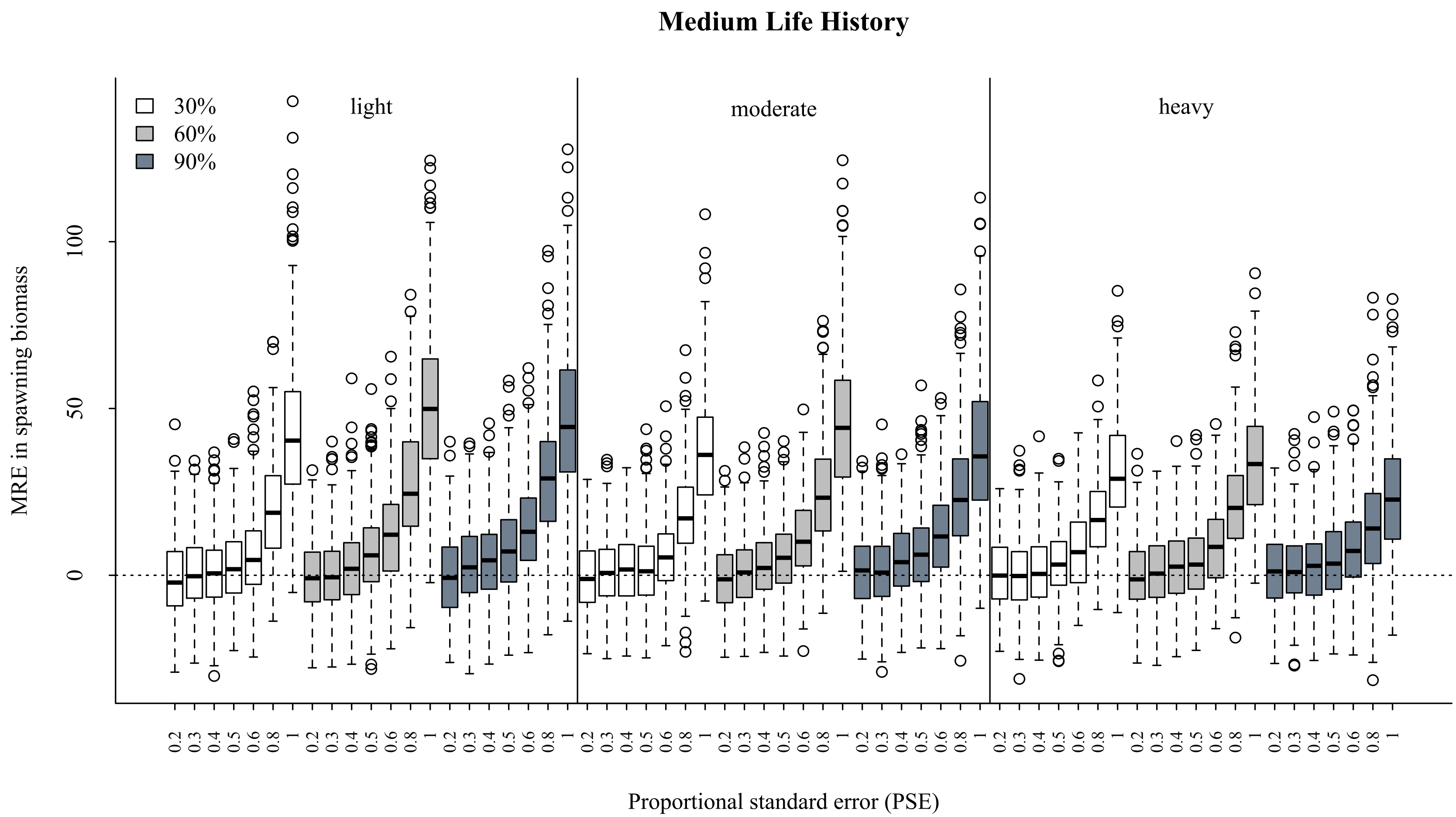

Figure 9. Similar to Figure 8, but showing the MRE in spawning biomass estimates for the medium life history.

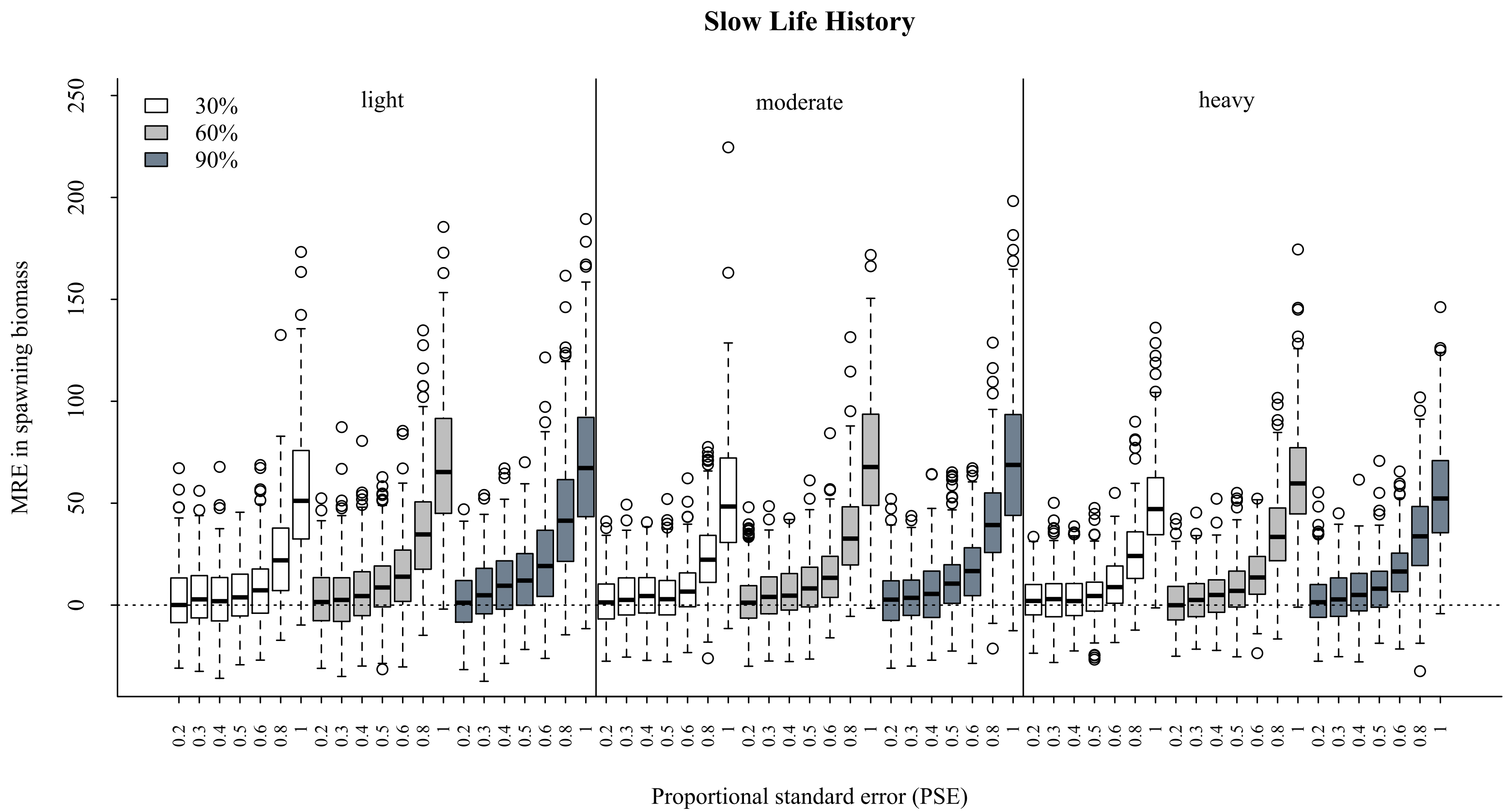

Figure 10. Similar to Figure 8, but showing the MRE in spawning biomass estimates for the slow life history.

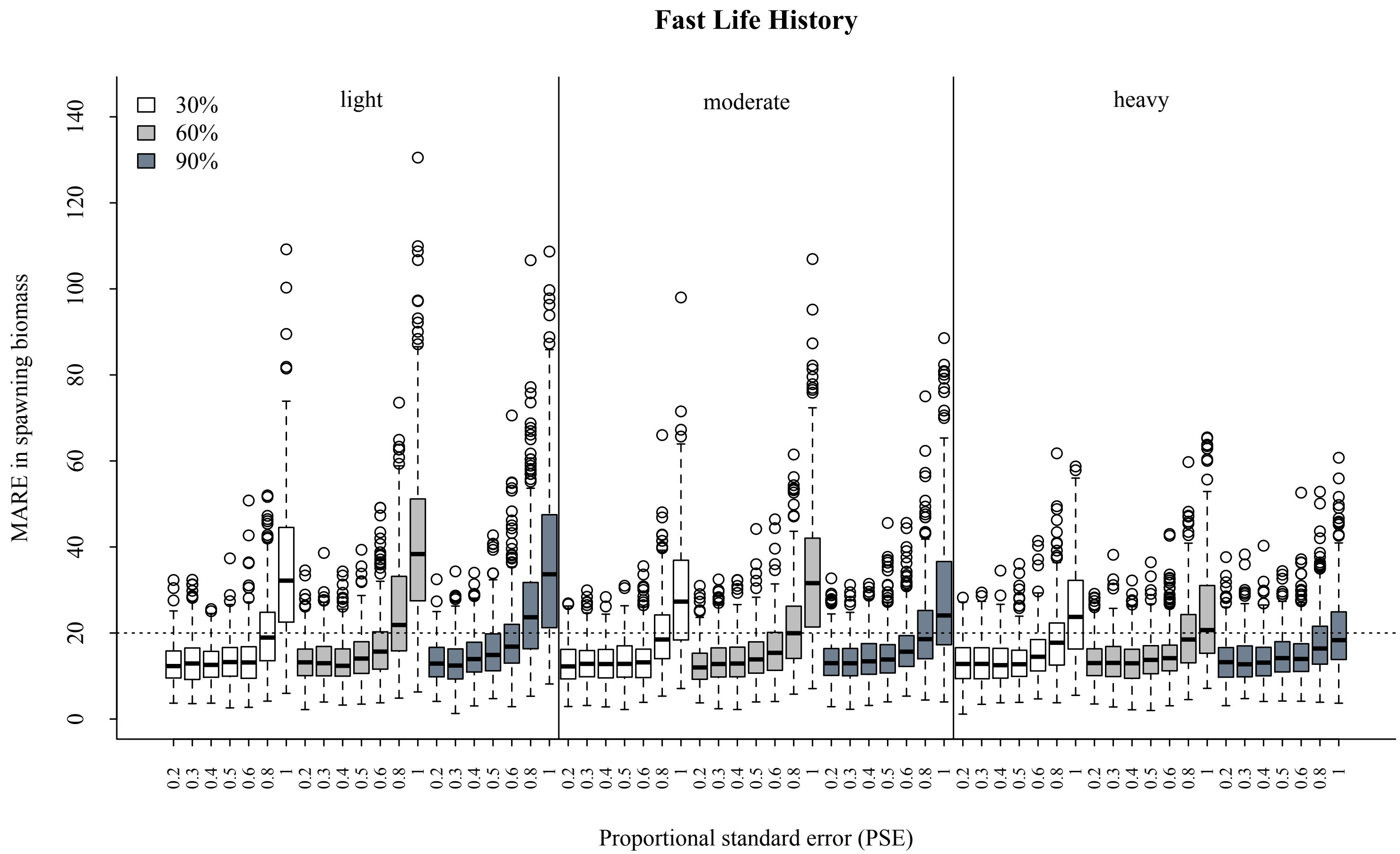

Figure 11. Similar to Figure 8, but showing the median absolute relative error (MARE) in spawning biomass estimates for the fast life history. The horizontal line at 0.2 is added as a reference to compare estimates across scenarios.

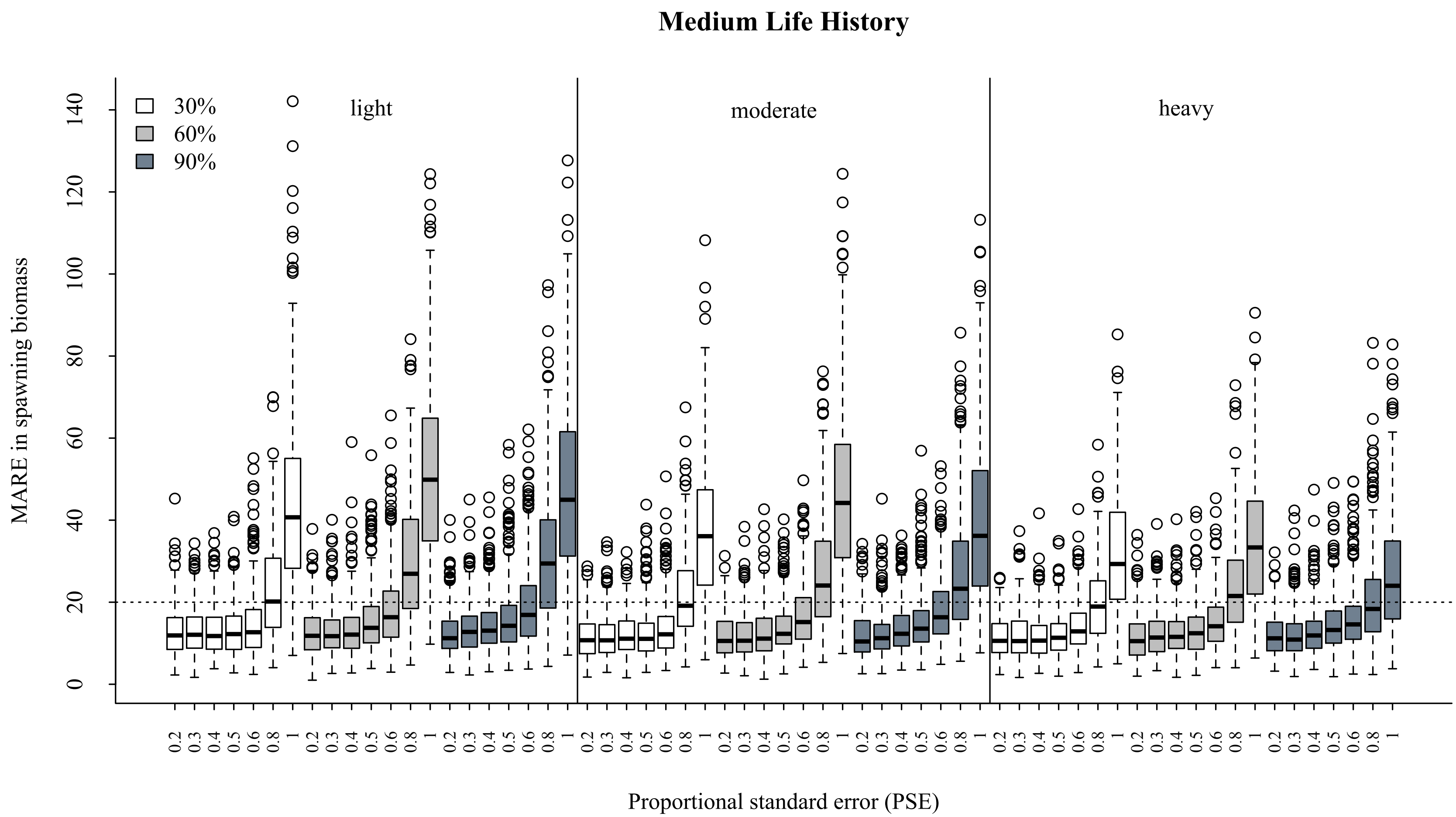

Figure 12. Similar to Figure 8, but showing the MARE in spawning biomass estimates for the medium life history. The horizontal line at 0.2 is added as a reference to compare estimates across scenarios.

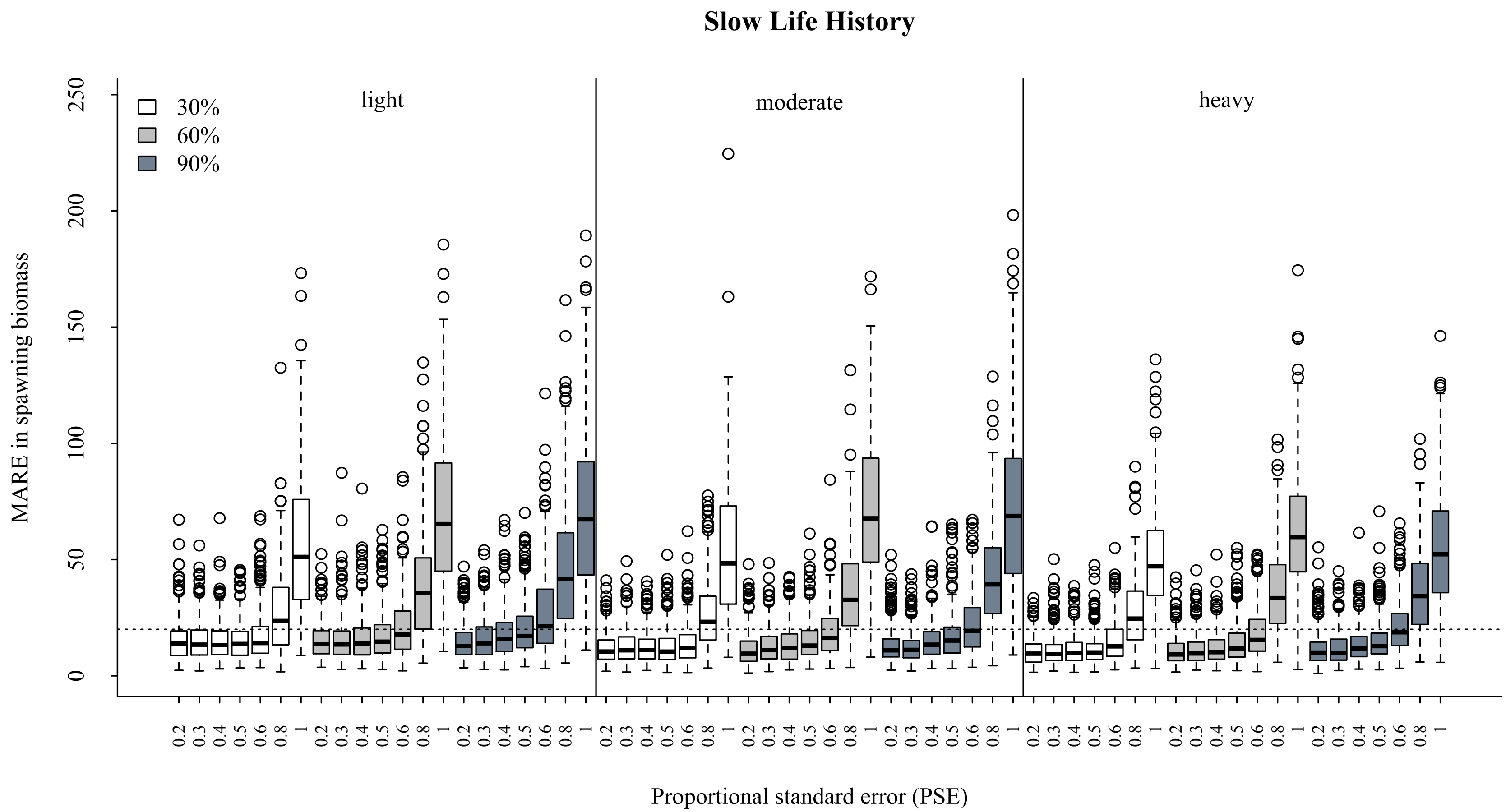

Figure 13. Similar to Figure 8, but showing the MARE in spawning biomass estimates for the slow life history. The horizontal line at 0.2 is added as a reference to compare estimates across scenarios.

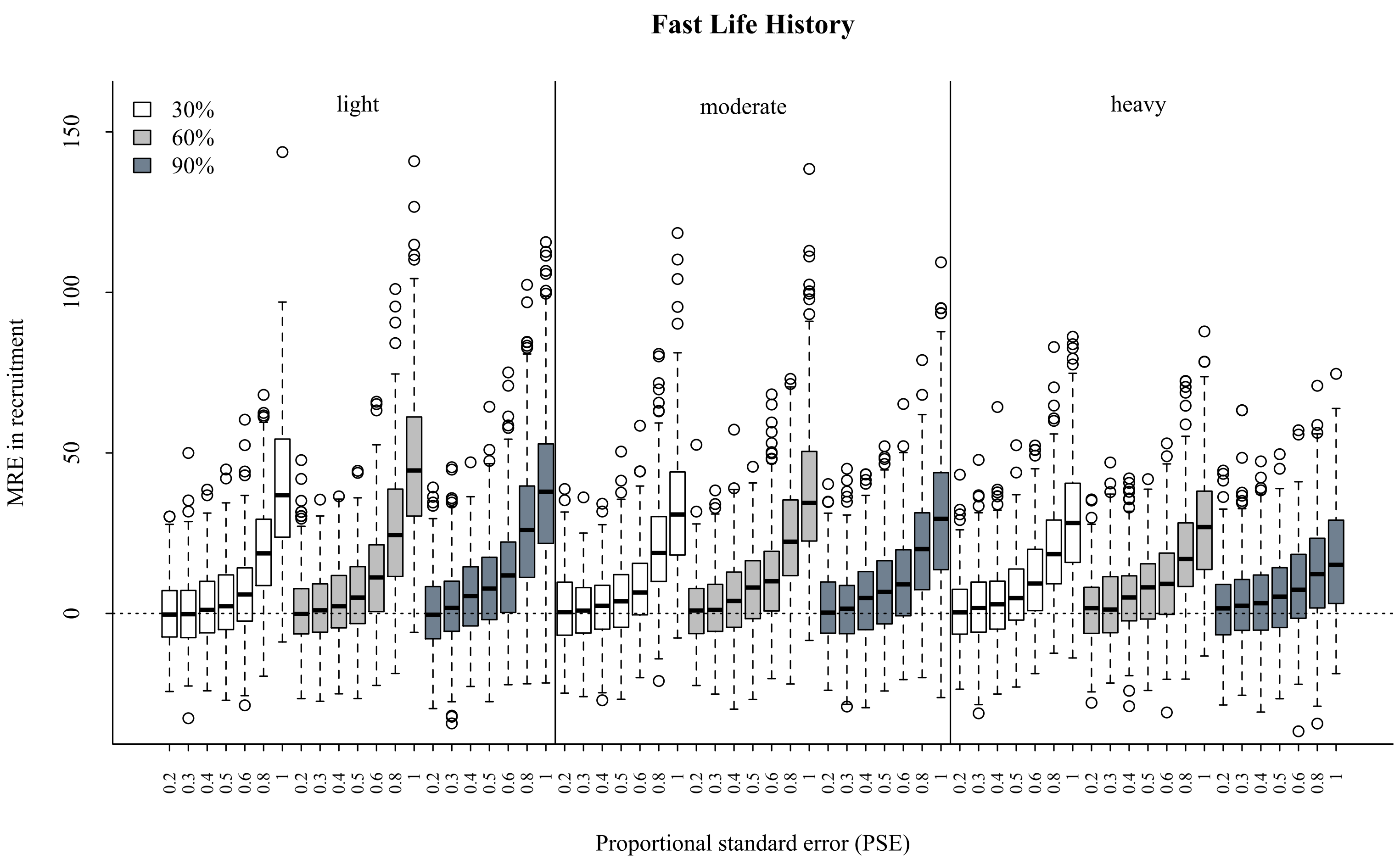

Figure 14. Similar to Figure 8, but showing the MRE in terminal recruitment estimates for the fast life history.

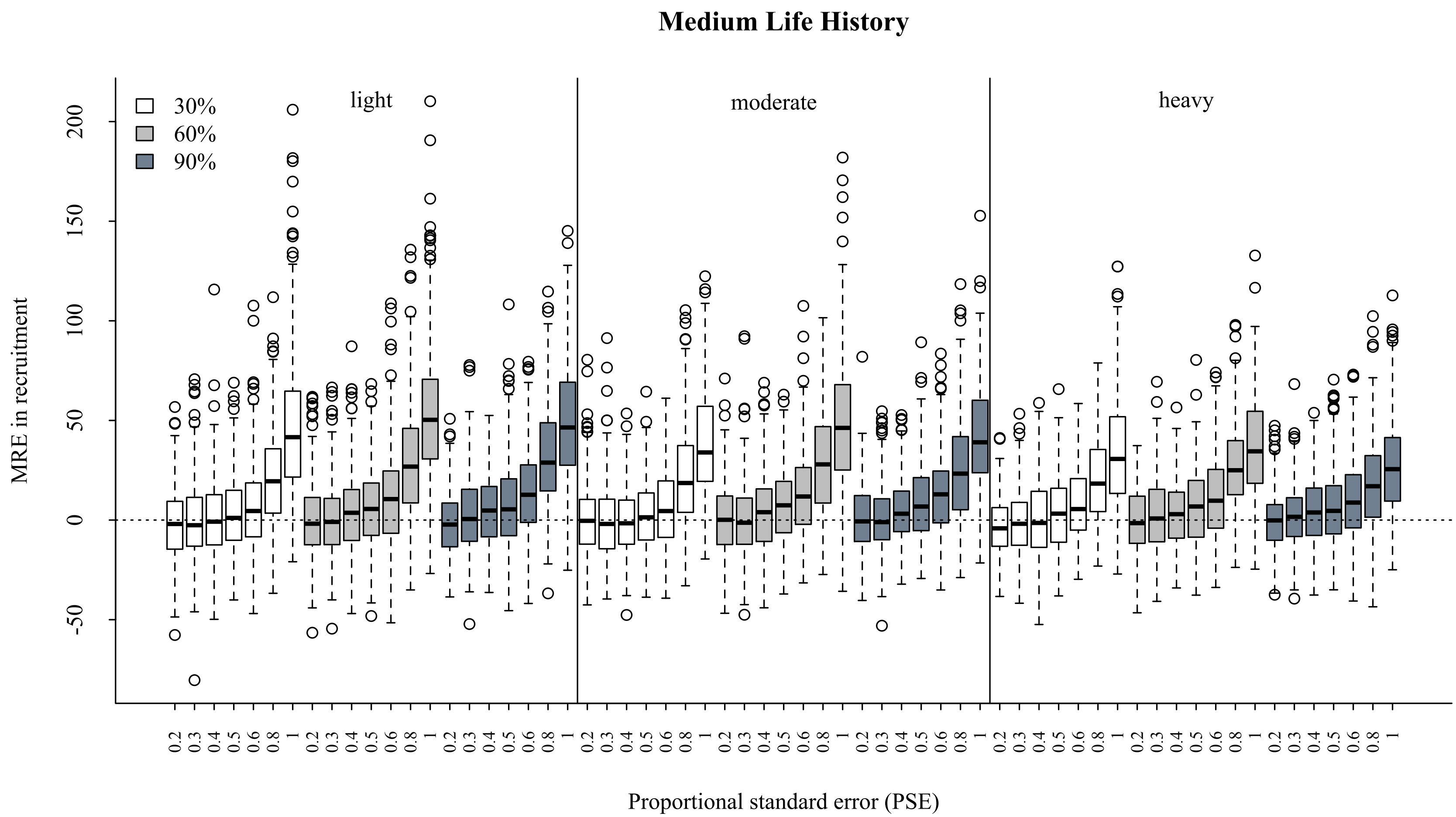

Figure 15. Similar to Figure 8, but showing the MRE in terminal recruitment estimates for the medium life history.

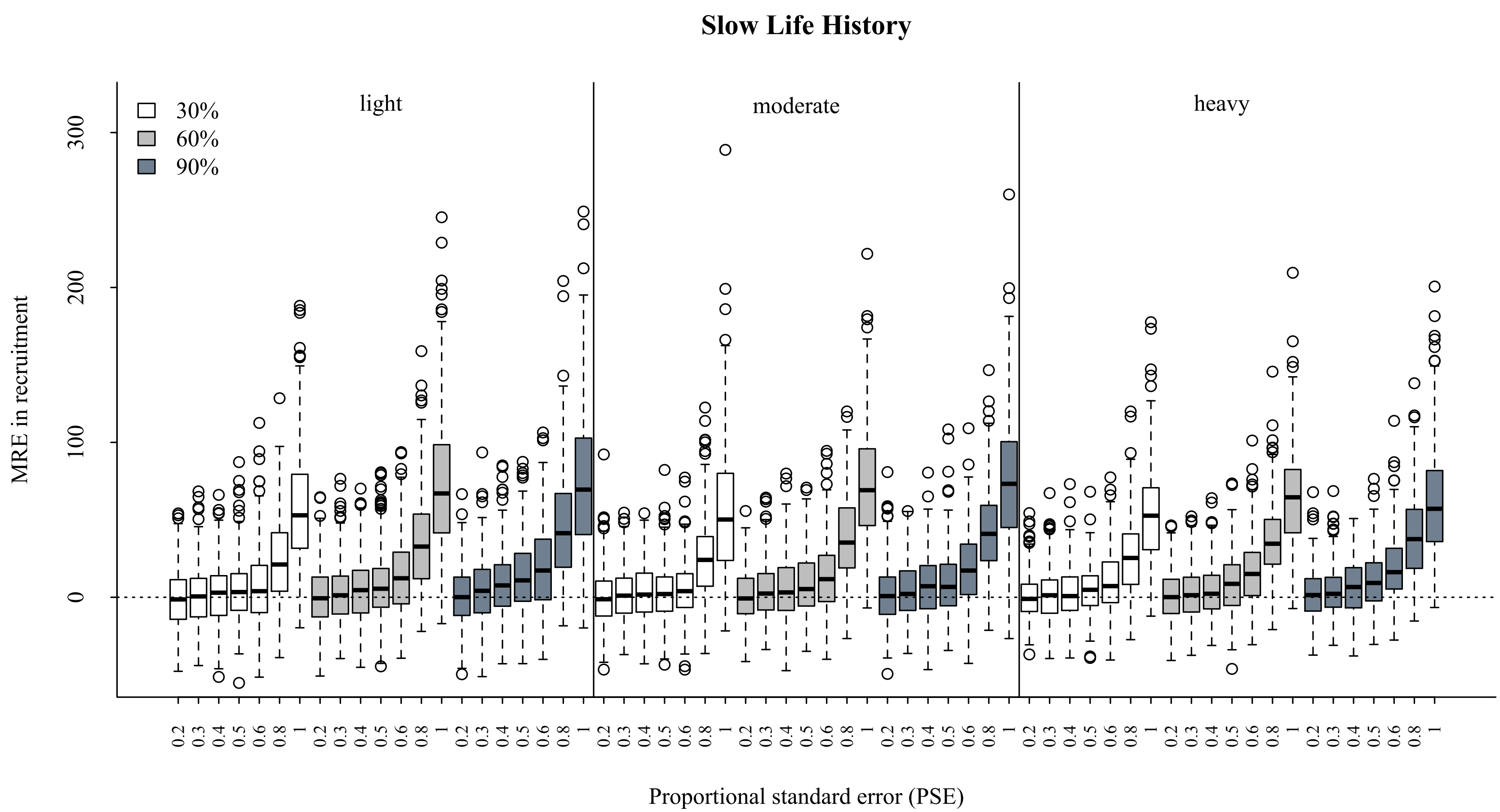

Figure 16. Similar to Figure 8, but showing the MRE in terminal recruitment estimates for the slow life history.

