THE INFLUENCE OF ALTERNATIVE ASSESSMENT APPROACHES ON YIELD AND POPULATION STATUS OF INTERMIXING LAKE WHITEFISH POPULATIONS

By

Yang Li

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ABSTRACT

THE INFLUENCE OF ALTERNATIVE ASSESSMENT APPROACHES ON YIELD AND POPULATION STATUS OF INTERMIXING LAKE WHITEFISH POPULATIONS

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Recent evidence suggests that lake whitefish (*Coregonus clupeaformis*) populations in lakes Huron and Michigan now intermix considerably during non-spawning periods, while lake whitefish stocks continue to be largely treated as discrete, independent units for management and assessment purposes, and stock status is usually assessed in each unit annually. The goals of my thesis were to: 1) compare fishery management performance and assessment estimation performance based on the current spatial structure for assessments (assuming non-mixing unit stocks) and two alternative approaches to addressing mixing among stocks, and 2) evaluate changes in performance that might results from less frequent assessments. The current target mortality rate (65%) was maintained in both chapters. I modeled the dynamics of four intermixing, age-structured populations using a management strategy evaluation framework to evaluate assessment approaches and frequencies. In chapter 1, I found that the relative performance of pooled and separate population assessments depends on mixing rates and productivity. While pooling can sometimes be advantageous, it can also sometimes lead to substantial overfishing, likely due to bias or inappropriate allocation among areas. In chapter 2, the results showed that compared to other things, like the actual mixing among areas and the choice of how to account for spatial structure, the frequency of assessment had modest effects. When conducting an annual assessment, removing the 1-year lag had little influence. My results suggest that conducting assessments every three or five years should be considered as part of a management strategy and may allow analytical efforts to be directed in other ways.

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PREFACE

The two chapters of this thesis following the Introduction and Summary were drafted as manuscripts that will be submitted for publication in peer-review journals. When submitted, both manuscripts will include Drs. James Bence and Travis Brenden as co-authors. Consequently, both chapters were written with first person, plural narratives, even though I am listed as the sole author of the thesis.

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INTRODUCTION AND SUMMARY

Lake whitefish generally reproduce during the late fall and demonstrate natal philopatry (Ebener et al. 2010). It was once believed that during the harvest season most lake whitefish near each spawning area were from that spawning area. Recent evidence shows that lake whitefish populations in lakes Huron and Michigan are now intermixing considerably during non-spawning periods (Ebener et al. 2010), possibly as a result of fish expanding their foraging areas to meet nutritional needs. Current management of lake whitefish in 1836 Treaty-Ceded waters of the upper Great Lakes is based on separate assessments and harvests calculations for nominally distinct unit stocks that are assumed to not mix (Ebener et al. 2005; Caroffino et al. 2012). In northern Lake Huron one of these assessment units was formed by combining several previously used units, in response to evidence of intermixing.

I simulated four lake whitefish spawning populations that have differing levels of productivity and varying degrees of mixing during the fishing season, but are spatially segregated during spawning. I assumed that the current approach of managing harvest to avoid exceeding a target total mortality rate of 65% was retained. I explored the influence, over the long term, of alternative spatial structure in the assessment models and different frequencies of assessments on population sustainability and the success of the lake whitefish commercial fishery.

The simulation framework

The simulation framework in both chapter 1 and 2 was based on management strategy evaluation methods (Kell et al. 2005, Punt 2008). This framework modeled the “true” system and “perceived” system (data collection, stock assessment, and harvest control rule application).

The “true” system is represented as “real” stock and fishery dynamics, from which the simulated data were sampled each year. These data were then used in a periodically (annually or less often) assessment procedure. The assessment procedure involved fitting a model to the (simulated) data, and the target yield was set each year based on applying the current treaty-water harvest control rule (constant 65% mortality) based on the most recent assessment result. The target yield, which we refer to as total allowable catch (TAC), was then fed back into the corresponding "real system", thereby influencing actual yield and the fishery performance in the next year. Performance statistics based upon the stock and fishery dynamics model were eventually used to evaluate the robustness of each assessment method.

The basic structure of my model for the "true" system is based on the approach developed by Molton et al. (2012). I used an age- structured forward-projection model, consisting of four hypothetical populations with a simulation length of 100 years, but used only results from the final 25 years to evaluate performance. Recruits were added as the youngest age each year based on the current stock size for the population and a stochastic Ricker stock recruitment function. During the fishing season fish from each population mixed with fish from other populations in four fishing grounds, which each surrounded the four spawning areas, but returned to the spawning area for an instantaneous spawning period. During the fishing season fish died due to natural mortality and fishing mortality. Fishing mortality in each area (fishing ground) was partially determined based on perceived stock size based on a stock assessment that was done each year during the simulations, in an attempt to achieve a defined annual target yield (referred to as TAC for "total allowable catch"). The four populations were assumed to have differing levels of "productivity" to mimic the likely range in productivity found in actual intermixing lake whitefish populations. We equated "productivity" with steepness, and set unfished equilibrium spawning biomass to be equal across the populations, so that differences between the populations were due only to our assumed productivity differences.

The annual TAC for each fishing ground was the means by which the real system was impacted by the perceived system. This TAC was set each year based on stock assessment results. My model generated observed data each year that included annual yield, fishing effort, and harvest age-compositions, and these differed from the true underlying values due to observation error. Within the simulation frame-work an age-structured stock assessment model was fit based on the observed data, either annually (Chapter 1) or sometimes less frequently (Chapter 2). TACs were calculated based on assessment estimates with the intent that this amount of yield would cause the target mortality of 65%. In the simulations I assumed that the full TAC was utilized, although I allowed actual yield to vary above or below this each year because of assumed implementation error.

Chapter 1: Evaluation of alternative assessment methods

In chapter 1, I evaluated the performance of three assessment methods with the current 65% total mortality target under different intermixing scenarios. Deroba et al. (2012) and Molton et al. (2012) previously used simulations to evaluate the status quo constant mortality rate target (65% annual mortality), as well as alternative rates and control rules (e.g., fishing mortality being a function of stock size), for lake whitefish. Deroba et al. (2012) used the existing assessment approach and evaluated alternative harvest control rules and concluded that the status quo mortality rate target was reasonable. Their analysis, however, assumed that the assumption of unit stocks used in the assessments was correct. Molton et al. (2012) concluded that the 65% mortality rate could put some lower productivity stocks at risk when population mixed, but assumed that assessments would continue to be done assuming unit stocks surrounding each spawning area. My work builds upon the previous studies by exploring both the influence of mixing and how that mixing is accounted for in assessments.

The main goal for this chapter is to evaluate how the choice among three assessment models, differing in how spatial structure was incorporated, would affect long-term fishery performance metrics (yield, spawning stock biomass, et al.). The assessment models are all variants of a statistical catch-at-age model (e.g., Fournier and Archibald 1982). The first assessment model is the current separate assessment approach, where data collected in the fishing grounds surrounding each spawning areas is taken as representing a distinct reproductive population, or unit stock. I refer to the first alternative to this as a “pooled assessment”, with all fish that might mix considered to be in one unit stock occupying a larger spatial area. As noted above, to some extent this approach has already been implemented in northern Lake Huron, where four assessment areas were merged into one. The second alternative approach, “meta-population assessment”, explicitly accounts for intermixing. This assessment approach keeps track of each population and how many of each population are present in each area during the harvest season. For the “pooled assessment”, only a pooled TAC could be calculated directly from the assessment and this needed to be allocated to fishing grounds. This was done according to two rules: a constant allocation rule with the pooled TAC separated in proportion to equilibrium yield for each of the four populations, and an annually varying allocation rule, with pooled TAC separated in proportion to the annual area-specific catch per effort (CPE) observed from the “true” system. All those assessment models were annually updated.

Scenarios consisting of different intermixing rates were examined to assess and compare the performances of three assessment methods with current 65% total annual mortality control rule. For one set of the scenarios, all populations mixed to the same extent, but a range of different mixing rates were evaluated, from low to high. For the other set of scenarios, different mixing rate were set for different populations based on the different assumption about how mixing and productivity were related. The last scenario assumed no consistent relationship between productivity and mixing. For this scenario each population had one of four distinct mixing rates. There were 24 possible combinations of how the four mixing rates and productivities were matched, and we equally weighted these possibilities.

I found that the “meta” population model could not provide useful assessment results when mixing rates were high, in the absence of population-specific data, which are currently unavailable as all assessment data represent the mixture present during the harvest season. My results showed that the choice between pooled and separate population assessments depends on mixing rates and productivity. While pooling can sometime provide advantages, in my simulations it led to substantial population depletion when actual mixing was very high. I also found that the separate assessment model could lead to extirpation or near extirpation of low productivity populations with a low mixing rate, which suggests that the current harvest control rule might be too aggressive for low productivity populations. That clearly reinforces a point made by Molton et al. (2012), that the current 65% total mortality control rule may be not conservative enough for the low productivity populations. Different TAC allocation rules for pooled methods performed quite differently from one another. In particular a pooled method that allocated yield among areas in proportion to equilibrium yield for the population spawning in that area did poorly in terms of protecting low productivity populations when mixing was high. This is likely because the population present in an area deviated from the assumed equilibrium populations when mixing was high.

Chapter 2: How alternative assessment frequency influenced the fishery performance

In chapter 2, I explored how changing the assessment frequency to less often than annual would affect long-term fishery performance metrics (yield, spawning stock biomass, etc.). I also explored the influence of how annual yield targets were set for years between assessments done less often than annually. These factors were applied using two of the alternative assessment models described for Chapter 1: separate and pooled. For the pooled assessment, the TAC for each area was based on the annual area-specific CPE observed from the "true" system.

I found that the influence of assessment frequency was modest compared to choices about how to account for spatial structure in the assessment model. In addition, the frequency of assessment had more impact on resulting levels of spawning biomass and yield when the separate assessment method was used than when the pooled method was used. Lake whitefish assessments are generally done with a one year lag between when data are collected and when assessment results using those data are available for management, but some fisheries strive to rapidly turn around assessments and avoid such a lag. I compared the performance of annual assessments with and without the 1 year lag, and found that only when mixing rate were low for all populations, did removal of the lag improve the performance of assessment. In the case where some improvement was seen this was with respect to higher yield and lower annual variation of yield across all areas, and lower risk of depletion of the low productivity population.

Overall conclusions and future directions

Our results clearly reinforce a point made by Molton et al. (2012), that the current 65% total mortality control rule may be not conservative enough for the low productivity populations. These results contrast with one overall conclusion of Deroba and Bence (2012), that the 65% mortality rate produces acceptable results. This contrast appears to be due to the fact that Deroba and Bence (2012) evaluated the probable performance of a management strategy applied to any single unit stock, and not what might happen to a low productivity stock among a collection of plausible populations ranging in productivity (Molton et al. 2012). As Molton et al. (2012) argued, when mixing is ignored the LP population can be falsely assessed to have high abundance and harvest. With substantial mixing, the harvest from the area surrounding the spawning grounds of the LP population is likely to be composed largely of fish from other more productive populations. This is clearly evident in our results, where yield for the area associated with the low productivity population increased as mixing rates increased. We reiterate Molton et al.'s (2012) point, that such mixing would also influence estimates of productivity, so that the productivity of low productivity stocks could be overestimated. To the extent to which such mixing influenced historical stock assessments, this in turn tends to make the lowest productivity values we assumed even more plausible.

We found this risk of depleting low productivity populations is still present for the pooled assessment method and can even be more severe for pooled methods when the mixing rate is high. When the mixing rate for each population was moderate, the "pooled" assessment method with TAC allocated by proportion of equilibrium yield was superior to the "separate" method. Specifically, the "pooled (EY)" method provided more protection for the SSB of the low productive population, with higher aggregate yield across the areas and the lowest annual variation in yield. Initially it was surprisingly to us that when the mixing rate was high, this "pooled" method lost its advantages. With high mixing, the "separate" method could provide the lowest risk for the SSB of LP populations below $B_{20\%}$. In retrospect this deterioration of the pooled (EY) with higher mixing makes sense. With higher mixing, the actual allocation of biomass among the fishing areas increasingly deviates from being in proportion to equilibrium yield for the populations.

In general, the differences in performance metrics due to assessment model (between separate versus pooled) were larger than the differences due to assessment frequency and approach to setting TACs during rotational periods. This finding should be useful to fishery managers as they consider where the right place is to put their time and resources. While our results are based on lake whitefish, this species has is not dissimilar to many harvested fishes, and may in fact be more prone to rapid changes in abundance than many. Consequently, we suspect that calls for annual assessments (e.g., Mace et al, 2001) may often be misplaced, and that it may make more sense to work on developing a correct assessment structure.

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CHAPTER 1

EVALUATING ALTERNATIVE ASSESSMENT APPROACHES FOR INTERMIXING LAKE WHITEFISH POPULATIONS

Abstract

Recent evidence suggests that lake whitefish populations in lakes Huron and Michigan intermix considerably during non-spawning periods, possibly from fish expanding foraging areas to meet nutritional needs. Simulations have shown that ignoring spatial structure can lead to unexpected risks of overexploitation, especially for low productivity populations. Currently, management of lake whitefish in the 1836 Treaty ceded waters of the upper Great Lakes is based on separate assessments and harvest calculations for nominally distinct unit stocks that are assumed to not mix. In northern Lake Huron one of these assessment units was formed by combining several previously used units, in response to evidence of intermixing. We simulated four lake whitefish spawning populations with differing levels of productivity and mixing rates during the fishing season, but which were assumed to be spatially segregated during spawning. We evaluated how alternative assessment methods performed with respect to supporting a thriving commercial fishery and ensuring long-term stock sustainability. Our first assessment approach treated each population and the region surrounding its spawning grounds as a unit stock ("separate populations"). The second approach lumped together the regions and populations into a "pooled population", so that all intermixed fish were treated as single unit stock occupying a larger area. The third assessment approach incorporated actual mixing rates and treated several populations as a "meta population". Our results show that the choice between pooled and separate population assessments depends on mixing rates and productivity. While pooling can sometimes be advantageous, it can lead to substantial overfishing when actual mixing is low or very high. The meta population assessment method can only work when rates of intermixing

between spawning populations were low. In order to improve this method, additional population-specific data, such as genetic information allowing the catch in an area to be allocated to source population, is needed.

Introduction

Stock-based assessment of exploited fish populations has long been used to estimate demographic rates (e.g., age-specific mortality) and population sizes, and these in turn have been used to establish appropriate levels of harvest. This management approach is typically implemented inside of each spatial management unit, which is commonly assumed to be composed of a single, rather than multiple spawning populations. Ignoring complex-population structure in management could lead to poor estimation of abundance and unintended depletion of local subunits, with unknown ecological consequence (Stephenson 1999, Hutchings 1996, 2000, Frank et al. 2000, Molton et al. 2012). When mixtures of multiple spawning populations occur on fishing grounds, a common response from assessment groups has been to modify boundaries of management units such as lumping areas among which substantial movement is known to occur (Powers et al. 2004, Kell et al. 2009, Ying et al. 2011). More complex assessment approaches that allow for movement among the areas could be an alternative, but this may require more information.

Management of lake whitefish in the 1836 Treaty-ceded waters of the upper Great Lakes has been based on separate SCAA assessments and calculation of harvests for nominally distinct unit stocks that are assumed to not mix (Ebener et al. 2005; Caroffino et al. 2012). Historically, managing lake whitefish as distinct management units began in the 1970s in order to protect distinct naturally reproducing populations. Management unit boundaries were designed to encompass the spatial distribution of either individual stocks or a fishery that exploited a stock (Ebener et al. 2010).

Recent evidence, however, has shown that many lake whitefish populations in the northern parts of lakes Huron and Michigan are intermixing considerably during non-spawning periods (Ebener et al. 2010), possibly as a result of fish expanding their foraging areas to meet nutritional needs in the face of environmental changes. Recent decline in benthic prey of lake whitefish -*Diporeia*, and increasing abundance of invasive dreissenid mussel (Nalepa et al., 1998, 2007, 2009a) may both influence the foraging behavior of lake whitefish populations (Nelepa et al. 2009b, Porthoven and Madenjian, 2008). Despite this observed increase in mixing, lake whitefish still exhibited strong spawning site fidelity (Ebener et al. 2010), which suggested that despite widespread mixing during periods of exploitation, strong genetic structuring of lake whitefish stocks within the Great Lakes should still exist. This assumption has been confirmed by studies of stock genetic diversity (VanDeHey et al. 2009; Stott et al. 2010).

Despite the widespread mixing now known to occur, many lake whitefish stocks in the vicinity of recognized spawning areas continue to be treated as discrete independent units for management purposes. For example, the statistical catch-at-age (SCAA) assessment models used to estimate year- and age-specific abundances and mortality rates for lake whitefish of lakes Huron, Michigan, and Superior do not allow for the possibility of fish moving between assessment areas. Stock assessment scientists have responded to information about the movement of lake whitefish in northern Lake Huron, by combining four formerly distinct assessment areas into one larger area (Caroffino et al. 2011). The assumption, however, remains that fish within this newly defined area do not move to other areas. This approach also assumes that fish in the new larger area are completely mixed. The mismatch between how fish actually move, and what is assumed in the assessments undoubtedly affects the SCAA estimates of mortality and abundance. Responses to knowledge about movement among spawning populations has so far been ad hoc for lake whitefish. Fishery managers in other systems have similarly lumped assessment areas when confronted with information about movement among areas. Our research aims to compare fishery management and assessment estimation performances based on the current “separate assessment” approach with two alternatives that attempt to take intermixing into consideration. They are all variants of the SCAA model. We refer to the first alternative as a “pooled assessment”, with all fish that might mix considered to be in one unit stock occupying a larger spatial area. As noted above, to some extent this approach has already been implemented in northern Lake Huron, where four assessment areas were merged into one. The second alternative approach, “meta-population assessment”, explicitly accounts for intermixing.

The current study is a simulation-based evaluation of the above three assessment approaches. Rather than simply looking at how well the estimation methods work at estimating stock size and mortality, we also consider resulting fishery performance metrics (e.g., yield, spawning biomass). Based on the information about lake whitefish in 1836 Treaty-ceded waters, we simulated four lake whitefish spawning populations that have differing levels of productivity and varying degrees of intermixing during the fishing season, but are spatially segregated during spawning. We then evaluated how assessment methods performed with respect to the trade-off between whitefish commercial fishery metrics and long-term population sustainability. Deroba et al. (2012) and Molton et al. (2012) previously used simulations to evaluate the status quo constant mortality rate policy (65% annual mortality) for lake whitefish. Deroba et al. (2012) concluded that the status quo mortality rate was reasonable, but they assumed that the actual fish population dynamics were consistent with the unit stock dynamics used in the current assessments. Molton et al. (2012) concluded that the 65% mortality rate could put some lower productivity stocks at risk when populations mixed, but their analysis assumed that assessments would continue to be based on the existing unit stock assessments for applied to fishing grounds surrounding spawning areas. Our work builds upon the previous studies by exploring both the influence of mixing and how that mixing is accounted for in assessments. Our approach to evaluating the alternative assessment approaches used management strategy evaluation (MSE) methods (Kell et al. 2005a, Punt 2008). Most MSE evaluations have compared different control rules (e.g., constant fishing rate or constant escapement) or different parameters for the rules, but keep the assessment constant (Kell et al. 2005b, Kell et al. 2006). Our study illustrates using MSE to compare different assessment approaches.

Methods

The simulation framework used to evaluate assessment approaches was based on management strategy evaluation (MSE) methods (Kell et al. 2005a, Punt 2008) (Figure 1.1). This framework modeled the “true” system and “perceived” system (data collection, stock assessment, and harvest control rule application). The “true” system was represented as “real” stock and fishery dynamics, from which the simulated data were sampled. These data were then used in an assessment procedure that establishes the status quo for resources. The three assessment methods were fitted separately and the current treaty-water harvest control rule was applied to each specific assessment result. The target yield, which we refer to as total allowable catch (TAC), was then fed back into the corresponding "real system" (in our simulations) thereby influencing actual yield and the fishery performance in the next year. Performance statistics based upon the stock and fishery dynamics model were eventually used to evaluate the robustness of each assessment method. The flexibility of this framework allowed us to incorporate a series of uncertainties, including process, sampling, estimation, and model error, as described below.

The “true” system

The basic structure of our model for the "true" system was based on the approach developed by Molton et al. (2012). We used an age- structured forward-projection model, consisting of four hypothetical populations with a simulation length of 100 years. Only the final 25 years were summarized to evaluate performance. Our intent here was to evaluate the long-term performance of the alternative approaches, independent of the starting conditions. Recruits were added as the youngest age each year based on the current stock size for the population and a stock recruitment function. During the fishing season fish from each population mixed with fish from other areas in four fishing grounds, which each surrounded the four spawning areas (Figure 1.2), but returned to the spawning area for an instantaneous spawning period, based on the known natal philopatry of the species. During the fishing season fish died due to natural mortality and fishing mortality. Fishing mortality was partially determined based on perceived stock size based on a stock assessment that was done each year during the simulations, in an attempt to achieve the TAC.