Fast Life History

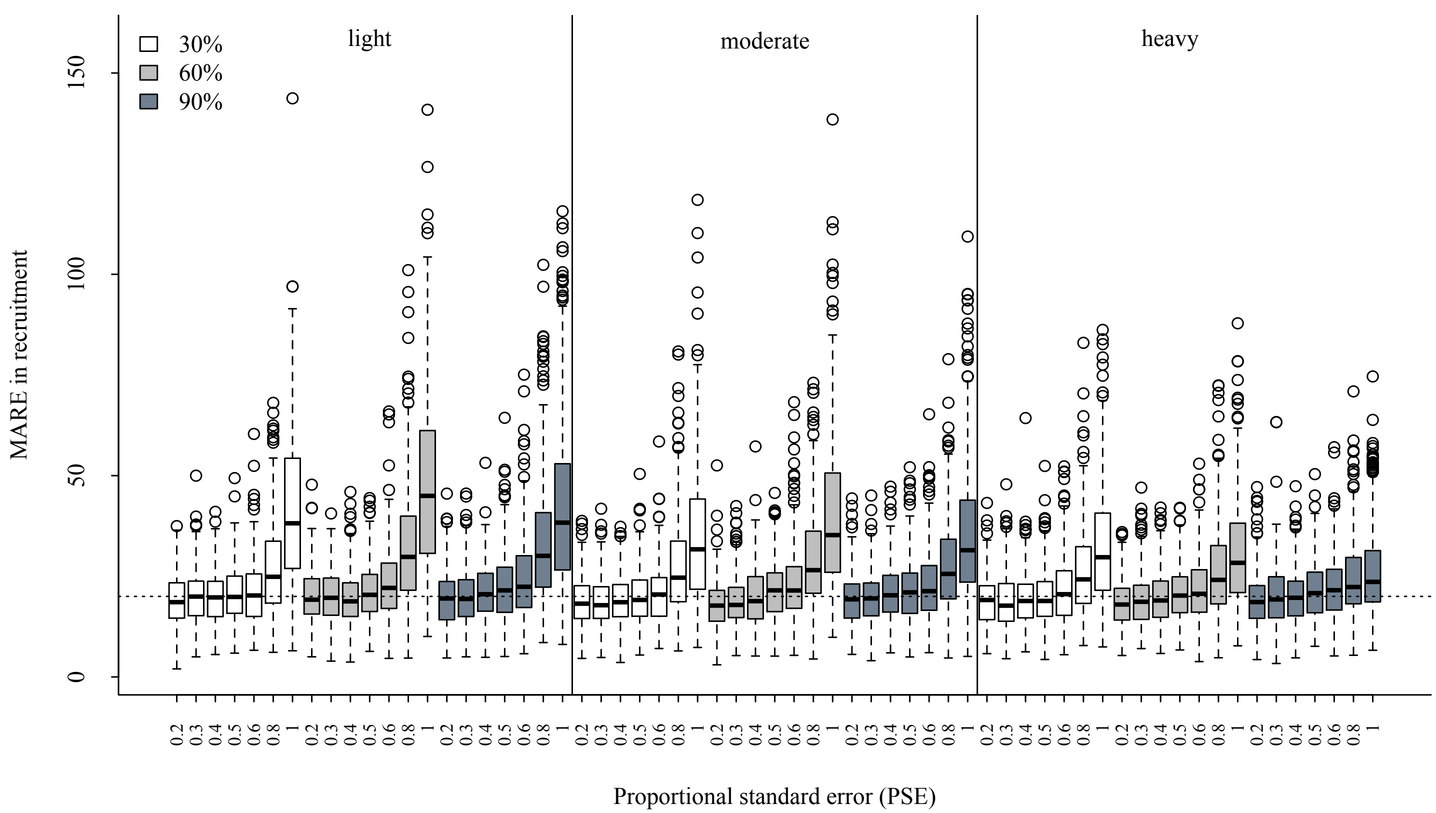

Figure 17. Similar to Figure 8, but showing the MARE in terminal recruitment estimates for the fast life history. The horizontal line at 0.2 is added as a reference to compare estimates across scenarios.

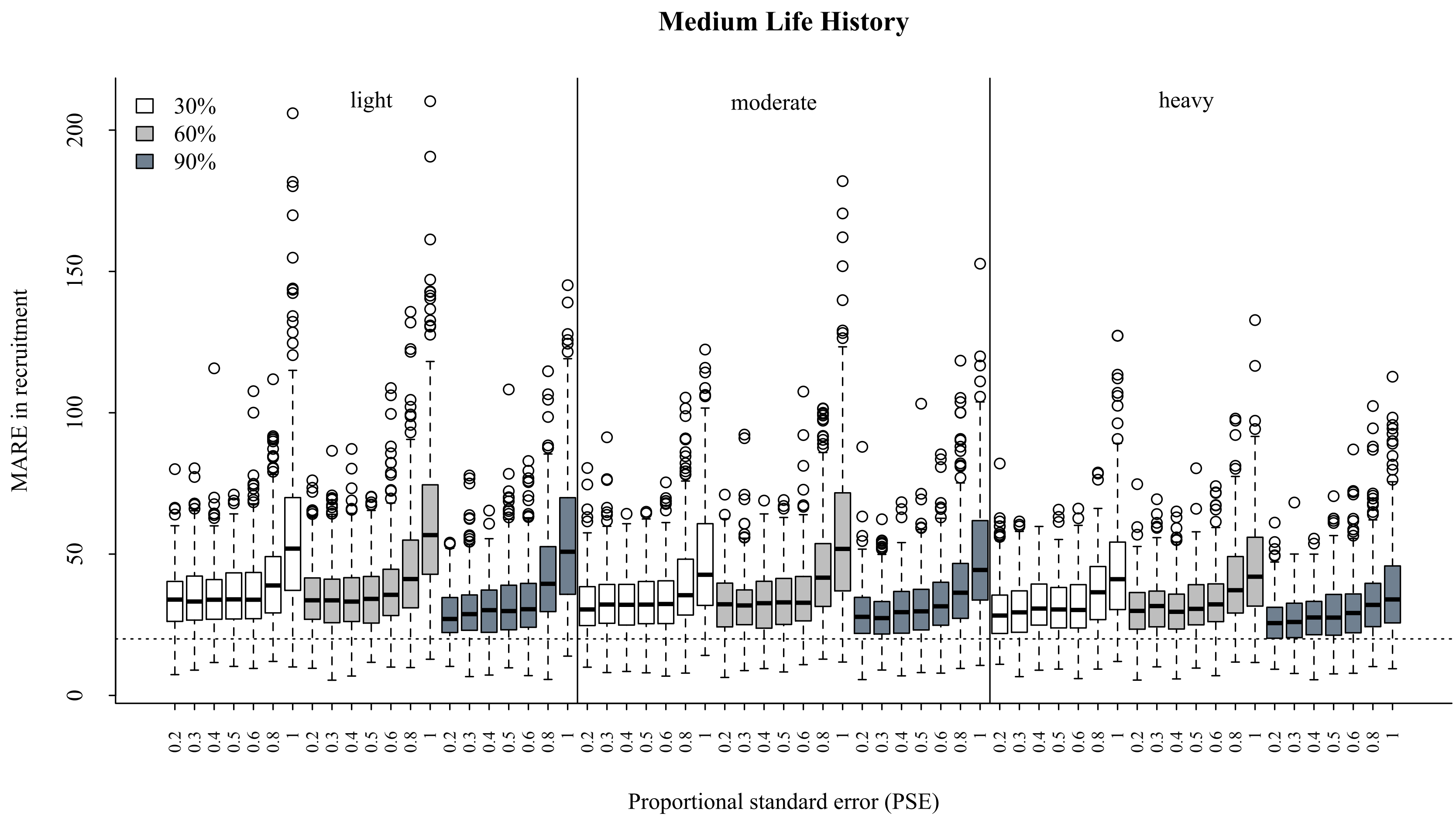

Figure 18. Similar to Figure 8, but showing the MARE in terminal recruitment estimates for the medium life history. The horizontal line at 0.2 is added as a reference to compare estimates across scenarios.

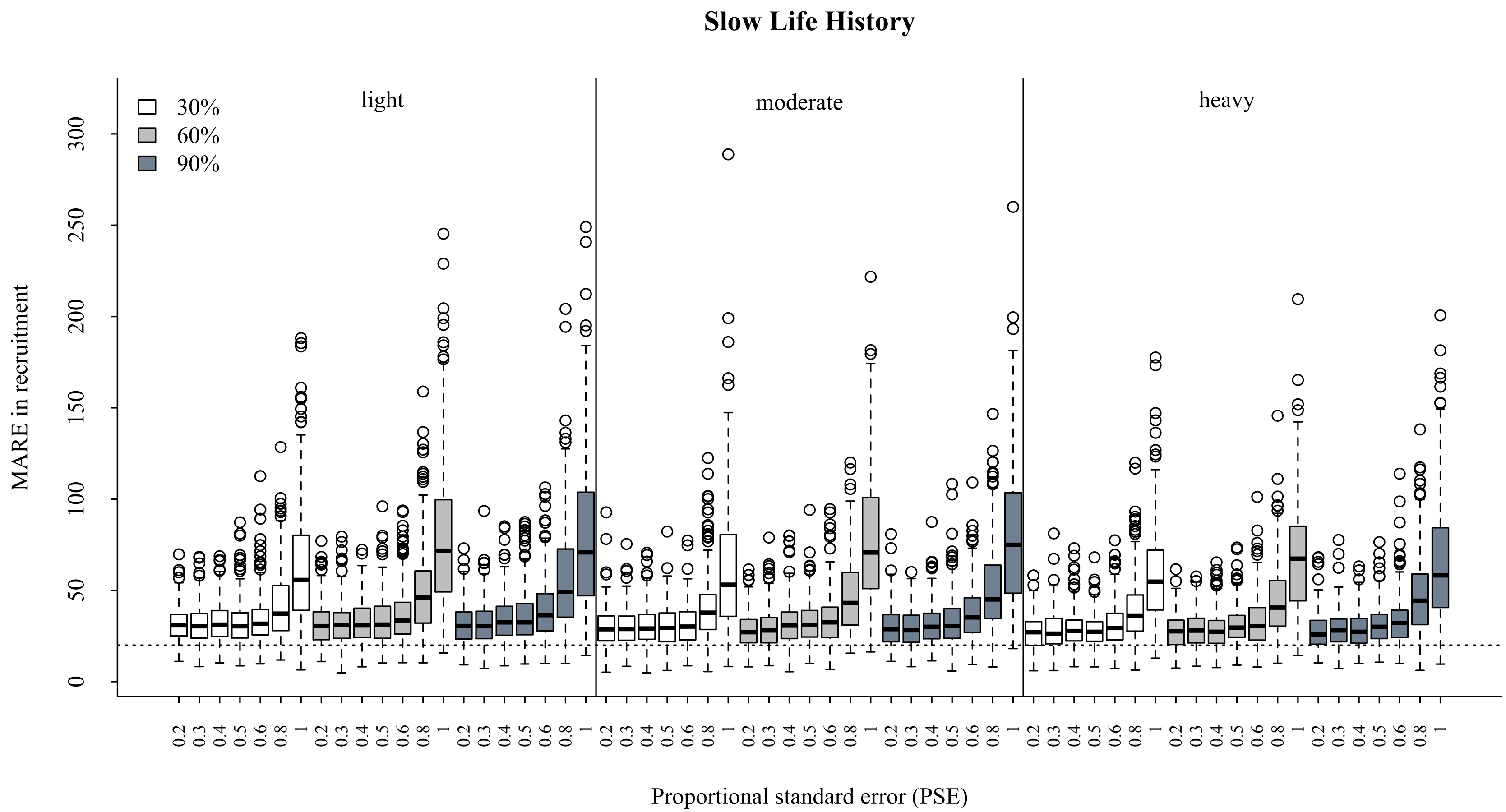

Figure 19. Similar to Figure 8, but showing the MARE in terminal recruitment estimates for the slow life history. The horizontal line at 0.2 is added as a reference to compare estimates across scenarios.

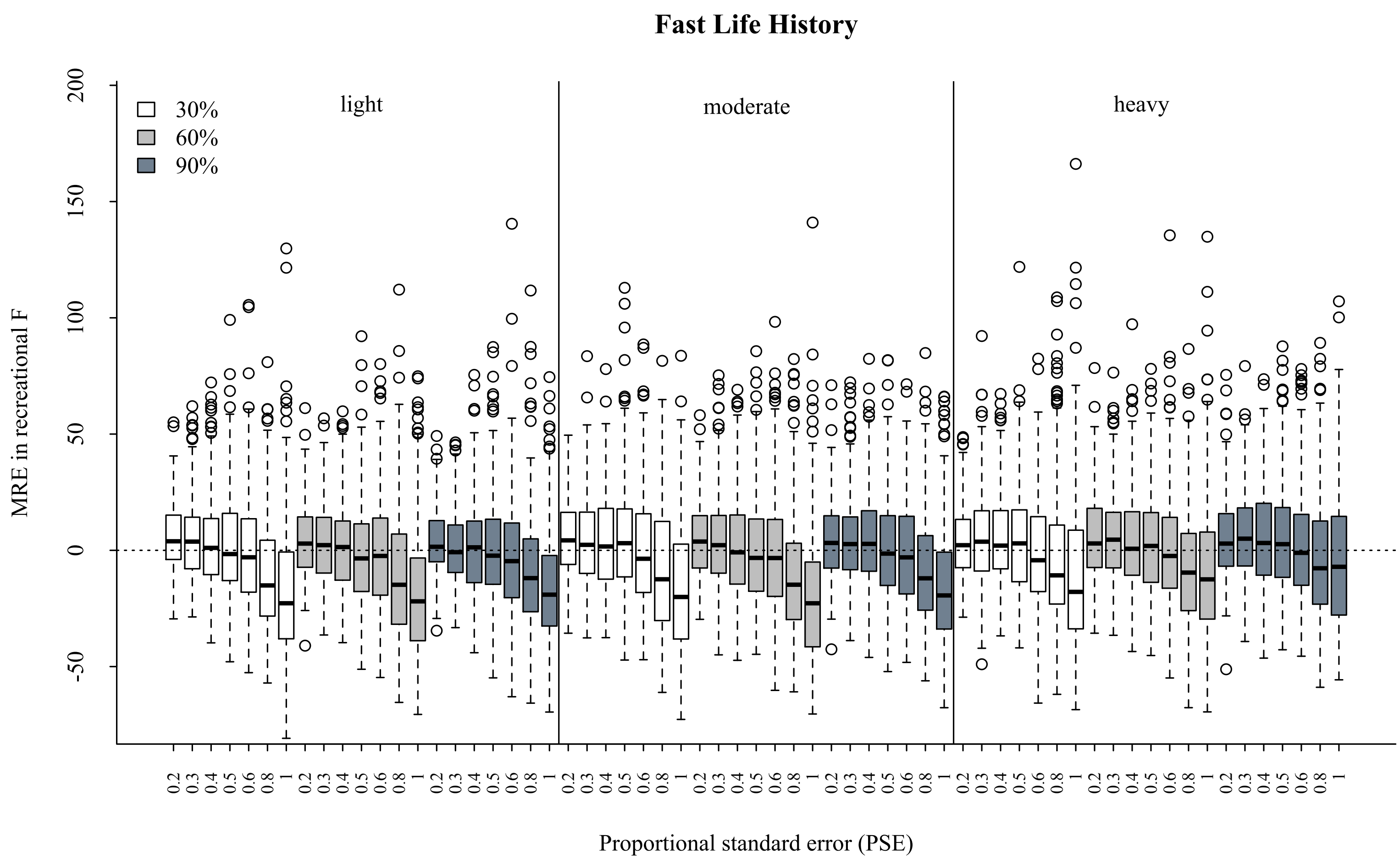

Figure 20. Similar to Figure 8, but showing the MRE in terminal estimates of fishing mortality in the recreational fishery for the fast life history. The horizontal line at 0.0 is added as a reference to compare estimates across scenarios.

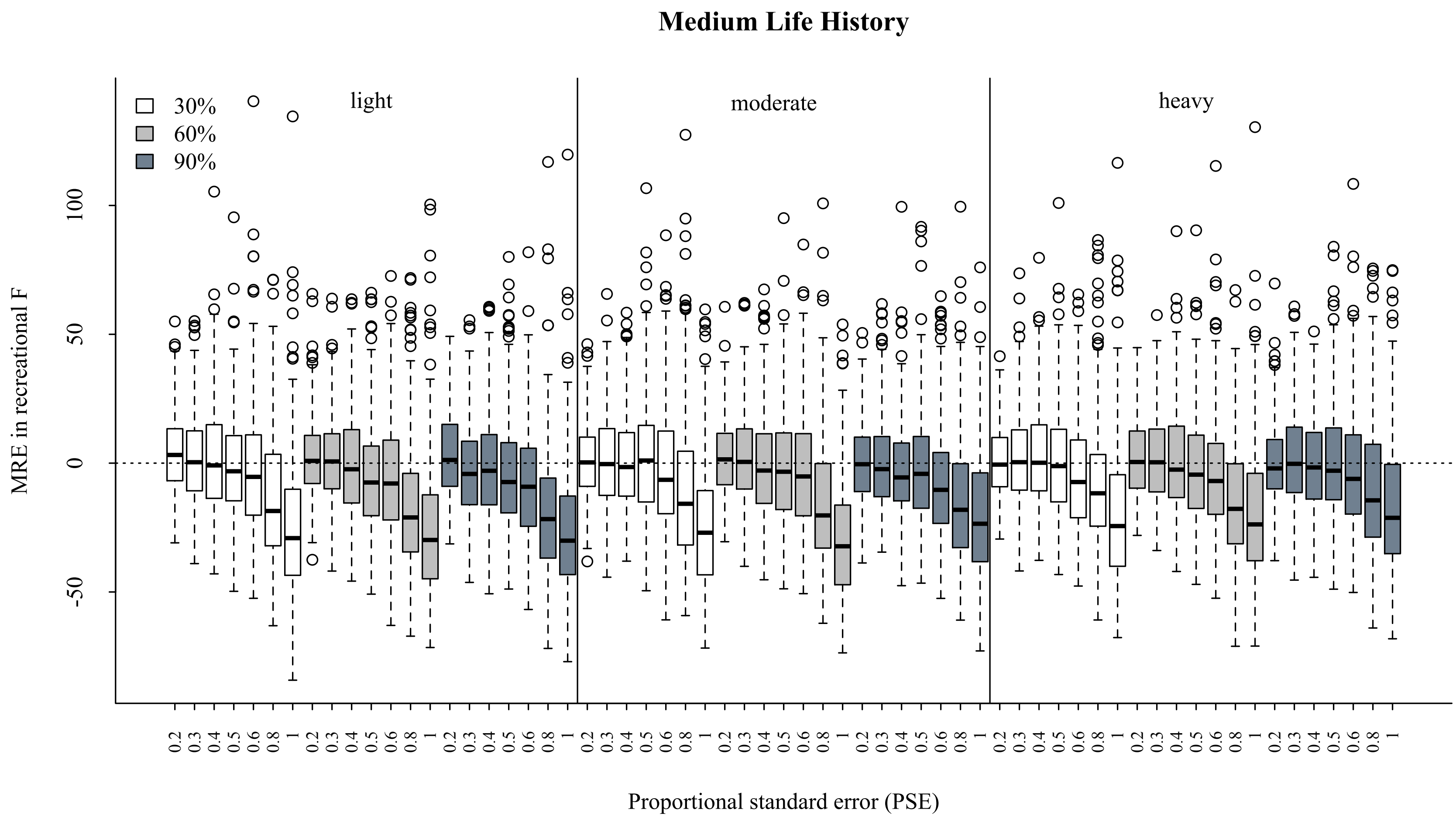

Figure 21. Similar to Figure 8, but showing the MRE in terminal estimates of fishing mortality in the recreational fishery for the medium life history. The horizontal line at 0.0 is added as a reference to compare estimates across scenarios.

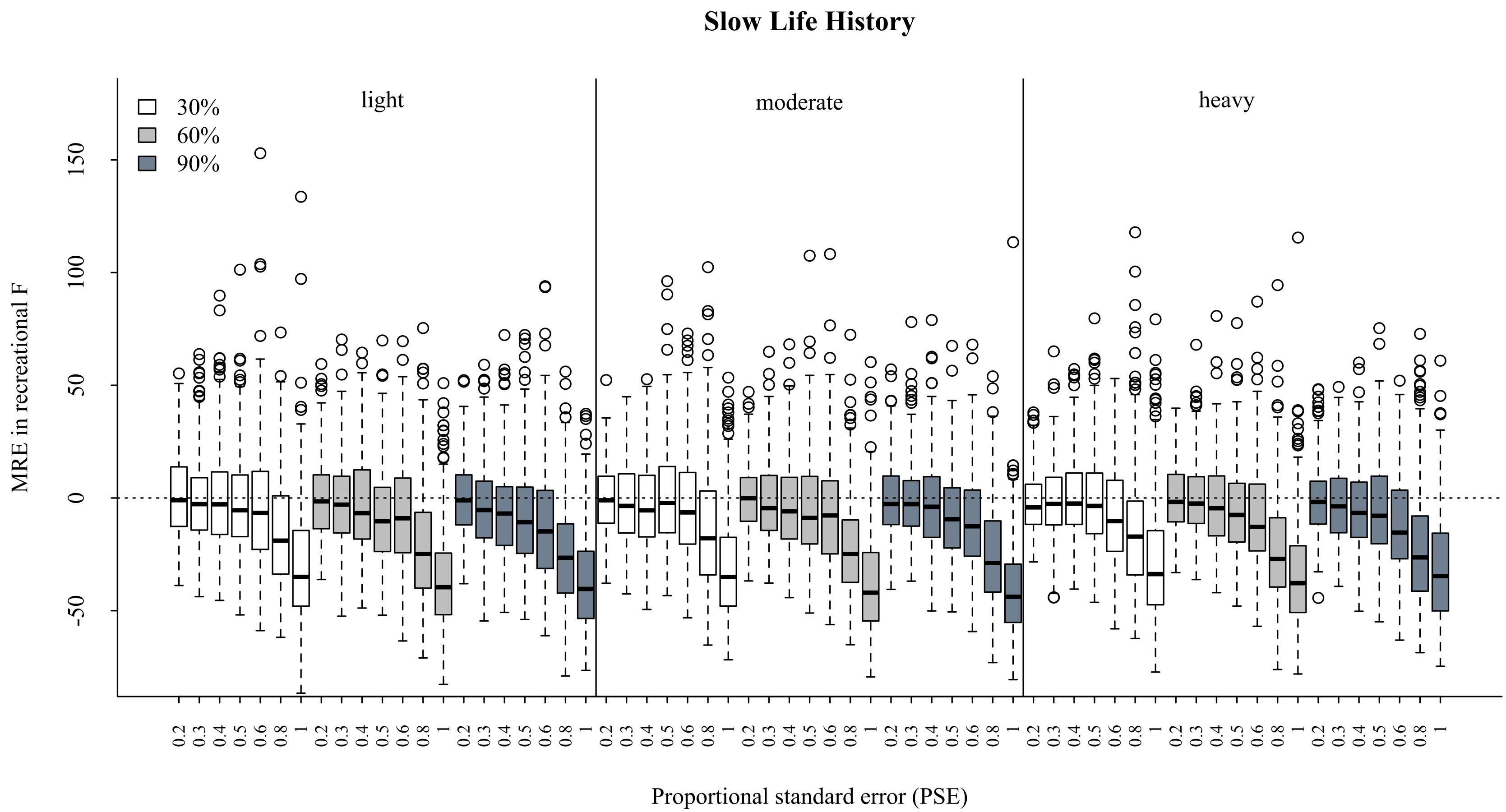

Figure 22. Similar to Figure 8, but showing the MRE in terminal estimates of fishing mortality in the recreational fishery for the slow life history. The horizontal line at 0.0 is added as a reference to compare estimates across scenarios.

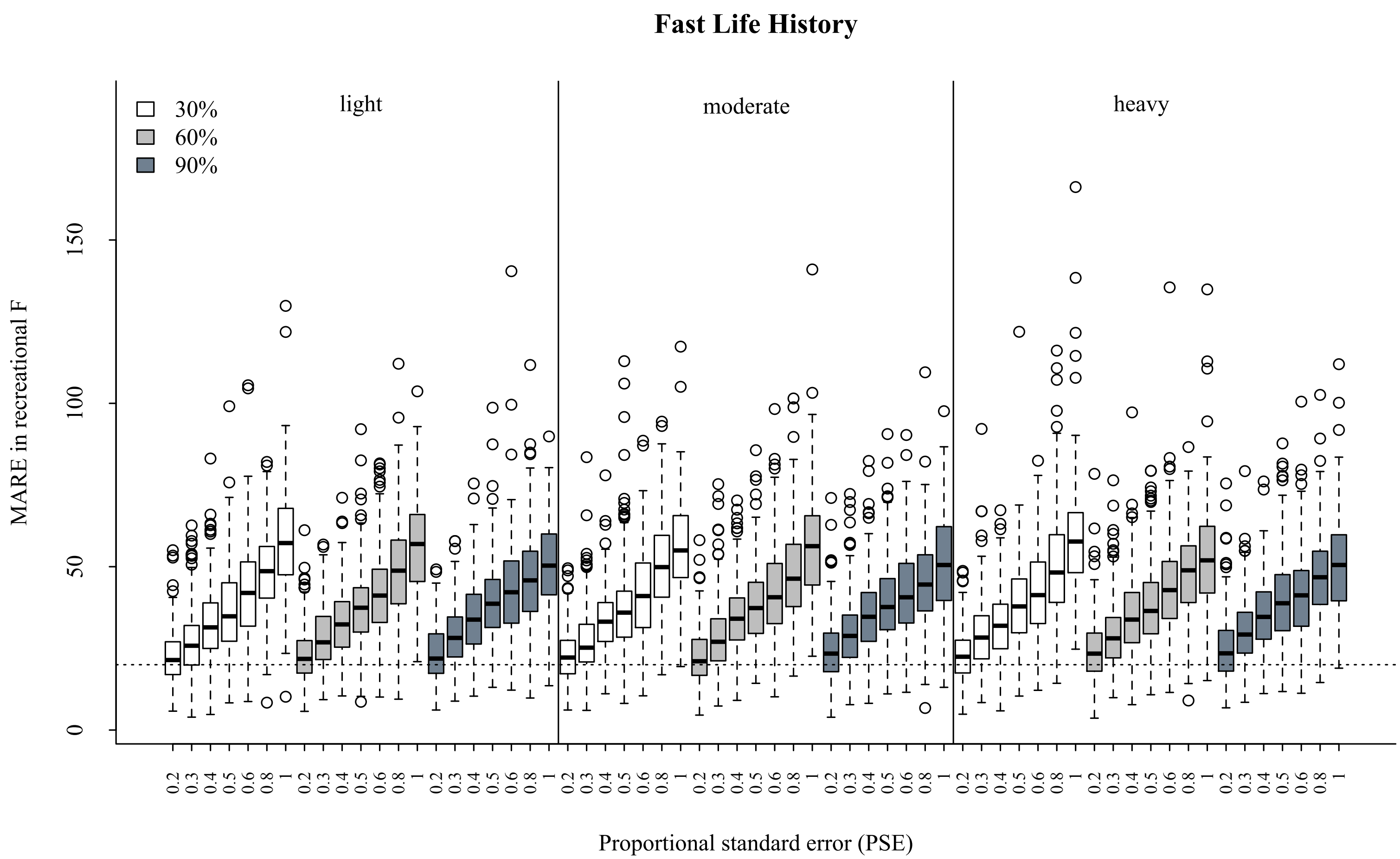

Figure 23. Similar to Figure 8, but showing the MARE in terminal estimates of fishing mortality in the recreational fishery for the fast life history. The horizontal line at 0.2 is added as a reference to compare estimates across scenarios.

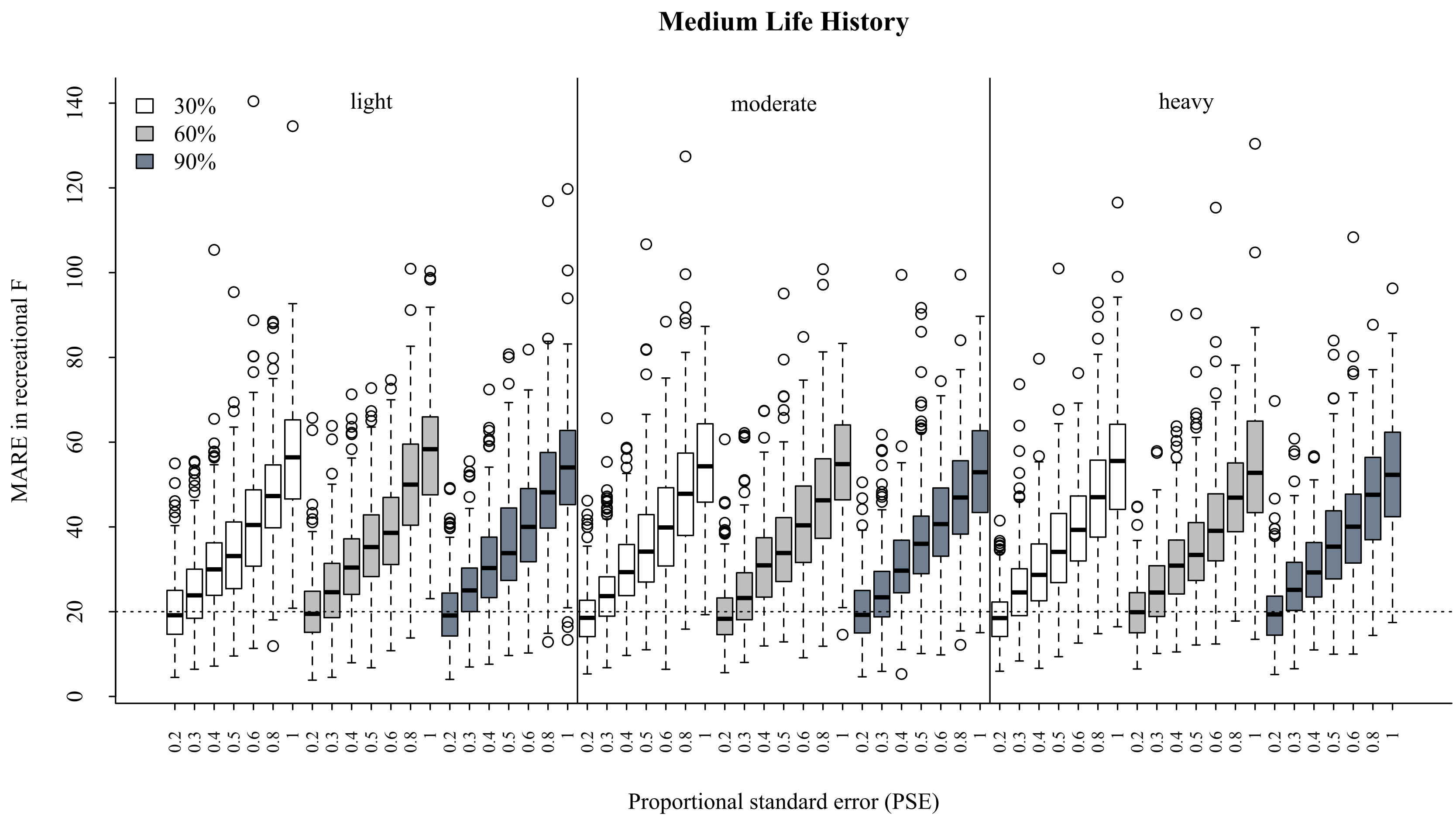

Figure 24. Similar to Figure 8, but showing the MARE in terminal estimates of fishing mortality in the recreational fishery for the medium life history. The horizontal line at 0.2 is added as a reference to compare estimates across scenarios.

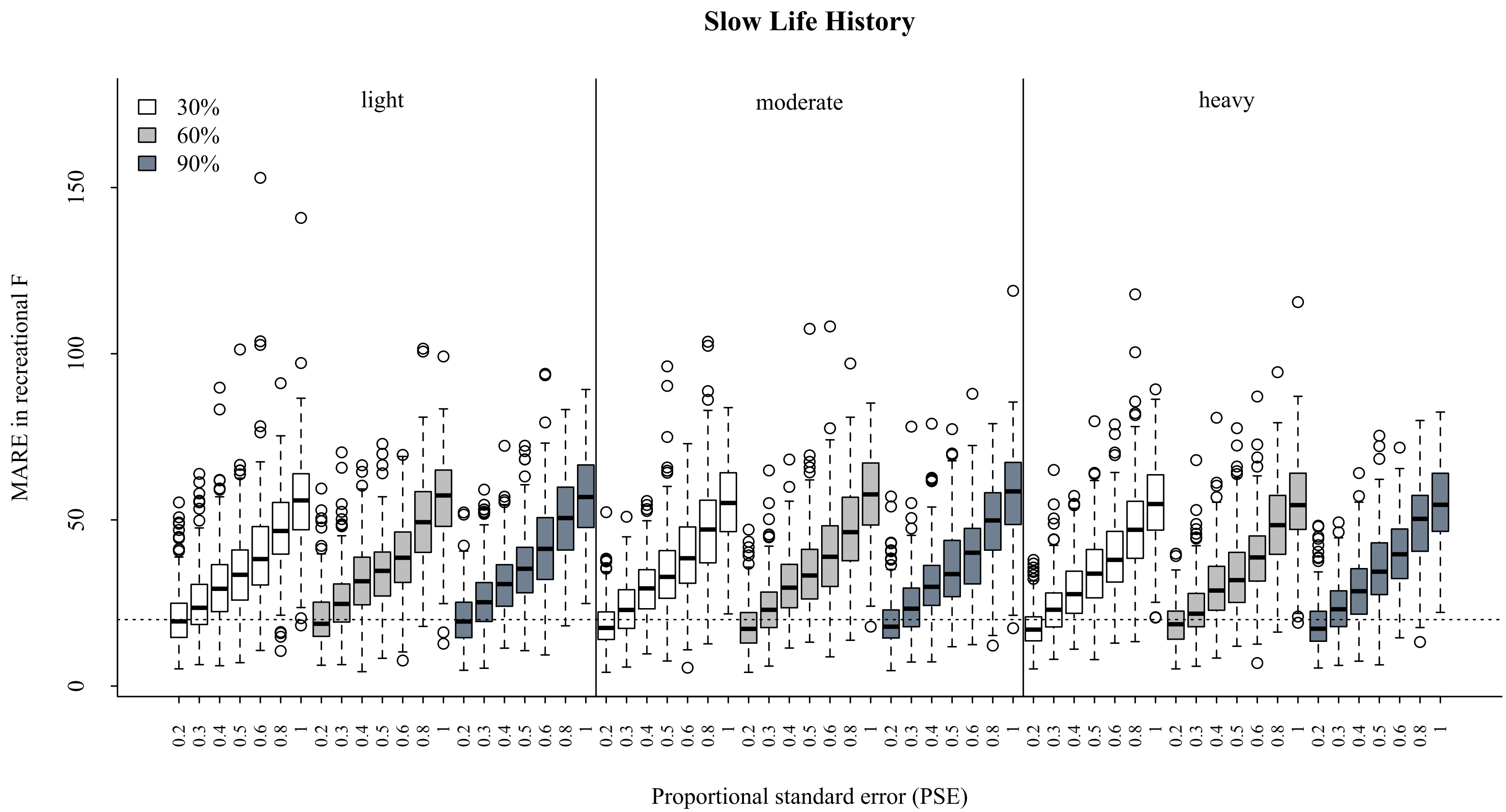

Figure 25. Similar to Figure 8, but showing the MARE in terminal estimates of fishing mortality in the recreational fishery for the slow life history. The horizontal line at 0.2 is added as a reference to compare estimates across scenarios.

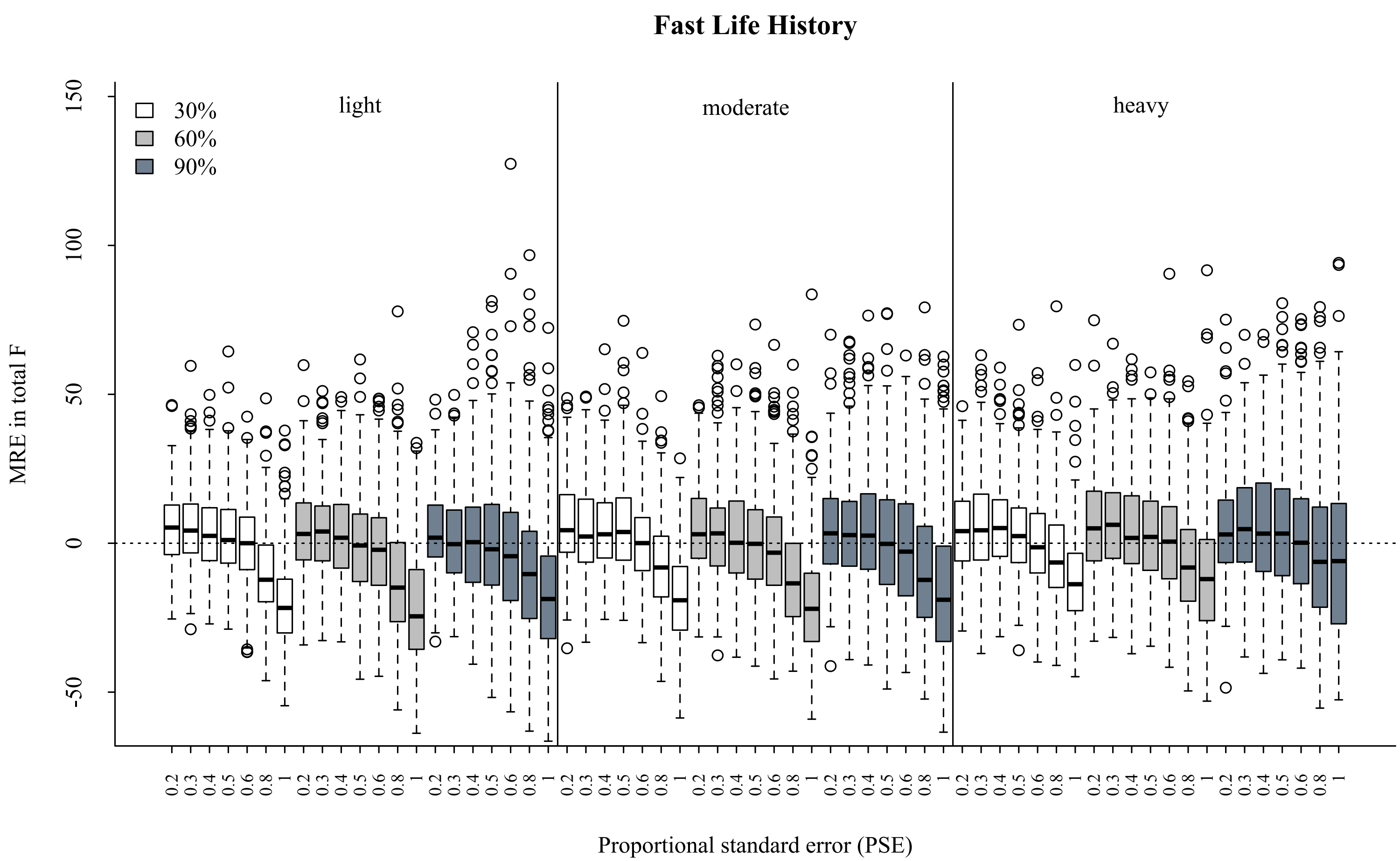

Figure 26. Similar to Figure 8, but showing the MRE in terminal estimates of total fishing mortality (recreational + commercial) for the fast life history. The horizontal line at 0.0 is added as a reference to compare estimates across scenarios.

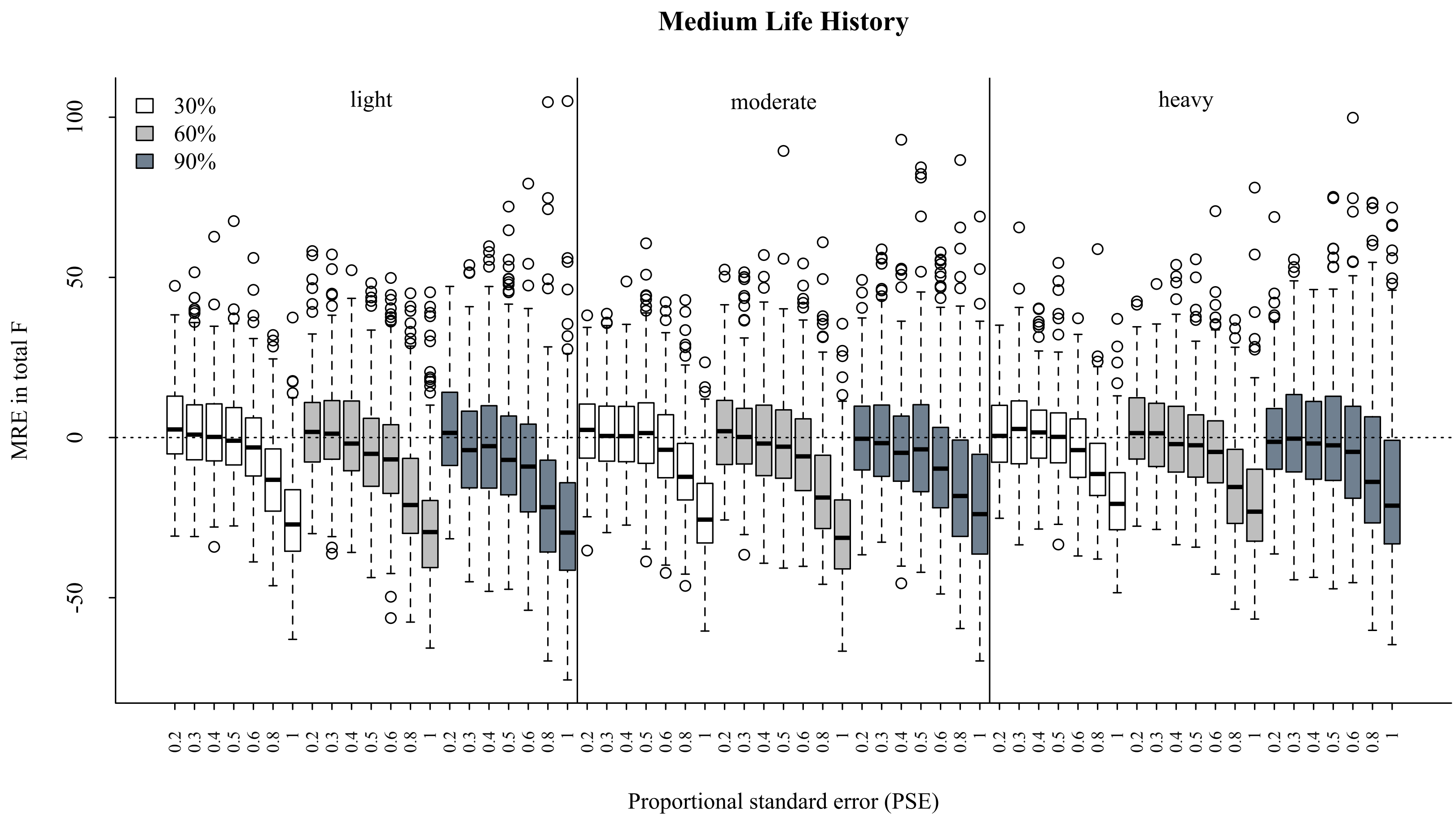

Figure 27. Similar to Figure 8, but showing the MRE in terminal estimates of total fishing mortality (recreational + commercial) for the medium life history. The horizontal line at 0.0 is added as a reference to compare estimates across scenarios.

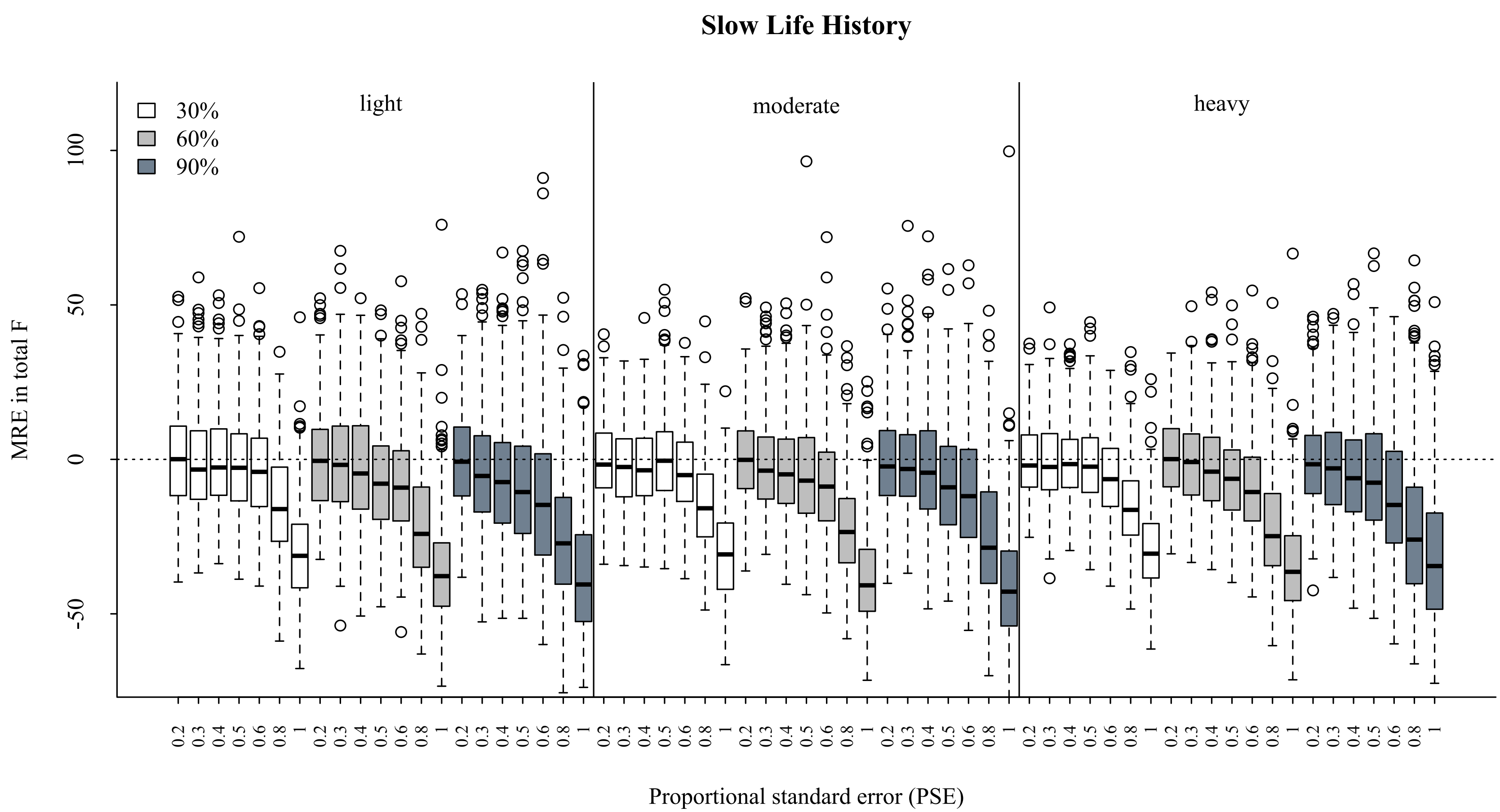

Figure 28. Similar to Figure 8, but showing the MRE in terminal estimates of total fishing mortality (recreational + commercial) for the slow life history. The horizontal line at 0.0 is added as a reference to compare estimates across scenarios.

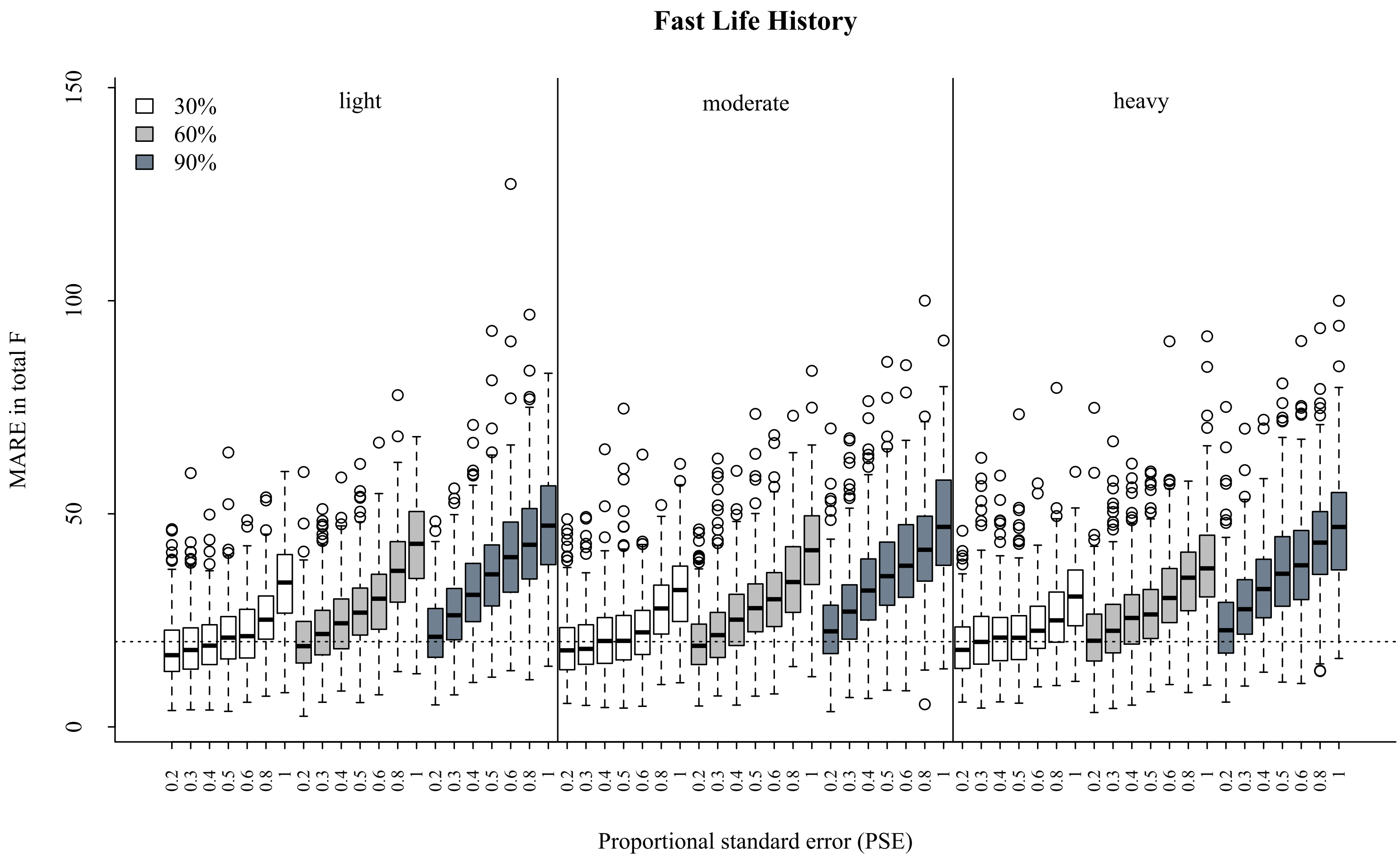

Figure 29. Similar to Figure 8, but showing the MARE in terminal estimates of total fishing mortality (recreational + commercial) for the fast life history. The horizontal line at 0.2 is added as a reference to compare estimates across scenarios.

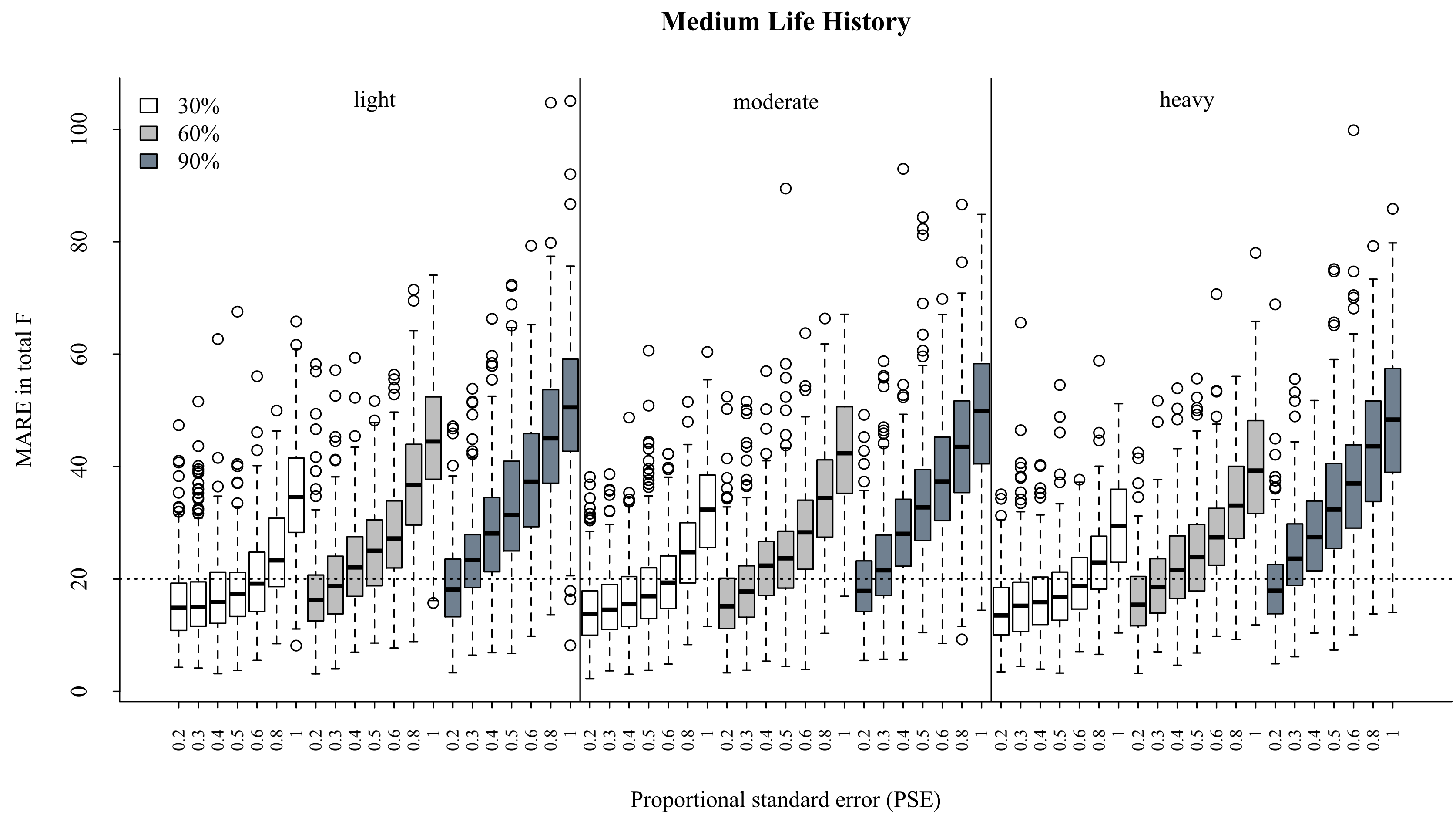

Figure 30. Similar to Figure 8, but showing the MARE in terminal estimates of total fishing mortality (recreational + commercial) for the medium life history. The horizontal line at 0.2 is added as a reference to compare estimates across scenarios

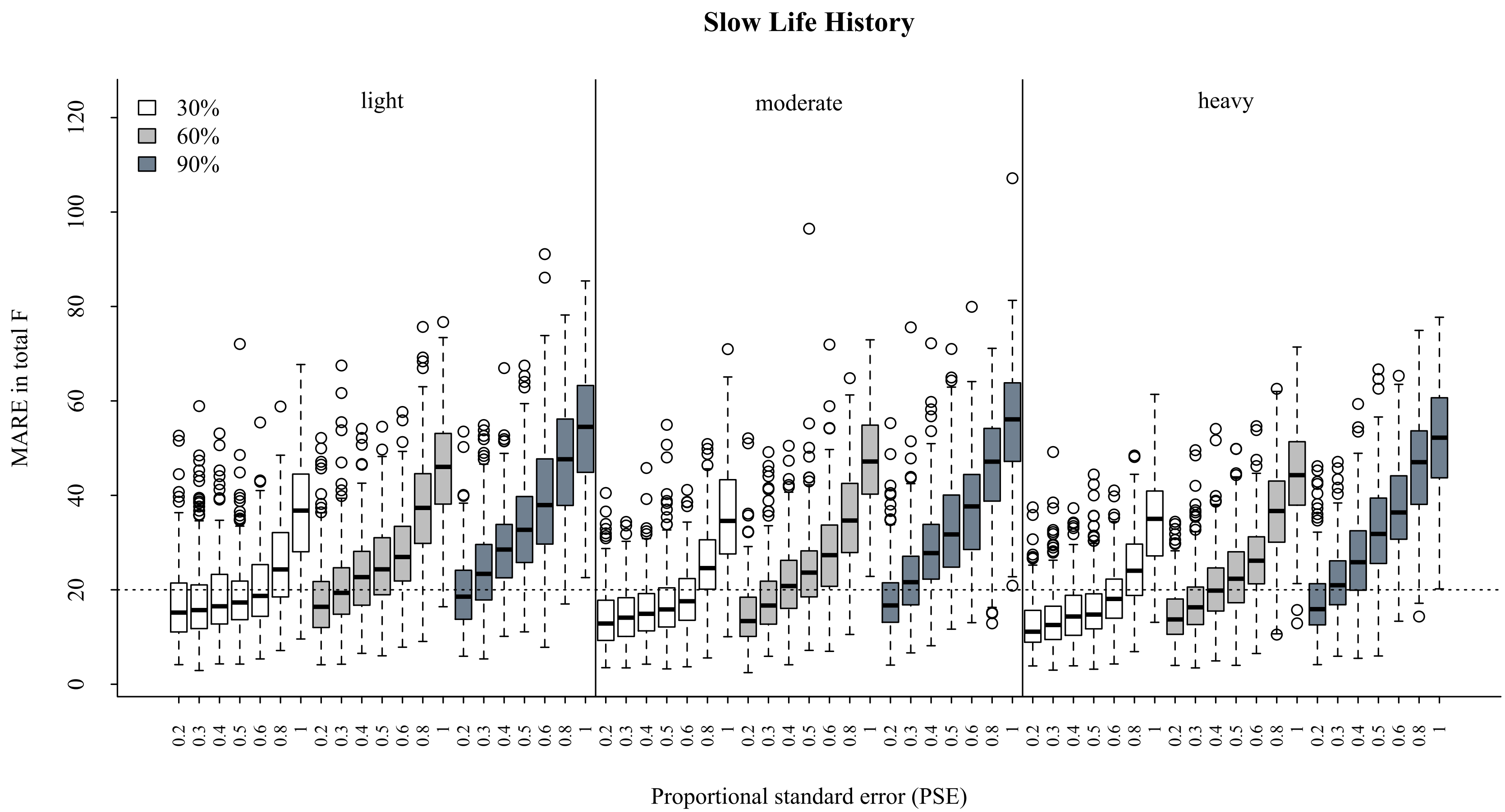

Figure 31. Similar to Figure 8, but showing the MARE in terminal estimates of total fishing mortality (recreational + commercial) for the slow life history. The horizontal line at 0.2 is added as a reference to compare estimates across scenarios.

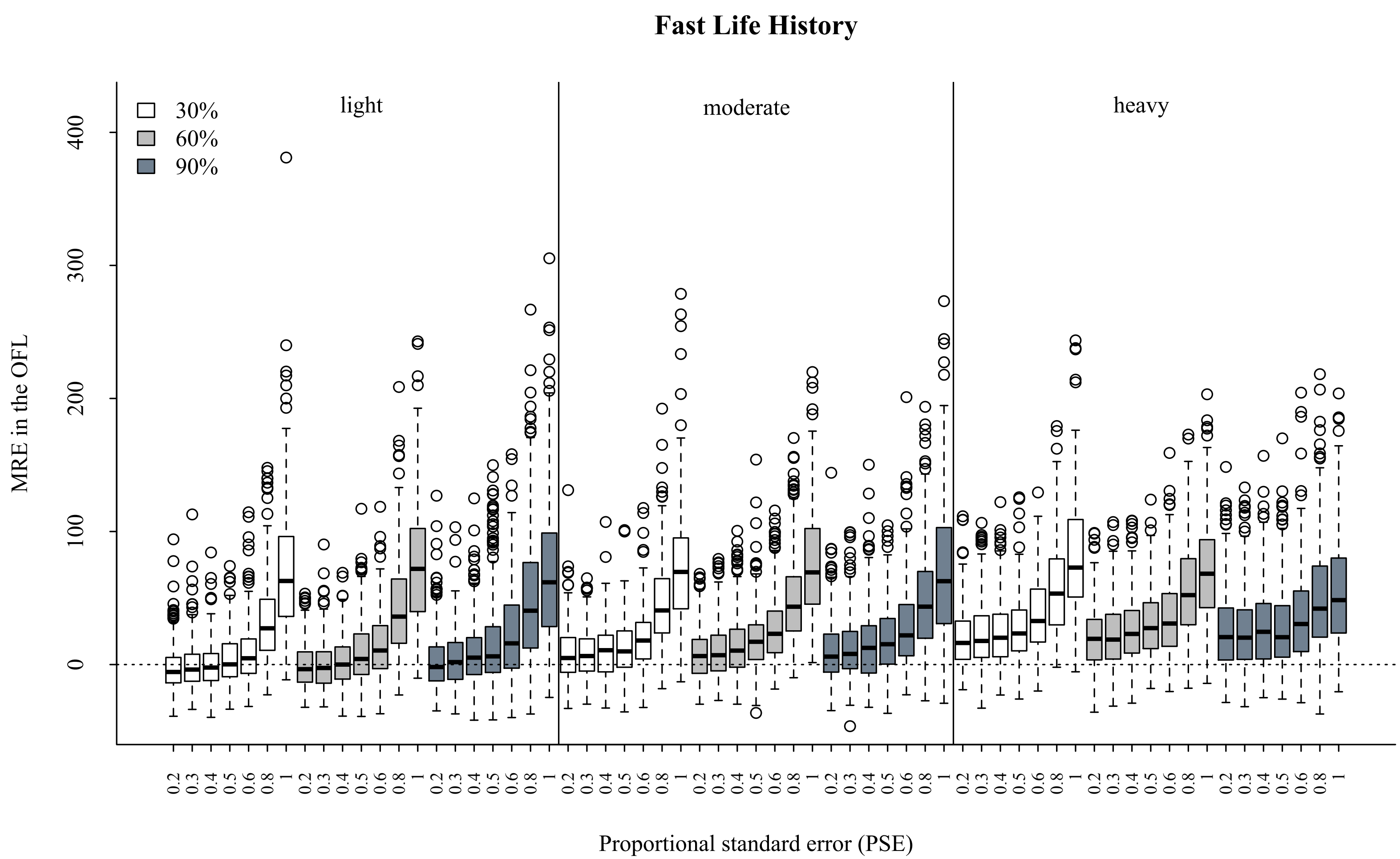

Figure 32. Similar to Figure 8, but showing the MRE in terminal estimates of overfishing limit (OFL; the catch at F_{lim}) for the fast life history. The horizontal line at 0.0 is added as a reference to compare estimates across scenarios.

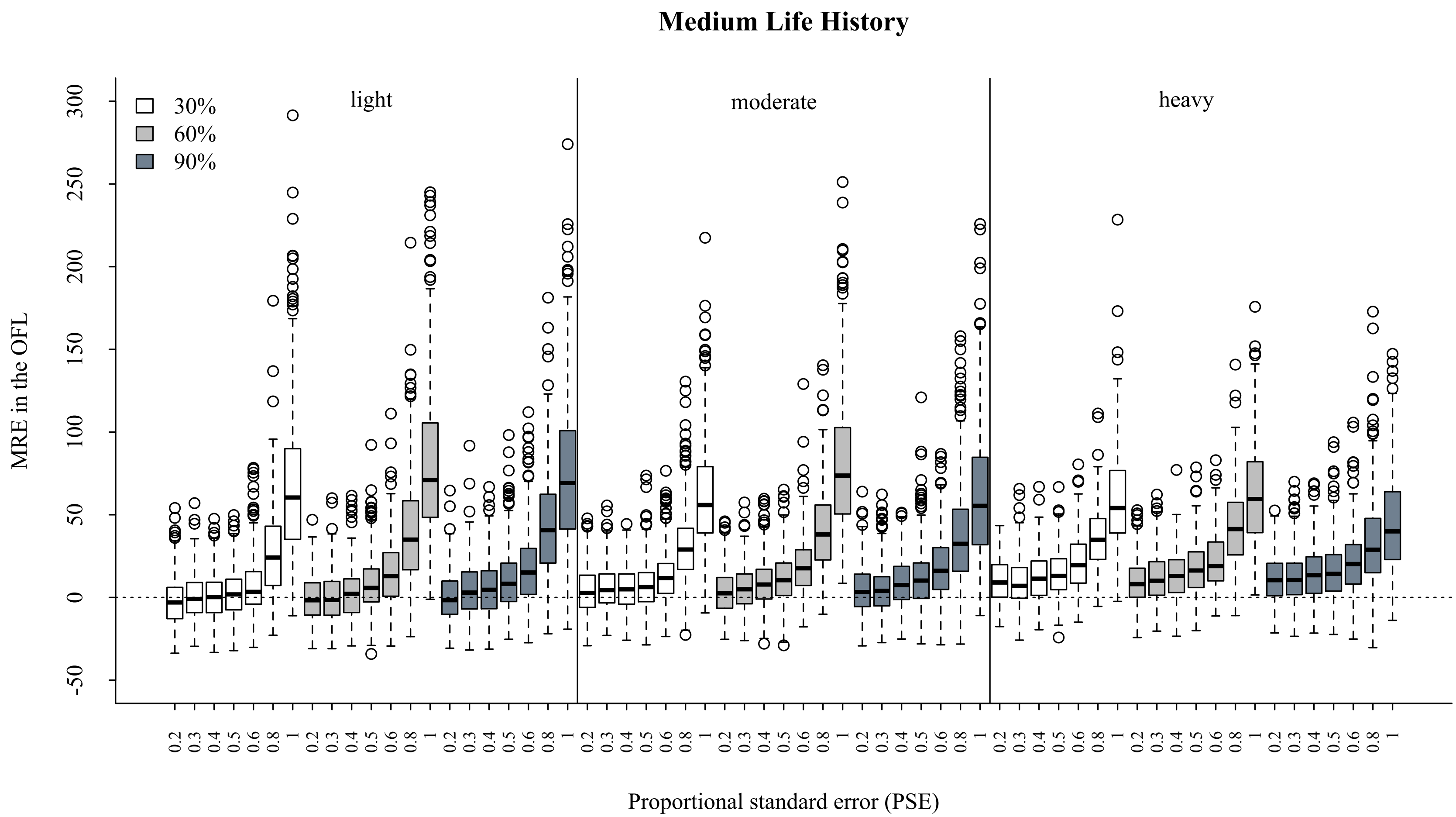

Figure 33. Similar to Figure 8, but showing the MRE in terminal estimates of overfishing limit (OFL; the catch at F_{lim}) for the medium life history. The horizontal line at 0.0 is added as a reference to compare estimates across scenarios.