These populations were assumed to have differing levels of "productivity". Differences in productivity among the four spawning populations were incorporated via adjustment of the recruitment function coefficients (Table 1). We used a stochastic Ricker recruitment model (Eq. (T.2.1)) because of strong evidence for over-compensation in lake whitefish populations (Healey 1978; Henderson et al. 1983; Kratzer 2006). The stochastic errors were multiplicative and lognormal. Given information on life history (maturity and weight at age schedule) the Ricker function can be parameterized in terms of steepness and the unfished spawning stock size. We equated "productivity" with steepness (NOAA Pacific Islands Fisheries Center, 2011), and chose four steepnesses for our simulated populations that were plausible for lake whitefish and produced meaningful differences in equilibrium yield. We set unfished equilibrium stock sizes to be equal, so that differences between the populations were due only to our assumed productivity differences. The steepness and equilibrium yield parameterization was then converted to the standard Ricker parameterization (Table 1). Calculations of equilibrium yield and spawning stock sizes to define the productivity of the populations in the simulations assumed unit stocks (no movement) and followed methods outlined by Quinn and Deriso (chapter 6 page 239, 1999). The values of life-history parameters were based on the most recent 1836 Treaty-ceded water assessment conducted by the Modeling Subcommittee (MSC) of the Technical Fisheries Committee (TFC) and our claim of plausible steepnesses is based on review of the last five years annual assessment of stock status [ftp://glpd.fw.msu.edu/MSCFTP/Assessment_models/]. The unfished spawning biomass was also based on assessment results, but this only sets the scale of results and otherwise does not influence the outcomes of our work. Each of the four simulated lake whitefish spawning populations was assigned one of the four levels of productivity so that there was a LP, MLP, MHP and HP population for each simulation.

Fish from a spawning population either remain in their natal area during the non-spawning season or move to one of the other three areas (Figure 1.2). Movement rate, θ_{ij} ($i \neq j$), is the proportion of fish belonging to spawning population *i* (i.e., they spawned in area *i*) that move to and live in area *j* during the non-spawning season. We refer to θ_{ii} as the stay rate, which is the proportion of fish belonging to spawning population *i* that stay in area *i* during the non-spawning season. The movement rates were calculated based on the stay rates, which was set based on results from ongoing and published studies (Ebener et al.2010, Stott et al. 2010, Stott et al. 2012). We assumed that a higher stay rate indicated a high quality habit, and that a high proportion of whitefish would tend to move to that area. The movement rate θ_{ij} ($i \neq j$) is:

$$\theta_{\mathrm{ij}} = (1 - \theta_{ii}) \frac{\theta_{jj}}{\sum_{k \neq i} \theta_{kk}} \tag{1}$$

where $(1 - \theta_{ii})$ is the total proportion of fish from population i that live in other areas during the non-spawning season, and $\frac{\theta_{jj}}{\sum_{k \neq i} \theta_{kk}}$ is the proportion of those fish residing in each destination area *j*. This approach of specifying movement rates diverges from the approach of Molton et al. (2012), who assumed that fish that did not stay in their natal area moved to other areas in equal proportions.

We projected abundance-at-age after recruitment using an exponential mortality model:

$$N_{i,y+1,a+1} = N_{i,y,a} \sum_j \theta_{ij} \exp(-M - F_{j,y,a}) \tag{2}$$

where $N_{i,y,a}$ is equal to the number of fish from spawning population *i* of age *a* in year *y*; *M* is the natural mortality rate; and $F_{j,y,a}$ is the year- and age-specific instantaneous fishing mortality rate of fish occurring in area *j* during harvest season. This instantaneous fishing mortality rate was calculated as:

$$F_{j,y,a} = s_a f_{j,y} \tag{3}$$

where s_α is the age specific selectivity (equal for all four stocks), and $f_{j,y}$ is the fully selected fishing mortality occurring in area *j* in year *y*. Thus the fishing mortality rate experienced by a population was a weighted sum of the fishing rates occurring in the different areas, with weights set by the θ. The fully selected fishing mortality rate for each area was calculated using a Newton-Raphson algorithm so that the true yield for each area was produced using the Baranov's catch equation (Equation T.1.2.7) and assumed harvest weight at age. The true yield was set equal to the Total Allowable Catch (TAC) (i.e., target yield) multiplied by a lognormal implementation error (Equation T.1.2.8). The TAC was determined via the stock assessment procedure described in the perceived system section.

Constant values of natural mortality, female proportion, and catchability were used. Selectivity-, length-, weight-at-age, and annual spawning stock biomass (SSB) were determined by deterministic functions. Selectivity was set as 0 for age-2 and younger whitefish because they are rarely harvested in treaty waters. Selectivity for other age classes was simulated by a gamma probability density function (Equation T.1.2.6) scaled by setting the fully selected age class (age 10) equal to 1.0; length-at-age was assumed to follow a Von Bertalanffy growth model (Equation T.1.2.3); weight-at-age was determined by a power function of length (Equation T.1.2.4); and the SSB (Equation T.1.2.2) was calculated as a function of abundance-at-age, maturity-at-age (Equation T.1.2.5), and weight-at-age. The four populations shared the same selectivity-, length-, and weight-at-age patterns.

The initial state of for each simulation in year 1was based on equilibrium recruitment and target mortality rates and calculated based on deterministic models with no mixing. The actual harvest policy and management process requires a twenty year time-series of data, which was not available during the initial 20 year period of each simulation. Within this "burn-in" period, population abundance at age was assumed to be known exactly before applying the harvest control rule and thus the assessment model step was skipped during the burn-in period of simulations. The intent here is merely to move the system closer to steady-state conditions during this period. Stochastic recruitment errors were still included during this period.

The "perceived" system

In the perceived system (Figure 1.2), the management procedure for the treaty water whitefish was duplicated, including data collection, stock assessment, and application of the harvest control rule. When generating the data we assumed that total catch was observed with error, and that observed age compositions also differed from actual age compositions due to sampling error. Observed proportions-at-age in the simulated data arose from a multinomial distribution with probabilities equal to the true age proportions of the harvest sample and an effective sample size of 200 for "separate" and "meta" approaches or of 800 for the "pooled" method. Observed fishing effort was calculated as:

$$E_{j,y} = \frac{F_{j,y}}{q} exp(\mu_{j,y} - 0.5\sigma^2{}_F) \quad (4)$$

$$\mu_{j,y} \sim N(0, \sigma^2{}_F)$$

$$\sigma^2{}_F = 4\,\sigma^2{}_c$$

where $F_{j,y}$ is the fully-selected fishing mortality rate for area *j* and year *y*; q is the catchability coefficient of 1.50×10e^{-6}; and $\mu_{j,y}$ is the an normally distributed random variable with expectation of 0 and variance of $\sigma^2{}_F$ (Equation T.1.2.10), which was assumed to equal to 0.04 (four times of $\sigma^2{}_C$).

The above data was collected annually and used as the input for stock assessments. The stock assessments were assumed to have knowledge of the true natural mortality rate and life-history parameters.

In the stock assessment process, three different assessment models were compared: separate population, meta-population, and pooled population assessment models. All models were variants of the SCAA model, which involves fitting a population dynamics model to observed data to estimate the parameters used to summarize stock status and determine TAC for each simulated population of the assessment year.

The first approach, the “separate population assessment”, assumed no movement among areas. We applied the model to data from each fishing ground separately. An age-specific fishing mortality was predicted by the same equations used in the population dynamics model. This is the most commonly used approach for assessing lake whitefish in treaty waters.

The second approach, the “meta-population assessment”, assumed that the actual rates of mixing were known. One combined assessment model for all four stocks was developed because movement was included in the process of tracking estimated abundance-at-age for each population and predicted catch-age-age for each area during the fishing season. Compared with the first approach, stay and movement rates were an additional input for this assessment model. The objective function was the summation of the negative log-likelihood components over the four areas.

The third approach, the “pooled population assessment”, treated all lake whitefish across the areas modeled as part of one well mixed population. This led to an exponential model for the pooled population, rather than for each stock (Equation T.1.2.1).

For all three assessment models, recruitment (area specific or pooled), the initial abundance-at-age for the first year, selectivity-at-age, and fishing mortality were estimated as free parameters during model fitting. Best fit parameters were estimated via iterative methods so as to minimize the negative penalized log-likelihood (i.e., the objective function). We assumed lognormal distributions of errors for annual fishery catch, a lognormal prior component associated with the fishing mortality-effort relationship, and the age compositions of the fishery were assumed to follow multinomial distributions. The objective function was the sum of above three negative log-likelihood or log prior components (T.2.9., T.2.10, T.2.11). Iterations proceeded until the maximum absolute value of the gradient (derivatives of objective function with respect to parameters) was below a specified criterion (0.001), although sometimes iterations stopped before reaching the criterion either because no further progress was being made in reducing the objective function or a maximum number of iterations (1000) were completed. Fits that ended without reaching the gradient criterion were classified as failing convergence. A second test of whether the solution after iterations was a minimum (i.e., true maximum for the penalized likelihood) was whether the Hessian was negative definite. If this was not the case we termed this a Hessian problem. A record was kept for each assessment on whether there was convergence failure or a Hessian problem. The negative log likelihood component for the age composition of the fishery harvest was weighted by effective sample size (800 for the pooled method and 200 for the separate and the "meta" methods). The 20 years of data prior to any given assessment year were included in the assessment model.

We mimicked the actual timing of assessments and setting of harvest guidelines based on them in lake whitefish fisheries. These assessments are done in a given year, based on data through the previous year, and are used to establish harvest targets for the next year. The stock assessment thus produces abundance-at-age for the start of the year when the assessment is done. Projections through the assessment year were based on an exponential population model, in which total mortality rate was assumed to be the mean of the last three years' values and recruitment were assumed to be the mean of the last ten years' values. For the year for which the TAC was set, the same level of recruitment was assumed but fishing mortality was adjusted so the target mortality rate was achieved (assuming the assessment point estimates were correct).

The current harvest control rule and policy parameter for lake whitefish in treaty waters, which equates to a constant fishing mortality rate policy, were used in the simulation. The control rule sets the maximum total annual mortality rate experienced by any age of fish at 65%. We used the same methodology to determine the TAC as the one applied by the MSC to determine the target maximum yield. This TAC was calculated from assessment-based estimates of abundance-at-age at the start of the year the TAC applies to and target fishing mortality-at-age using the Baranov catch equation. The age-specific fishing mortality rates were based on the estimated selectivity-at-age from assessment multiplied by the target fishing mortality rates, which was the target instantaneous total mortality rate minus the natural mortality rate as assumed in the assessment model. For the "separate" and "meta" assessment methods, a TAC for each area was calculated separately because the assessment results were area-specific for those methods. For the pooled population assessment, only a pooled TAC could be calculated and this was allocated to the areas according to two rules: a constant allocation rule and an annually varying allocation rule. The first allocated the TAC in proportion to equilibrium yield for the population that spawned within a given area. The assumption was that we had pre-assessment knowledge about how productive each population was, and the allocation remained constant over time. The second allocation rule was based on the annual area-specific CPE observed from the "true" system. The higher the CPE, the more TAC was allocated to each area. To reduce annual variation of yield, we used the average CPE over the last three years of available data (preliminary simulations suggested this averaging outperformed alternative averaging periods).

Experimental design

For four hypothetical populations with differing productivity (Table 3), we evaluated how assessment methods performed under different intermixing scenarios. Scenarios 1 to 4

(“SR=0.9”, “SR=0.75”, “SR=0.5”, “SR=0.25”) represented the cases where all areas shared the same stay rate ordered from high to low (so the case of less mixing is first). We referred to scenarios 1 to 4 as “same mixing” scenarios. Scenario 5 (i.e., “po-cor”) assumed that productivity and stay rate for each area were positively correlated (fish from higher productivity populations tended to stay in natal areas). Scenario 6 (i.e., “ne-cor”) assumed a negative correlation between productivity and stay rate for each population. Scenario 7 (i.e., “unpredictable”) assumed no consistent relationship between productivity and stay rate. For this scenario each population had one of four distinct stay rates. There were 24 possible combinations of how the four stay rates and productivities were matched, and we equally weighted these possibilities. In order to conduct approximately 1000 total simulation for this scenario, 42 simulations were conducted for each combination.

Within each mixing scenario, four assessment and management methods were examined: 1. The separate population model (“separate”); 2. the pooled model with TAC allocated by CPE (“pooled (CPE)”); 3. the pooled model with TAC allocated by a constant ratio of equilibrium yields (“pooled (EY)”); and 4. the meta-population model (“meta”).

Performance statistics

For each method under Scenarios 1 to 6, a 100-year simulation was performed 1000 times by using AD Model Builder (Fournier et al., 2012). For scenario 7, we conducted 1008 simulations for each method. Performance statistics were generated from the “true” system, which was used to describe the real status of stock and fishery. The statistics allowed us to compare the performance of alternative assessment and management methods under different mixing scenarios with respect to the management objectives (i.e., long-term sustainability, high and stable yield, and the trade-off between them) and the accuracy of SSB estimation. Given that most performance statistics appeared to approach a long-term mean by year 75, we based our evaluation of performance on the last 25 years of the simulations. Under different scenarios, the performance statistics were:

1. Average yield over the last 25 years for each area.
2. Average SSB over the last 25 years for each population.
3. Inter annual variation of yield over the last 25 years for each area.
4. Proportion of years spawning stock biomass (SSB) being less than 20% of the unfished SSB level
5. Median relative error (MRE) and median absolute relative error (MRE) of estimating SSB for each assessment method over the last 25 years.

Results

The "meta" assessment model is only included in model comparisons under Scenarios 1 and 2, when the stay rate for each area was high or medium-high. For other assessment models, the convergence rates for the optimization were all above 99.95% among all scenarios (results not shown), while for the "meta" assessment model, the convergence rate became low once higher mixing occurred (Table 4). This indicates that the assessment model cannot always minimize the objective function. In Scenario 4, the well-mixed case in which all areas shared the same population composition, all simulations ran into problems calculating the Hessian for the meta population assessment model. All of these results are likely a consequence of population-specific data not being available. The area specific data in addition to the mixing rate were not enough for the model to distinguish which population was actually producing recruits, especially in Scenario 4 where all areas have the same population composition at the start of each year because of complete mixing.

The performance statistics of assessment methods differed depending on the mixing rate of spawning populations. For each assessment model under each mixing scenario, the expected average annual SSB and yield (Figure 1.3a and 1.3b, respectively) over the last 25 years are summarized by modified boxplots to represent its long-term performance. The relative performance of “separate” and “pooled (CPE)” models was similar across all “same mixing” scenarios (Scenarios 1 to 4). The major difference was the SSB of the LP population. With increasing mixing rate, the “pooled (CPE)” method was more likely to drive the SSB of the LP population below $B_{20\%}$, while the “separate” method tended to allow SSB to be above $B_{20\%}$. This same trend was also observed in the “ne-cor” scenario. However, the opposite happened in the “po-cor” scenario, in which “pooled (CPE)” was superior to the “separate” and “pooled (EY)” methods, in that it had both the greatest SSB and high yield.

The first row in Figure 1.3 (SR=0.9) shows that the “pooled (CPE)” method outperformed the others with respect to greater SSB of LP population and higher yield among all areas, followed by the “separate” method. The “meta” method had the highest risk of over-exploitation of the LP population. The “pooled (EY)” method surprisingly provided the greatest SSB for the LP population across all populations, and the SSB of the other three populations were much lower than the results obtained by the other three assessment methods, especially for the MLP population.

In the second row in Figure 1.3 (SR=0.75), median SSB fell to less than $B_{20\%}$ only for the “meta” method, without significant yield benefit. In contrast, the “pooled (EY)” method outperformed the others by maintaining high levels of biomass for the LP population and highest yields among all areas. Even losing some yield in the LP area (Figure 1.2), more yields was attained in the other three areas by this method, with acceptable levels of biomass. The third row

(SR=0. 5) illustrates similar results to those from Scenario 2. In Scenario 4 (SR=0. 25), however, the "pooled (EY)" method showed high risk of median SSB falling to less than $B_{20\%}$ for the LP population, with yield from the LP area being negligible. This is not unexpected given that, during the fishing season under the high mixing scenario, only 25% of the LP population stayed in the LP area while most fish moved out and experienced high exploitation in the other areas.

Except for the "pooled (CPE)" method, in the "ne-cor" scenario (the fifth row of Figure 1.3) there were high risks of median SSB of the LP populations being below $B_{20\%}$. Especially for the "pooled (EY)" method, almost all of our simulations for the SSB of the LP population were below $B_{20\%}$, and the SSB of the MLP population were also substantially lower than for the other two methods. The "pooled (CPE)" were superior to other methods, with the greatest SSB of LP population and high yield across all areas. In the "po-cor" scenario (scenario 6), the "separate" method outperformed the others by providing higher yield and greatest SSB across all areas. In the unpredictable scenario (the last row of Figure 1.3), the "separate" and the "pooled (CPE)" performed equally and better than the "pooled (EY)". The median SSB and yield varied in a larger range compared with the other scenarios, likely because this scenario includes all the 24 combinations of mixing rate and productivity.

The inter-annual variation (IAV) of yield ranged from 10 to 25% across most scenarios. The "pooled (EY)" method provided the least IAV of yield under all mixing scenarios except the unpredictable mixing relationship to productivity scenario (Figure 1.4). Under all "same mixing" scenarios (scenarios 1 to 4), for the "separate" and "pooled (EY)" methods, the IAVs of yield across all simulations decreased with increases in mixing rate. Not surprisingly, for the two "pooled" methods, all four areas shared almost the same level of IAV of yield. For the "Separate" method at low (SR=0.9) and mid low (SR=0.75) mixing scenarios, larger IAV of yield was observed in the area with higher productivity.

For the “Separate”, “Pooled (EY)”, and “Meta” methods, only the LP populations had a substantial risk of being below $B_{20\%}$ (Fig. 5) For the “pooled (EY)” methods under the low mixing (SR=0.9), correlated and random scenarios, there is some risk of being below $B_{20\%}$ for MLP as well as LP populations. For the “separate” method across all the same mixing scenarios (Scenarios 1 to 4), there was an inverse relationship between the risk of SSB being lower than $B_{20\%}$ for the LP population and the mixing rates. For the “pooled (CPE)” method, the risk was similar across all same mixing scenarios. The “pooled (EY)” method provided substantially lower risk under scenarios 2 and 3, compared with other methods.

We used median relative error (MRE) to evaluate median bias, and median absolute relative error (MARE) to characterize the magnitude of errors for SSB estimation over the last 25 years. The “pooled (CPE)” method was the most median-unbiased method, with median value of MRE close to zero. The “separate” method had negative median-bias in estimating SSB (underestimated the real total SSB) under all scenarios; while for the “pooled (EY)”, the negative bias decreased and the estimator approached being unbiased as stay rate went from high to medium high, and then increased to positive bias with higher mixing. The meta method was negatively median-biased for SSB for those scenarios it was feasible. Under unpredictable productivity versus mixing scenarios, the two pooled method both were essentially median-unbiased estimators of SSB.

The “separate” method had the lowest MARE, followed by “pooled (CPE)”, “meta”, and “pooled (EY)”. For the “pooled (CPE)”, “meta”, and “pooled (EY)” methods, the MARE of SSB decreased as mixing rate increased. Under the correlated and random scenarios, the MAREs for "pooled (EY)" method were at least two times larger than those for the other two assessment methods.

Discussion

Our goal was to evaluate different assessment methods for use with intermixing lake whitefish populations under the current constant mortality control rule. The "separate" assessment method, based on a SCAA model, has been used for the assessment of lake whitefish in 1836 Treaty-Ceded water since 1998. The "pooled" method, also based on an SCAA model, is essentially the response that was taken by the Technical Fisheries Committee and Modeling Sub Committee in northern Lake Huron for lake whitefish in response to information about high levels of mixing. Our study was not attempting to make tactical advice for specific lake whitefish populations because actual mixing rates and productivity for each population are unknown in the real world. Instead, we used the lake whitefish case as an example to address the more general problem about how to deal with intermixing fish populations, and to evaluate whether there might be some overriding messages applicable to whitefish or other species regardless of the exact mixing and productivity values. Previously for lake whitefish, Jacobson and Taylor (1985) and Deroba and Bence (2012) evaluated different harvest control rules based on simulation studies without considering intermixing and alternative assessment methods. Later, Molton et al. (2012) found that with mixing low productivity populations had high risk to be overfished under the current constant mortality control rule, although they only applied the "separate" assessment method. They found that mixing had little influence on either aggregate yield or the population specific status in terms of SSB, but did have a large influence on area specific yield, with higher yields in areas near low productivity populations when mixing was high. The “true” system in the management strategy evaluation process in our study was based on the approach developed by Molton et al (2012). We extended the work of Molton et al. by again considering the performance of the current 65% mortality target for lake whitefish, but now considering three alternative assessment approaches, rather than just the single separate approach they used. We also refined the overall MSE approach (e.g., our assumption that the movement rates into an area would be related to the tendency of fish from that areas' spawning population to remain in that area).