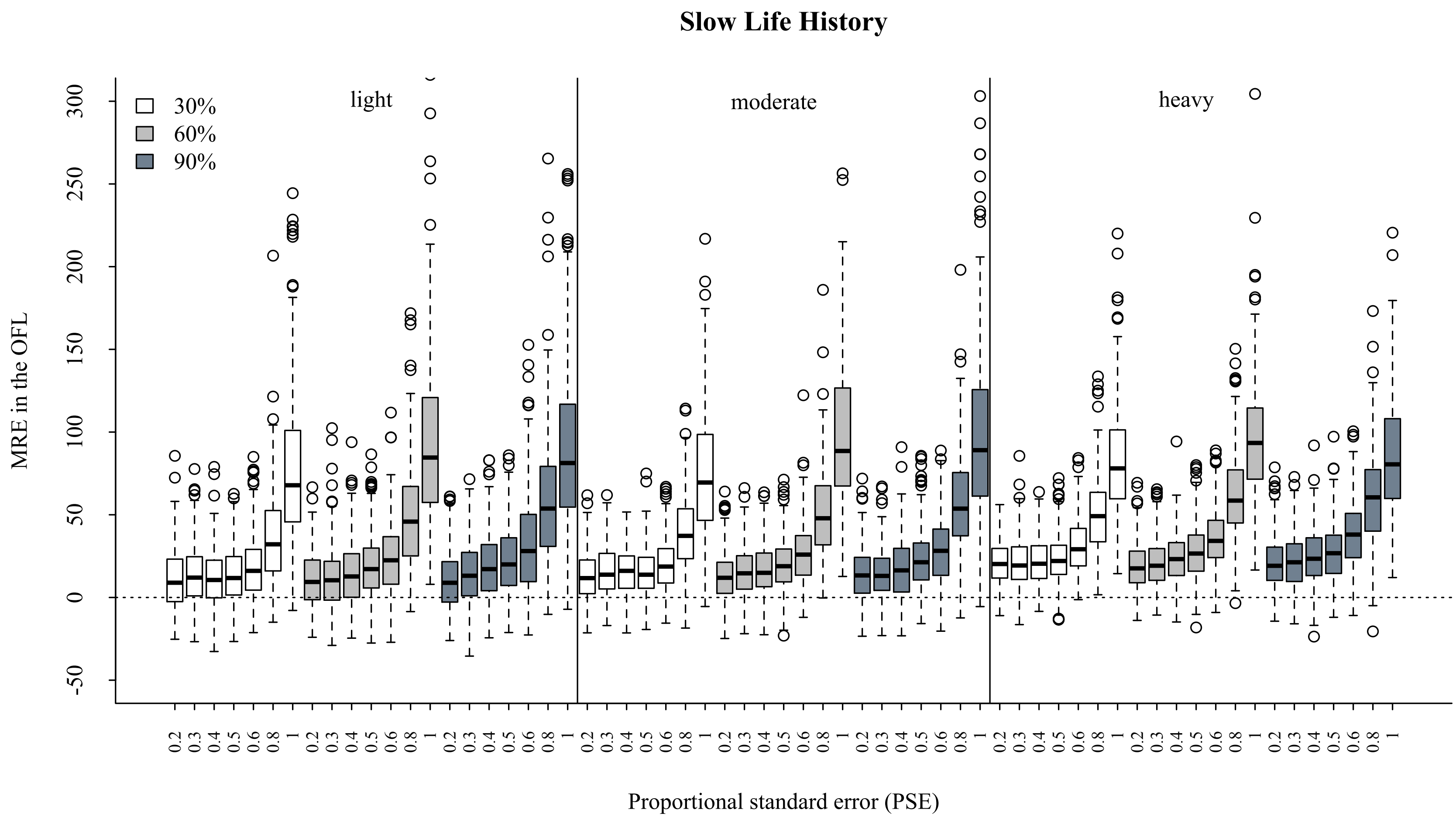

Figure 34. Similar to Figure 8, but showing the MRE in terminal estimates of overfishing limit (OFL; the catch at F_{lim}) for the slow life history. The horizontal line at 0.0 is added as a reference to compare estimates across scenarios.

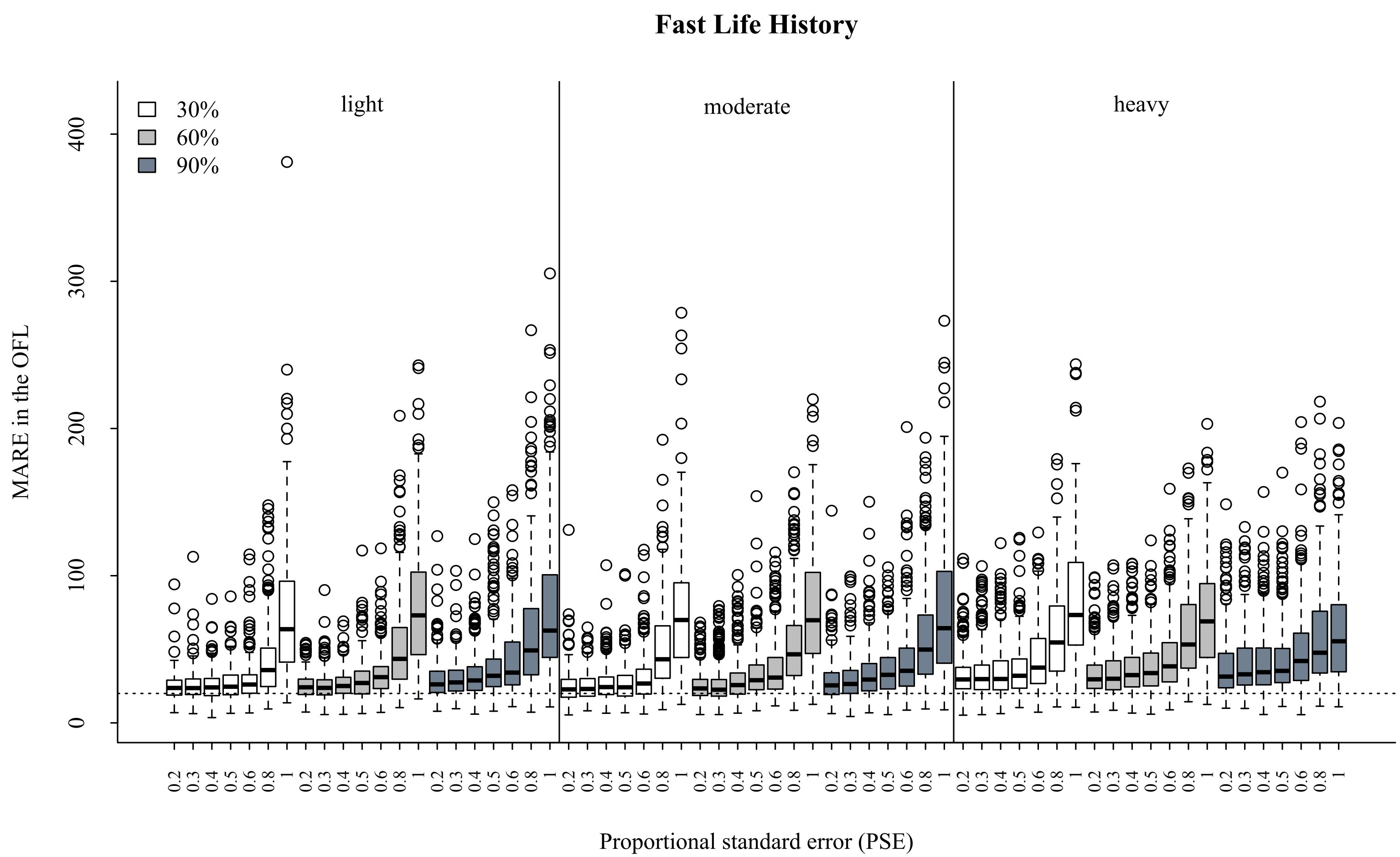

Figure 35. Similar to Figure 8, but showing the MARE in terminal estimates of overfishing limit (OFL; the catch at F_{lim}) for the fast life history. The horizontal line at 0.2 is added as a reference to compare estimates across scenarios.

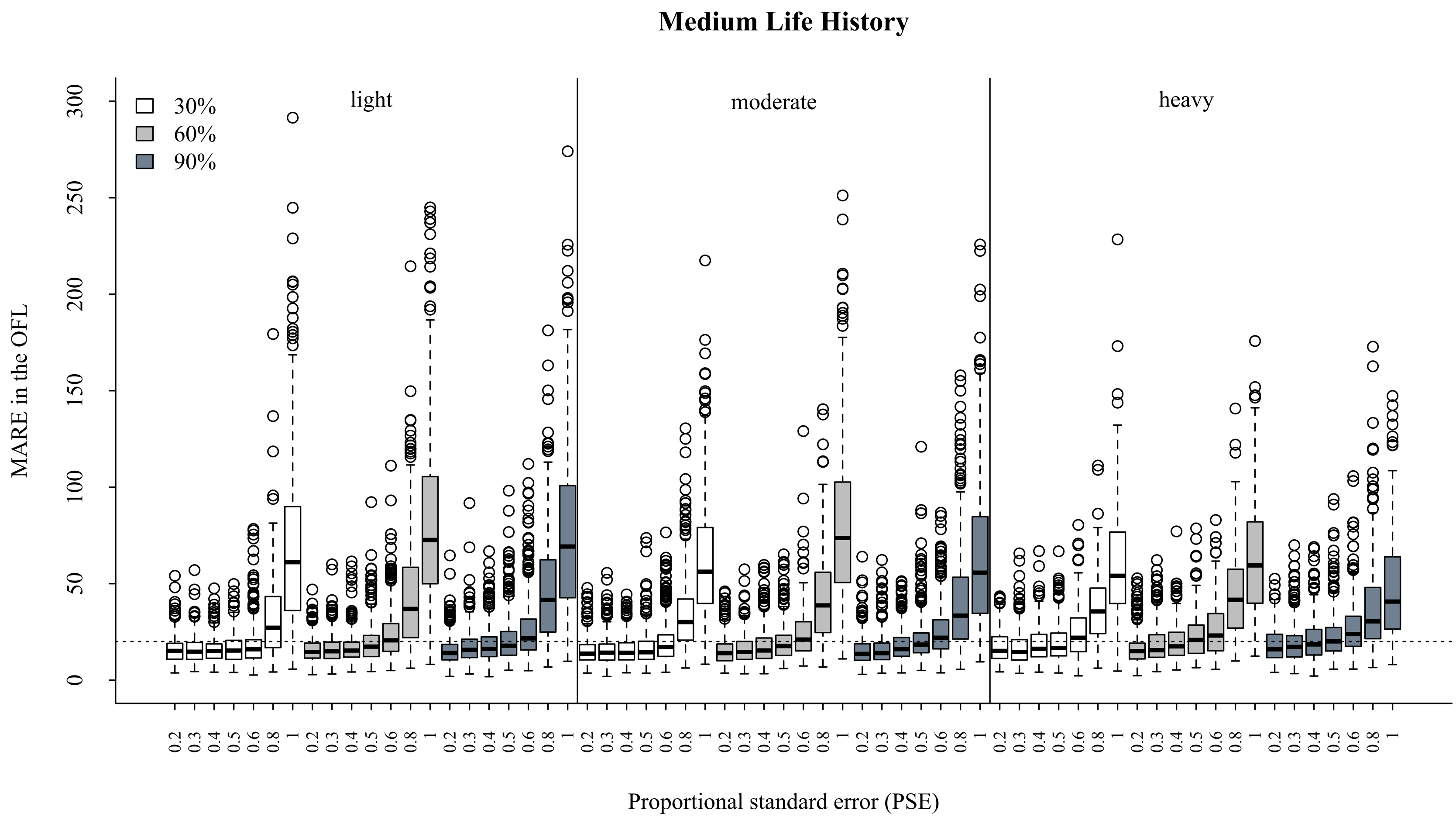

Figure 36. Similar to Figure 8, but showing the MARE in terminal estimates of overfishing limit (OFL; the catch at F_{lim}) for the medium life history. The horizontal line at 0.2 is added as a reference to compare estimates across scenarios.

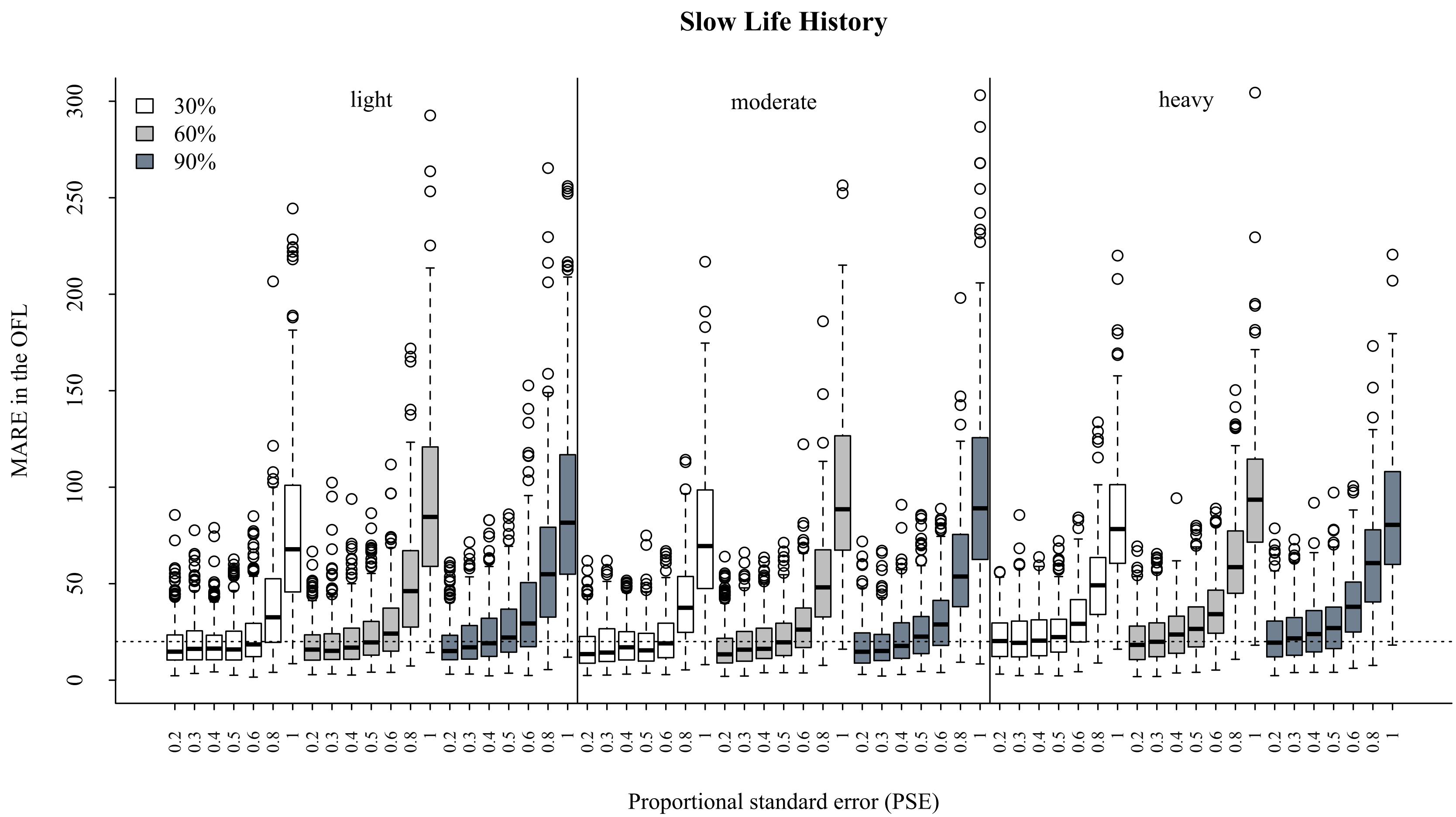

Figure 37. Similar to Figure 8, but showing the MARE in terminal estimates of overfishing limit (OFL; the catch at F_{lim}) for the slow life history. The horizontal line at 0.2 is added as a reference to compare estimates across scenarios.

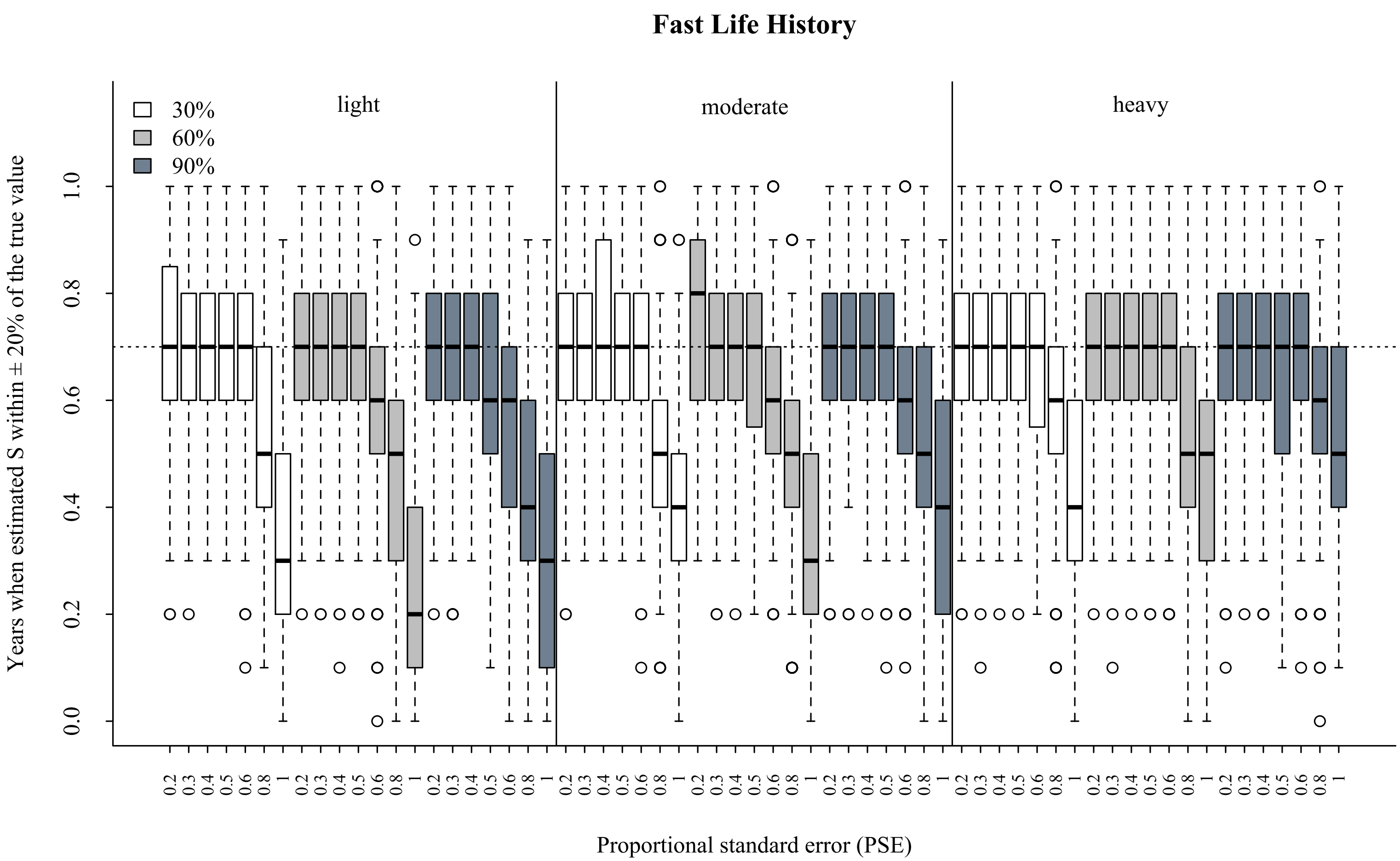

Figure 38. Similar to Figure 8, but showing the proportion of years when terminal estimates of spawning biomass (*S*) are within ± 20% of the true for the fast life history. The horizontal line at 0.7 is added as a reference to compare estimates across scenarios.

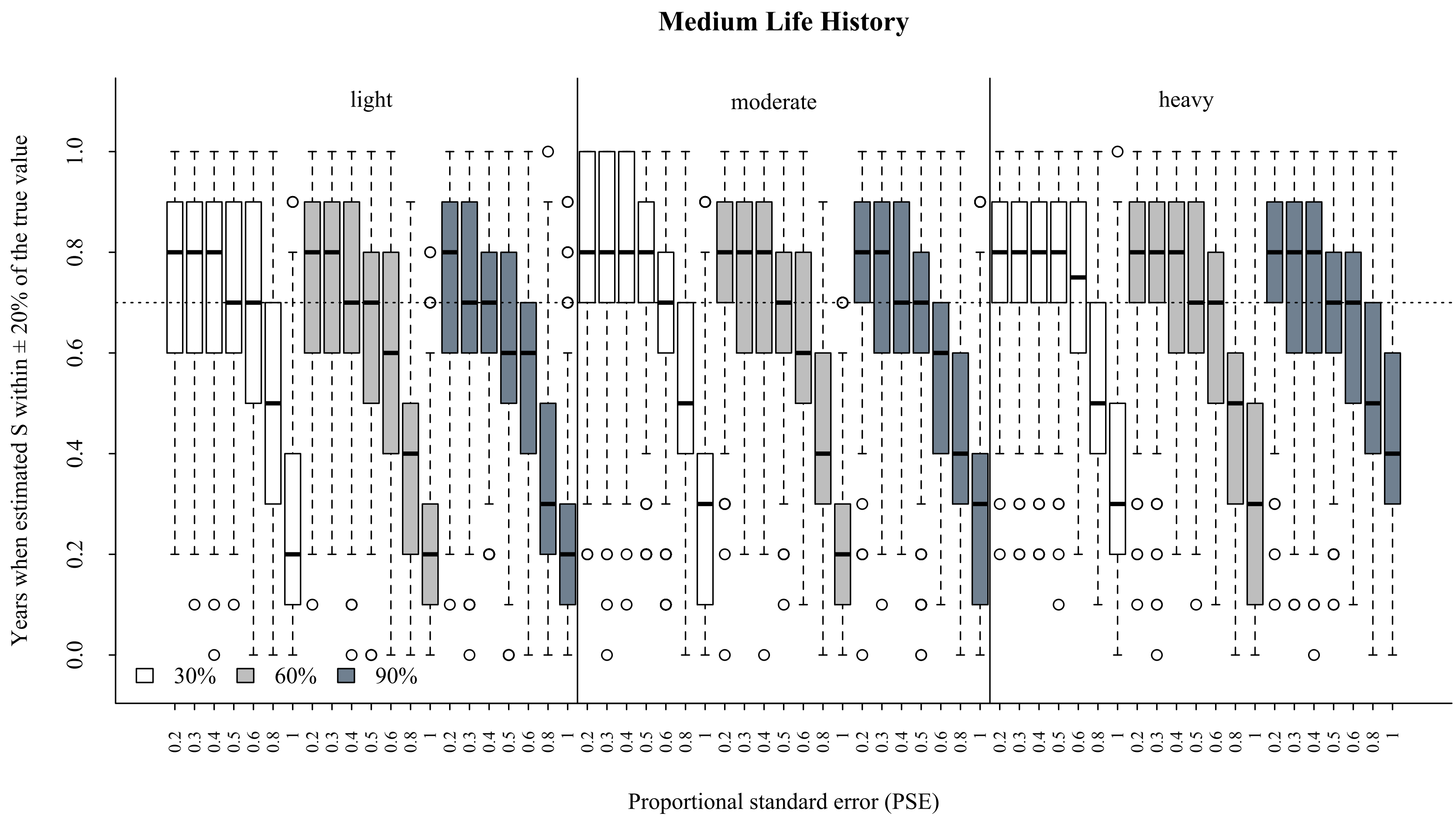

Figure 39. Similar to Figure 8, but showing the proportion of years when terminal estimates of spawning biomass (*S*) are within ± 20% of the true for the medium life history. The horizontal line at 0.7 is added as a reference to compare estimates across scenarios.

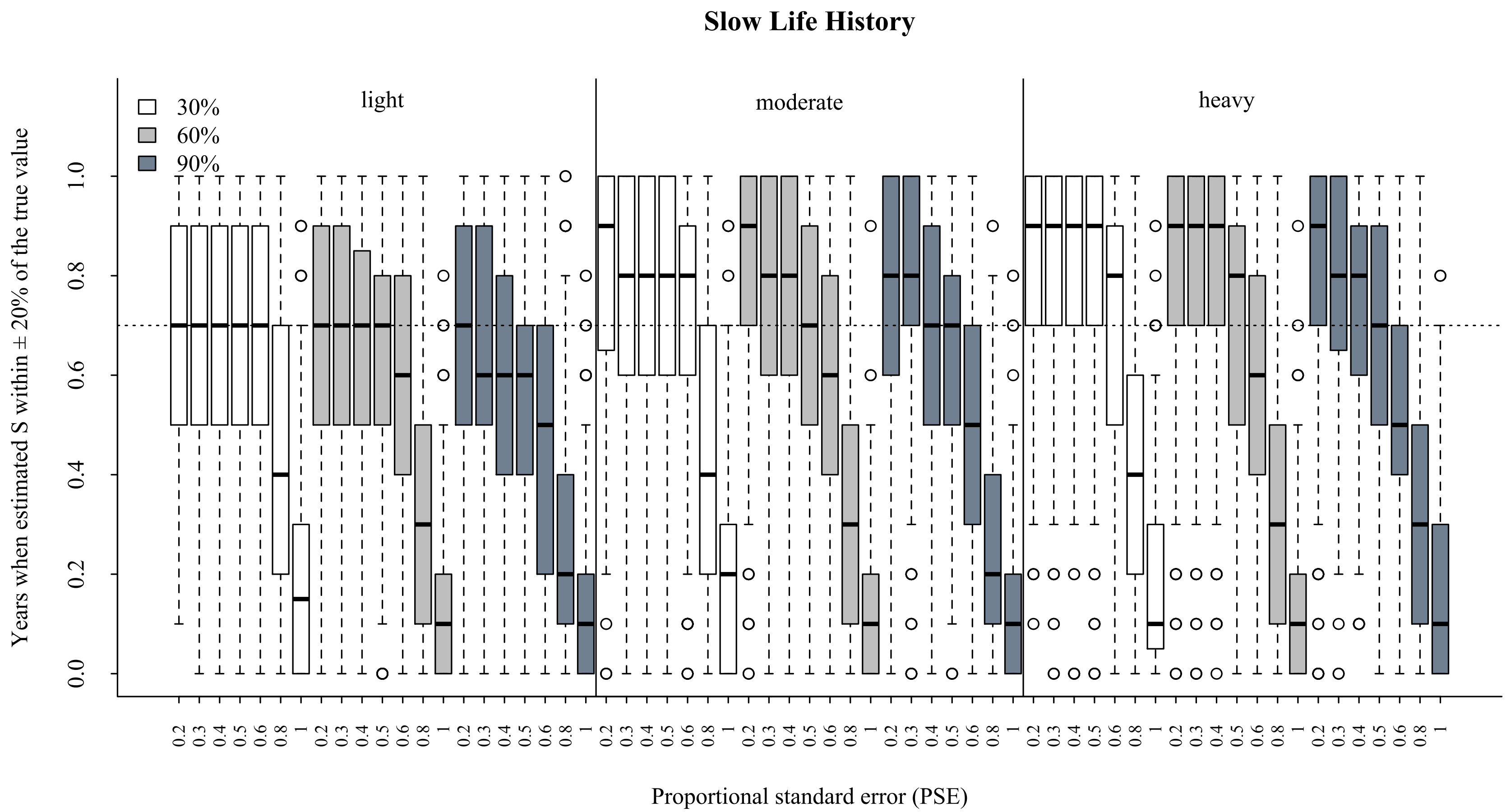

Figure 40. Similar to Figure 8, but showing the proportion of years when terminal estimates of spawning biomass (*S*) are within ± 20% of the true for the slow life history. The horizontal line at 0.7 is added as a reference to compare estimates across scenarios.

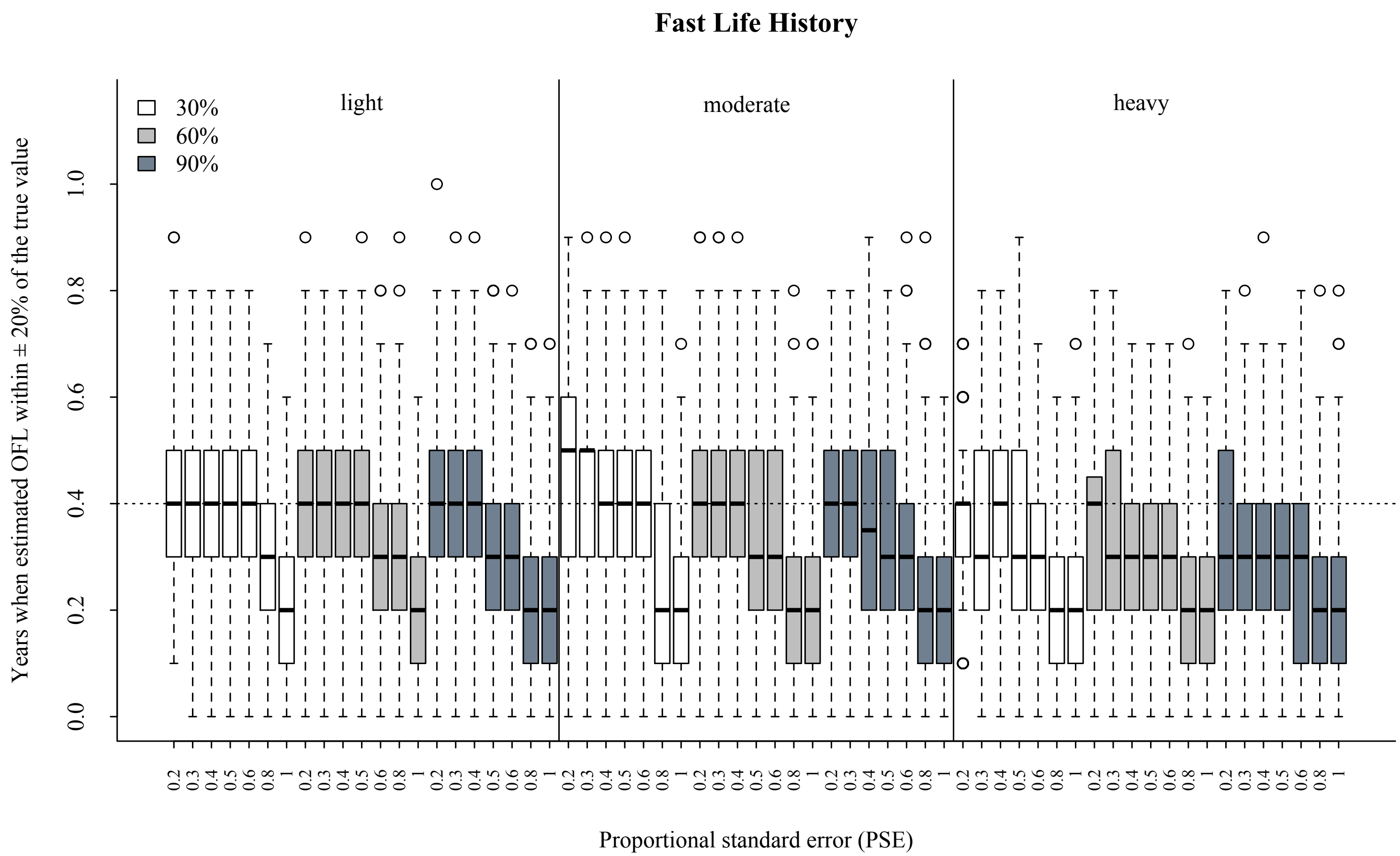

Figure 41. Similar to Figure 8, but showing the proportion of years when terminal estimates of the OFL are within ± 20% of the true for the fast life history. The horizontal line at 0.4 is added as a reference to compare estimates across scenarios.

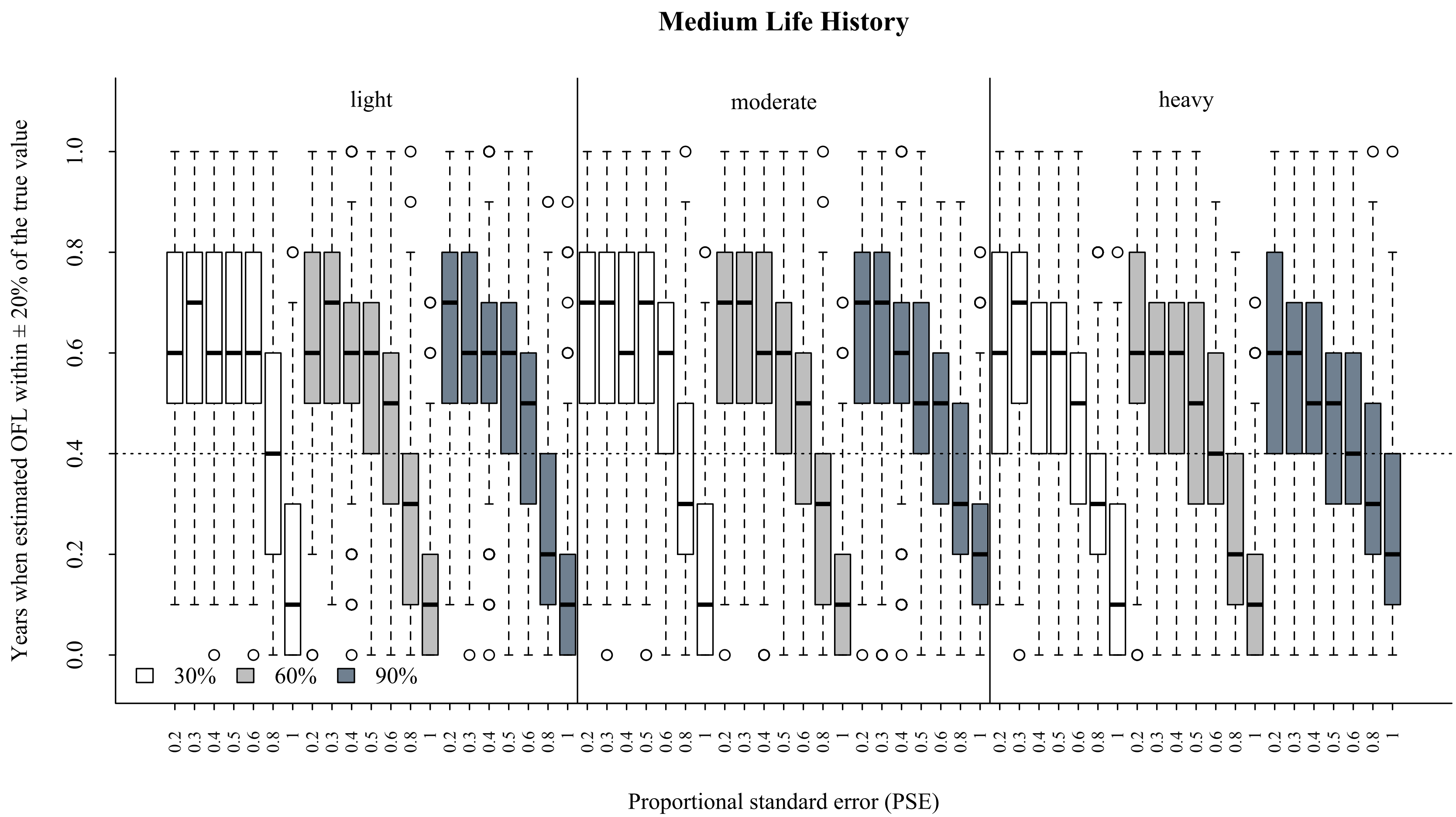

Figure 42. Similar to Figure 8, but showing the proportion of years when terminal estimates of the OFL are within ± 20% of the true for the medium life history. The horizontal line at 0.4 is added as a reference to compare estimates across scenarios.

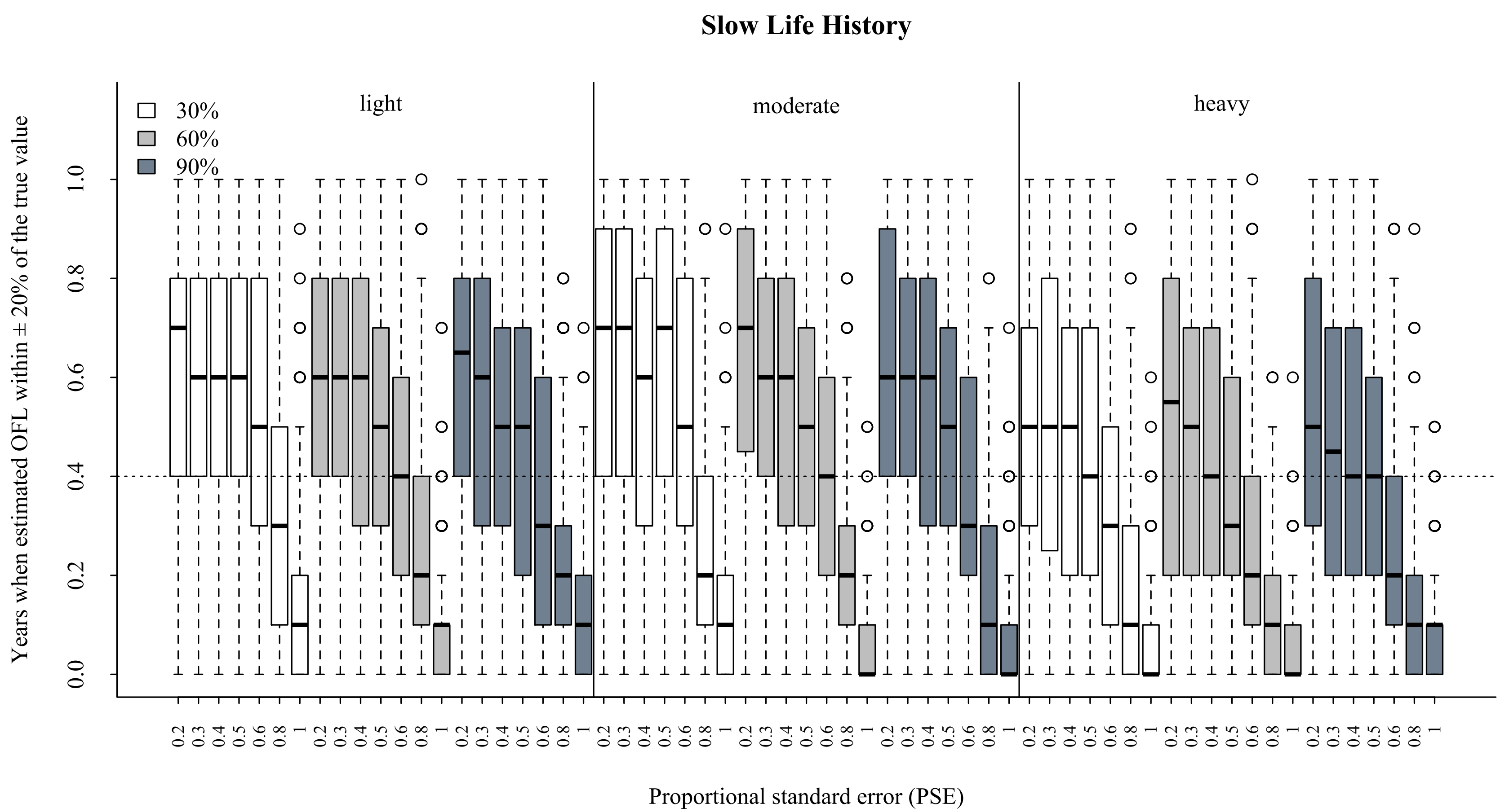

Figure 43. Similar to Figure 8, but showing the proportion of years when terminal estimates of the OFL are within ± 20% of the true for the slow life history. The horizontal line at 0.4 is added as a reference to compare estimates across scenarios.

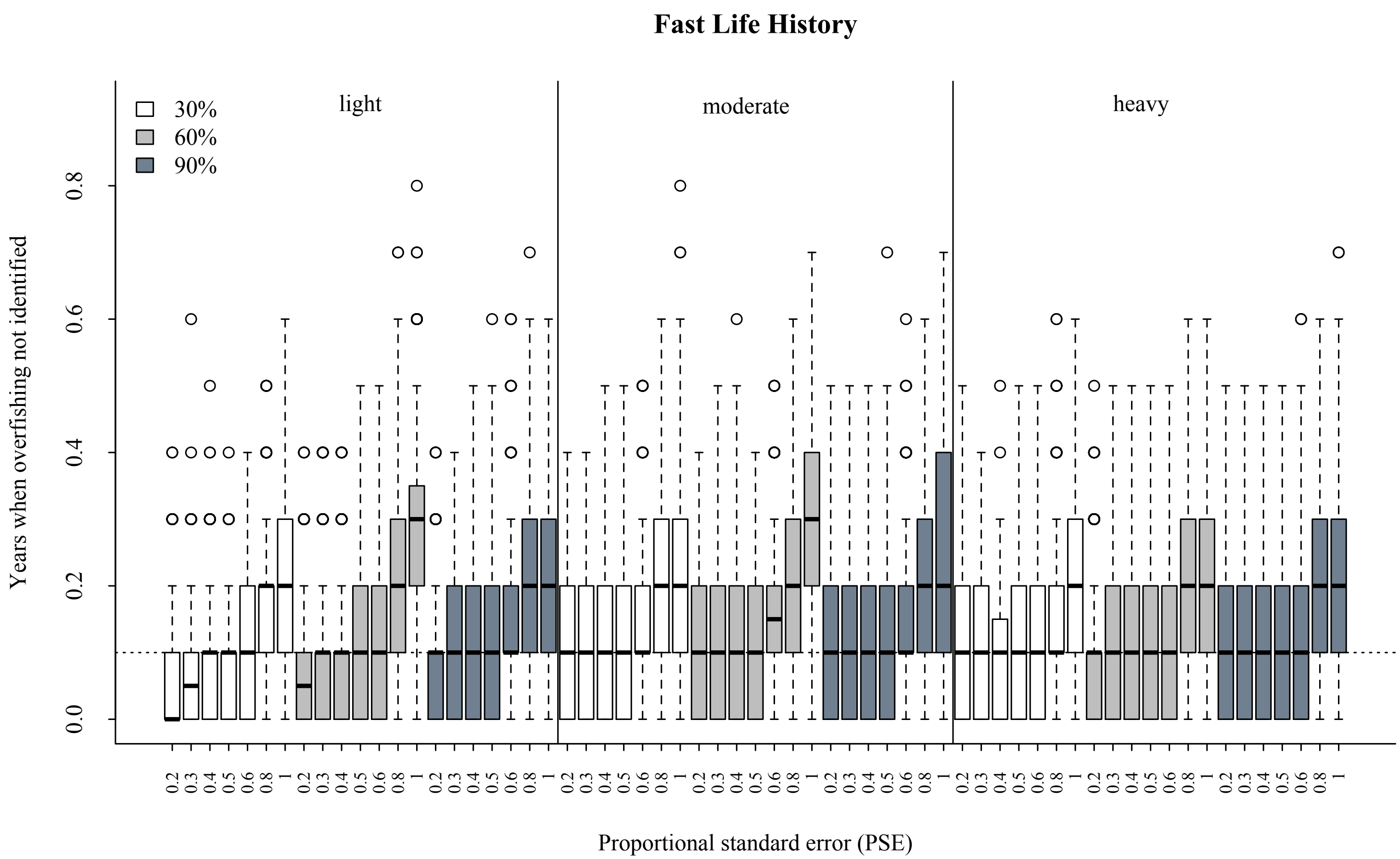

Figure 44. Similar to Figure 8, but showing the proportion of years when overfishing occurs in the terminal year but is not identified in the assessment for the fast life history. The horizontal line at 0.1 is added as a reference to compare estimates across scenarios

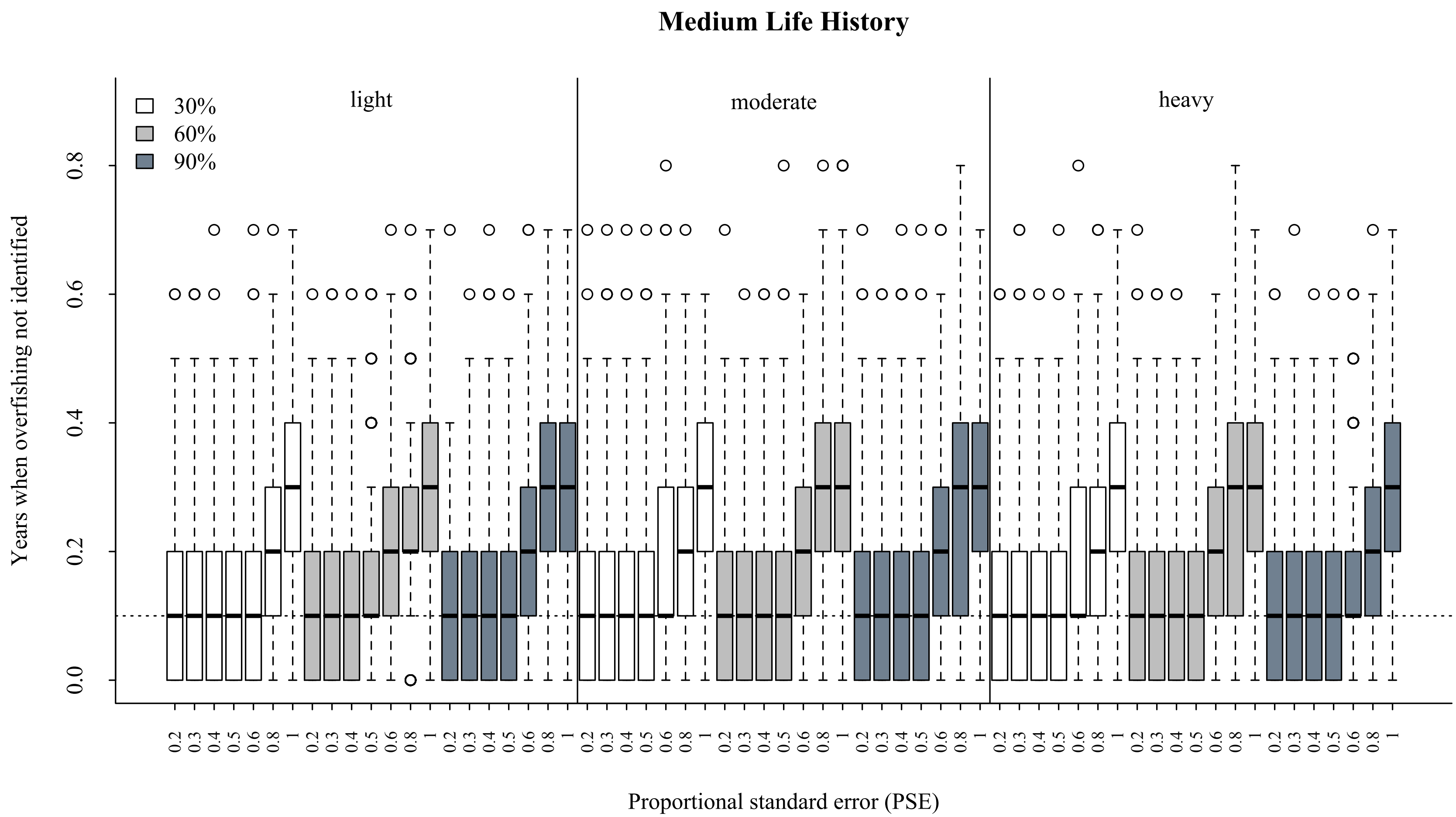

Figure 45. Similar to Figure 8, but showing the proportion of years when overfishing occurs in the terminal year but is not identified in the assessment for the medium life history. The horizontal line at 0.1 is added as a reference to compare estimates across scenarios

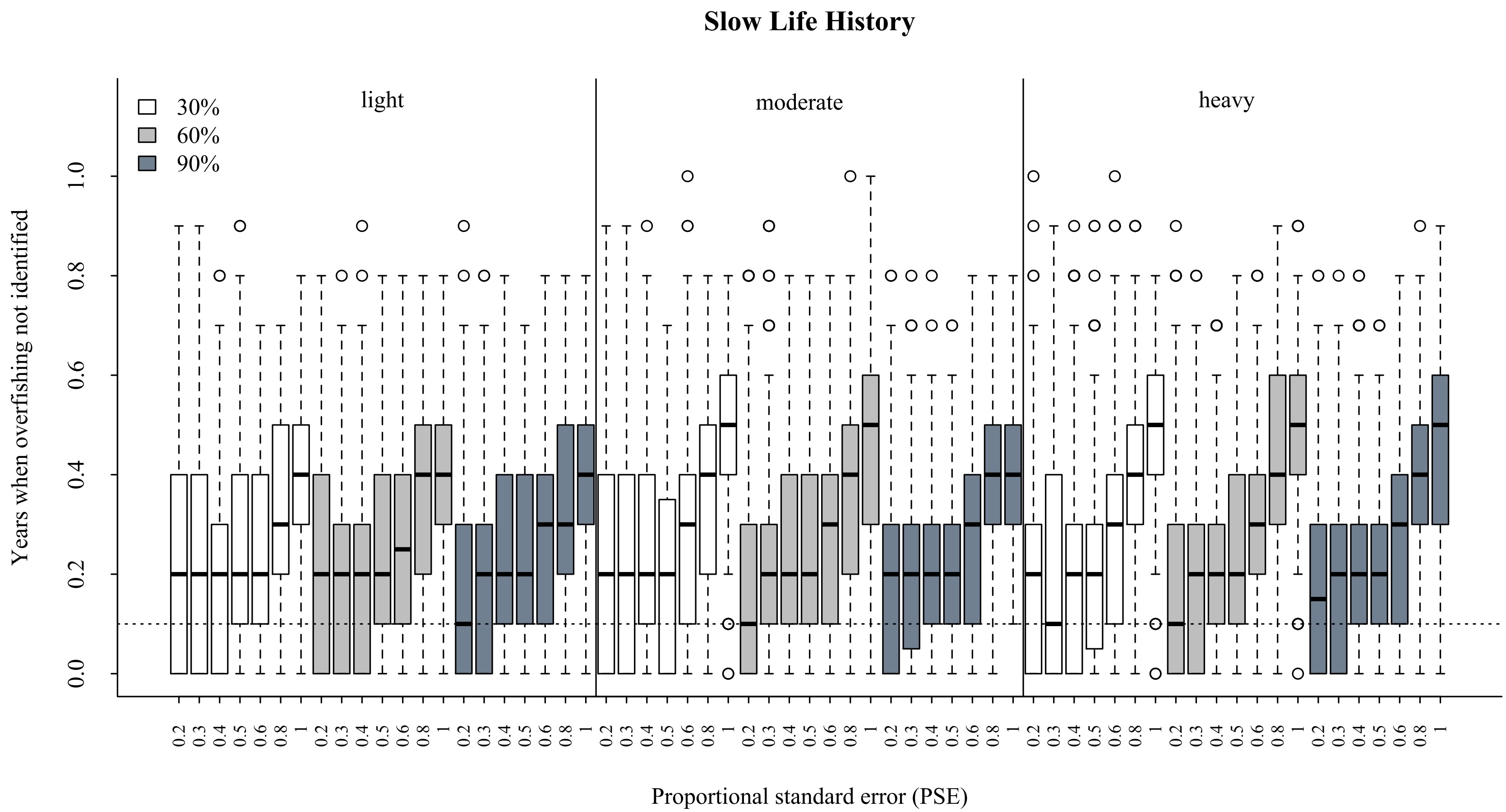

Figure 46. Similar to Figure 8, but showing the proportion of years when overfishing occurs in the terminal year but is not identified in the assessment for the slow life history. The horizontal line at 0.1 is added as a reference to compare estimates across scenarios

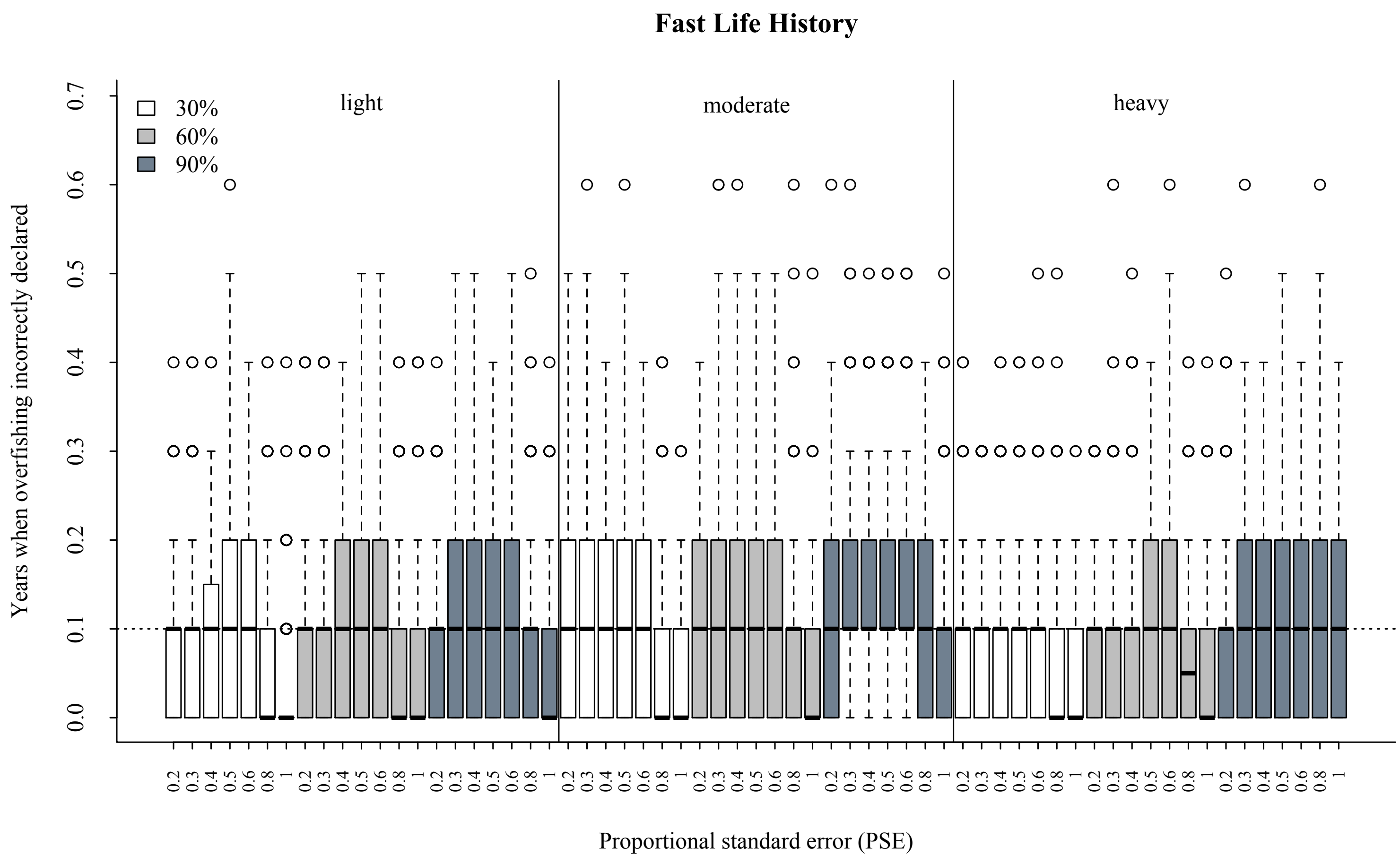

Figure 47. Similar to Figure 8, but showing the proportion of years when overfishing does not occur in the terminal year but is estimated to have occurred by the assessment for the fast life history. The horizontal line at 0.1 is added as a reference to compare estimates across scenarios

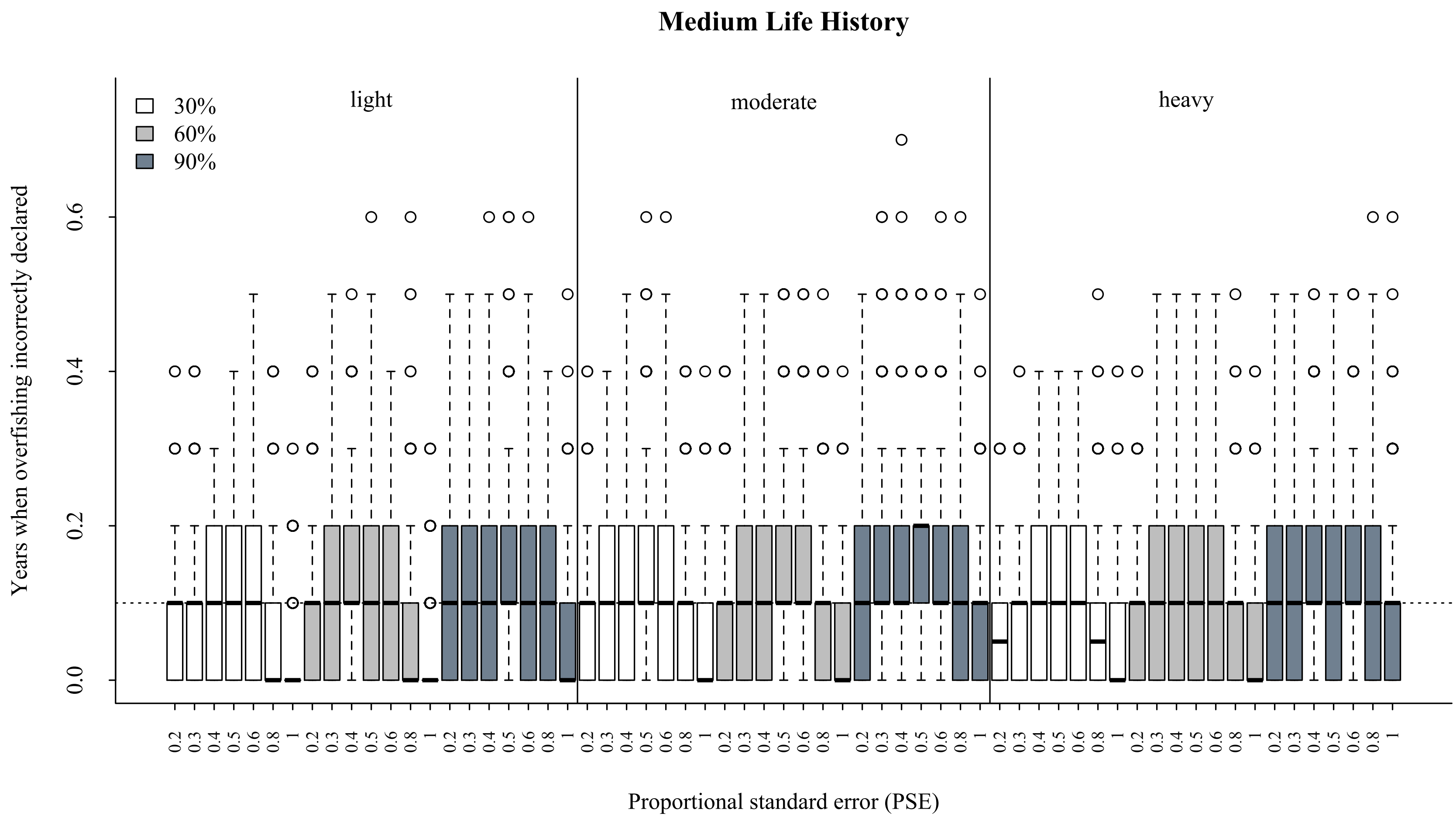

Figure 48. Similar to Figure 8, but showing the proportion of years when overfishing does not occur in the terminal year but is estimated to have occurred by the assessment for the medium life history. The horizontal line at 0.1 is added as a reference to compare estimates across scenarios

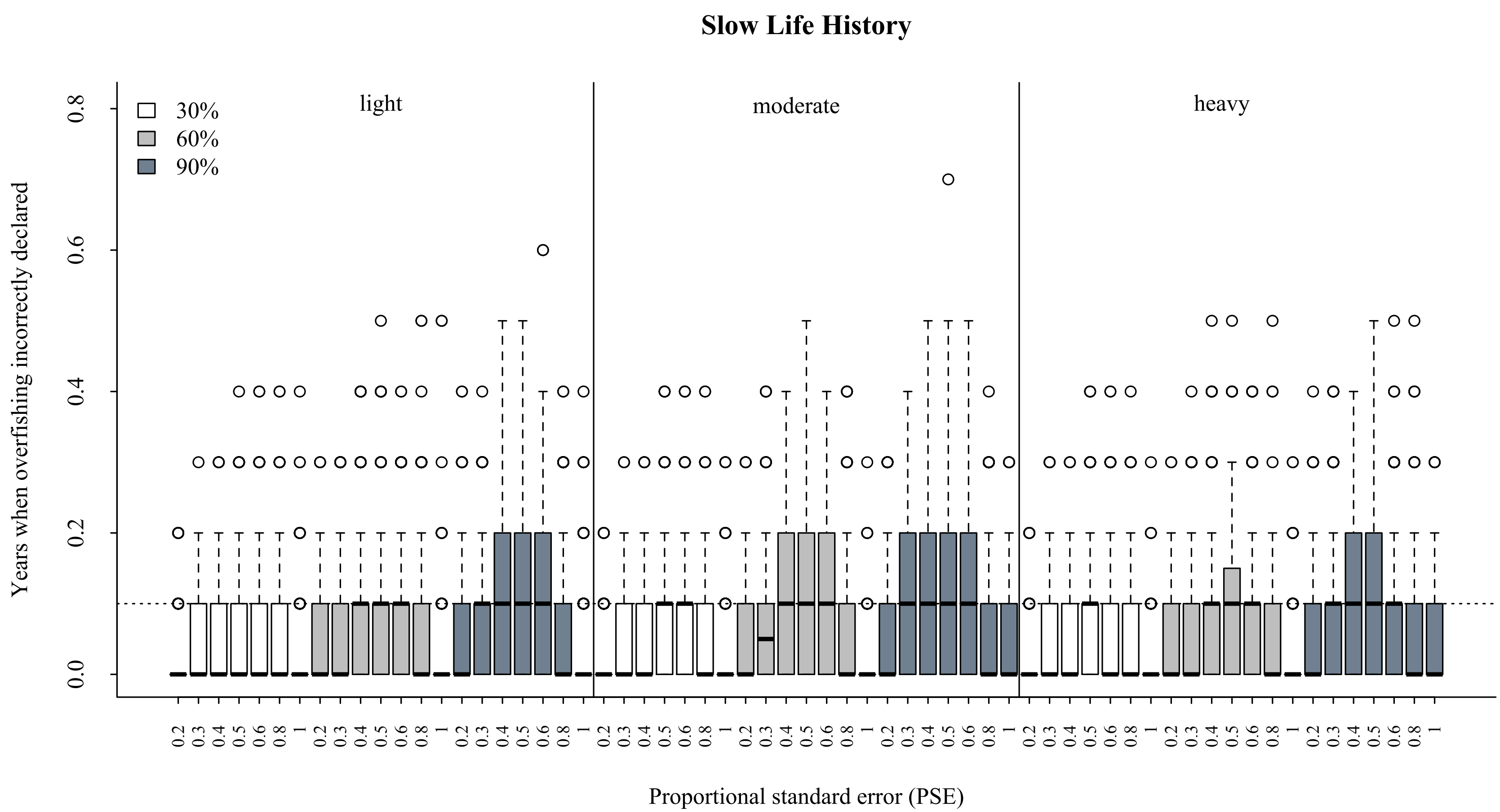

Figure 49. Similar to Figure 8, but showing the proportion of years when overfishing does not occur in the terminal year but is estimated to have occurred by the assessment for the slow life history. The horizontal line at 0.1 is added as a reference to compare estimates across scenarios.