High levels of intermixing tended to make sub populations effectively a pooled one, while low intermixing tended to make them close to unit stocks. Our study illustrated some results matching our prior expectations based on this and some surprises. For the scenarios with low mixing rate (SR=0.9), consistent with the results from previous study for other species (Crurtis et al. 2008, Kell et al. 2009, Ying et al. 2011), the “separate” assessment method performed better than the “pooled” assessment method, when for the latter TAC allocated by constant proportion based on the equilibrium yields. But the “pooled” assessment method with TAC allocated by varying proportion based on area specific CPE performed even better than the “separate” method, with regard to greater SSB for the low productivity area. This result was surprising and we do not fully understand it, although the explanation likely rests with depletion resulting from sequences of correlated assessment errors and inappropriate TACs, which may be avoided with the pooled assessment and use of CPE for allocation, due in part to its conservative bias.

Our observation that low productivity populations are at risk of depletion is consistent with Molton et al (2012)’s results, although counter to their results, we found the risk of depletion was actually higher for the lowest mixing rates for the separate assessment approach. This difference may stem from the specific productivity levels we chose and our equating productivity with steepness, while keeping unfished stock sizes the same across populations, a somewhat different approach than that used by Molton et al. (2012). Perhaps more importantly, we found this risk of depleting low productivity populations is still present for the pooled assessment method and can even be more severe for pooled methods when the mixing rate is high. When the mixing rate for each population was moderate, the “pooled” assessment method with TAC allocated by proportion of equilibrium yield was superior to the “separate” method. Specifically, the “pooled (EY)” method provided more protection for the SSB of the low productive population, with higher aggregate yield across the areas and the lowest annual variation in yield. Initially it was surprisingly to us that when the mixing rate was high, this “pooled” method lost its advantages. With high mixing, the “separate” method could provide the lowest risk for the SSB of LP populations below $B_{20\%}$. In retrospect this deterioration of the pooled (EY) with higher mixing makes sense. With higher mixing, the actual allocation of biomass among the fishing areas increasingly deviates from being in proportion to equilibrium yield for the populations.

Our results clearly reinforce a point made by Molton et al. (2012), that the current 65% total mortality control rule may be not conservative enough for the low productivity populations. These results contrast with one overall conclusion of Deroba and Bence (2012), that the 65% mortality rate produces acceptable results. This contrast appears to be due to the fact that Deroba and Bence (2012) evaluated the probable performance of a management strategy applied to any single unit stock, and not what might happen to a low productivity stock among a collection of plausible populations ranging in productivity (Molton et al. 2012). As Molton et al. (2012)

argued, when mixing is ignored the LP population can be falsely assessed to have high abundance and harvest. With substantial mixing, the harvest from the area surrounding the spawning grounds of the LP population is likely to be composed largely of fish from other more productive populations. This is clearly evident in our results, where yield for the area associated with the low productivity population increased as mixing rates increased. We reiterate Molton et al.'s (2012) point, that such mixing would also influence estimates of productivity, so that the productivity of low productivity stocks could be overestimated. To the extent to which such mixing influenced historical stock assessments, this in turn tends to make the lowest productivity values we assumed even more plausible.

Differences in the bias in estimating stock status may be one of the explanations for the relative performances of different assessment methods. The pooled methods regarded the four populations to be one pooled population and this misspecification led to substantial negative bias when mixing was low. The assessment bias for the separate model was negative across all mixing scenarios, which could help to explain the conservative performance of the separate assessment models under medium-high mixing (SR=0.9) and positive correlation (pocor) scenarios. Kell et al. (2009) reported that, overall, pooling stocks together can provide a less biased estimation of total spawning stocks than a separate assessment, which corresponds to our results when mixing was moderate to high and for the unpredictable scenarios. We found that without knowing the relationship between mixing rate and productivity, pooling stocks together can provide an essentially unbiased estimator of SSB, while the separate method led to a significant negative bias. Thus the advantages sometimes seen for the separate approach may stem from it being accidentally more conservative than intended. This argues for future research comparing a range of target mortality rates, to see if these occasional advantages could be more than made up by using the less biased pooled method and a lower target mortality rate. Unlike when allocating by CPE, positive bias arose as the mixing rate became quite high for the pooled method that allocated based on equilibrium yield. We do not fully understand what led to this result, but in this case fishing mortality is varying substantially among areas, and this is being ignored in the assessment. This bias too may in part explain the higher depletion for the pooled population when allocating this way in the face of high mixing.

Accurately quantifying mixing rate remains important for managing mixing lake whitefish populations. Even if we can identify strategies that are robust to mixing rates, it is clear that appropriate mortality rates depend upon the productivity of the populations. Without information on the population source of fish caught in different areas, population productivity levels cannot be refined nor can it be assessed if they are changing. The current critical task for managing mixing populations, such as the pooled management unit for northern Lake Huron, is to collecting data to identify the intermixing among the four spawning populations and how this might be associated with population productivity. If the mixing rate were high, a low productivity population has high risk to be overfished and there could be adverse ecological consequences of loss of spawning components in terms of stock sub-structure and in terms of preserving specific genes or genetic variations (Stephenson 1999).

We also considered a modification of the current SCAA model that used assumed known mixing rates. Unfortunately this method did not produce useable estimates except when mixing rates were relatively low. This emphasizes the need for collecting population-specific data, such as genetic information that would allow separating catch from each area by its population source (Porch, 1997). These problems arise because even with known mixing rates the SCAA still has problems identifying which population was producing the recruits in a given year. Power and

Porch (2004) and Kell (2009) both emphasized that misinterpretations of mixing rate could lead to even higher bias than just ignoring mixing. We believe further investigation is warranted, but at this point it does seem clear that at least additional population specific data is required in addition to prior information on mixing rates to apply the meta approach.

Our simulation framework for each assessment model can be considered as a variant of management strategy evaluation (Kirkwood, 1992, 1996). We incorporated multiple assessment models and applied the current harvest control rule with assessment and implementation error. But like Irwin et al. (2008) said, “not all uncertainty can be captured by any model and unexpected changes could occur”. Like other simulation studies (Irwin et al. 2008, Deroba and Bence 2012), we made a number of simplifying assumptions and choices, such as mixing pattern, different levels of mixing rate and productivity of each population and which levels of productivity were most representative. Likewise, we ignored the temporal variation in parameters such as catchability and natural mortality. These assumptions and choices may influence the final results. Our application of the “pooled (EY)” method assumed that the ratio of equilibrium yields between populations is known without uncertainty, and similar assumptions are commonly used in other studies (Deroba and Bence 2012, Irwin et al. 2008, Punt et al. 2008). In general, we based our simplifications on previous studies suggesting that qualitative results would be robust to the simplifications, or as an initial evaluation to see if an approach would even be effective at the limit of perfect information. While the assumptions and simplifications deserve scrutiny, we believe that the necessary simplifications we made are of secondary importance, in comparison with the large uncertainties regarding productivity and mixing.

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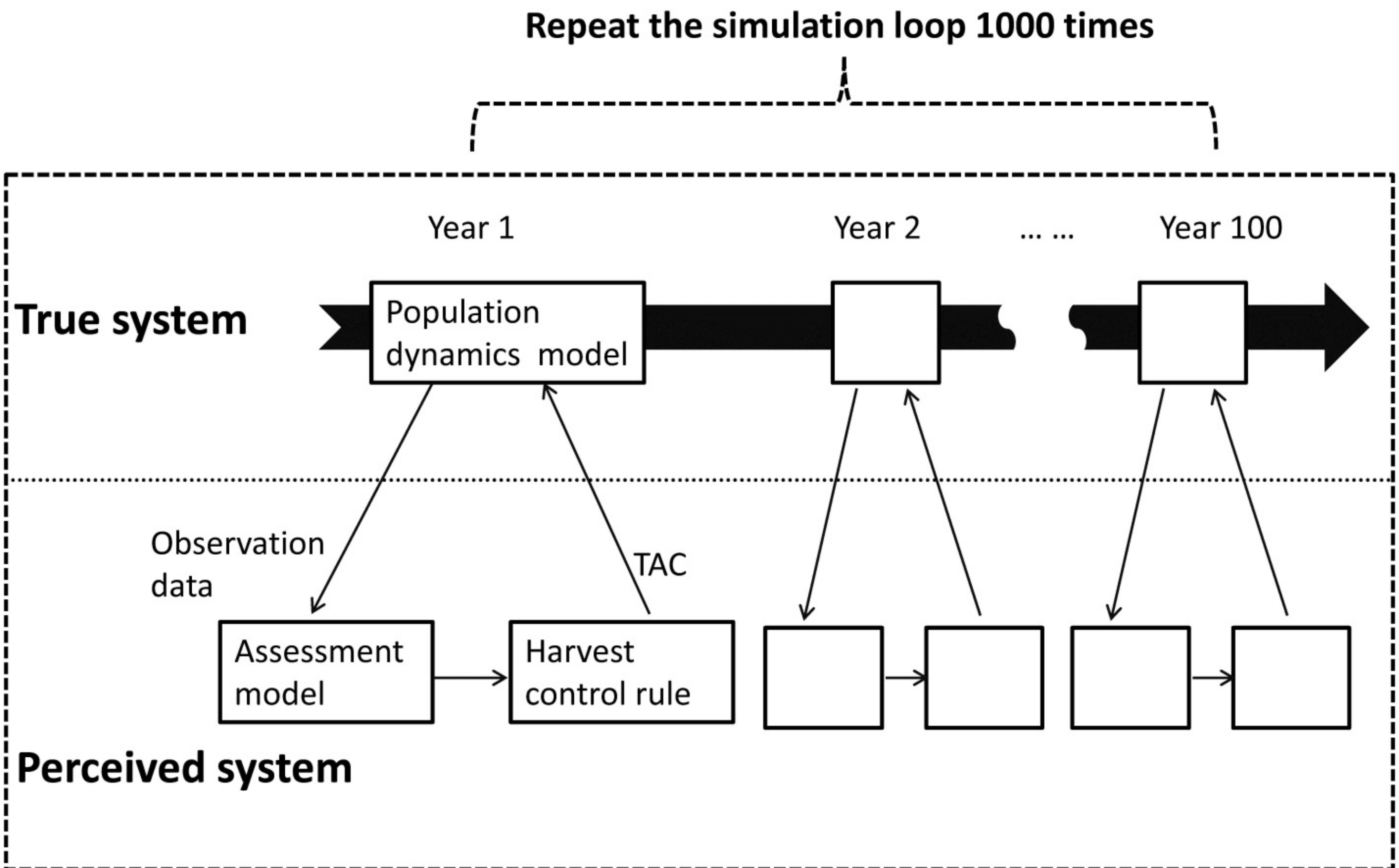


Figure 1.1: Structure of a simulation framework for evaluating stock assessment models' performance.

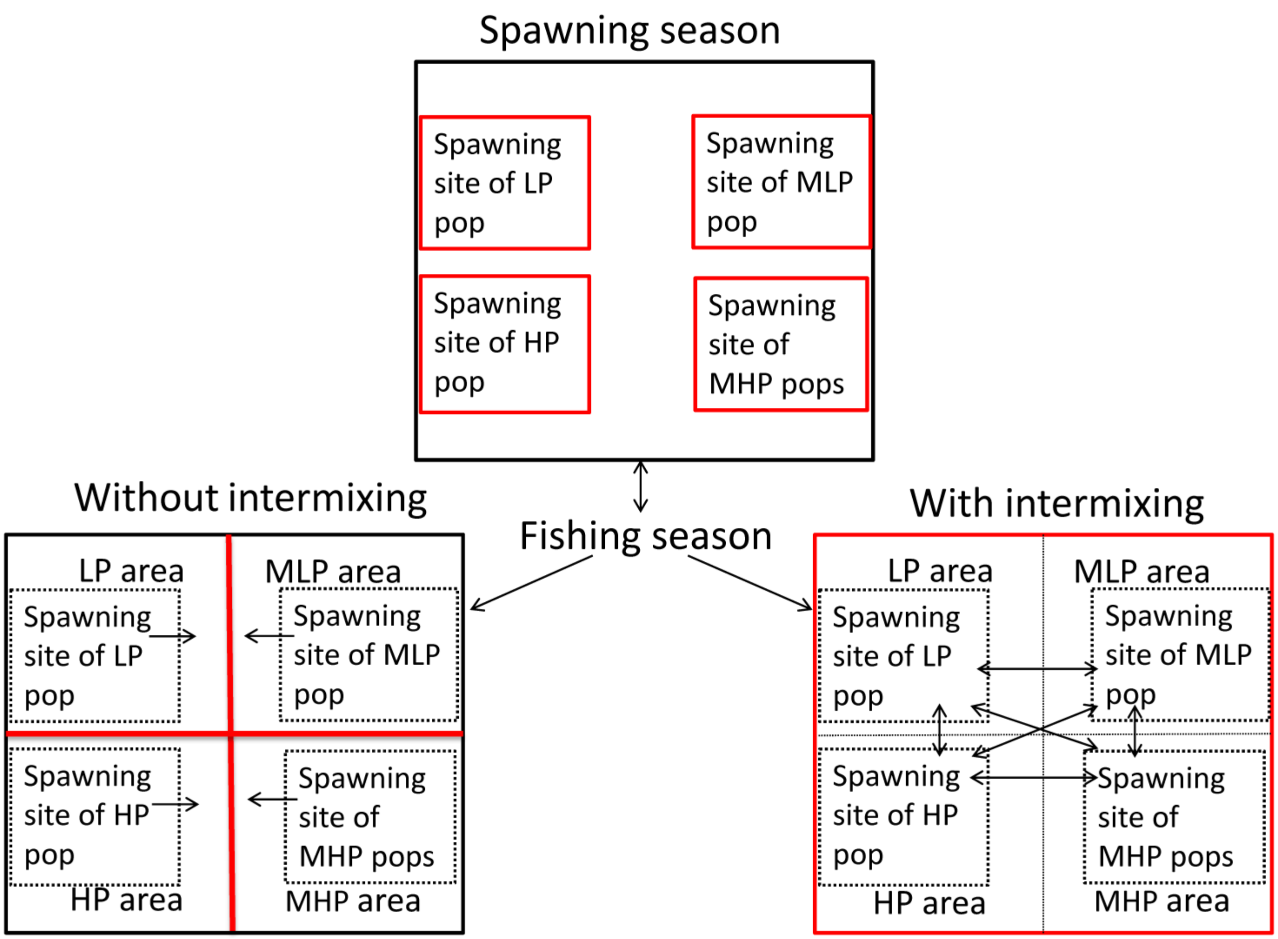
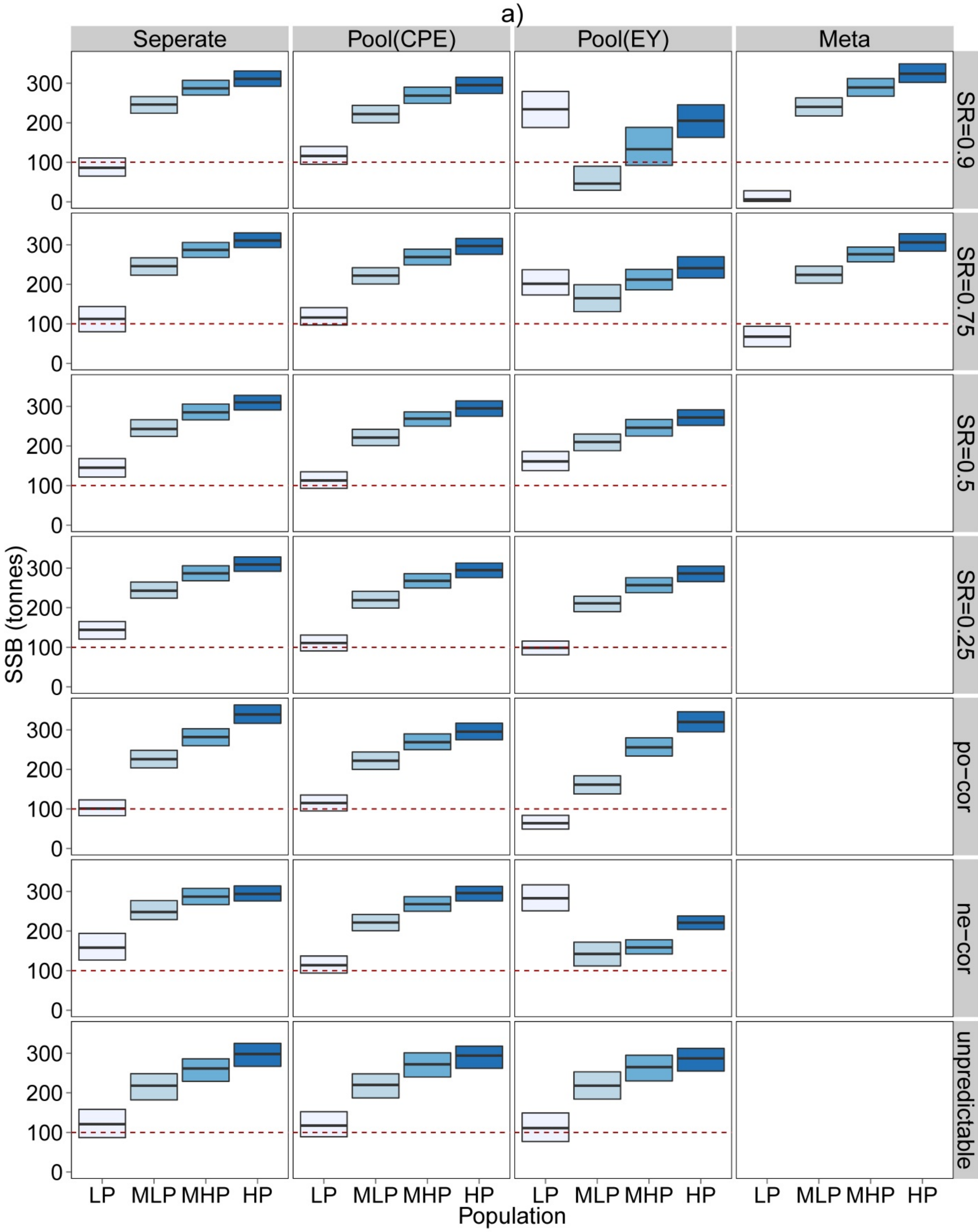


Figure 1.2: A conceptual diagram of stock intermixing for four hypothetical lake whitefish populations that are spatially segregated during spawning, but subsequently intermix during the non-spawning period when exploitation takes place. For interpretation of the references to color in this and all other figures, the reader is referred to the electronic version of this thesis.



a)
Seperate
Pool(CPE)
Pool(EY)
Meta
SR=0.9
SR=0.75
SR=0.5
SR=0.25
po−cor
ne−cor
unpredictable
SSB (tonnes)
0
100
200
300
LP
MLP
MHP
HP
Population

Figure 1.3

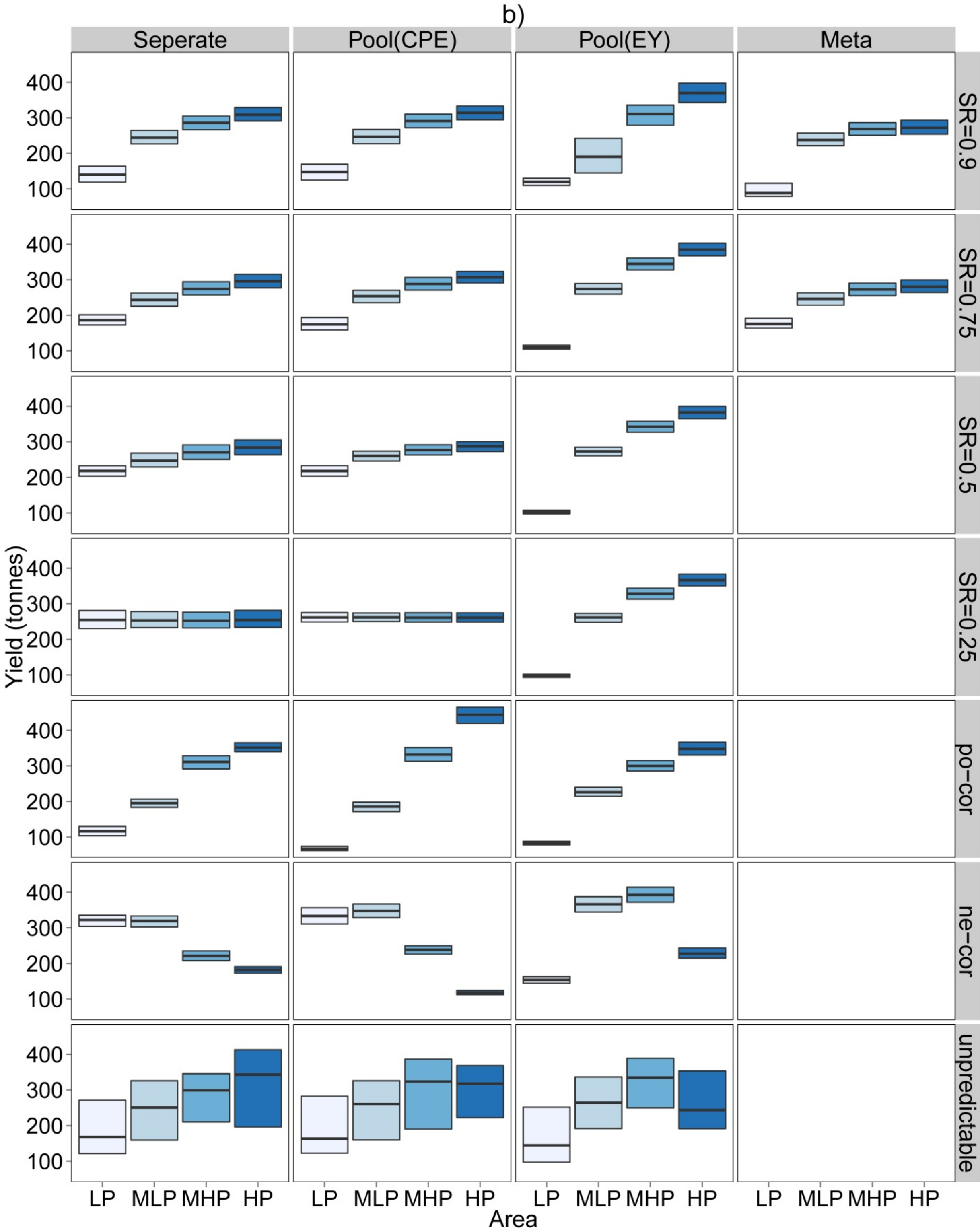


Figure 1.3 (cont'd)

Figure 1.3(cont'd): Mean annual spawning stock biomass (SSB) for each population and fishery yield for fishing areas surrounding each spawning area over the last 25 years of simulations. The X-axis of each section in Figure 1.3a represents all four simulated populations, from the low productivity (LP) population to the high productivity (HP) population. The dashed line is at 20% of unfished SSB ($B_{20\%}$). In Figure 1.3b, the X-axis identifies the four fishing areas surrounding the spawning areas of the LP to HP populations separately. The box tops and bottoms cover the interquartile range; the horizontal middle line represents the median value of all simulations for each scenario.