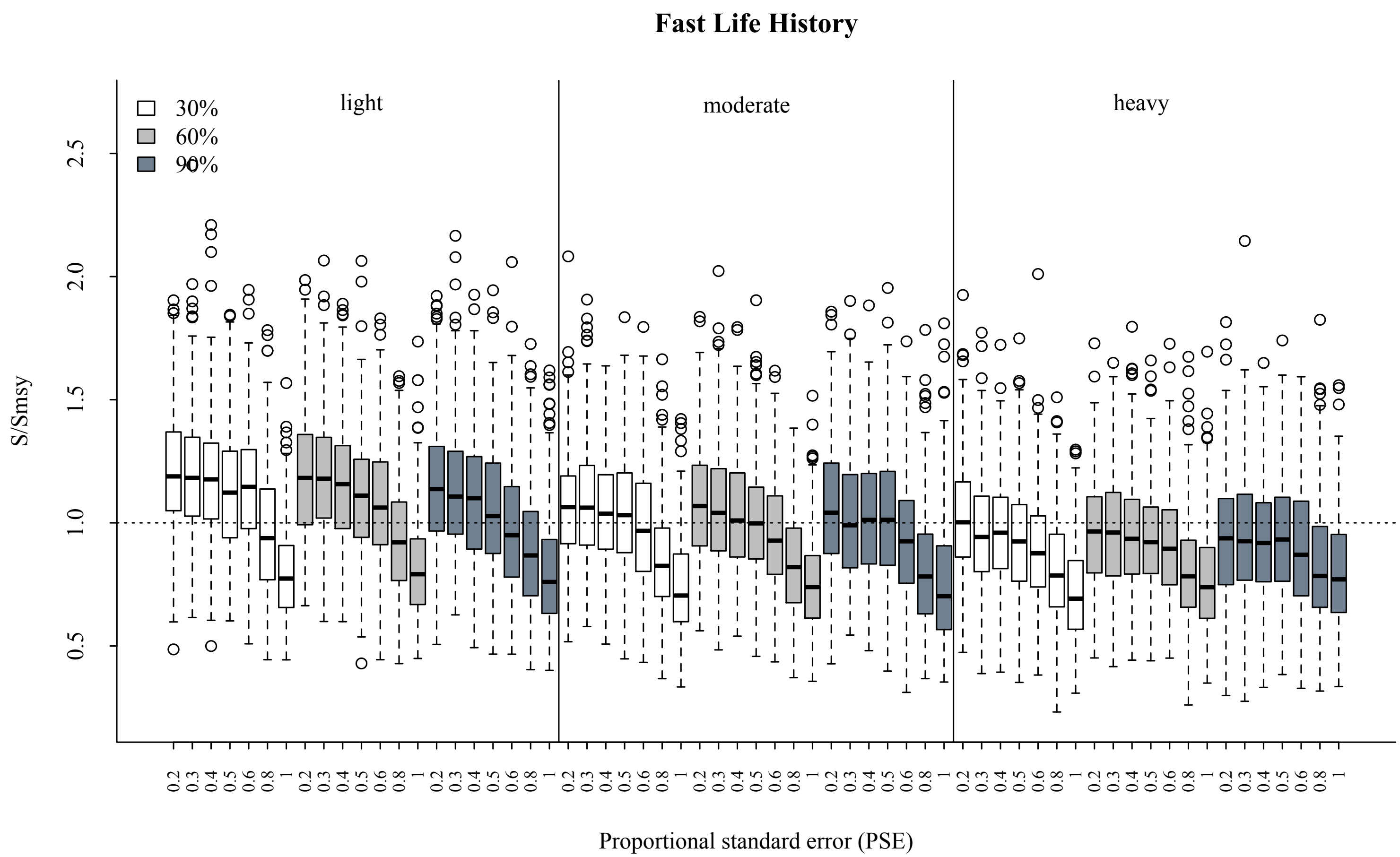

Figure 50. Similar to Figure 8, but showing the true ratio of the mean population spawning biomass, *S,* to the biomass that produces MSY, $S_{MSY,}$ over the last 18 years of the model for the fast life history. The horizontal line at 1.0 is added as a reference to compare estimates across scenarios, indicating the mean biomass is at S_{MSY}

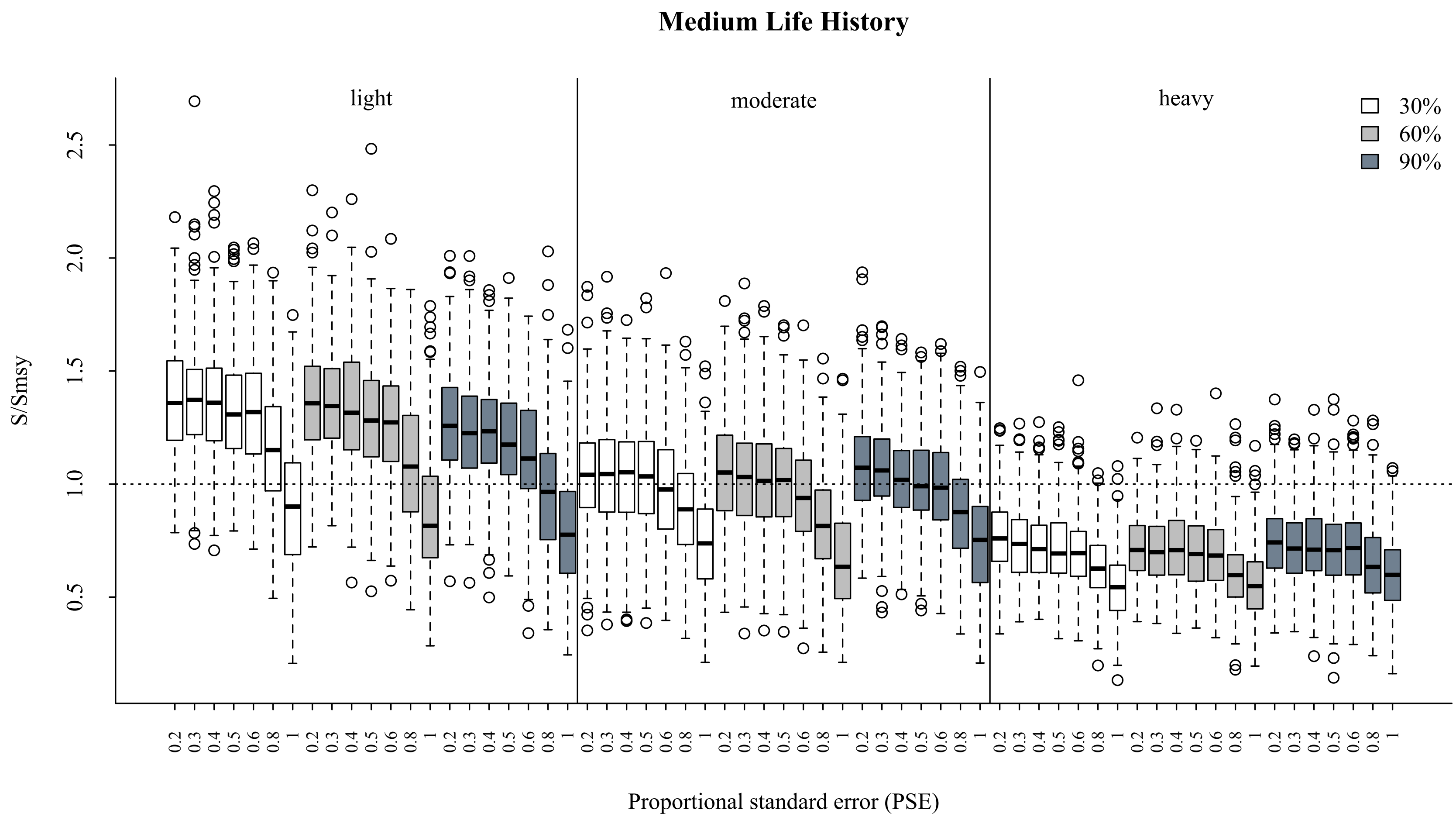

Figure 51. Similar to Figure 5, but showing the true ratio of the mean population spawning biomass, *S,* to the biomass that produces MSY, S_{MSY}, over the last 18 years of the model for the medium life history. The horizontal line at 1.0 is added as a reference to compare estimates across scenarios, indicating the mean biomass is at S_{MSY}

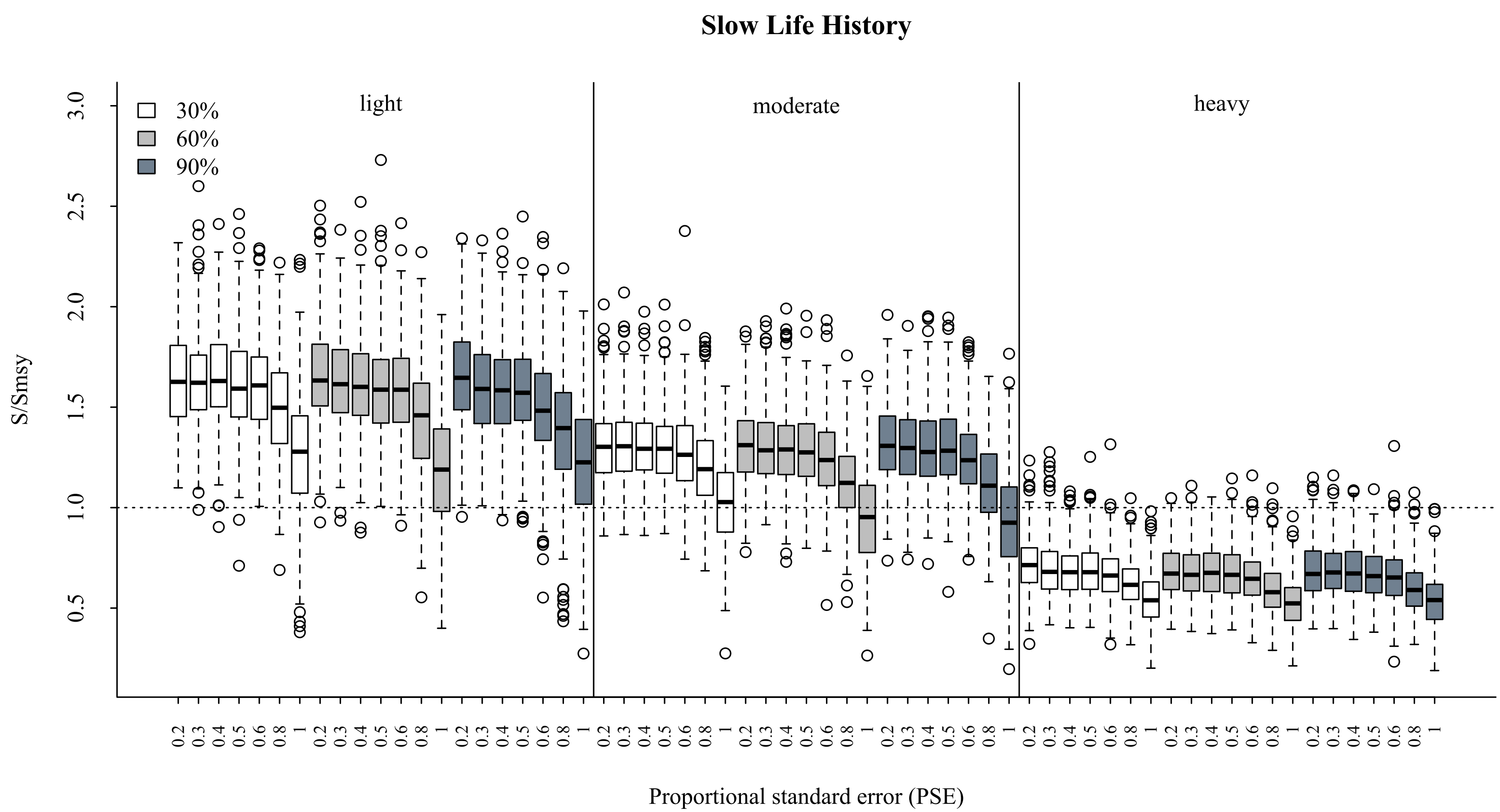

Figure 52. Similar to Figure 8, but showing the true ratio of the mean population spawning biomass, *S,* to the biomass that produces MSY, S_{MSY}, over the last 18 years of the model for the slow life history. The horizontal line at 1.0 is added as a reference to compare estimates across scenarios, indicating the mean biomass is at S_{MSY}

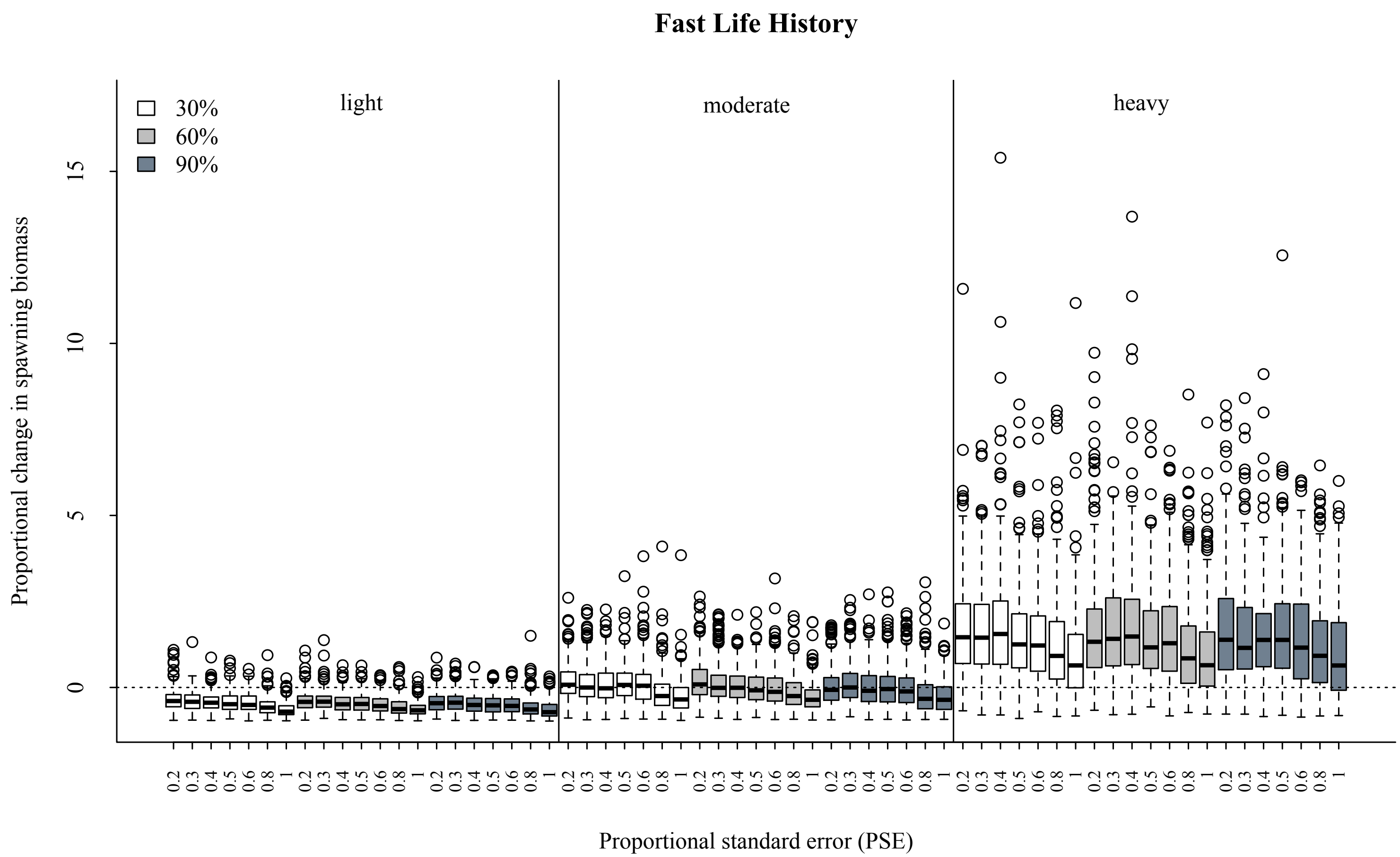

Figure 53. Similar to Figure 8, but showing the proportional change in spawning biomass over the final 18 years of the model for the fast life history. The horizontal line at 0 is added as a reference to compare estimates across scenarios, indicating no change in biomass.

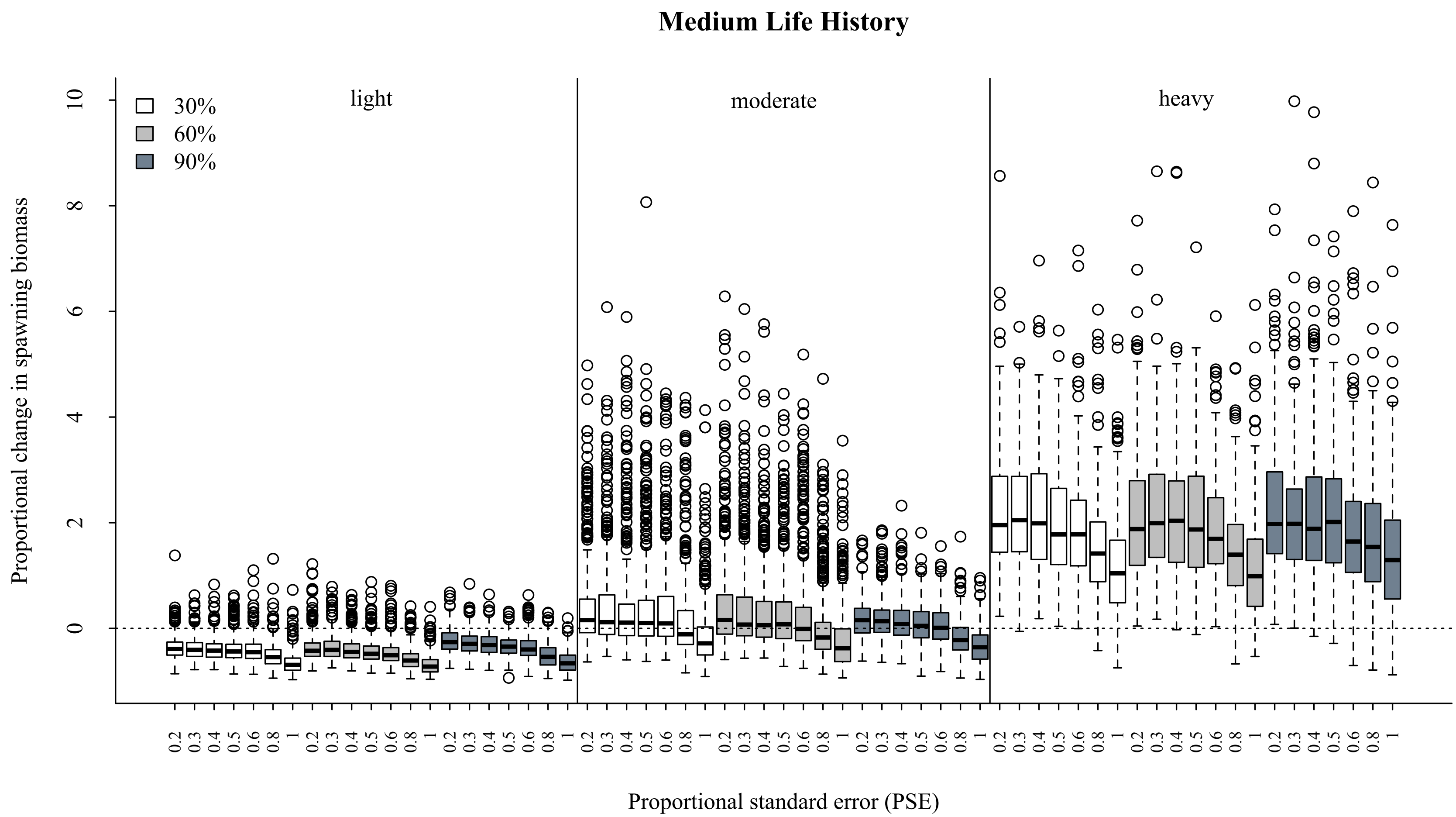

Figure 54. Similar to Figure 8, but showing the proportional change in spawning biomass over the final 18 years of the model for the medium life history. The horizontal line at 0 is added as a reference to compare estimates across scenarios, indicating no change in biomass.

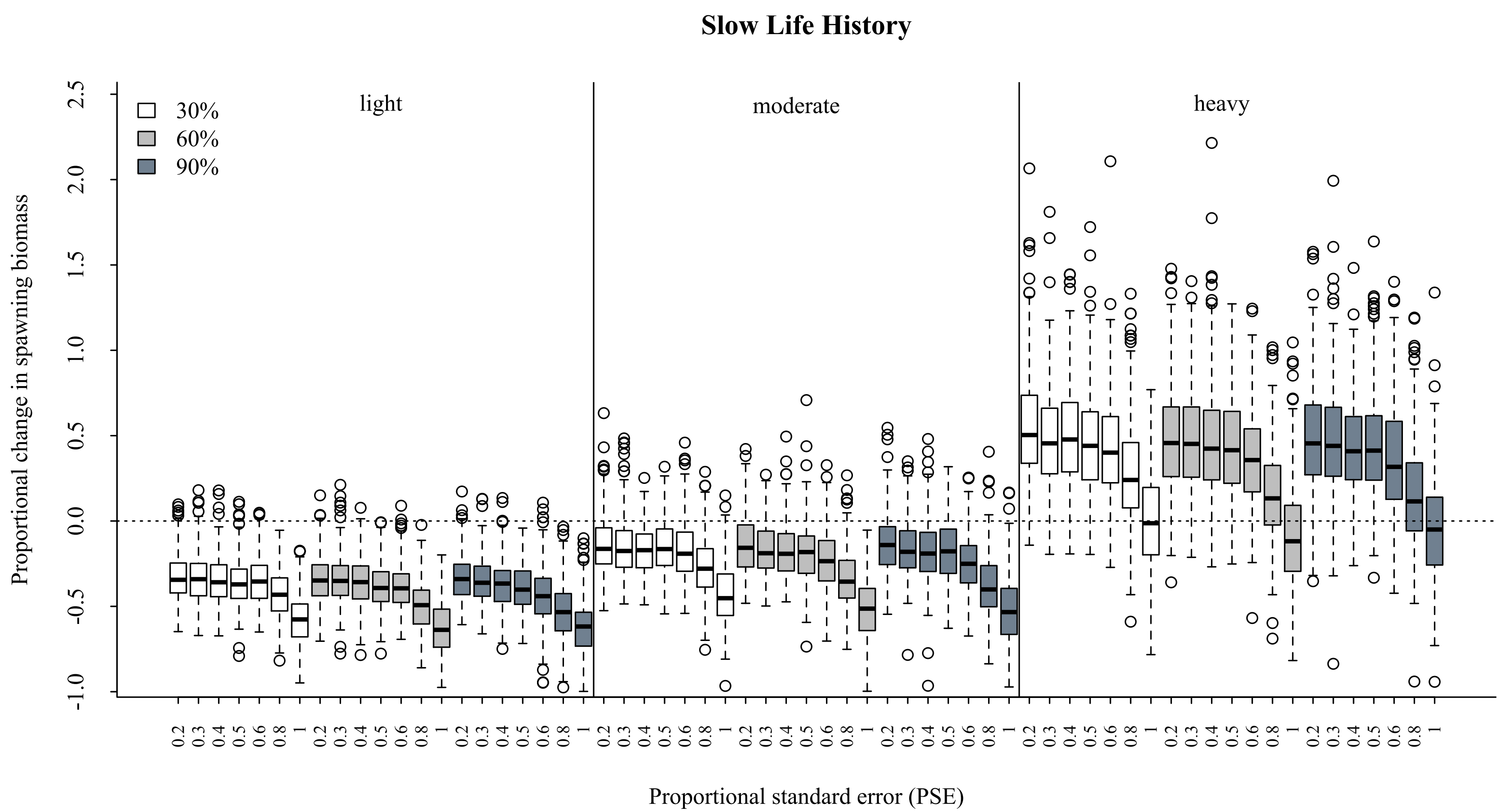

Figure 55. Similar to Figure 8, but showing the proportional change in spawning biomass over the final 18 years of the model for the slow life history. The horizontal line at 0 is added as a reference to compare estimates across scenarios, indicating no change in biomass.

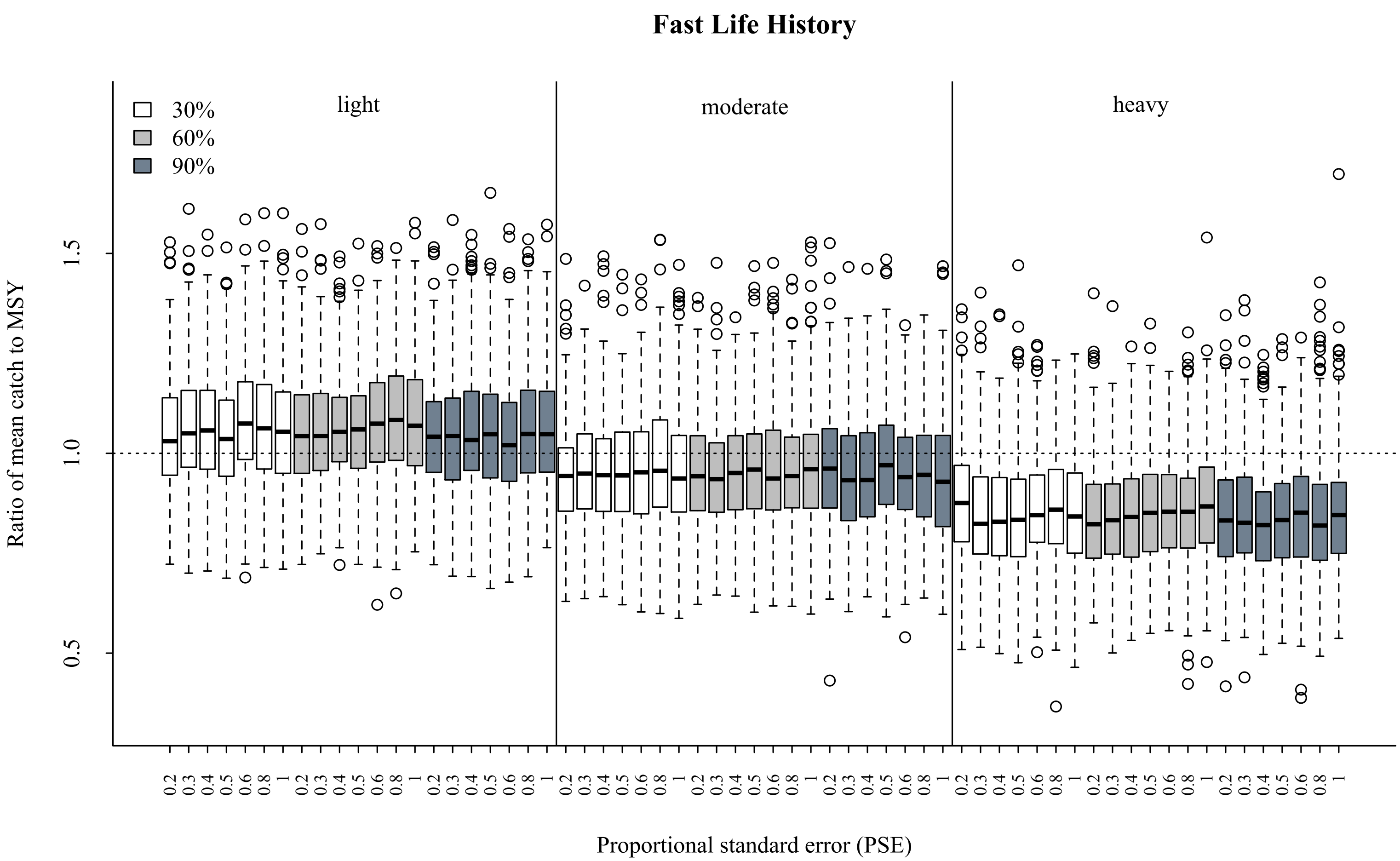

Figure 56. Similar to Figure 8, but showing the ratio of the mean catch to MSY over the final 18 years of the model for fast life history. The horizontal line at 1.0 is added as a reference to compare estimates across scenarios, indicating the mean catch = MSY.

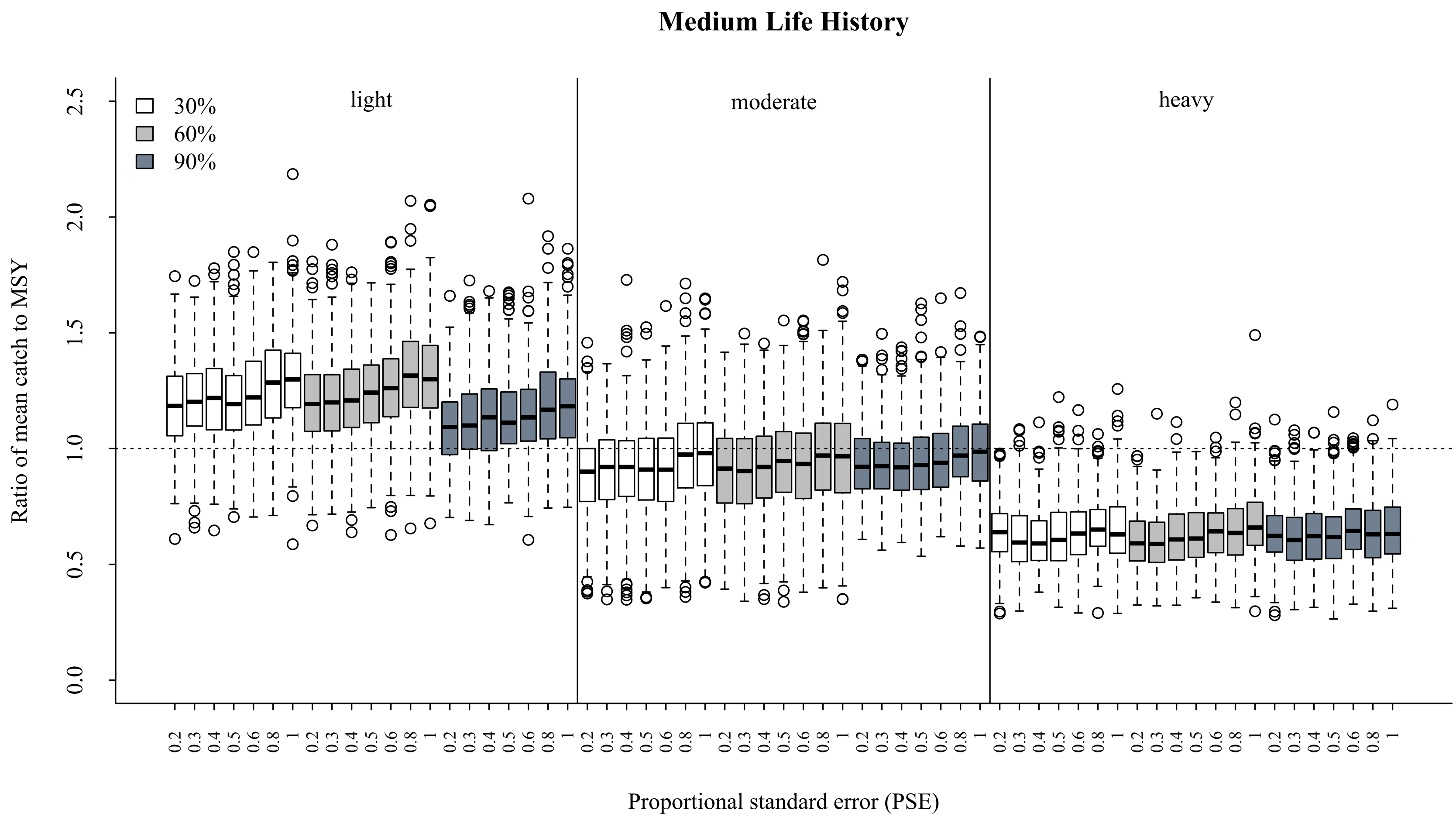

Figure 57. Similar to Figure 8, but showing the ratio of the mean catch to MSY over the final 18 years of the model for the medium life history. The horizontal line at 1.0 is added as a reference to compare estimates across scenarios, indicating the mean catch = MSY.

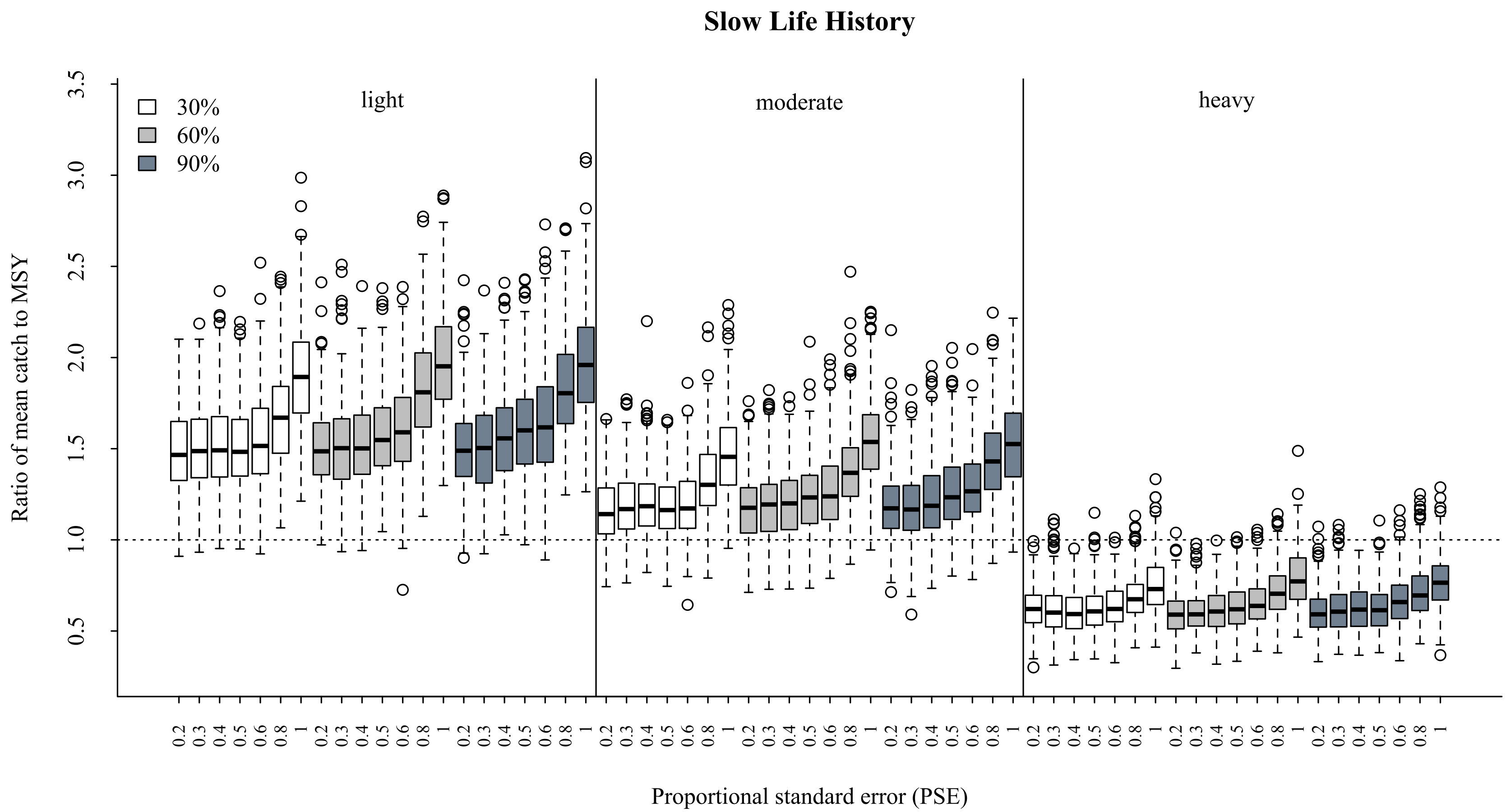

Figure 58. Similar to Figure 8, but showing the ratio of the mean catch to MSY over the final 18 years of the model for the slow life history. The horizontal line at 1.0 is added as a reference to compare estimates across scenarios, indicating the mean catch = MSY.