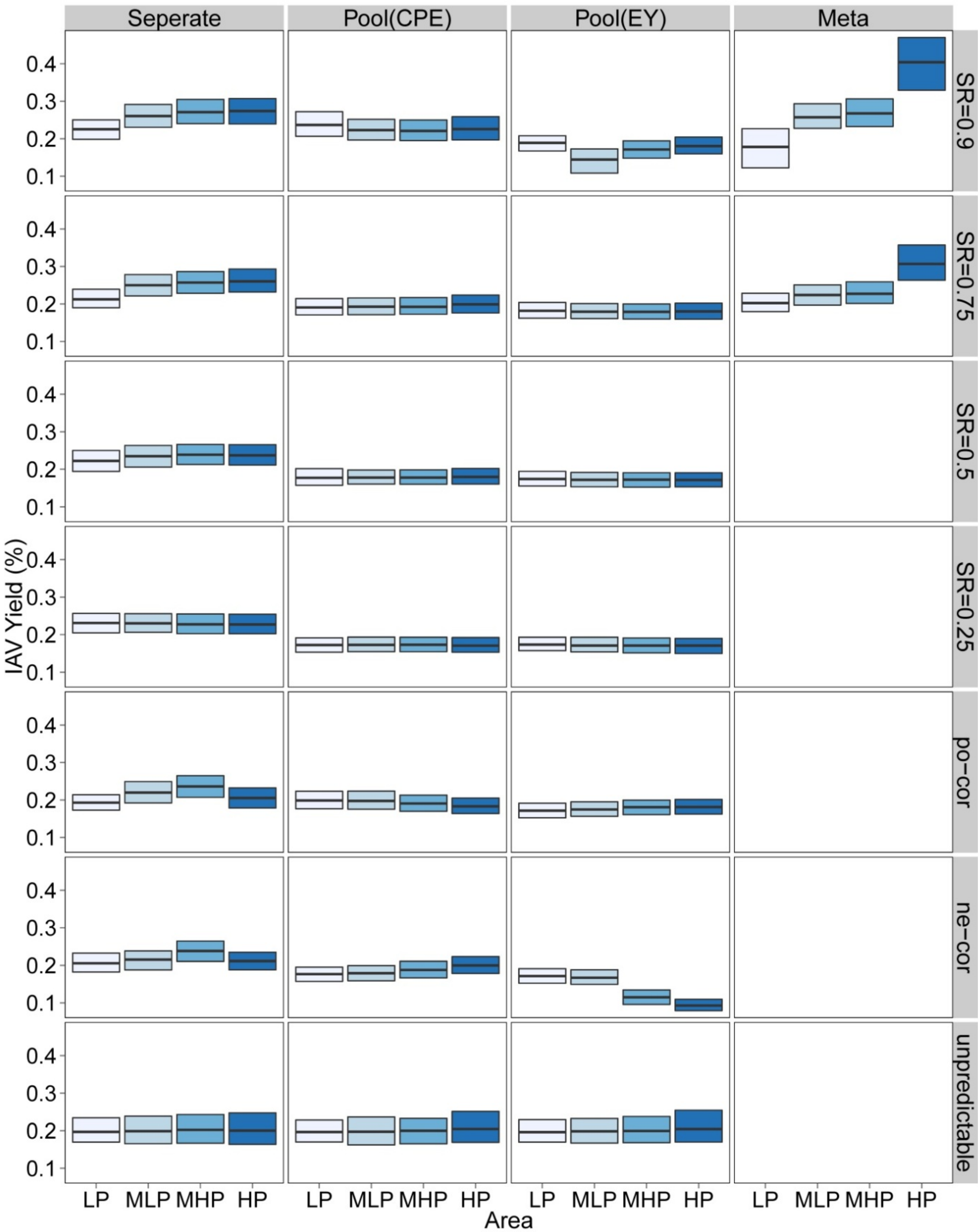


Figure 1.4: As for Figure 1.3b, except y-axis is mean inter-annual percent variation in fishery yield

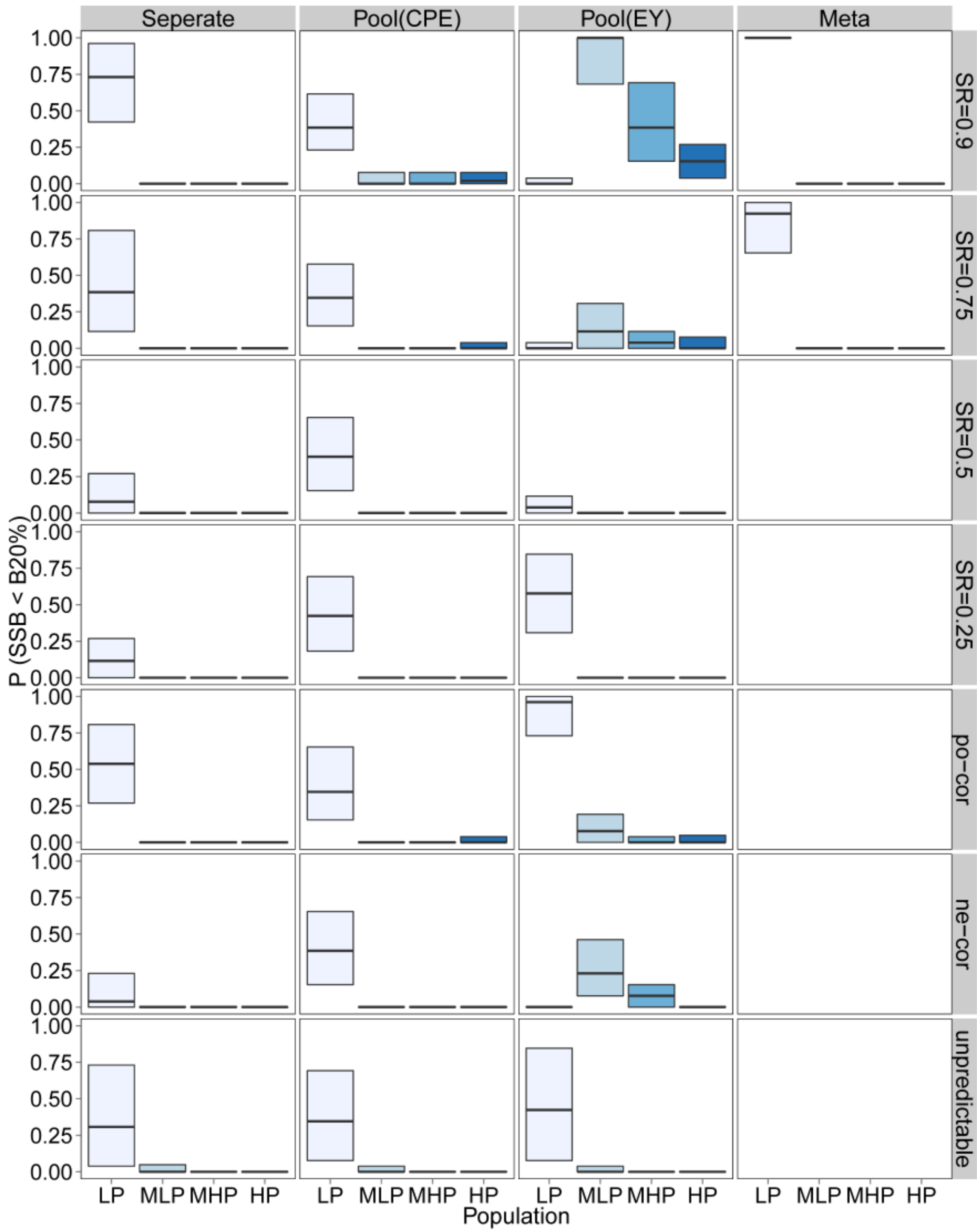


Figure 1.5: Proportion of years spawning stock biomass (SSB) being less than 20% of the unfished SSB level

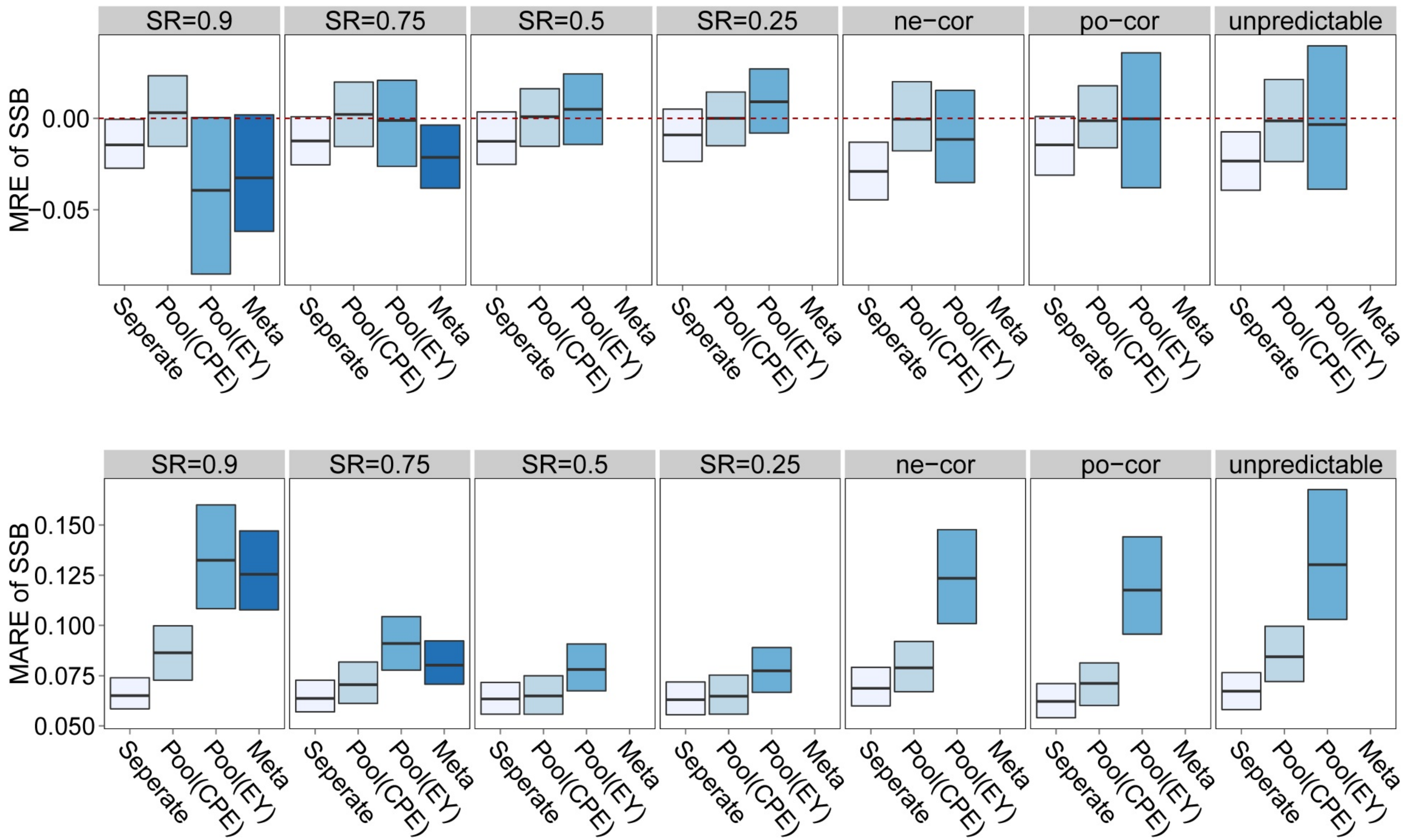


Figure 1.6: Median relative error (MRE) and Median absolute relative error (MRE) of estimating SSB for each assessment method over the last 25 years.

Table 1.1: Four different levels of productivity for lake whitefish used in simulations and associated steepness, equilibrium yield (tonnes), and the corresponding standard Ricker parameters α and β.

Population index	Productivity level	Steepness	α	β	Equilibrium Yield
LP population	Low	0.7	5.23×10^{-4}	1.51×10^{-10}	80
MLP population	Mid-low	1.1	9.19×10^{-4}	2.06×10^{-10}	219
MHP population	Mid-high	1.5	1.35×10^{-3}	2.43×10^{-10}	278
HP population	High	1.9	1.82×10^{-3}	2.72×10^{-10}	312

Table 1.2: Equations used in stochastic simulation model

Equation index	Description of equation	Equation	Parameter
(T.1.2.1)	Ricker stock-recruitment function by year (y) and population (i)	$R_{i,y} = \alpha_i SSB_{i,y-1} e^{-\beta_i SSB_{i,y-1}} e^{\varepsilon_{R,i,y}}$	α: see Table 1 β: see Table 1 $\varepsilon_{R,i,y}$ ~ N(0, ${\sigma_R}^2$) $\sigma_R = 0.6$

Table 1.2 (cont'd)

(T.1.2.2)	age-specific SSB by year (y)	$SSB_y = \sum_a Fem\ N_{y,a} m_a W_a$	Fem =0.5
(T.1.2.3)	Length at age	L_a=$L_\infty(1 - \exp(-\kappa(a - t_0)))$	L_∞=60.9
			κ=0.1686
			t_0=0.0
(T.1.2.4)	Weight at age	$W_a = \gamma {L_a}^\psi$	γ= 8.06×10^{-5}
			ψ=2.45

Table 1.2 (cont'd)

(T.1.2.5)	Maturity at age	$m_a = \frac{m_\infty}{1 + \exp(-\vartheta(L_a - \delta))}$	ϑ=0.315 δ=37.9
(T.1.2.6)	Selectivity at age	$s_a = \frac{a^\eta \exp(-\tau\alpha)}{10^\eta \exp(-\tau 10)}$	η= 13.074 τ= 1.26

Table 1.2 (cont'd)

(T.1.2.7)	Actual catch by Baranov's catch equation by year (y) and population (i), given fishing mortality rates and abundance	$$C_{i,y} = \sum_{a=1}^{n} \frac{F_{i,y,a}}{M + F_{i,y,a}} (1 - e^{-M-F_{i,y,a}})\ N_{i,y,a}$$	M= 0.25

Table 1.2 (cont'd)

(T.1.2.8)	Actual catch by year (y) and population (i) given the TAC.	$C_{j,y} = TAC_{j,y}\, exp(\upsilon_{i,y} - 0.5{\sigma_c}^2)$	$\upsilon_{i,y}$ ~ N(0, ${\sigma_c}^2$) σ_c= 0.1
(T.1.2.9)	likelihood component for total catch	$\ell_c = n_c log_e(\hat{\sigma}_c) + (\frac{1}{2{\hat{\sigma}_c}^2})\sum_y log_e(\frac{\hat{c}_y}{\hat{\hat{c}}_y})^2$ $n_c = \hat{c}_y - \hat{\hat{c}}_y$	

Table 1.2 (cont'd)

(T.1.2.10)	Likelihood component for fishing mortality-effort relationship	$\ell_{\varepsilon F} = n_{\varepsilon F} log_e\left(\frac{\hat{\sigma}_c}{\sqrt{0.25}}\right) + (\frac{0.25}{2\hat{\sigma}_c{}^2}) \sum_y log_e(\varepsilon F)^2$
(T.1.2.11)	Likelihood component for age composition of the fishery harvest	$\ell_p = -\sum_y 200 \sum_a (\tilde{p}_{y,a} log_e \tilde{p}_{y,a})$

Table 1.3: Simulation scenarios. In all scenarios each of the four populations had different productivity, with one population taking each of the four alternative productivity levels (Table 1).

Scenario	*Description*
Scenario 1	All populations have same high stay rate (0.9)
Scenario 2	All populations have same medium high stay rate (0.75)
Scenario 3	All populations have same medium-low stay rate (0.5)
Scenario 4	All populations have same low stay rate (0.25)
Scenario 5	Positive-correlated stay rates and productivity. Four stay rates (0.25, 0. 5, 0.75, 0.9) matched in rank order to productivity of four populations
Scenario 6	Negative-correlated stay rates and productivity. Four stay rates (0.25, 0. 5, 0.75, 0.9) matched in reverse rank order to productivity of four populations
Scenario 7	Unpredictable stay and productivity relationship. Four stay rates attached to populations of different productivities using all possible combinations

Table 1.4: The convergence rate and Hessian warning percentage for the “meta” assessment method under each scenario.

	Scenario 1 (SR=0.9)	Scenario 2 (SR=0.75)	Scenario 3 (SR=0.5)	Scenario 4 (SR=0.25)	Scenario 5 (po-cor)	Scenario 6 (ne-cor)	Scenario 7 (Unpredictable)
Convergence rate (%)	95.4	94.8	81.6	99.8	88.8	21.0	52.9
Hessian warning (%)	0	0	0	100	0	0	0.03

CHAPTER 2

DOES STOCK ASSESSMENT FREQUENCY REALLY MATTER? A CASE STUDY FOR INTERMIXING LAKE WHITEFISH POPULATIONS IN 1836 TREATY CEDED WATER

Abstract

Stock assessment resources are limited and need to be focused in an efficient manner. One tradeoff faced by assessment groups is the frequency with which to update assessments versus investing efforts in identifying improvements in assessment model structure. We address this issue using Management Strategy Evaluation type simulations for a spatially structured stock, based on characteristics of lake whitefish in the Laurentian Great Lakes of North America. Populations of lake whitefish exhibit philopatry, returning to spawning grounds in the fall and winter, but often moving into areas near spawning grounds of other populations during the harvest season. These populations are managed with the equivalent of a constant fishing mortality rate policy. We modeled a hypothetical set of four populations, with proportions of each reproductive population moving to areas surrounding the spawning grounds of the other populations during the harvest season, and applied the status quo harvest policy. We explored how assessment frequency (every year, every three years, and every five years) and lag between data collection and use (with and without lag) influenced fishery performance as measured by average yield, average spawning biomass, frequency of low stock sizes, and inter-annual variation in yields. We also considered several alternative ways of setting harvest limits during the years between assessments. The results showed that compared to other things like the actual mixing among areas and the choice of how to account for spatial structure, the frequency of assessment had modest effects. When conducting an annual assessment, removing the 1-year lag had little influence. Our results suggest that conducting assessments every three or five years

should be considered as part of a management strategy and may allow analytical efforts to be directed in other ways.

Introduction

Conducting stock assessments soon enough after the most recent data that are included were collected and at an appropriate frequency is of great importance to establishing an effective and sustainable fishery management system. Human resources that can be devoted to stock assessment are limited, thus the optimal stock assessment process should be both provide high-quality science information to managers while saving as much assessment resources as possible. One trade-off faced by assessment groups is the frequency with which to update assessments versus investing more efforts on identifying improvements in assessment model structure or perhaps turning attention to another population that is completely unassessed. Some stock assessment groups, such as ICES Study Group on Multiannual Assessment Procedures (SGMAP), Modeling Subcommittee (MSC) of the Technical Fisheries Committee (TFC) of 1836 Treaty Ceded waters, and National Marine Fisheries Service (NMFS) National Task Force for Improving Fish Stock Assessments, have already included "identifying appropriate assessment frequency" or similar topics as their objects of discussions (Mace et al., 2001, Woldt et al. 2005, ICES 2012). Some fishery scientists have suggested that the high frequency of assessment could increase our capacity of monitoring fish populations and prevent early overfishing (Mace et al., 2001). Other scientists have suggested the possibility of a rotation of stock assessments (i.e. doing assessments at less than an annual frequency) because they thought the time and resources saved from not annually assessment could be used for doing something else such as improving models and verifying model performance (Woldt et al. 2005). Furthermore, maintaining the amount and quality of assessment work when each assessment is done annually can be a challenge in some circumstances (ICES 2012).

ICES (2012) suggested that the appropriate time period between stock assessments, in theory, can be determined by two main factors: (a) biological attributes of the assessed population that determine the rate of change in stock size that is possible, and (b) the current and anticipated fishing pressure. These factors will clearly influence how much change is likely to occur over a given time period, and this will clearly influence the amount of beneficial information that can be obtained by doing an assessment sooner rather than later. We addressed this issue using Management Strategy Evaluation (MSE) simulations for spatially structured populations, based on characteristics of lake whitefish in the Laurentian Great Lakes of North America. We explored how the lag between data collection and establishing a harvest recommendation (the lag) and the frequency of assessments affected long-term fishery performance metrics (yield, spawning stock biomass, et al.) for intermixing lake whitefish populations. We chose lake white fish as an example because lake whitefish harvest across that region has been well below established harvest limits in at least the most recent 9 years from 2005 to 2013 (Woldt et al. 2006, 2007, 2008, Caroffino et al. 2009a, 2009b,2011a, 2011b, 2012), which illustrates that past and current fishing pressure was low. However, the current stock assessment models are annually updating with a one-year time lag.

Most MSE-style simulation studies have focused on evaluation of alternative harvest control rules. Our study uses an MSE-style simulation approach but is distinguished from most others in that we emphasized the influence of how the assessment step of fishery management was conducted. During simulations, data is generated on observed yield, harvest at age, and fishing effort and stock assessments are done periodically (annually or less frequently). Each year target yield levels are set based on the most recent assessment, and actual yield deviates from this due to implementation error. Our research objective was to compare fishery management and assessment estimation performances based on the current annual assessment (with a 1-year lag) with alternative timings of the assessments.

An additional consideration for the assessments is recent evidence that has shown that many lake whitefish populations in the northern parts of lakes Huron and Michigan are intermixing considerably during non-spawning periods, and this may be a change from past spatial distributions (Ebener et al. 2010). Nevertheless, lake whitefish stocks continue to be largely treated as discrete, independent units for management purposes, whereas our results (Chapter 1) show that using a pooled procedure can sometimes be superior in the face of mixing, at least with an annual assessment and a 1 year lag. This may reflect a specific situation where time spent improving the current assessment model in response to intermixing information, such as by lumping assessment areas when confronted with information that there is substantial movement among areas, may deserve higher priority than maintaining an annual assessment frequency. Given these considerations we have incorporated spatial structure in our simulations and applied both the pooled (all areas combined) and separate (by area) stock assessment procedures for each frequency/lag scenario we considered. Thus, our study can not only provide quantitative evaluation of proposed alternative assessment frequencies for management decision making of intermixing lake whitefish population as well as other mixing species, but also weight the relative importance between the assessment frequency and the choice of assessment models.

Methods

Overall simulation framework

The simulation framework used to evaluate the design of assessment process was based on management strategy evaluation (MSE) methods (Kell et al. 2005, Punt 2008) (Figure 2.1). This framework modeled the “true” system and “perceived” system (data collection, stock assessment and harvest control rule application). The “true” system is represented as “real” stock and fishery dynamics, from which the simulated data were sampled. These data were then used in an assessment procedure that establishes the status quo for resources. During each assessment year, the two assessment methods (i.e., “separate” and “pooled”) were fitted separately and the current treaty-water harvest control rule was applied to each specific assessment result. As for multiannual assessments, there were three way to calculate harvest limits for rotation years, as described later. Each total allowable catch (TAC) was then fed back into the corresponding real system, by its influence on the harvest in the next-year. Performance statistics based upon the stock and fishery dynamics model were eventually used to evaluate the robustness of each assessment frequency and assessment model. The flexibility of this framework allowed us to incorporate a series of uncertainties, including process, sampling, estimation, and model error, as described below.

Four simulated populations

Four lake whitefish populations were assumed to have differing levels of "productivity". Differences in productivity among the four spawning populations were incorporated via adjustment of the recruitment function coefficients (Table 1). We used a Ricker recruitment model because of strong evidence for over-compensation in lake whitefish populations (Healey 1978; Henderson et al. 1983; Kratzer 2006). Given information on life history (maturity and weight at age schedule) the Ricker function can be parameterized in terms of steepness and the unfished spawning stock size. We equated "productivity" with steepness (NOAA Pacific Islands Fisheries Science Center, 2011), and chose four steepnesses for our simulated populations that were plausible for lake whitefish and produced meaningful differences in equilibrium yield. We set unfished equilibrium stock sizes to be equal so that differences between the populations were due only to our assumed productivity differences. The steepness parameterization was then converted to the standard Ricker parameterization. Calculations of spawning stock sizes to define the productivity of the populations in the simulations assumed unit stocks (no movement) and followed methods outlined by Quinn and Deriso (chapter 6 page 239, 1999). The values of life-history parameters were based on the most recent 1836 Treaty- Ceded water assessment conducted by the Modeling Subcommittee (MSC) of the Technical Fisheries Committee (TFC) and our claim of plausible steepnesses is based on review of the annual assessment models of lake whitefish harvest recommendations from 2001 to 2012 [ftp://glpd.fw.msu.edu/MSCFTP/Assessment_models/]. The unfished spawning biomass was also based on assessment results, but only sets the scale of results and otherwise does not influence the outcomes of our work.

Each of the four simulated lake whitefish spawning populations was assigned one of the four levels of productivity so that there was a LP, MLP, MHP and HP population for each simulation. The dynamics of four hypothetical lake whitefish spawning populations had varying degrees of intermixing during the fishing season, but were spatially segregated during the spawning season (Figure 2.2). Intermixing was assumed to occur immediately after spawning, with varying fractions of each population either staying within their natal areas or moving to areas where the other stocks spawn. Fish residing in each area (a “stock”) were exploited during the rest of the year and surviving fish then moved back to their natal area to spawn.

The “true” system

The basic structure of our model for the "true" system is based on the approach developed by Molton et al. (2012). We used an age- structured forward-projection model, consisting of four hypothetical populations with a simulation length of 100 years. Only the final 25 years were summarized to evaluate performance. Our intent here was to evaluate the long-term performance of the alternative approaches with different timetables and frequency of assessment, independent of the starting conditions. Recruits were added as the youngest age each year based on the current stock size for the population and a stock recruitment function. During the fishing season fish from each population mixed with fish from other areas in four fishing grounds, which each surrounded the four spawning areas (Figure 2.2), but returned to the spawning area for an instantaneous spawning period, based on the known natal philopatry of the species. During the fishing season fish died due to natural mortality and due to fishing mortality, and the latter was set based on perceived stock size based on a stock assessment that was done periodically (annually or less often) as part of the simulations.

Fish from a spawning population either remain in their natal area during the non-spawning season or move to one of the other three areas (Figure 2.2). Movement rate, θ_{ij} ($i \neq j$), is the proportion of fish belonging to spawning population i (i.e., they spawned in area i) that move to and live in area j during the non-spawning season. We refer to θ_{ii} as the stay rate, which is the proportion of fish belonging to spawning population i that stay in area i during the non-spawning season. The movement rates were calculated based on the stay rates, which was set based on results from ongoing and published studies (Ebener et al.2010, Stott et al. 2010, Stott et al. 2012). We assumed that a higher stay rate indicated a high quality habit, and that a high proportion of whitefish would tend to move to that area. The movement rate θ_{ij} ($i \neq j$) is:

$$\theta_{\mathrm{ij}} = (1 - \theta_{ii}) \frac{\theta_{jj}}{\sum_{k \neq i} \theta_{kk}} \qquad (1)$$

Where (1- θ_{ii}) is the total proportion of fish from population i that live in other areas during the non-spawning season, and $\frac{\theta_{jj}}{\sum_{k \neq i} \theta_{kk}}$ is the proportion of those fish residing in each destination area *j*. This approach of specifying movement rates diverges from the approach of Molton et al. (2012), who assumed that fish that did not stay in their natal area moved to other areas in equal proportions.

We projected abundance-at-age after recruitment using an exponential mortality model:

$$N_{i,y+1,a+1} = N_{i,y,a} \sum_j \theta_{ij} \exp(-M - F_{j,y,a}) \qquad (2)$$

where $N_{i,y,a}$ is equal to the number of fish from spawning population *i* of age *a* in year *y*; *M* is the natural mortality rate; and $F_{j,y,a}$ is the year- and age-specific instantaneous fishing mor**t**ality rate of fish occurring in area *j* during harvest season. This instantaneous fishing mor**t**ality rate was calculated as:

$$F_{j,y,a} = s_a f_{j,y} \qquad (3)$$

where s_α is the age specific selectivity (equal for all four stocks), and $f_{j,y}$ is the fully selected fishing mortality occurring in area *j* in year *y*. Thus the fishing mortality rate experienced by a population was a weighted sum of the fishing rates occurring in the different areas, with weights set by the θ. The fully selected fishing mortality rate for each area was calculated using a Newton-Raphson algorithm so that the true yield for each area was produced using the Baranov's catch equation (Equation T.2.2.7) and assumed harvest weight at age). The true yield was set equal to the Total Allowable Catch (TAC) (i.e., target yield) multiplied by a lognormal implementation error (Equation T.2.2.8). The TAC was determined via the stock assessment procedure described in the perceived system section.

Constant values of natural mortality, female proportion, and catchability were used. Selectivity-, length-, weight-at-age, and annual spawning stock biomass (SSB) were determined by deterministic functions. Selectivity was set as 0 for age-2 and younger whitefish because they are rarely harvested in treaty waters. Selectivity for other age classes was simulated by a gamma probability density function (Equation T.2.2.6) scaled by setting the fully selected age class (age 10) equal to 1.0; length-at-age was assumed to follow a Von Bertalanffy growth model (Equation T.2.2.3); weight-at-age was determined by a power function of length (Equation T.2.2.4); and the SSB (Equation T.2.2.2) was calculated as a function of abundance-at-age, maturity-at-age (Equation T.2.2.5), and weight-at-age. The four populations shared the same selectivity-, length-, and weight-at-age patterns.

The initial state of for each simulation in year 1was based on equilibrium recruitment and target mortality rates and calculated based on deterministic models with no mixing. The actual harvest policy and management process requires a twenty year time-series of data, which was not available during the initial 20 year period of each simulation. Within this "burn-in" period, population abundance at age was assumed to be known exactly before applying the harvest control rule and thus the assessment model step was skipped during the burn-in period of simulations. The intent here is merely to move the system closer to steady-state conditions during this period. Stochastic recruitment errors were still included during this period.

The "perceived" system

In the perceived system (Figure 2.2), the management procedure for the treaty water whitefish was duplicated, including data collection, stock assessment, and application of the harvest control rule. When generating the data we assumed that total catch was observed with error, and that observed age compositions also differed from actual age compositions due to sampling error. Observed proportions-at-age in the simulated data arose from a multinomial distribution with probabilities equal to the true age proportions of the harvest sample and an effective sample size of 200 for "separate" and "meta" approaches or of 800 for the "pooled" method. Observed fishing effort was calculated as:

$$\mathrm{E_{j,y}} = \frac{\mathrm{F_{j,y}}}{\mathrm{q}} \exp(\mu_{j,y} - 0.5\sigma^2{}_F) \quad (4)$$

$$\mu_{j,y} \sim N(0, \sigma^2{}_F)$$

$$\sigma^2{}_F = 4\,\sigma^2{}_c$$

where $F_{j,y}$ is the fully-selected fishing mortality rate for area *j* and year *y*; q is the catchability coefficient of $1.50\times10e^{-6}$; and $\mu_{j,y}$ is the an normally distributed random variable with expectation of 0 and variance of $\sigma^2{}_F$ (Equation T.1.2.10), which was assumed to equal to 0.04 (four times of $\sigma^2{}_C$).

The above data was collected annually and used as the input for stock assessments. The stock assessments were assumed to have knowledge of the true natural mortality rate and life-history parameters.

In the stock assessment process, two different assessment models were compared: separate population, and pooled population assessment models. Both models were variants of the SCAA model, which involves fitting a population dynamics model to observed data to estimate the parameters used to summarize stock status and determine TAC for each simulated population of the assessment year.

The first approach, the “separate population assessment”, assumed no movement among areas. We applied the assessment model to each stock. An age-specific fishing mortality was predicted by the same equations used in the population dynamics model. This is the most commonly used approach for assessing lake whitefish in treaty waters.

The second approach, the “pooled population assessment”, treated all lake whitefish across the areas being assessed as part of one well mixed population. This led to an exponential model for the pooled population, rather than for each stock (Equation T.2.2.1).

For the two assessment models, recruitment (area specific or pooled), the initial abundance-at-age for the first year, selectivity-at-age, and fishing mortality were estimated as free parameters during model fitting. Best fit parameters were estimated via iterative methods so as to minimize the negative penalized log-likelihood (i.e., the objective function). We assumed lognormal distributions of errors for annual fishery catch, a lognormal prior component associated with the fishing mortality-effort relationship, and the age compositions of the fishery were assumed to follow multinomial distributions. The objective function was the sum of above three negative log-likelihood or log prior components (Equations T.2.2.9., T.2.2.10, T.2.2.11). Iterations proceeded until the maximum absolute value of the gradient (derivatives of objective function with respect to parameters) was below a specified criterion (0.001), although sometimes iterations stopped before reaching the criterion either because no further progress was being made in reducing the objective function or a maximum number of iterations (1000) were completed. Fits that ended without reaching the gradient criterion were classified as failing convergence. A second test of whether the solution after iterations was a minimum (i.e., true maximum for the penalized likelihood) was whether the Hessian was negative definite. If this was not the case we termed this a Hessian problem. A record was kept for each assessment on whether there was convergence failure or a Hessian problem. The negative log likelihood component for the age composition of the fishery harvest was weighted by effective sample size (800 for the pooled method and 200 for the separate and the "meta" methods). The 20 years of data prior to any given assessment year were included in the assessment model.

We mimicked the actual timing of assessments and setting of harvest guidelines based on them in lake whitefish fisheries and three alternative frequencies. We refer to the current assessment timetable and frequency as "L1", in which the assessments have been updated annually, with a one-year lag of data availability. More specifically, these assessments are done in a given year, based on data through the previous year, and are used to establish harvest targets for the next year.

The first alternative called "L0" was also an annual assessment, but without a 1-year lag. So data from year y are available in time to conduct an assessment and use the assessment results to manage the fishery during year y+1. The other two multiannual alternatives did assessments every 3 years and every 5 years, with a 1-year lag. During the simulations, harvest targets (which we will refer to as TACs) were established for each year, even though assessments may not have been, and in the case multiannual assessments these are based on projections from the most recent assessment.

The details of how TACs are set for multiple year assessments can become complex. As a starting point we describe how the TAC is set for the L1 and L0 scenarios, and then turn to the more complex rotational scenarios. For L1, the stock assessment produces abundance-at-age for the start of the year when the assessment is done (the lag year). Projections through the assessment (lag) year were done based on an exponential population model, in which total mortality rate was assumed to be the mean of the last three years' values and the recruits were assumed to be the mean of the last ten years' values. During the year for which the TAC was set the projections assumed the same level of recruitment but fishing mortality was adjusted so the target mortality rate was achieved (this was also done for L0 where projection through a lag year was not required). The current harvest control rule for lake whitefish in treaty waters, which equates to a constant fishing mortality rate policy, were used in the simulation. The control rule sets the maximum total annual mortality rate experienced by any age of fish at 65%. We used the same methodology to determine the TAC as the one applied by the MSC to determine the target maximum yield. This TAC was calculated from assessment-based estimates of abundance-at-age at the start of the year the TAC applies to and target fishing mortality-at-age using the Baranov catch equation. The age-specific fishing mortality rates were based on the estimated selectivity-at-age from assessment multiplied by the target fishing mortality rates, which was the target instantaneous total mortality rate minus the natural mortality rate as assumed in the assessment model. For the "separate" assessment methods, TAC for each area was calculated separately because the assessment results were area-specific for those methods. For the pooled population assessment, only a pooled TAC could be calculated and was allocated according to an annually varying allocation rule, which was based on the annual area-specific CPE observed from the "true" system. The higher the CPE, the more TAC was allocated to each area. To reduce annual variation of yield, we used the average CPE of the last three years.

For three and five year assessment frequencies, there are actually many ways to set the TACs in the years between assessments, and we evaluated three different ways in our simulations. First a “Constant TAC” or “CT” approach was to apply the same total allowable catch (TAC) determined based on the last full assessment projected through the "lag" year. Second, a “Target F” or “TF” approach was based on multiyear projections after the 1-year data lag, and assumed fish populations experienced the target fishing mortality during subsequent years before the next assessment results were available for use in management. Third, an “Add yield information” or “AY” approach was to project annually in the years between assessments to set the next year's TAC, taking into account each additional year of yield information. In this case, the estimated fully selected fishing mortality was calculated using a Newton-Raphson algorithm so that the projection predicted an amount of yield equal to the observed yield for each area. For a given level of fully selected fishing mortality, the predicted yield was generated from Baranov’s catch equation (Equation T.2.2.7) and assumed harvest weight at age). Then that estimated fully selected fishing mortality could be used to project abundance to the start of the next year and thus the TAC for that year could then be calculated in the same way as for annual assessments.

For the CT and TF approaches for setting TACs in the years between assessments, the lag year occurred immediately prior to the first year the TAC was set for, and TACs could be set at one time for the entire period until new assessment results would be available. Projections through the lag year were based on an exponential population model, again using a total mortality rate of the mean of the last three years of values from the assessment and recruitment were assumed to be the mean of the last ten years of values from the assessment. For the CT method the TAC was calculated by projecting an additional year assuming the same level of recruitment but with fishing mortality adjusted so the target mortality rate was achieved (assuming the assessment point estimates were correct). This same TAC was then used in subsequent years until the next assessment results were available. For the TF method, projections were done over the entire period that TACs were set. Over the entire period the same level of recruitment was used as for the L1 and CT projections, but the target fishing mortality rate assumed to occur each year after the lag year. Thus, in contrast with the CT method, the TF method produced different TACs for each year.

For the AY method, the TAC was set in an identical manner to the way the TAC was set for the CT and TF methods for the first year that TACs were needed after the most recent assessment. However, to set the TAC for the second year the projection for the initial lag was first replaced with a projection that matched the observed yield for that year as described above, and then from that starting point the lag procedure and the projection during the second TAC year were done in the same way as when the TAC in the first year was set. For each subsequent year a TAC was needed this same updating procedure was repeated, with the previous lag year replaced with a projection based on a fishing mortality rate that now matched the observed yield.

For each combination of assessment frequency and harvest limit setting approach for the rotation years, we denote it with a name that captures information on both aspects of the approach. Say when we used the "Constant TAC" method to set the harvest limit between assessments of a 3-year assessment frequency scenario, we referred it as "CT3". In all we compared the eight scenarios denoted: "L0", "L1", "CT3", "CT5", "TF3", "TF5", "AY3", and "AY5" (Table 3) .

Experimental design

For four hypothetical populations with differing productivity (Table 1), we evaluated how assessment methods performed with respect to different frequencies of assessment as well as lag choices, and alternative ways of setting harvest limits for the rotation years (Table 3). Within each assessment scenario, five mixing scenarios were examined as listed in table 4: Scenarios 1 to 3 (“SR=0.9”, “SR=0.5”, “SR=0.25”) represented the cases that all areas shared the same stay rate ordered from high to low (so the case of less mixing is first). We referred scenarios 1 to 3 as four “same mixing” scenarios. Scenario 4 (“po-cor”) assumed that productivity and stay rate for each area were positively correlated (fish from higher productivity populations tended to stay in natal areas). Scenario 5 (“ne-cor”) assumed a negative correlation between productivity and stay rate for each area. Under each mixing scenarios, the MSE model was run at each combination of assessment models (separate population model (“separate”) or pooled model with TAC allocated by CPE (“pooled”) and eight assessment timetable and frequency choices (“L0”, “L1”, “CT3”, “CT5”, “TF3”, “TF5”, “AY3”, and “AY5”). Each of the total 16 combinations of assessment model and timing are referred to below as “assessment process designs” because fishery managers can affect those two characters during assessment.