Fast Life History

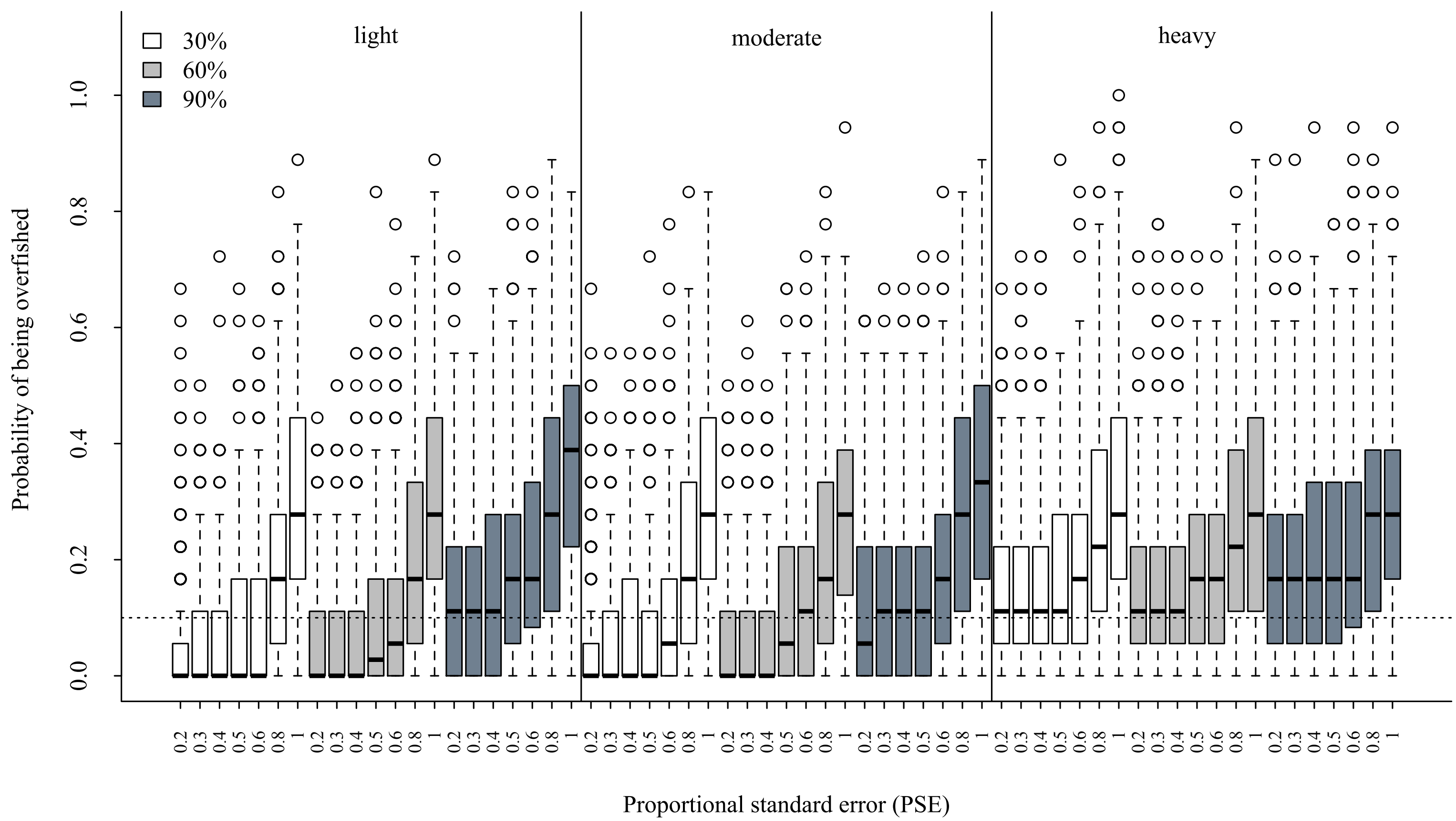

Figure 59. Similar to Figure 8, but showing the probability of being overfished (i.e., the proportion of the final 18 years when $S < 0.5$ S_{MSY}) for the fast life history. The horizontal line at 0.1 is added as a reference to compare estimates across scenarios.

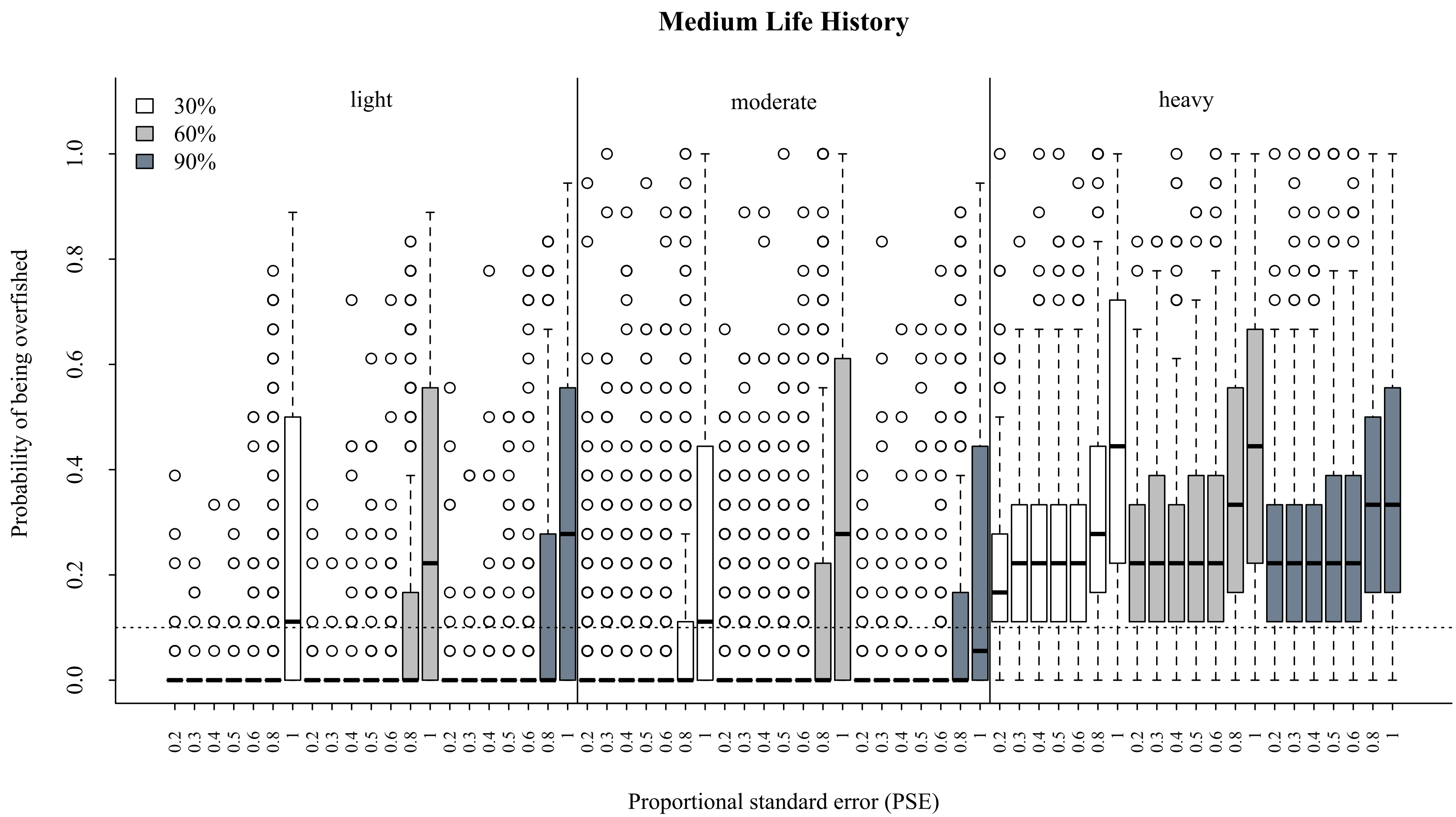

Figure 60. Similar to Figure 8, but showing the probability of being overfished (i.e., the proportion of the final 18 years when $S < 0.5\ S_{MSY}$) for the medium life history. The horizontal line at 0.1 is added as a reference to compare estimates across scenarios.

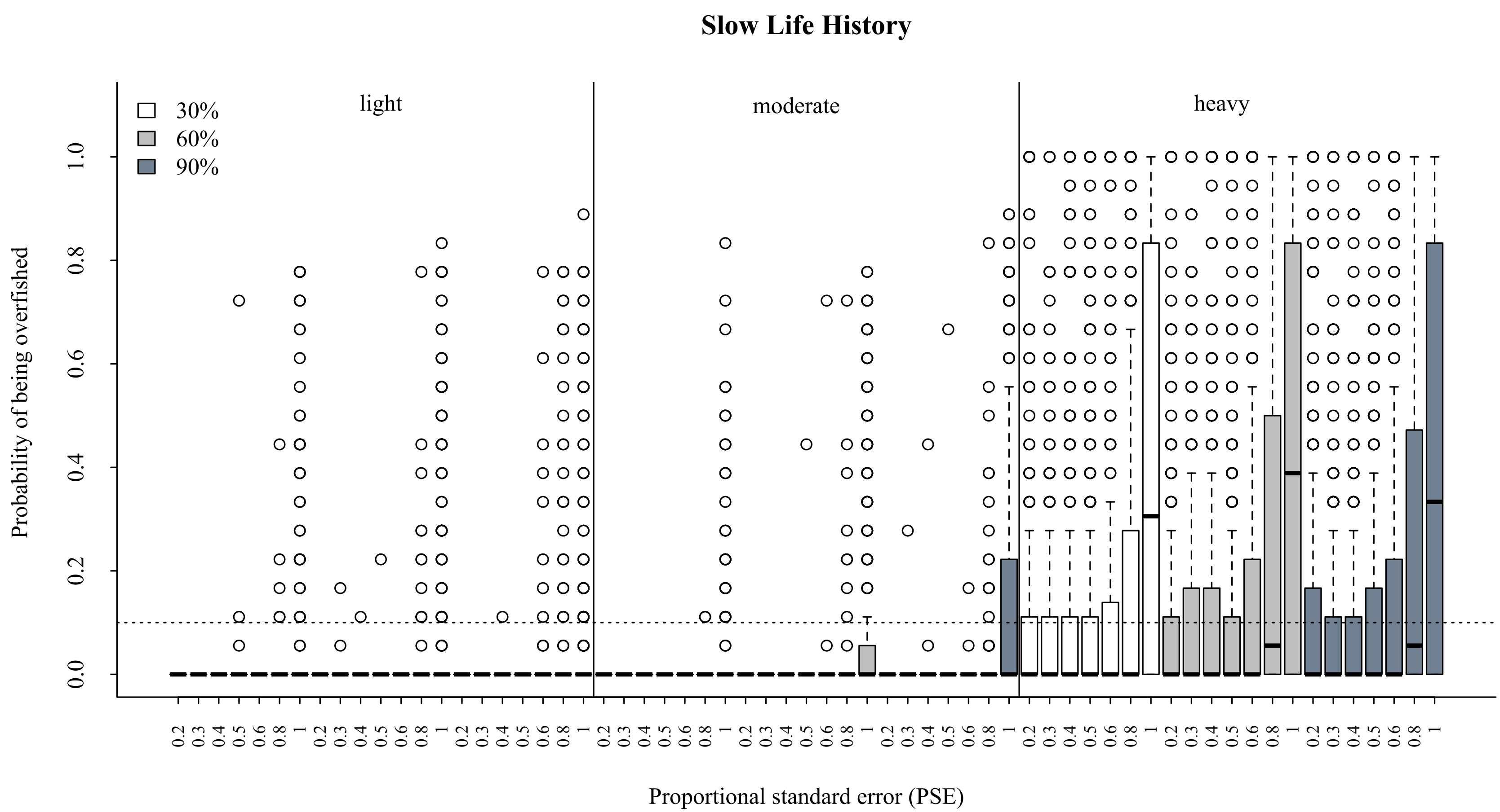

Figure 61. Similar to Figure 8, but showing the probability of being overfished (i.e., the proportion of the final 18 years when $S < 0.5\ S_{\mathrm{MSY}}$) for the slow life history. The horizontal line at 0.1 is added as a reference to compare estimates across scenarios.

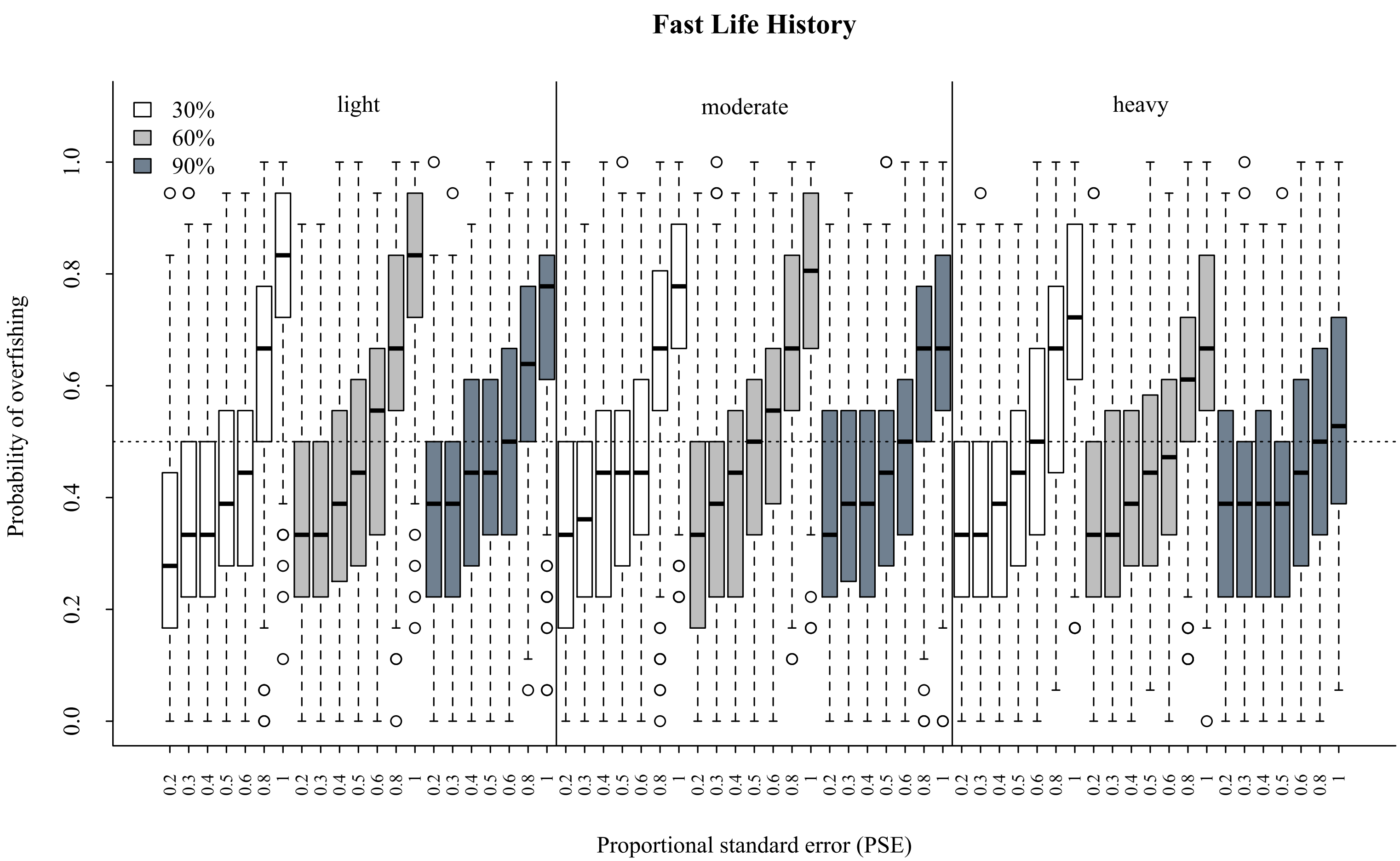

Figure 62. Similar to Figure 8, but showing the probability of overfishing (i.e., the proportion of the final 18 years when $F > F_{\text{lim}}$) for the fast life history. The horizontal line at 0.5 is added as a reference to compare estimates across scenarios, indicating scenarios when overfishing is more or less likely to occur (> 0.5 and < 0.5, respectively).

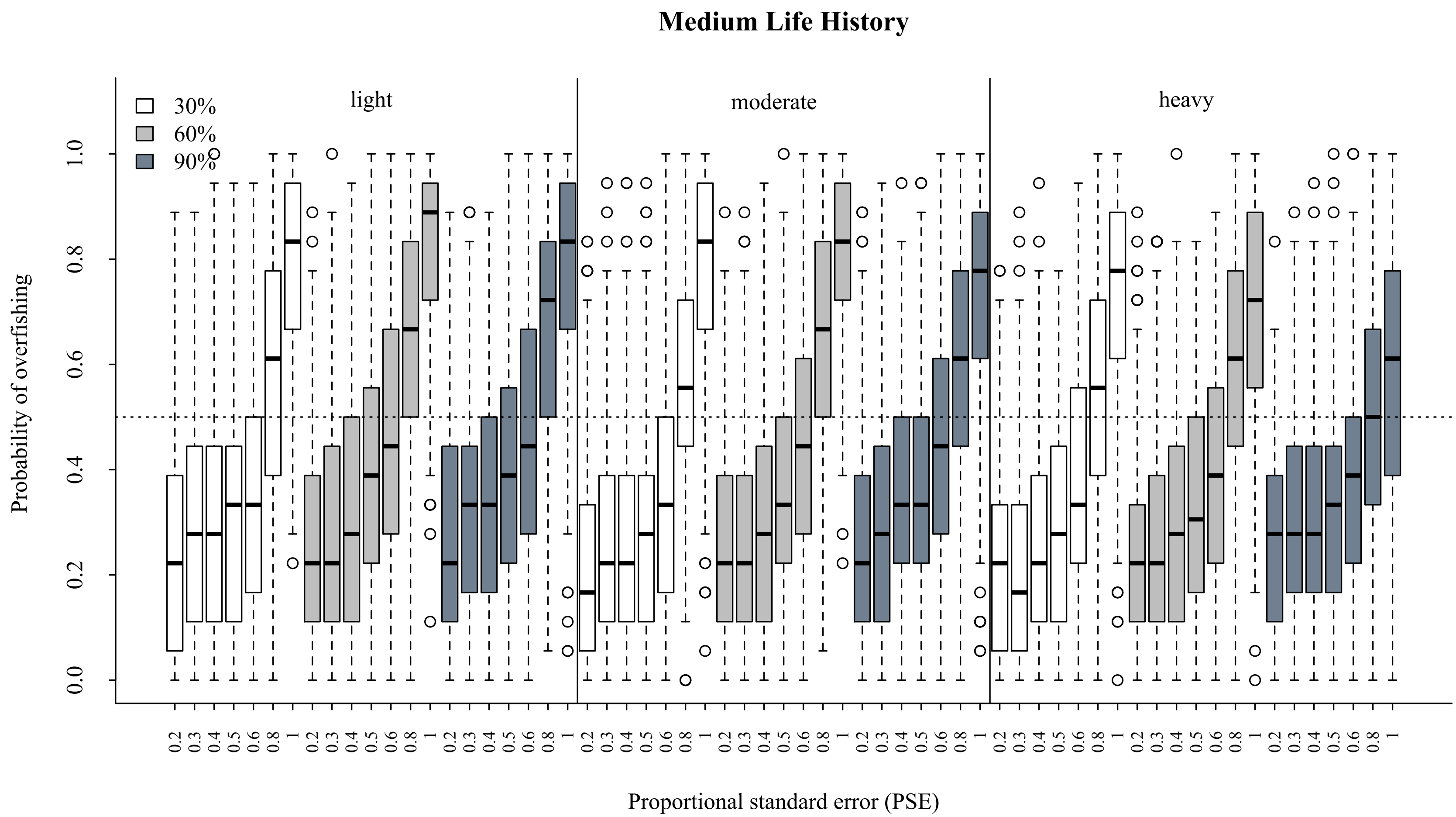

Figure 63. Similar to Figure 8, but showing the probability of overfishing (i.e., the proportion of the final 18 years when $F > F_{\mathrm{lim}}$) for the medium life history. The horizontal line at 0.5 is added as a reference to compare estimates across scenarios, indicating scenarios when overfishing is more or less likely to occur (> 0.5 and < 0.5, respectively).

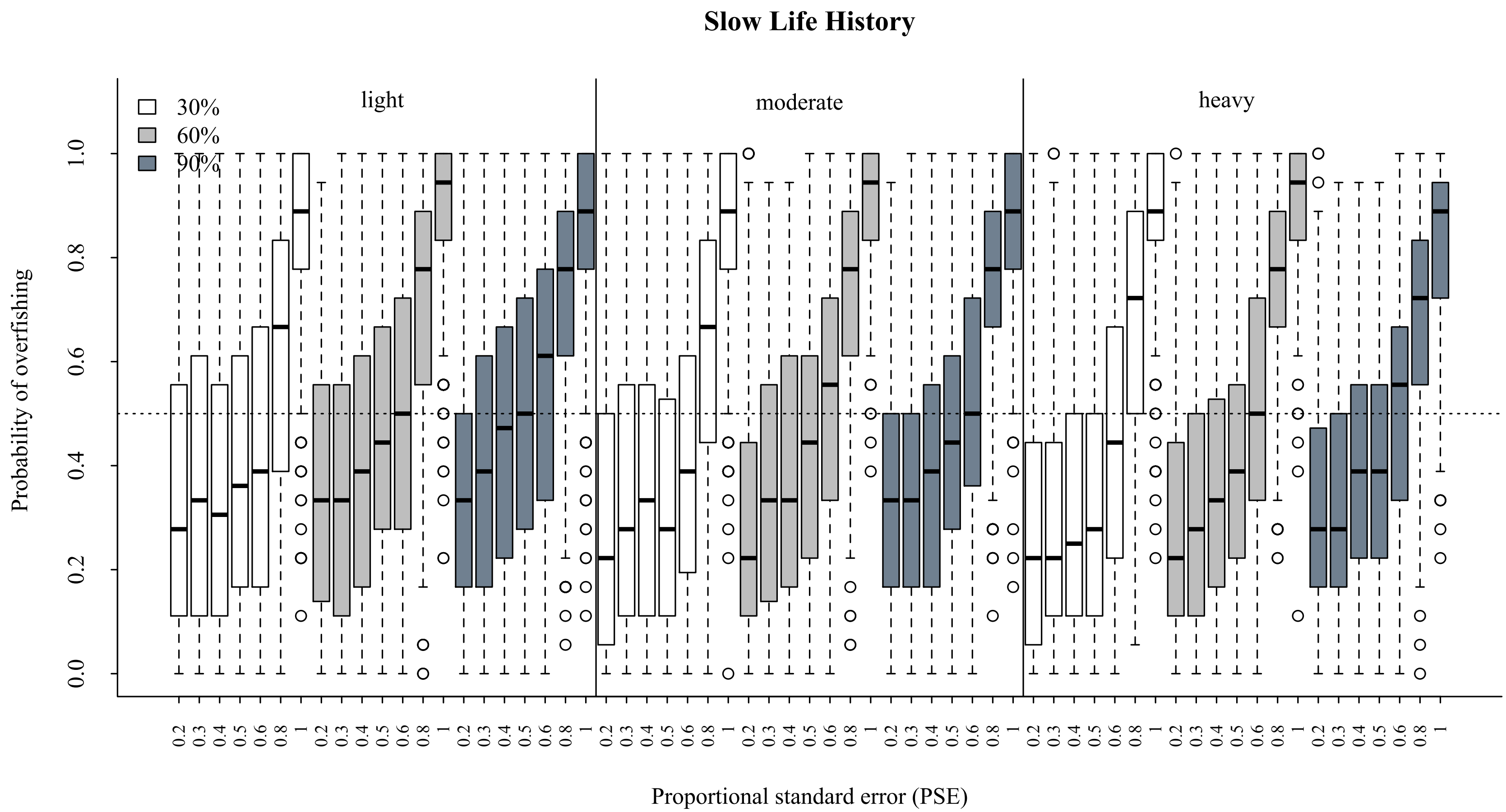

Figure 64. Similar to Figure 8, but showing the probability of overfishing (i.e., the proportion of the final 18 years when $F > F_{\text{lim}}$) for the slow life history. The horizontal line at 0.5 is added as a reference to compare estimates across scenarios, indicating scenarios when overfishing is more or less likely to occur (> 0.5 and < 0.5, respectively).

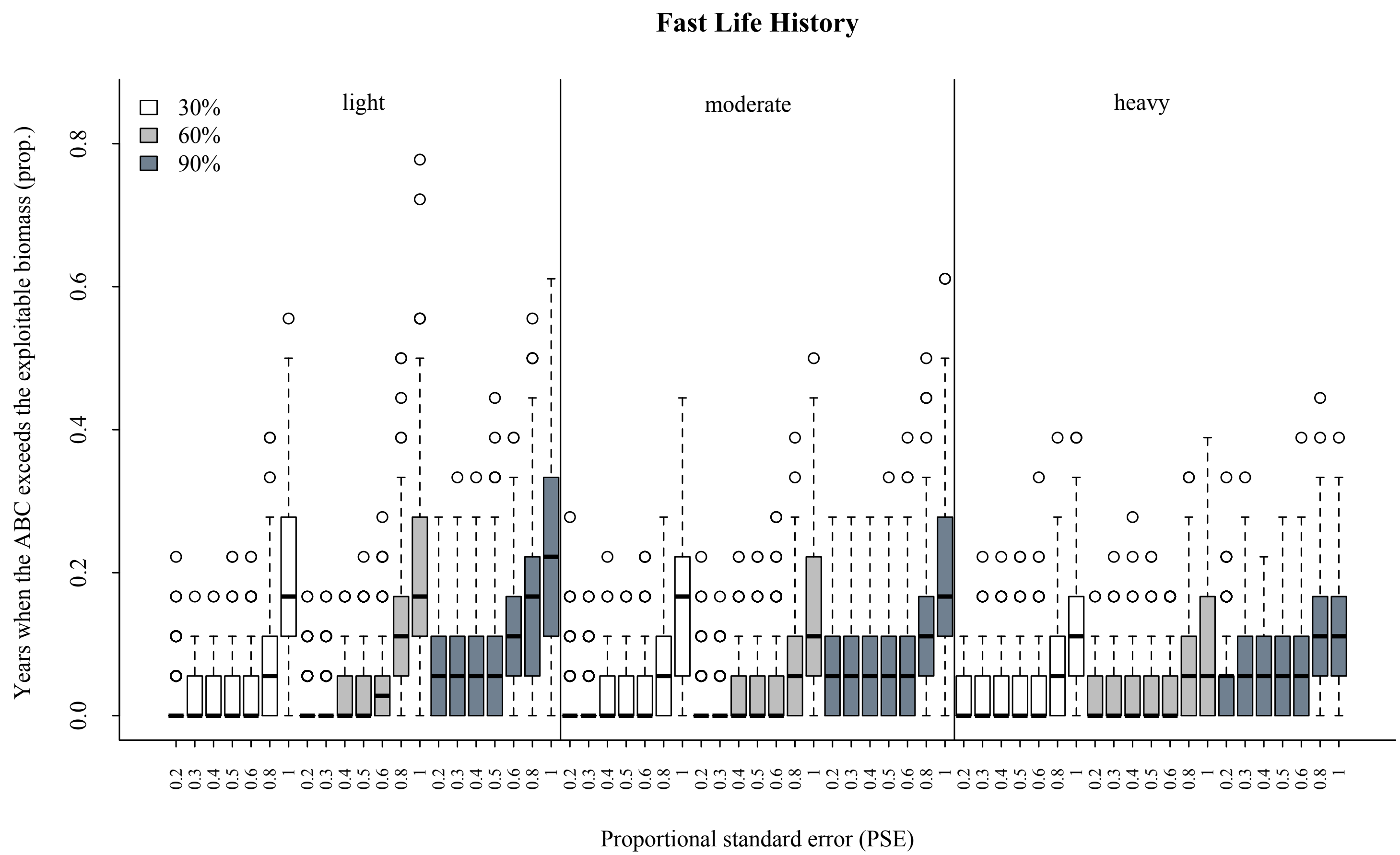

Figure 65. Similar to Figure 8, but showing the proportion of years (over the final 18 year period) when the ABC exceeds the total exploitable biomass for the fast life history.

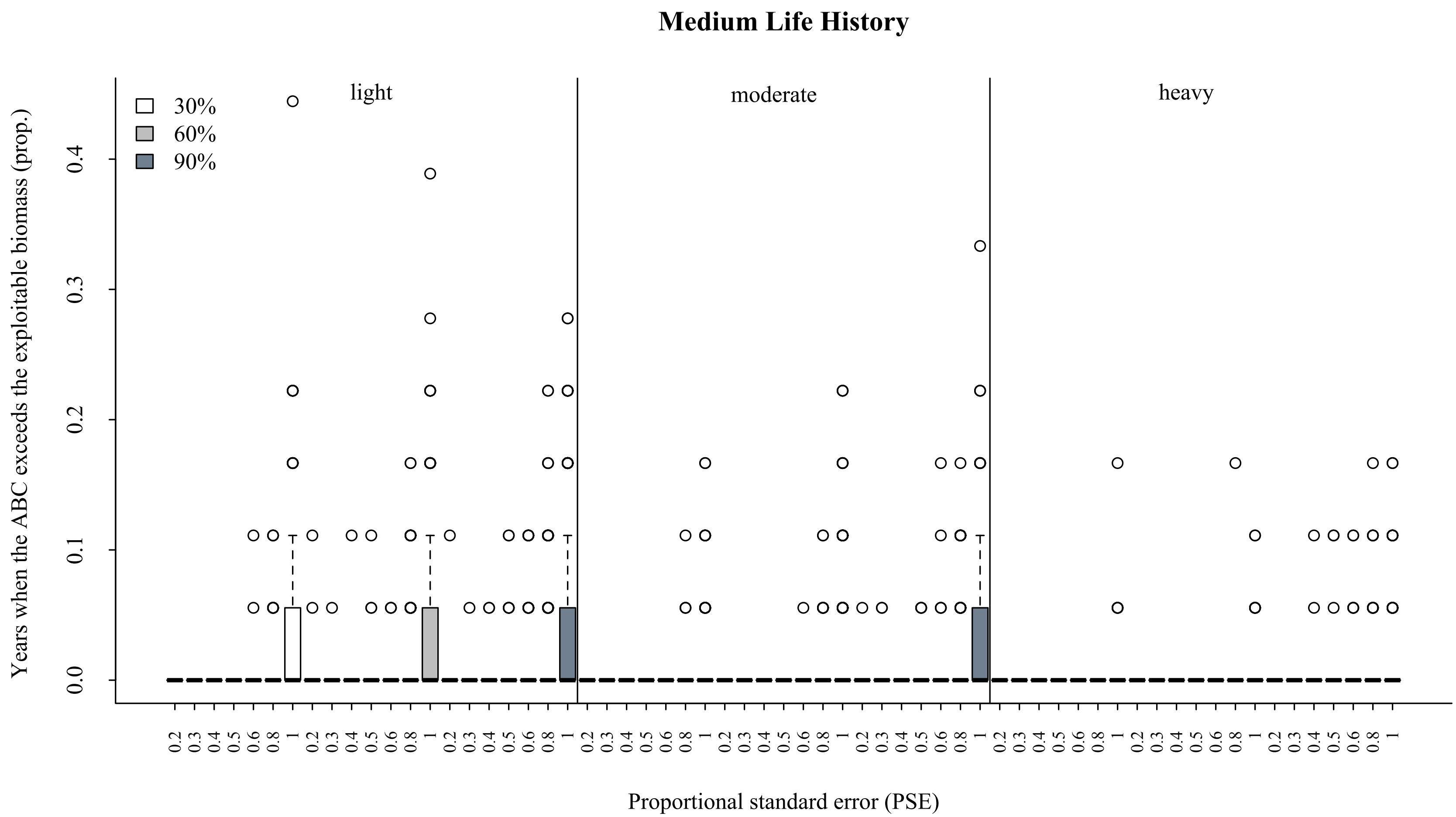

Figure 66. Similar to Figure 8, but showing the proportion of years (over the final 18 year period) when the ABC exceeds the total exploitable biomass for the medium life history.