Performance statistics

For each “assessment process design” under five mixing scenarios, a 100-year simulation was performed 1000 times by using AD Model Builder (Fournier et al., 2012). Performance statistics were generated from the “true” system, which was used to describe the real status of stock and fishery. The statistics allowed us to compare the performance of alternative assessment and management methods under different mixing scenarios with respect to the management objectives (i.e., long-term sustainability, high and stable yield, and the trade-off between them) and the accuracy of SSB estimation. Since most performance statistics appeared to approach a long-term mean by year 75, all performance statistics were calculated based on the last 25 years of the simulations. Under different mixing scenarios with different assessment method/frequency/lag, the performance statistics were:

1. Average yield over the last 25 years for each area.

2. Average SSB over the last 25 years for each population.

3. Proportion of years spawning stock biomass (SSB) was less than 20% of the unfished SSB level.

4. Inter-annual variation of yield over the last 25 years for each area.

5. Total average yield over the last 25 years for four populations.

Results

Comparison of annual assessment quotas with and without 1-year lag

Overall, compared with L1, there was no substantial or obvious advantage of “L0”, when the one year lag was removed (Figure 2.3). There were some slight differences with respect to SSB (Figure 2.3a) and yield (Figure 2.3b). For example, for the LP population, when stay rates were high for all populations (SR=0.9), for the separate method SSB was slightly higher for L0 than for L1 (first row of Figure 2.3a). For the same population and approach, when stay rate was positively correlated with productivity of populations, yield was slightly higher for L0 than L1 (fourth row in Figure 2.3b). Patterns for probability of SSB being less than 20% tended to be an inverse mirror of those for SSB, albeit more variable (Figure 2.3c). Generally, the inter-annual variation (IAV) of yield for L1 is slightly higher than L0 with a separate assessment model, especially when all populations shared the same mixing rate (L0 versus L1, Figure 2.3b). That difference in IAV decreased with the mixing rates increased. As for the pooled assessment method, there was no clear difference between the IAVs of yield with and without a lag.

Comparison of annual and multiannual assessments

Here we present only results for the stay rate of 0.5, which reasonably illustrates the impact of assessment frequency across the full experimental design (see Appendix).

Comparison of three rules for setting TACs for the years between assessments

For the same assessment frequency (annual, 3 year or 5 year in Figure 4a and 4b), three rules (CT, TF, and AY) performed differently with separate assessment method. TF was the most conservative rule among the three with respect to the highest SSB and the lowest probability of SSB being less than 20% (Figure 2.4a and Figure 2.5a). The AY rule had relatively better fishery performance in terms of higher yield and lower IAV of yield across all areas (Figure 2.4b and Figure 2.5b), but with the cost of increasing risk of the depletion of the low productive (LP) population (Figure 2.5a). The CT rule showed no obvious advantage compared with the others with respect to SSB and yield, and could sometimes produce the highest IAV of yield across all areas. As for the pooled assessment method, there was no clear difference between the performances of the three harvest setting rules.

Comparison among assessment frequencies

The pattern of differences among an assessment frequency of annual, 3 years and 5 years was quite similar for the different methods of setting TACs between assessments, although the illustrated differences for the Constant TAC tended to be larger than for the Target F and Add Yield approaches (Figure 2.4a, Figure 2.5a). More specifically, for CT rule, increasing assessment frequency led to some modest increases in SSB with the separate assessment model, while for other rules, there was no obvious benefit for SSB when increased assessment frequency from annual to 5 year. For both assessment models with all three rules for setting TACs during rotation years, higher assessment frequency could slightly improve the fishery performance (higher yield and lower IAV of yield), but the improvements were much smaller for the pooled model than the separate model (Figure 2.4a and Figure 2.4b).

Among the three rules for setting TACs during rotation years with the separate assessment method, the TF rule was always the most conservative rule and performed about the same with either annual or multiannual assessment frequencies. For example, for the 5 year assessment with TF rule, the median value of the proportion of years spawning stock biomass (SSB) being less than $B_{20\%}$ was very similar compared with annual assessment(Figure 2.5a).

By increasing assessment frequency, with the separate model, the inter-annual changes in area-specific yield within a set of simulations was decreased (Figure 2.5b), suggesting that a constant exploitation rate was more closely adhered to with more frequent assessment, and both median yield and IAV increased. For the pooled assessment model when increasing assessment frequency to annual from 5 years, only the median yield of each area increased very slightly, while the range of variation in yield were similar for the two frequencies. The IAV of yield increased with the TF and AY rules and decreased with the CT rule. For both assessment methods with the CT and AY rules, increasing assessment frequency led to a lower risk for LP populations of falling below $B_{20\%}$ (Figure 2.5a).

Comparison of the relative magnitude of effects due to assessment frequency and assessment model under different mixing scenarios

Assessment frequency and assessment model (separate versus pooled) both influenced the performance of the assessments. One of our goals was to investigate whether the impacts of assessment frequency were large enough to warrant annual assessments at the potential expense of efforts to choose the most appropriate assessment model. We found that in most mixing scenarios, the difference between assessment models for a given frequency of doing assessments (or approaches for setting TACs in the years between assessments) were larger than the differences due to frequency or TAC setting approach for a given model (Table 2.2 and Table 2.3).

We included the current annual assessment (L1) and 5 year assessment with TACs setting for rotation years based on TF rule (TF5) to represent the effect of assessment frequency, and incorporated two assessment models (separate and pooled) across all mixing scenarios to explore the effect due to assessment model. We compared which effect had a larger influence by looking at the SSB of the LP population and the total yield aggregated over areas. We focused on SSB for the LP population because this population had the highest risk of population depletion in all cases (Figure 2.3c and Figure 2.5a).

The relative change of the median of the SSB of LP population (Table 2.5) due to the decrease of assessment frequency were almost all negative across all mixing scenarios, and varied from -0.163 to 0.034 across all mixing scenarios with both assessment models. The negative value illustrates that decreases of assessment frequency from L1 to TF5 led to the slight depletion of LP populations. When switching the assessment model from separate to pooled, the relative changes across all mixing scenarios ranged from -0.293 to 0.514. The pooled method led to a positive relative change in the SSB of the LP population in some scenarios, when stay rates for populations were high (SR=0.9) or positively correlated with productivity (po-cor), while in the other scenarios, the relative changes were negative. For each mixing scenario, the absolute relative changes of the SSB of LP populations caused by assessment models were much larger than those caused by assessment frequency (Table 2.5). We interpret this to mean that the overall effect of assessment method was consistently larger than the influence of assessment frequency.

The relative changes of the median of total yield across all areas due to the decrease of assessment frequency (Table 2.6) were at the same scale compared with the changes caused by different assessment models. All those absolute relative changes were below 0.08. Decreasing assessment frequency from annual to 5 year could slightly decrease the median of total yield across all mixing scenarios (with negative relative change), while pooled assessment methods could provide a slightly higher total yield across almost all mixing (with positive relative change) (Table 2.6).

So the overall effects due to the assessment model were larger than those due to assessment frequency; because although both factors (assessment model and frequency) have similar magnitude of effects on total yield, whereas the choice of assessment model influenced the SSB of the LP population more than assessment frequency did. For example, in the first two rows of Table 6 (SR=0.9), the pooled method performed markedly better than separate method, no matter which assessment frequency was applied, with higher SSB of the LP populations, and higher yield across all areas. In contrast, only slight differences can be detected within a method when comparing the results among varying assessment frequencies and approaches to setting TACs for rotation years.

Discussion

Our goal was to evaluate how various factors in the design of the assessment process affect intermixing lake whitefish populations and fishery outcomes under the current approach of attempting to limit total mortality to a constant 65% for the fully selected ages. Those factors included whether to use area specific or a pooled assessment model, whether there would be a one year or no lag between the end of the last year for which data were included and when the assessment results were available for management, assessment frequency (every year, three years or five years), and the approach to setting TACs in rotation years for multi-annual assessment. In our application we simulated four lake whitefish populations based on biological data, stock assessment results, and management practices in 1836 Treaty-Ceded waters of Lakes Michigan, Huron and Superior. The assessment of lake whitefish in that region has been largely based on a "separate" statistical catch at age assessment (SCAA) method since 1998. The pooled method aggregates data over areas known to contain distinct spawning grounds, and treats the populations within the larger area like it was a single population, also using an SCAA. After increased mixing between management units was observed, the Modeling Subcommittee (MSC) of the Technical Fisheries Committee (TFC) combined four nominal populations in North Lake Huron into one single assessment unit beginning in 2011 (Caroffino et al. 2011). They thus implemented an assessment model similar to our pooled method, although in the real system fish can still move into and from the pooled region. As of 2013 these assessments are updated annually with 1-year lag between the year data are available and when assessment results are available for use in management. Based on recommendations from the MSC the TFC had implemented a rotation plan for three management units of lake trout in 1836 treaty ceded water since 2011, by switching from annual assessments to assessments every three years in those units (Caroffino et al. 2009b). We are not aware of published peer-reviewed studies where the performance of different assessment frequencies has been evaluated. This topic is clearly of interest to fishery management, and the topic is discussed in several reports from workshops and in improvement plans for assessment models (Mace et al. 2001, Woldt et al. 2005, ICES 2012). One such workshop report provides results from a management strategy evaluation approach to evaluating the risk engendered by doing a multiannual assessment instead of annual assessment (ICES 2012). That study found that when starting conditions for the populations suggested a downward trend (weak year classes in age-structure), there could be significant depletion for a 5 year frequency that was avoided with an annual assessment. This is not totally unexpected because they fixed the TACs rather than projecting forward when setting harvest for rotation years, so the weak year classes became fully selected during rotation years.

We know of no other published studies than ours that have evaluated what the influence of a lag between when data are collected and when an assessment is completed and the results used for management. Many management agencies make substantial efforts so that data from the previous year are processed and used in an assessment completed early in the year for which a harvest recommendation based on that assessment is applied. For example this approach has been applied for walleye in Lake Erie and lake trout 1836 treaty waters (Thomas et al. 2005, Caroffino et al.2009b). Our results suggest that such a rush to complete an assessment is unnecessary, at least for fish that with similar or lower mortality rates and recruitment variability as lake whitefish. In our study the influence of the lag was generally small and sometimes undetectable.

When we compared three different rules of setting harvest limits for rotation years, the Constant TAC (CT) rule performed the worst in terms of all performance metrics. Forward projection based on Target F (TF) was the most conservative rule, with respect to greatest SSB for each population and lowest risk of SSB falling below $B_{20\%}$. Calculating TACs during the rotation years based on updating TACs to match observed yield from previous lag years (AY) had the best fishery performance with highest yield across all areas and lowest annual variation. While the effect is not large, it does seem like accounting for known yields can be useful when setting TACs over multiple years when a full assessment is not done each year.

When comparing annual and multi-annual assessments, the performance of both "separate" and "pooled" assessment was best for the annual assessment and worst for the longest period between assessments, for all performance metrics except inter-annual variation of yield. Higher assessment frequency always resulted in increasing IAV of yield. The magnitude of these differences varied, and depended on the harvest limit setting rules for the rotation years. Across all mixing scenarios, the difference in results between 3 and 5 year assessment frequency was largest for the CT rule. For this rule SSB was larger and yield was higher across all populations and areas for the 3 year frequency than for the 5 year frequency. For the AY rule, the 3 year frequency had only slightly higher yield and no clear benefit in terms of higher SSB than the 5 year frequency. For the TF rule, increasing assessment frequency from 5 to 3 years provided no benefit in terms of yield or SSB. This qualitative effect is not too surprising and is consistent with ICES (2012), which used CT rules for setting TAC during rotation years and found that changing from an annual assessment to a 5 year assessment could cause depletion of populations. However, in contrast with ICES (2012), we found the effect of longer periods between assessments to be quite modest, especially with the pooled assessment method.

In general, the differences in performance metrics due to assessment models (separate versus pooled) were larger than the differences due to assessment frequency and approach to setting TACs during rotational periods. This finding should be useful to fishery managers as they consider where the right place is to put their time and resources. While our results are based on lake whitefish, this species has is not dissimilar to many harvested fishes, and may in fact be more prone to rapid changes in abundance than many. Consequently, we suspect that calls for annual assessments (e.g., Mace et al, 2001) may often be misplaced, and that it may make more sense to work on developing a correct assessment structure.   Another concern based on our result is that current 65% total mortality control rule may be not conservative enough for the low productivity populations. We discuss this in detail in Chapter 1.

Like other simulation studies (Irwin et al. 2008, Deroba and Bence 2012), we made a number of simplifying assumptions and choices, such as mixing pattern, different levels of mixing rate and productivity of each population and which levels of productivity were most representative. But we believe that our major qualitative conclusions are robust to those assumption and simplifications. We emphasize here that our intent was not to make specific tactical advice for a specific population, but rather to provide results that could provide general guidance for managing the assessment process for populations somewhat similar to lake whitefish. For example it might be reasonable to elect to move from annual to three year assessments for a species with a similar life history, and use the resources freed up by this to evaluate evidence for movement patterns (or other assumptions of the assessment) with a view toward changing the assessment model based on the results. In our simulations the only temporally varying process other than fishing was recruitment, and recruitment variation was assumed to be distributed about a stationary stock recruitment relationship with uncorrelated errors. When recruitment process are in flat or on other critical rates, such as natural mortality are changing, these factors need to be considered when deciding on assessment frequency.

The basic premise of this study is that annual TACs would be set on the basis of a fitted stock assessment model and that when the model was not fit every year TACs in rotational years would be based on model projections since the last stock assessment. Alternatively, one could view the periodic assessments as providing a calibration between some empiric quantity (such as catch per effort) and an appropriate harvest level (Cox et al. 2008, Holland et al. 2010). One version of this simply might treat periodic assessments as a way to update catchability estimates to translate catch per effort to abundance. Alternatively, one could revise our view of assessments to be primarily about gaining an understanding about how population dynamics work, for use in evaluating alternative strategies (McDonald et al. 1997, Punt et al. 2008). In our study the only use of data we considered for the period between assessments was in making projections consistent with observed yield. Survey or fishery catch per effort might be more informative and potentially could extend the period between assessments.

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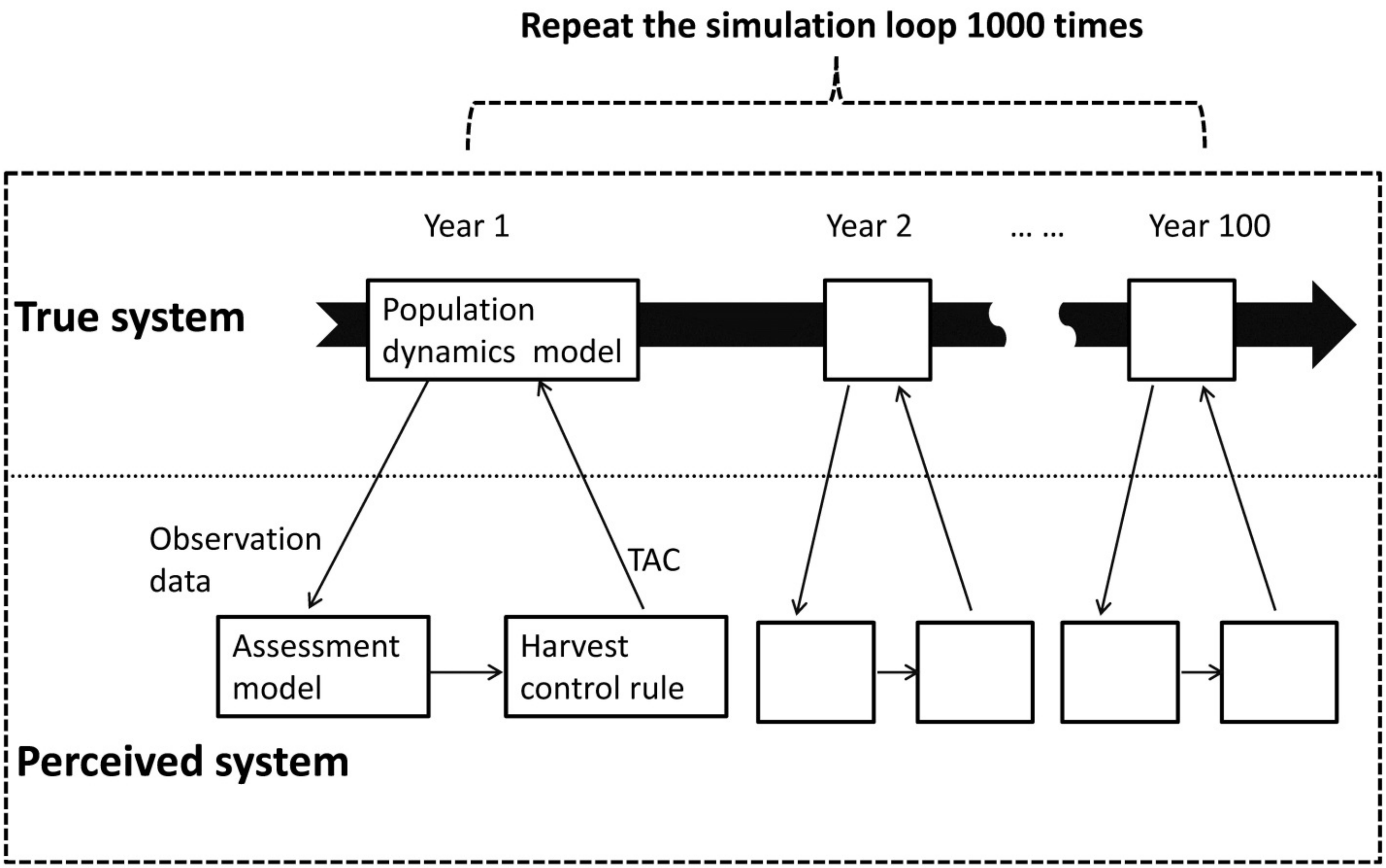


Figure 2.1: Structure of a simulation framework for evaluating stock assessment models' performance.

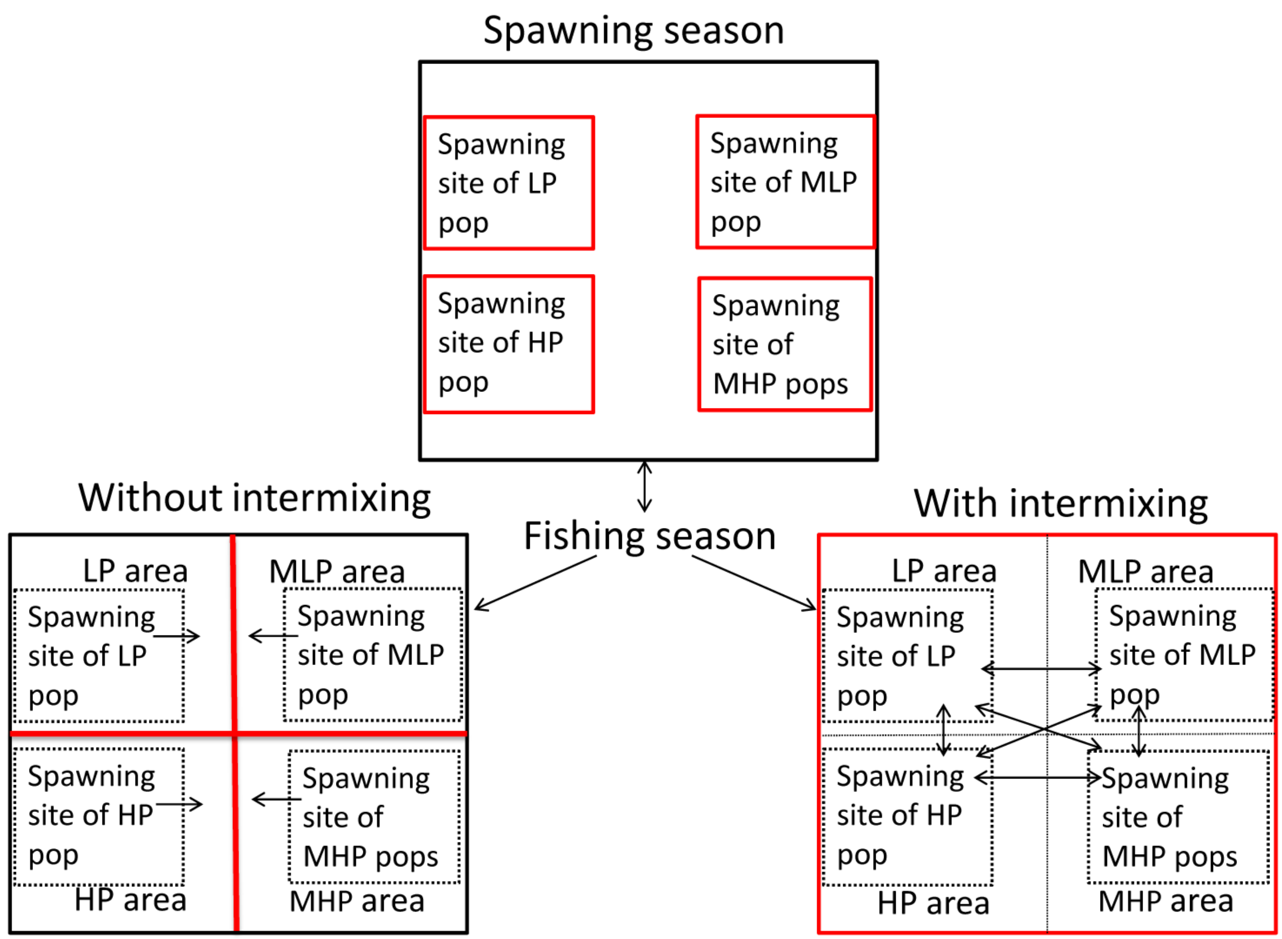


Figure 2.2: A conceptual diagram of stock intermixing for four hypothetical lake whitefish populations that are spatially segregated during spawning, but subsequently intermix during the non-spawning period when exploitation takes place. For interpretation of the references to color in this and all other figures, the reader is referred to the electronic version of this thesis.