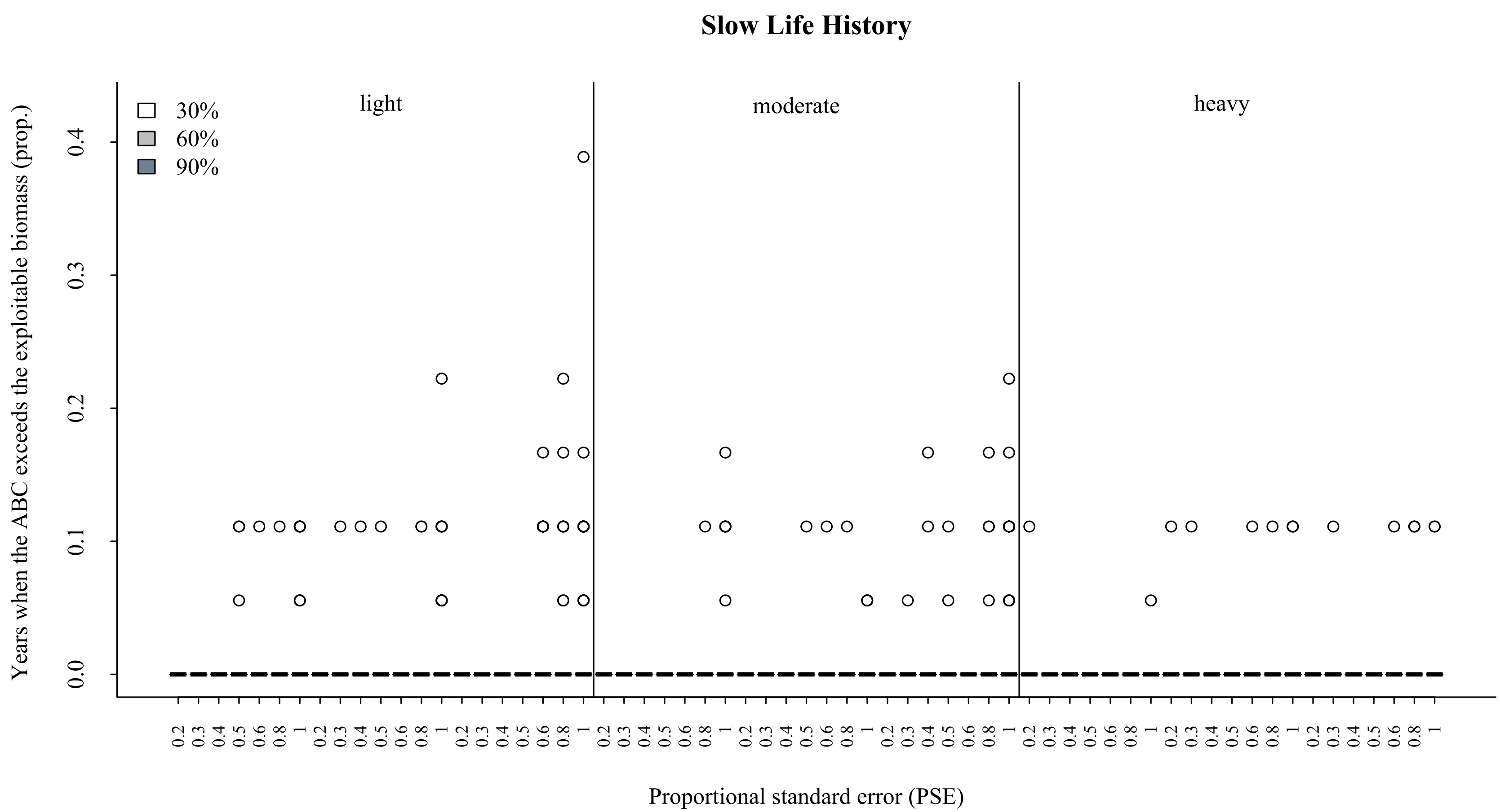

Figure 67. Similar to Figure 8, but showing the proportion of years (over the final 18 year period) when the ABC exceeds the total exploitable biomass for the slow life history.

Fast Life History

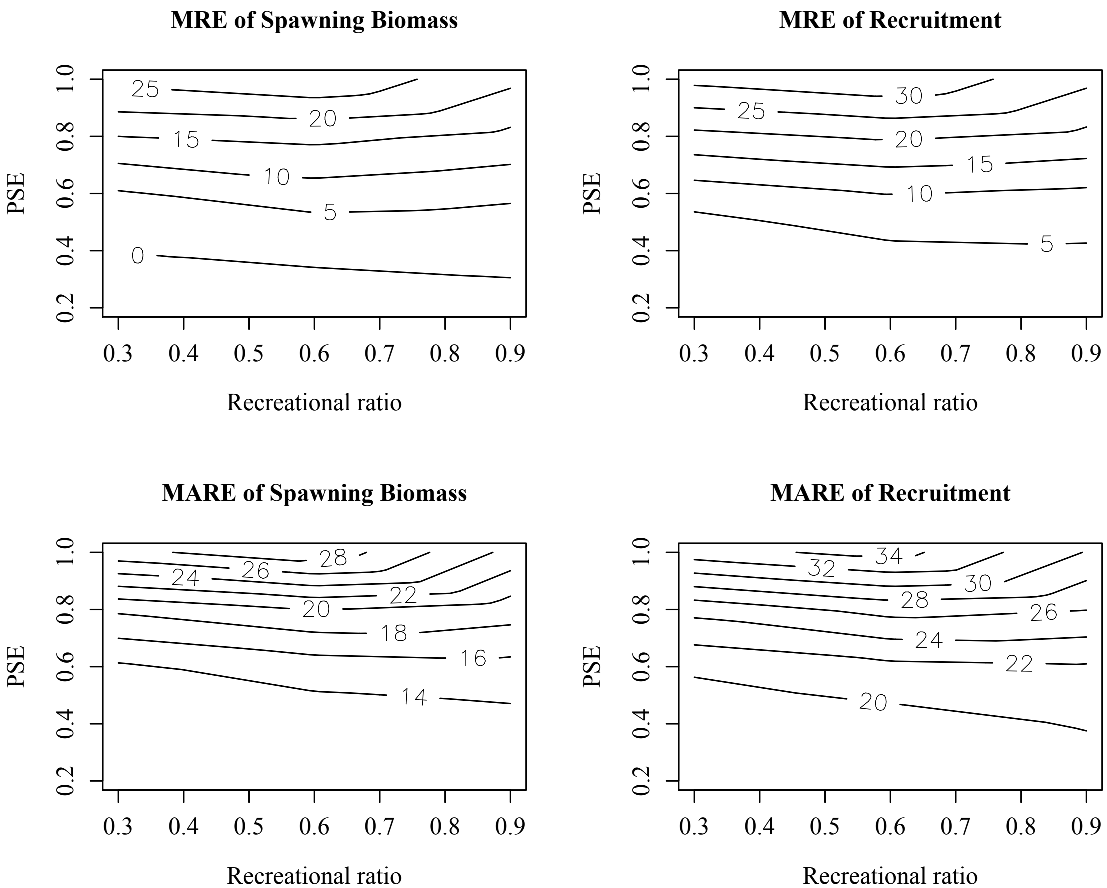

Figure 68. Contour plots showing the relative error in terminal estimates (MRE and MARE) of spawning biomass and recruitment across the different sizes of recreational fisheries (labeled the recreational ratio) and PSEs for the fast life history. The contour lines represent the median value across all exploitation histories. Values for scenarios not explored (e.g., recreational ratios of 0.4, 0.5, 0.7 and 0.8) were based on interpolations.

Medium Life History

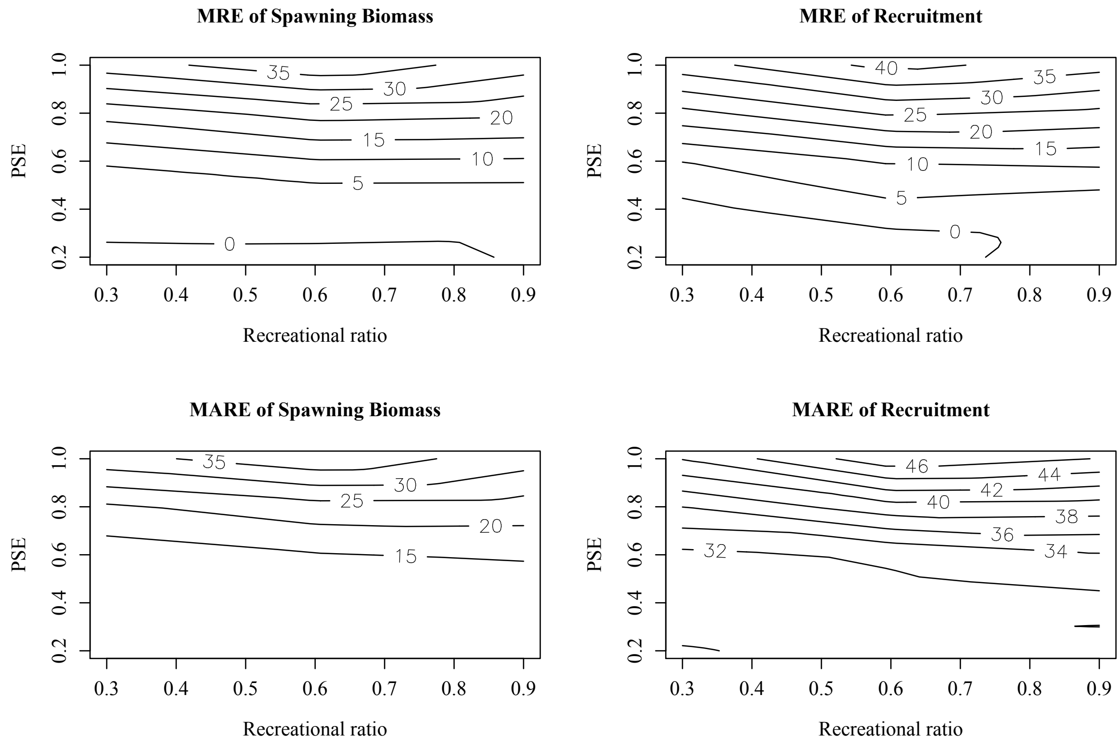

Figure 69. Contour plots showing the relative error in terminal estimates (MRE and MARE) of spawning biomass and recruitment across the different sizes of recreational fisheries (labeled the recreational ratio) and PSEs for the medium life history. The contour lines represent the median value across all exploitation histories. Values for scenarios not explored (e.g., recreational ratios of 0.4, 0.5, 0.7 and 0.8) were based on interpolations.

Slow Life History

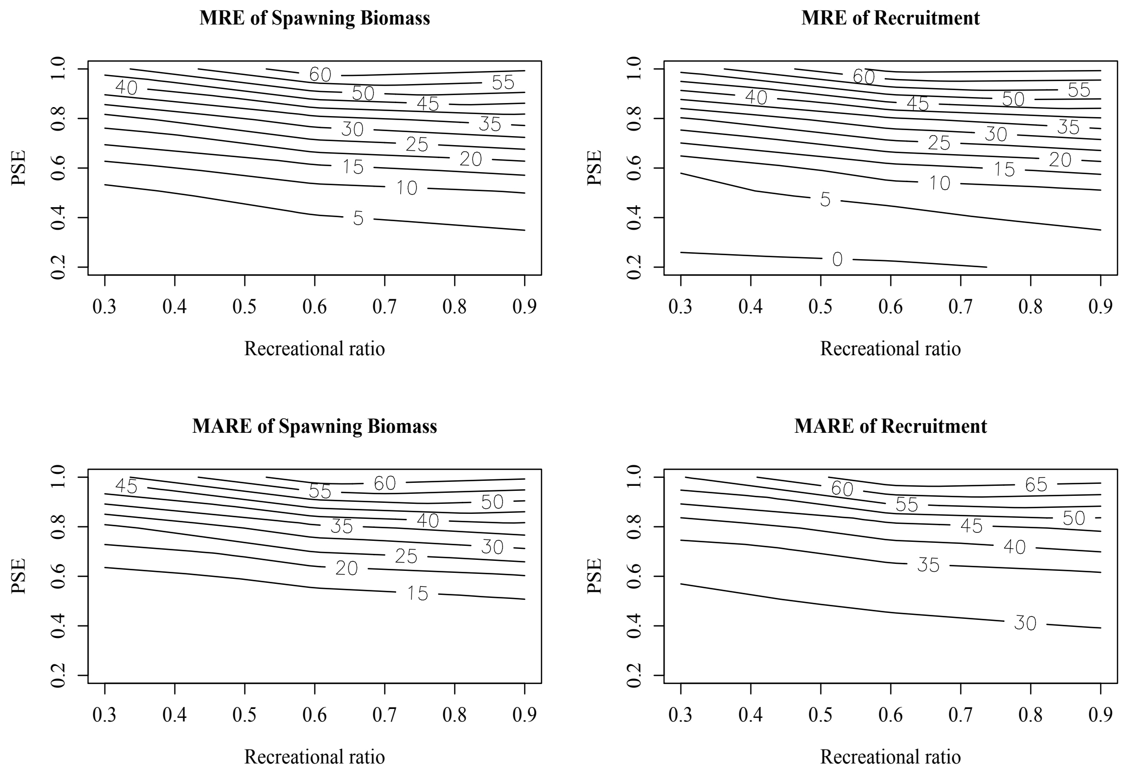

Figure 70. Contour plots showing the relative error in terminal estimates (MRE and MARE) of spawning biomass and recruitment across the different sizes of recreational fisheries (labeled the recreational ratio) and PSEs for the slow life history. The contour lines represent the median value across all exploitation histories. Values for scenarios not explored (e.g., recreational ratios of 0.4, 0.5, 0.7 and 0.8) were based on interpolations.

Fast Life History

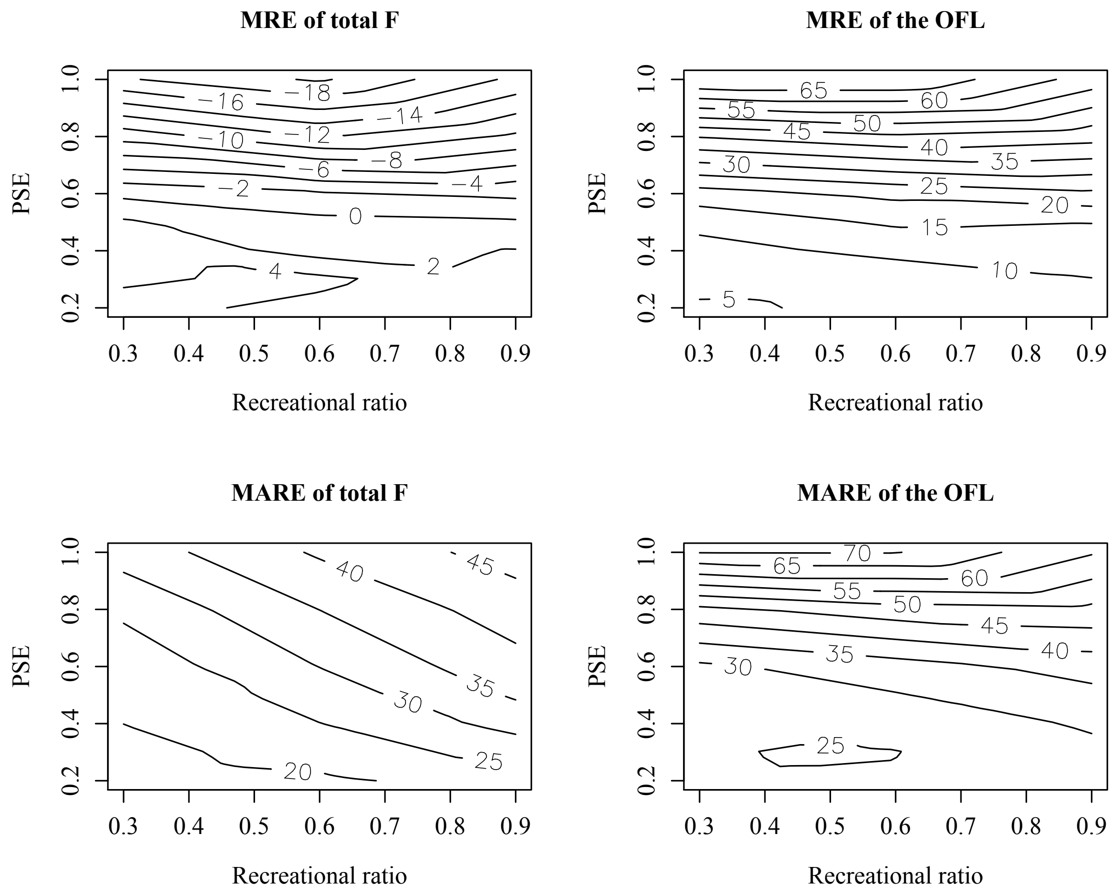

Figure 71. Contour plots showing the relative error in terminal estimates (MRE and MARE) of total *F* and the OFL across the different sizes of recreational fisheries (labeled the recreational ratio) and PSEs for the fast life history. The contour lines represent the median value across all exploitation histories. Values for scenarios not explored (e.g., recreational ratios of 0.4, 0.5, 0.7 and 0.8) were based on interpolations.

Medium Life History

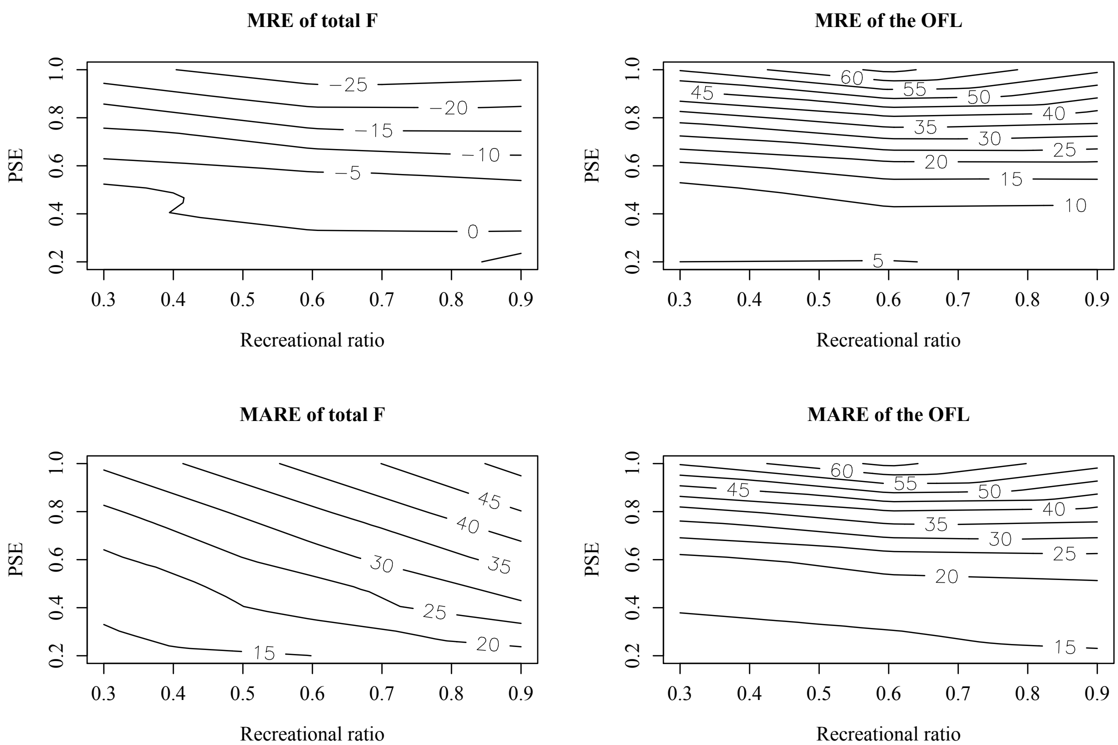

Figure 72. Contour plots showing the relative error in terminal estimates (MRE and MARE) of total *F* and the OFL across the different sizes of recreational fisheries (labeled the recreational ratio) and PSEs for the medium life history. The contour lines represent the median value across all exploitation histories. Values for scenarios not explored (e.g., recreational ratios of 0.4, 0.5, 0.7 and 0.8) were based on interpolations.

Slow Life History

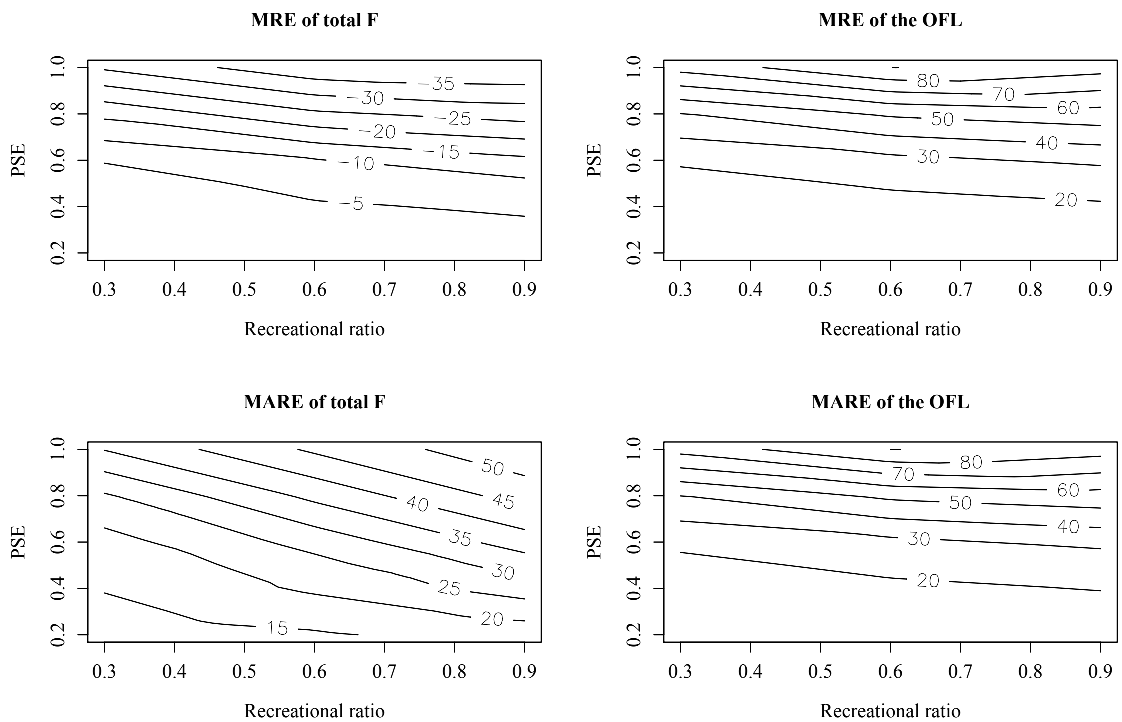

Figure 73. Contour plots showing the relative error in terminal estimates (MRE and MARE) of total *F* and the OFL across the different sizes of recreational fisheries (labeled the recreational ratio) and PSEs for the slow life history. The contour lines represent the median value across all exploitation histories. Values for scenarios not explored (e.g., recreational ratios of 0.4, 0.5, 0.7 and 0.8) were based on interpolations.

Fast Life History

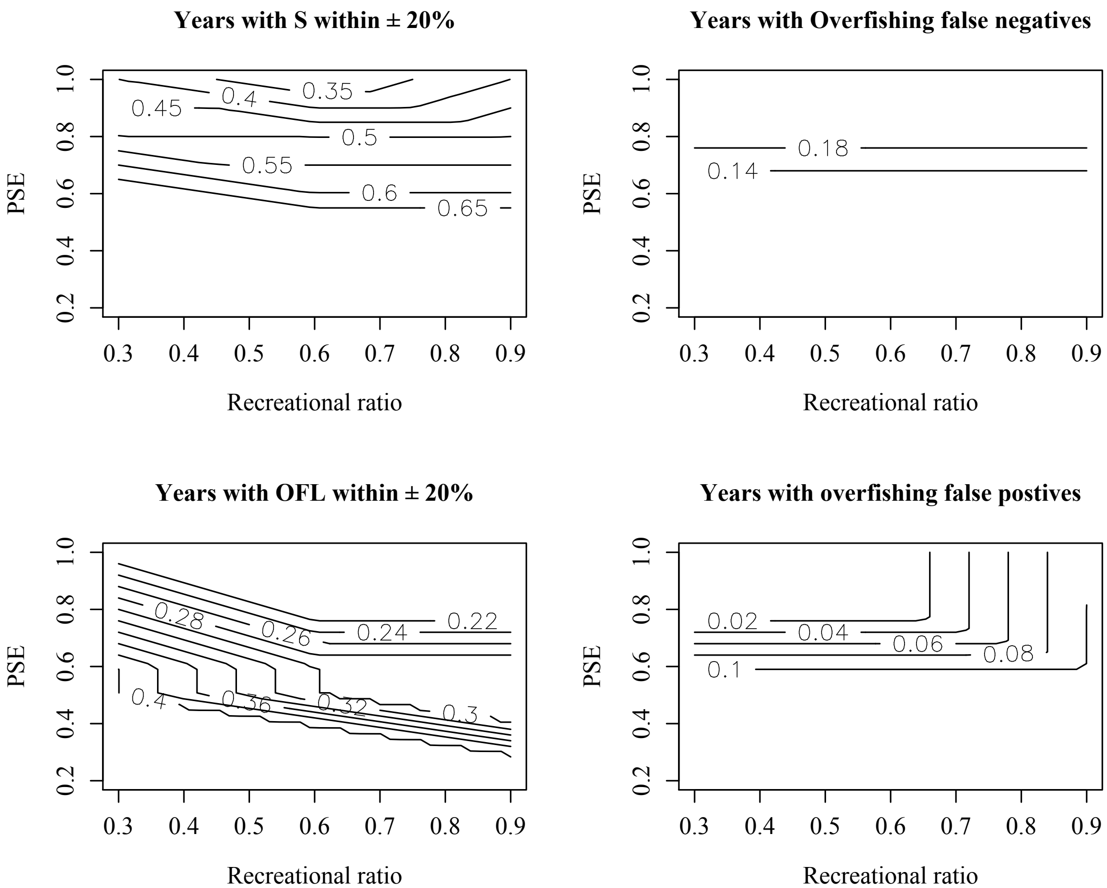

Figure 74. Contour plots showing the proportion of years with *S* and OFL estimates within ± 20% of the true value, and the proportion of years when overfishing is not identified (i.e., a false negative) and incorrectly declared (i.e., a false positive) across the different sizes of recreational fisheries (labeled the recreational ratio) and PSEs for the fast life history. The contour lines represent the median value across all exploitation histories. Values for scenarios not explored (e.g., recreational ratios of 0.4, 0.5, 0.7 and 0.8) were based on interpolations.

Medium Life History

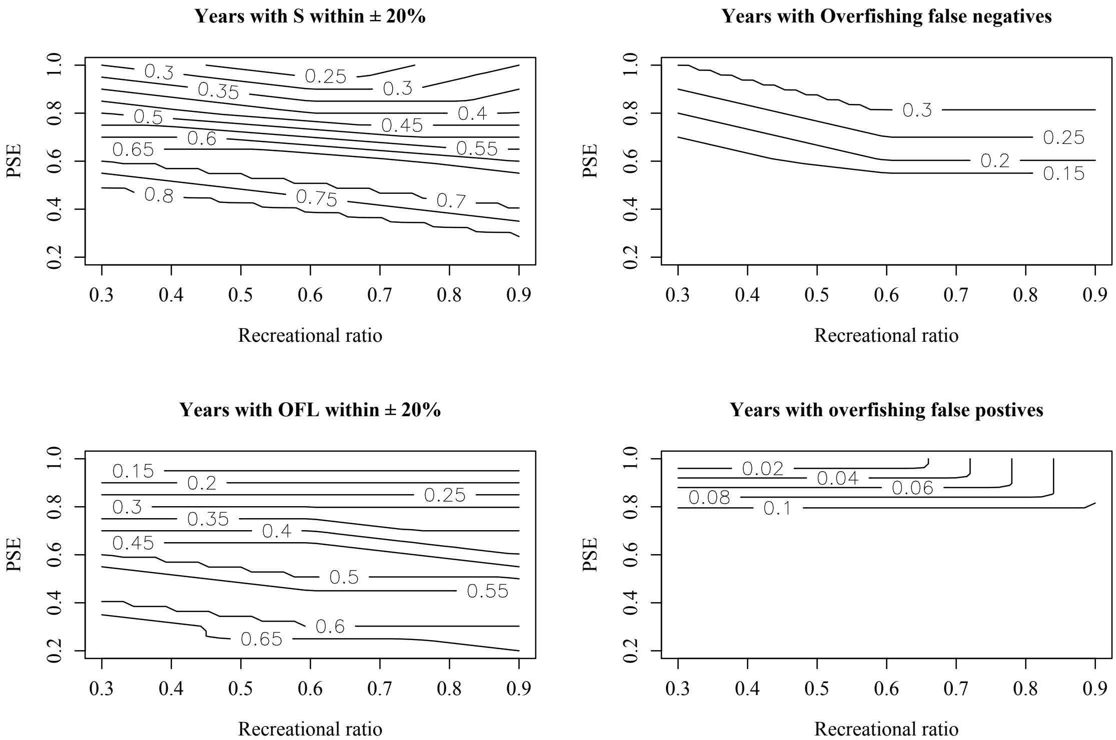

Figure 75. Contour plots showing the proportion of years with *S* and OFL estimates within ± 20% of the true value, and the proportion of years when overfishing is not identified (i.e., a false negative) and incorrectly declared (i.e., a false positive) across the different sizes of recreational fisheries (labeled the recreational ratio) and PSEs for the medium life history. The contour lines represent the median value across all exploitation histories. Values for scenarios not explored (e.g., recreational ratios of 0.4, 0.5, 0.7 and 0.8) were based on interpolations.

Slow Life History

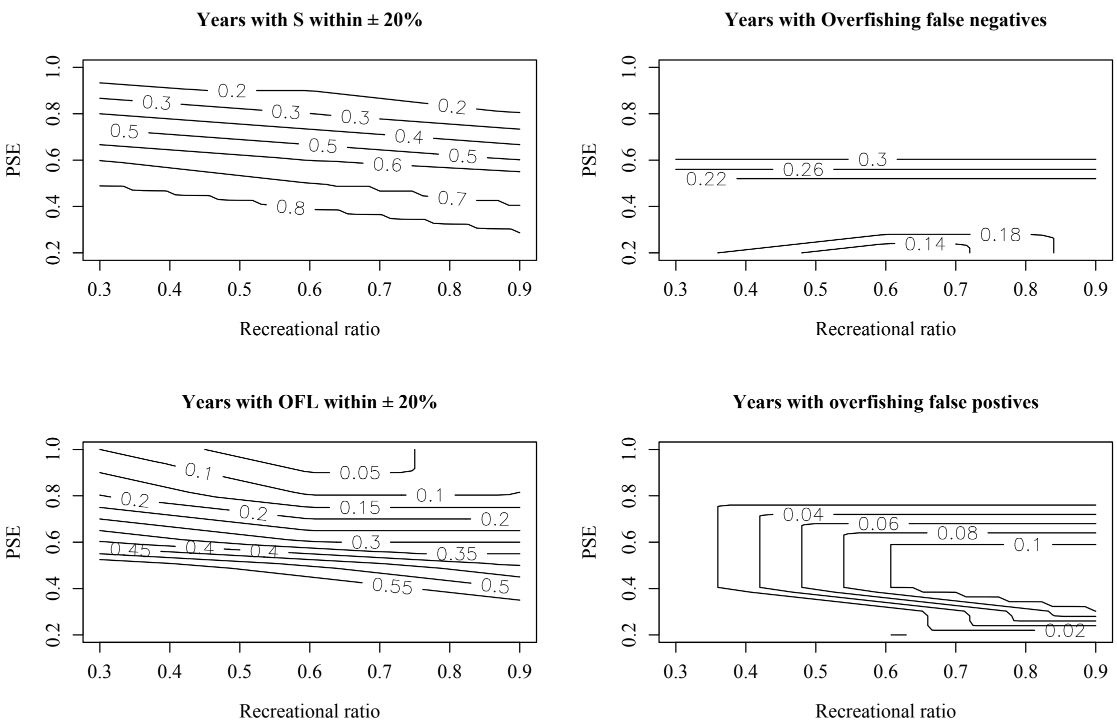

Figure 76. Contour plots showing the proportion of years with *S* and OFL estimates within ± 20% of the true value, and the proportion of years when overfishing is not identified (i.e., a false negative) and incorrectly declared (i.e., a false positive) across the different sizes of recreational fisheries (labeled the recreational ratio) and PSEs for the slow life history. The contour lines represent the median value across all exploitation histories. Values for scenarios not explored (e.g., recreational ratios of 0.4, 0.5, 0.7 and 0.8) were based on interpolations.