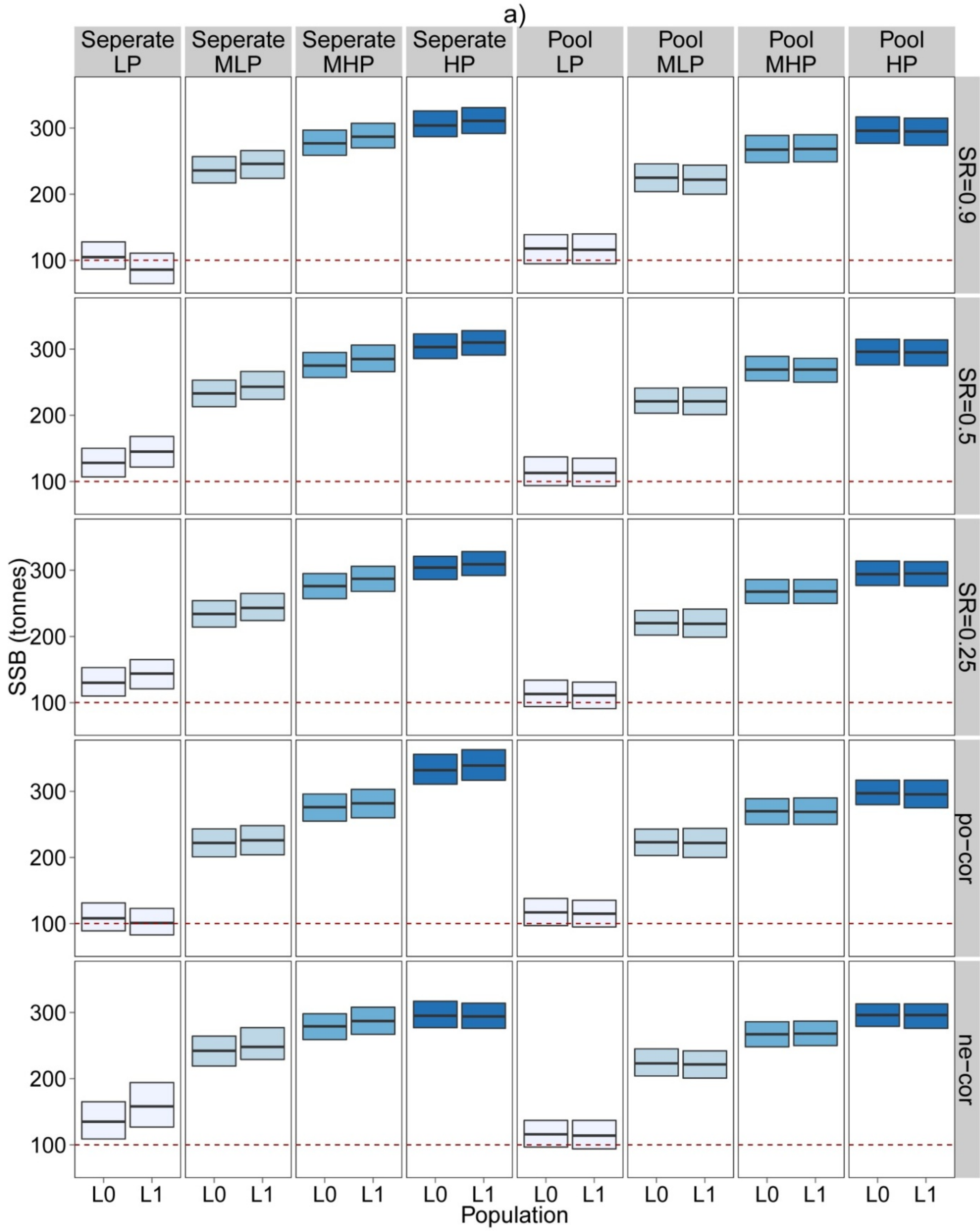

a)
Seperate LP
Seperate MLP
Seperate MHP
Seperate HP
Pool LP
Pool MLP
Pool MHP
Pool HP
SR=0.9
SR=0.5
SR=0.25
po−cor
ne−cor
SSB (tonnes)
100
200
300
L0
L1
Population

Figure 2.3

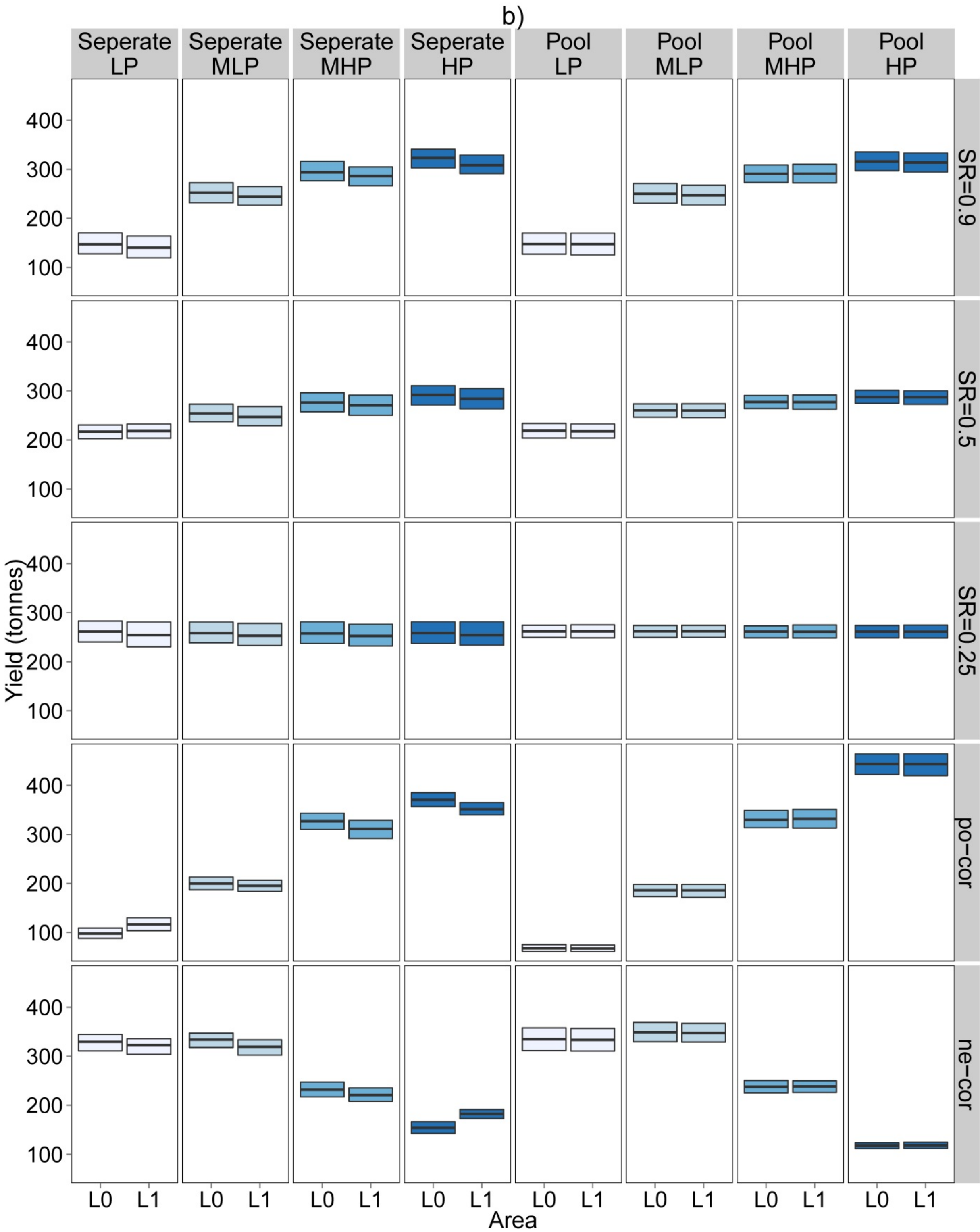


Figure 2.3 (cont’d)

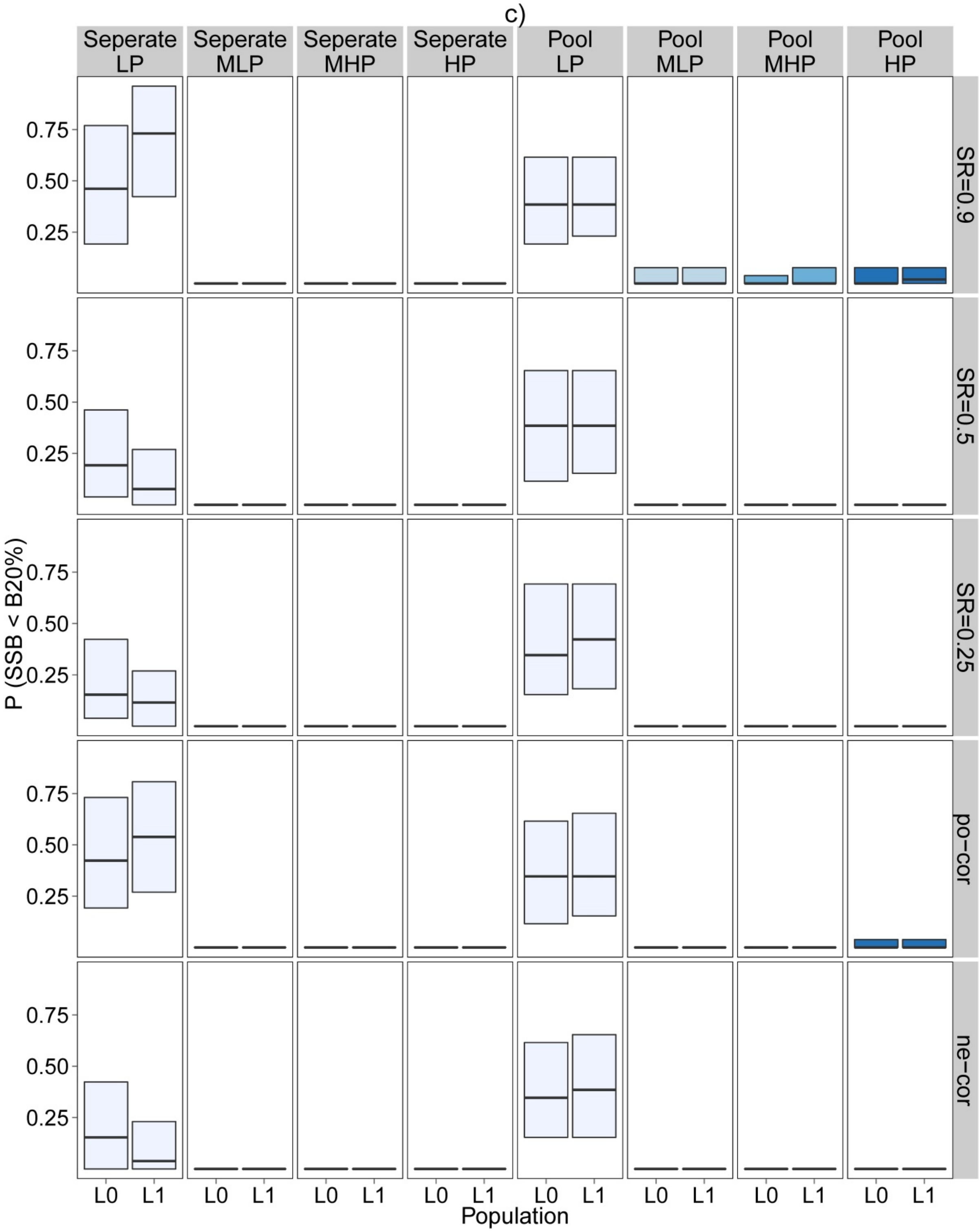


Figure 2.3 (cont’d)

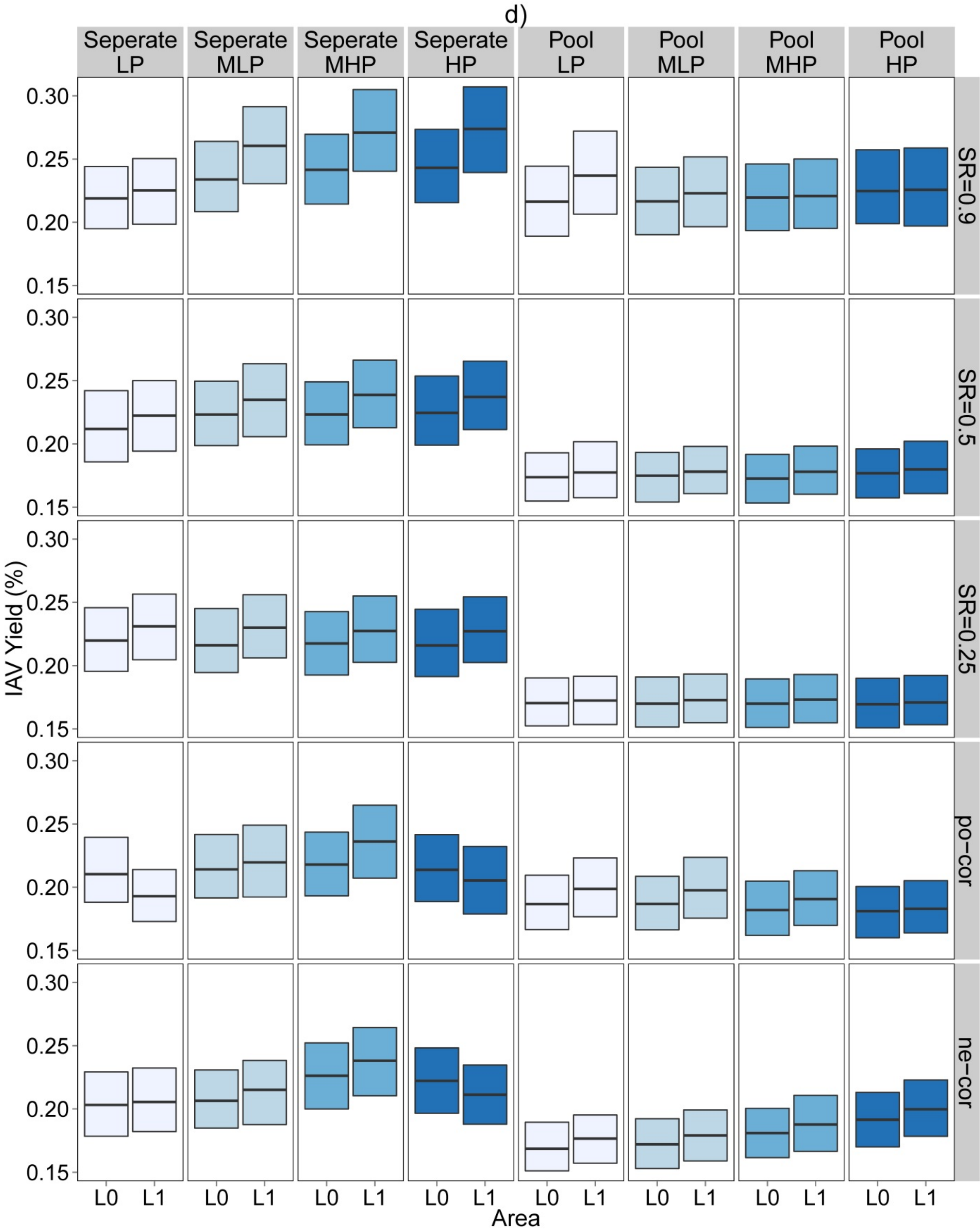
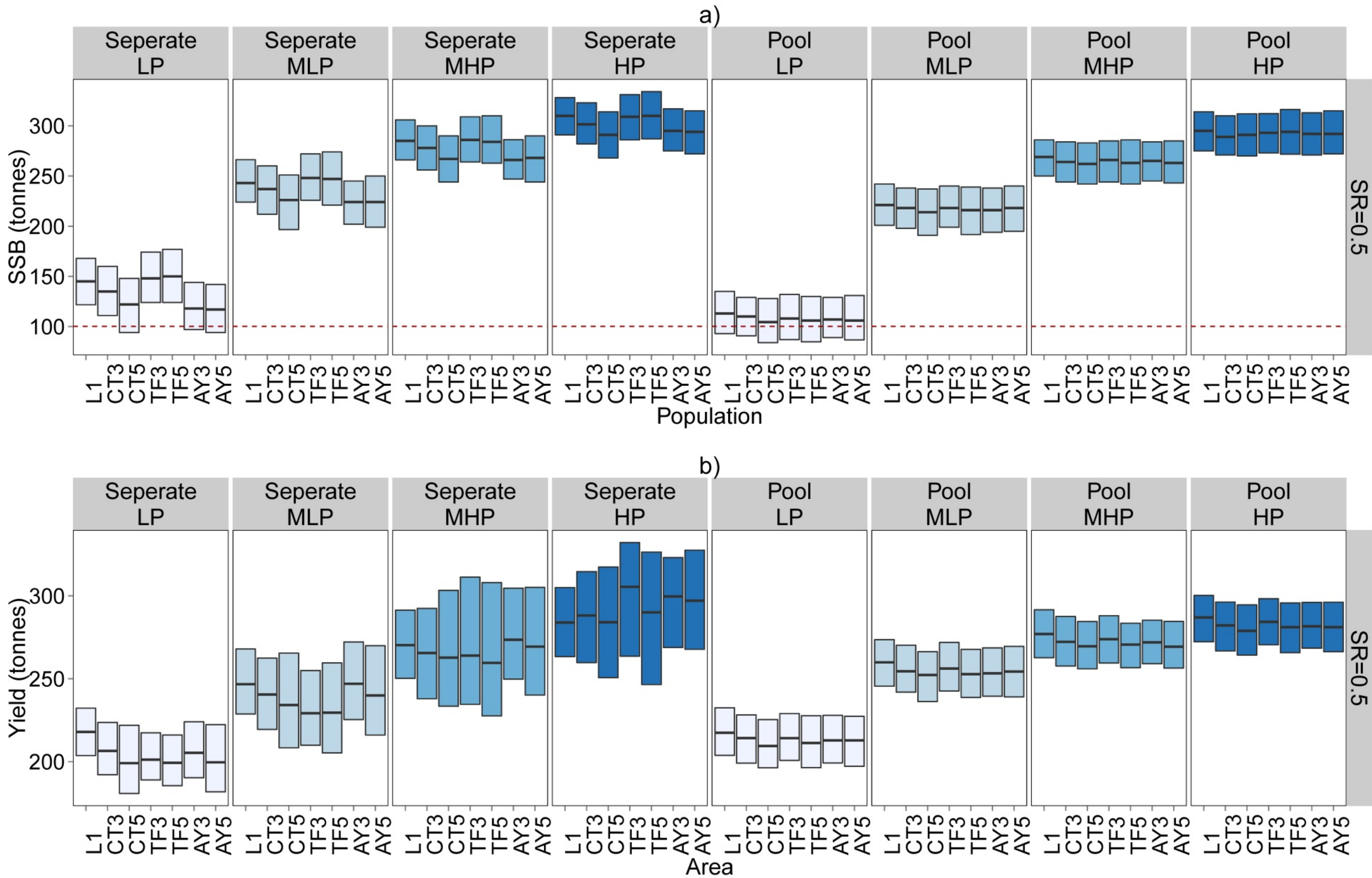


Figure 2.3 (cont'd)

Figure 2.3 (cont'd): Influence of one year lag. Shown are mean annual spawning stock biomass (SSB) for each population (Figure 2.3a), fishery yield for fishing areas surrounding each spawning area over the last 25 years of simulations (Figure 2.3b), the percentage of years SSB falling below $B_{20\%}$ for each population (Figure 2.3c), and inter annual variation of yield(Figure 2.3d). The X-axis of each section indicates whether there was no lag (L0) or a one year lag (L1). The horizontal section name represents the assessment model and population information (for 2.3a and 2.3c) from the low productivity (LP) population to the high productivity (HP) population. The dashed line is the 20% of unfished SSB ($B_{20\%}$). In Figure 2.3b and 2.3d, the horizontal section name identifies the assessment model names and the four fishing areas surrounding the spawning areas of the LP to HP populations separately. The box tops and bottoms cover the interquartile range; the horizontal middle line represents the median value of all simulations for each scenario.



a)
Seperate LP
Seperate MLP
Seperate MHP
Seperate HP
Pool LP
Pool MLP
Pool MHP
Pool HP
SSB (tonnes)
300
250
200
150
100
SR=0.5
L1
CT3
CT5
TF3
TF5
AY3
AY5
Population
b)
Yield (tonnes)
300
250
200
Area

Figure 2.4

Figure 2.4 (cont'd): The influence of assessment frequency and harvest limit setting rule. Shown are mean annual spawning stock biomass (SSB) for each population (Figure 2.4a), fishery yield for fishing areas surrounding each spawning area (Figure 2.4b). The X-axis of each section represents six annual and multiannual quotas: "CT3", "CT5", "TF3", "TF5", "AY3", and "AY5". The horizontal section name represents the assessment model and population information (for 2.4a) from the low productivity (LP) population to the high productivity (HP) population. The dashed line is the 20% of unfished SSB ($B_{20\%}$). In Figure 2.4b, the horizontal section name identifies the assessment models and the four fishing areas surrounding the spawning areas of the LP to HP populations separately. The box tops and bottoms cover the interquartile range; the horizontal middle line represents the median value of all simulations for each scenario.

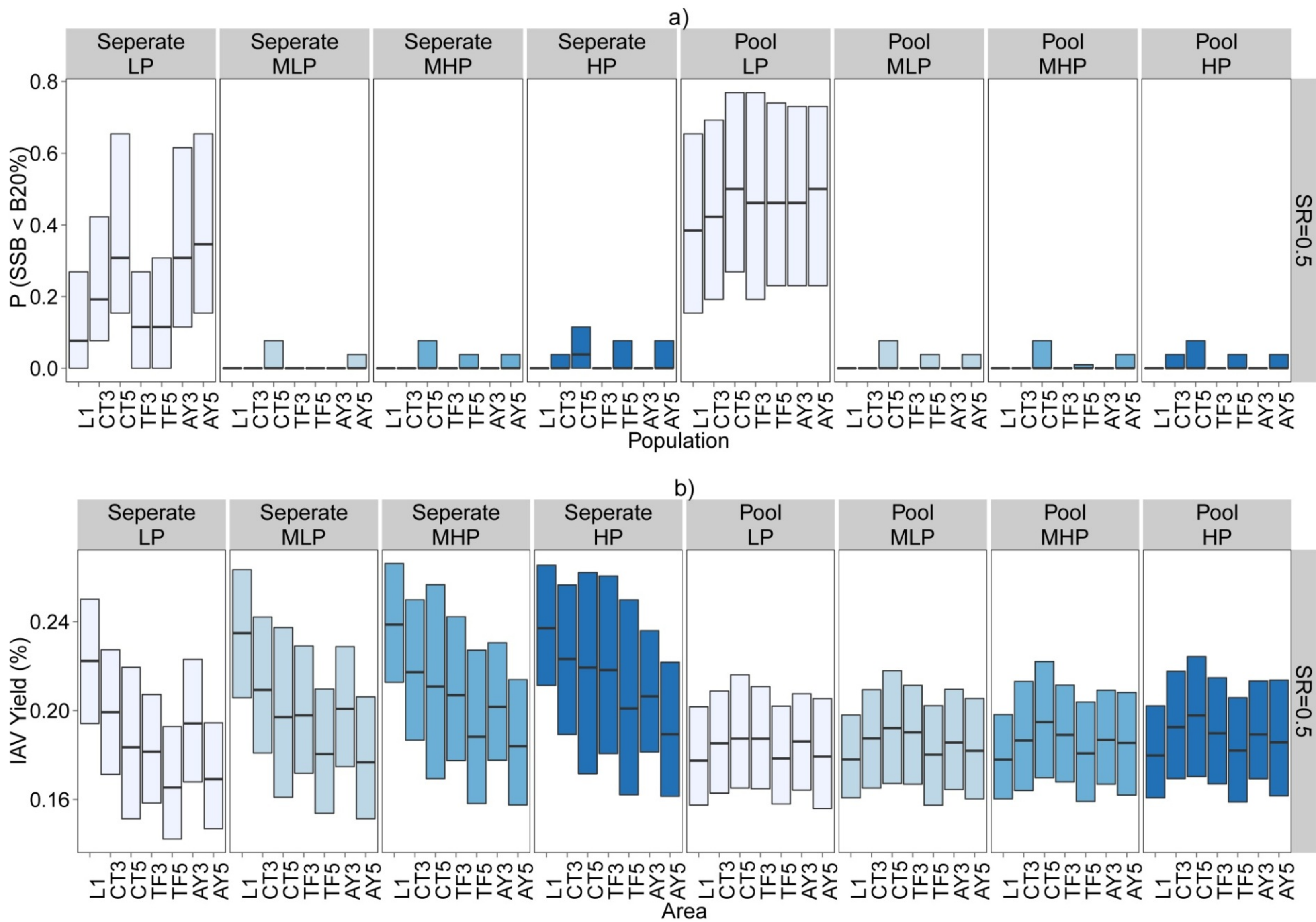

a)
Seperate LP
Seperate MLP
Seperate MHP
Seperate HP
Pool LP
Pool MLP
Pool MHP
Pool HP
P (SSB < B20%)
0.0
0.2
0.4
0.6
0.8
SR=0.5
L1 CT3 CT5 TF3 TF5 AY3 AY5
Population
b)
Seperate LP
Seperate MLP
Seperate MHP
Seperate HP
Pool LP
Pool MLP
Pool MHP
Pool HP
IAV Yield (%)
0.16
0.20
0.24
SR=0.5
L1 CT3 CT5 TF3 TF5 AY3 AY5
Area

Figure 2.5

Figure 2.5 (cont'd): The influence of assessment frequency and harvest limit setting rule. Shown are the proportion of years SSB falling below $B_{20\%}$ for each population (Figure 2.5a), and inter annual variation of yield (Figure 2.5b) under mixing scenario "SR=0.5". All results are for the last 25 years of simulations. The X-axis of each section represents six annual and multiannual quotas: "CT3", "CT5", "TF3", "TF5", "AY3", and "AY5". The horizontal section name represents the assessment model and population information (for 2.5a) from the low productivity (LP) population to the high productivity (HP) population. In Figure 2.5b, the horizontal section name identifies the assessment models and the four fishing areas surrounding the spawning areas of the LP to HP populations separately. The box tops and bottoms cover the interquartile range; the horizontal middle line represents the median value of all simulations for each scenario.

Table 2.1: Four different levels of productivity for lake whitefish. Simulated populations have different levels of productivity and steepness values. Their population indexes were defined based on their productivities, from low productivity (LP) to high productivity (HP). Alpha and beta are the Ricker stock–recruitment coefficients that were adjusted by different steepness levels for lake whitefish spawning populations.

Population index	Productivity level	Steepness	α	β
LP population	Low	0.7	5.23×10^{-4}	1.51×10^{-10}
MLP population	Mid-low	1.1	9.19×10^{-4}	2.06×10^{-10}
MHP population	Mid-high	1.5	1.35×10^{-3}	2.43×10^{-10}
HP population	High	1.9	1.82×10^{-3}	2.72×10^{-10}

Table 2.2: Equations used in stochastic simulation model

Equation index	Description of equation	Equation	Parameter
(T.2.2.1)	Ricker stock-recruitment function by year (y) and population (i)	$R_{i,y} = \alpha_i SSB_{i,y-1} e^{-\beta_i SSB_{i,y-1}} e^{\varepsilon_{R,i,y}}$	α: see Table 1 β: see Table 1 $\varepsilon_{R,i,y}$ ~ N(0, ${\sigma_R}^2$) $\sigma_R = 0.6$

Table 2.2 (cont'd)

(T.2.2.2)	age-specific SSB by year (y)	$SSB_y = \sum_a Fem\, N_{y,a} m_a W_a$	Fem =0.5
(T.2.2.3)	Length at age	L_a=$L_\infty(1 - \exp(-\kappa(a - t_0)))$	L_∞=60.9
			κ=0.1686
			t_0=0.0
(T.2.2.4)	Weight at age	$W_a = \gamma {L_a}^{\psi}$	γ= 8.06×10^{-5}
			ψ=2.45

Table 2.2 (cont'd)

(T.2.2.5)	Maturity at age	$m_a = \dfrac{m_\infty}{1 + \exp(-\vartheta(L_a - \delta))}$	ϑ=0.315 δ=37.9
(T.2.2.6)	Selectivity at age	$s_a = \dfrac{a^\eta \exp(-\tau\alpha)}{10^\eta \exp(-\tau 10)}$	η= 13.074 τ= 1.26

Table 2.2 (cont'd)

(T.2.2.7)	Actual catch by Baranov's catch equation by year (y) and population (i), given fishing mortality rates and abundance	$$C_{i,y} = \sum_{a=1}^{n} \frac{F_{i,y,a}}{M + F_{i,y,a}} (1 - e^{-M-F_{i,y,a}})\ N_{i,y,a}$$	M= 0.25

Table 2.2 (cont'd)

(T.2.2.8)	Actual catch by year (y) and population (i) given the TAC.	$C_{j,y} = TAC_{j,y}\, exp(\upsilon_{i,y} - 0.5{\sigma_c}^2)$	$\upsilon_{i,y}$ ~ N(0, ${\sigma_c}^2$) σ_c= 0.1
(T.2.2.9)	likelihood component for total catch	$\ell_c = n_c log_e(\hat{\sigma}_c) + (\frac{1}{2{\hat{\sigma}_c}^2}) \sum_y log_e(\frac{\hat{c}_y}{\hat{\hat{c}}_y})^2$ $n_c = \hat{c}_y - \hat{\hat{c}}_y$	

Table 2.2 (cont'd)

(T.2.2.10)	Likelihood component for fishing mortality-effort relationship	$\ell_{\varepsilon F} = n_{\varepsilon F} log_e\left(\frac{\hat{\sigma}_c}{\sqrt{0.25}}\right) + (\frac{0.25}{2\hat{\sigma}_c{}^2})\sum_y log_e(\varepsilon F)^2$
(T.2.2.11)	Likelihood component for age composition of the fishery harvest	$\ell_p = -\sum_y 200 \sum_a (\tilde{p}_{y,a} log_e \tilde{p}_{y,a})$

Table 2.3: Design of assessment process based on different timetable and frequency of assessment, and harvest limit setting rules for rotation years.

Scenario names	Assessment Frequency (Year)	Lag (Year)	Harvest limit setting between assessments
L0	1	0	/
L1 (status quo)	1	1	/
CT3	3	1	Constant TAC
CT5	5	1	Constant TAC
CF3	3	1	Target F
CF5	5	1	Target F
AY3	3	1	Add yield information
AY5	5	1	Add yield information

Table 2.4: Mixing scenarios. In all scenarios each of the four populations had different productivity, with one population taking each of the four alternative productivity levels (Table 1).

Mixing Scenario	*Description*
Scenario 1	All populations have same high stay rate (0.9)
Scenario 2	All populations have same medium-low stay rate (0.5)
Scenario 3	All populations have same low stay rate (0.25)
Scenario 4	Positive-correlated stay rates and productivity. Four stay rates (0.25, 0. 5, 0.75, 0.9) matched in rank order to productivity of four populations
Scenario 5	Negative-correlated stay rates and productivity. Four stay rates (0.9, 0.75, 0. 5, 0.25) matched in rank order to productivity of four populations

Table 2.5: The relative change of the median of LP SSB due to assessment frequency and assessment model under different mixing scenarios

Mixing Scenarios	Change due to assessment frequency		Change due to assessment model	
	Model	Relative change	Frequency	Relative change
SR=0.9	Separate	-0.163	L1	0.349
	Pool	-0.060	TF5	0.514
SR=0.5	Separate	0.034	L1	-0.221
	Pool	-0.062	TF5	-0.293
SR=0.25	Separate	-0.007	L1	-0.229
	Pool	-0.063	TF5	-0.273
po-cor	Separate	-0.010	L1	0.139
	Pool	-0.052	TF5	0.090
ne-cor	Separate	-0.082	L1	-0.278
	Pool	-0.061	TF5	-0.262

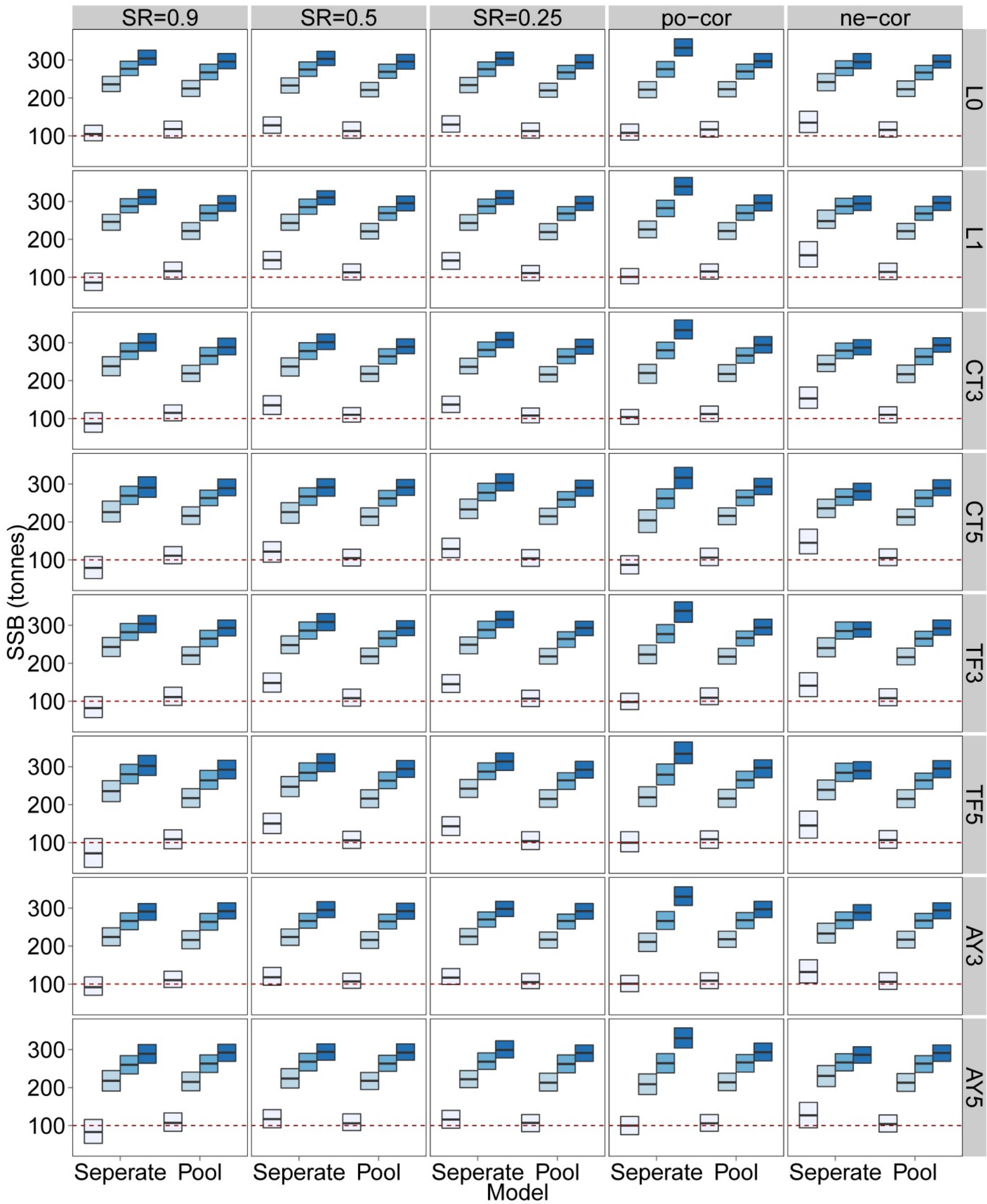
Table 2.6: The relative change of the median of total yield due to assessment frequency and assessment model under different mixing scenarios

	change due to assessment frequency		change due to assessment model	
Mixing Scenarios	Model	Relative change	Frequency	Relative change
SR=0.9	Separate	-0.078	L1	0.013
SR=0.9	Pool	-0.018	TF5	0.079
SR=0.5	Separate	-0.028	L1	0.019
SR=0.5	Pool	-0.024	TF5	0.023
SR=0.25	Separate	-0.040	L1	0.019
SR=0.25	Pool	-0.025	TF5	0.035
po-cor	Separate	-0.041	L1	0.050
po-cor	Pool	-0.023	TF5	0.069
ne-cor	Separate	-0.031	L1	-0.002
ne-cor	Pool	-0.023	TF5	0.007

APPENDIX

APPENDIX

This appendix presents additional plots beyond those presented in the main text. Displayed are all the results for four performance metrics, four populations with different levels of productivity, three assessment models, five levels of intermixing rate, and eight assessment frequency, lag, and TACs for rotation years setting rules.



SR=0.9
SR=0.5
SR=0.25
po−cor
ne−cor
L0
L1
CT3
CT5
TF3
TF5
AY3
AY5
SSB (tonnes)
300
200
100
Seperate
Pool
Model

Figure 3.1

Figure 3.1 (cont’d): Mean annual spawning stock biomass (SSB) for each population over the last 25 years of simulations. The X-axis of each section indicates the assessment design scenarios. The horizontal section name represents the five mixing scenarios. The horizontal section name represents the five mixing scenarios. The labels in X-axis showed two assessment models. For each assessment model, four boxes represent four populations from the low productivity (LP) population to the high productivity (HP) population. The dashed line is the 20% of unfished SSB ($B_{20\%}$). The box tops and bottoms cover the interquartile range; the horizontal middle line represents the median value of all simulations for each scenario.

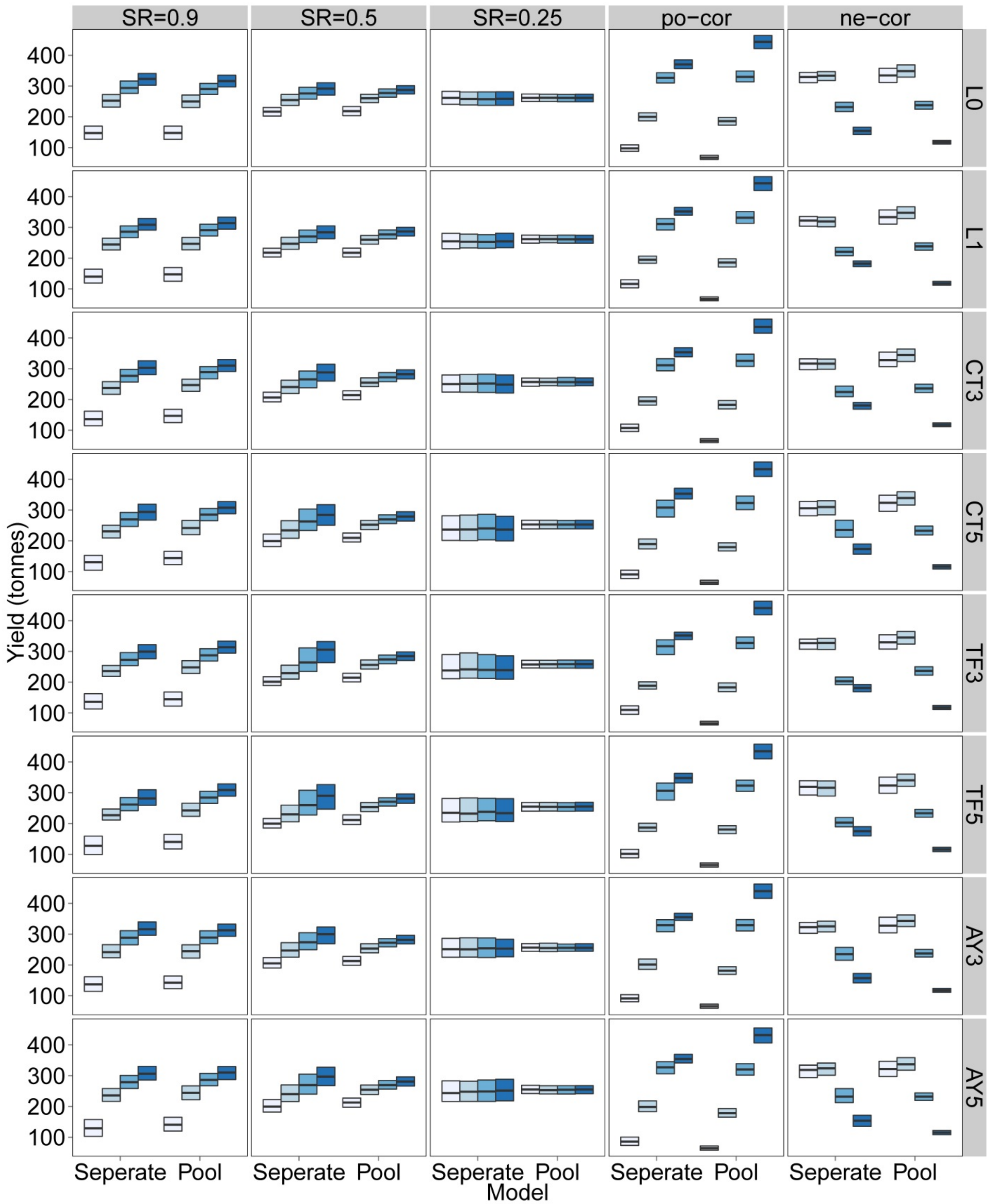


Figure 3.2: As for Figure 3.1, except y-axis is mean annual fishery yield for fishing areas surrounding each spawning area.

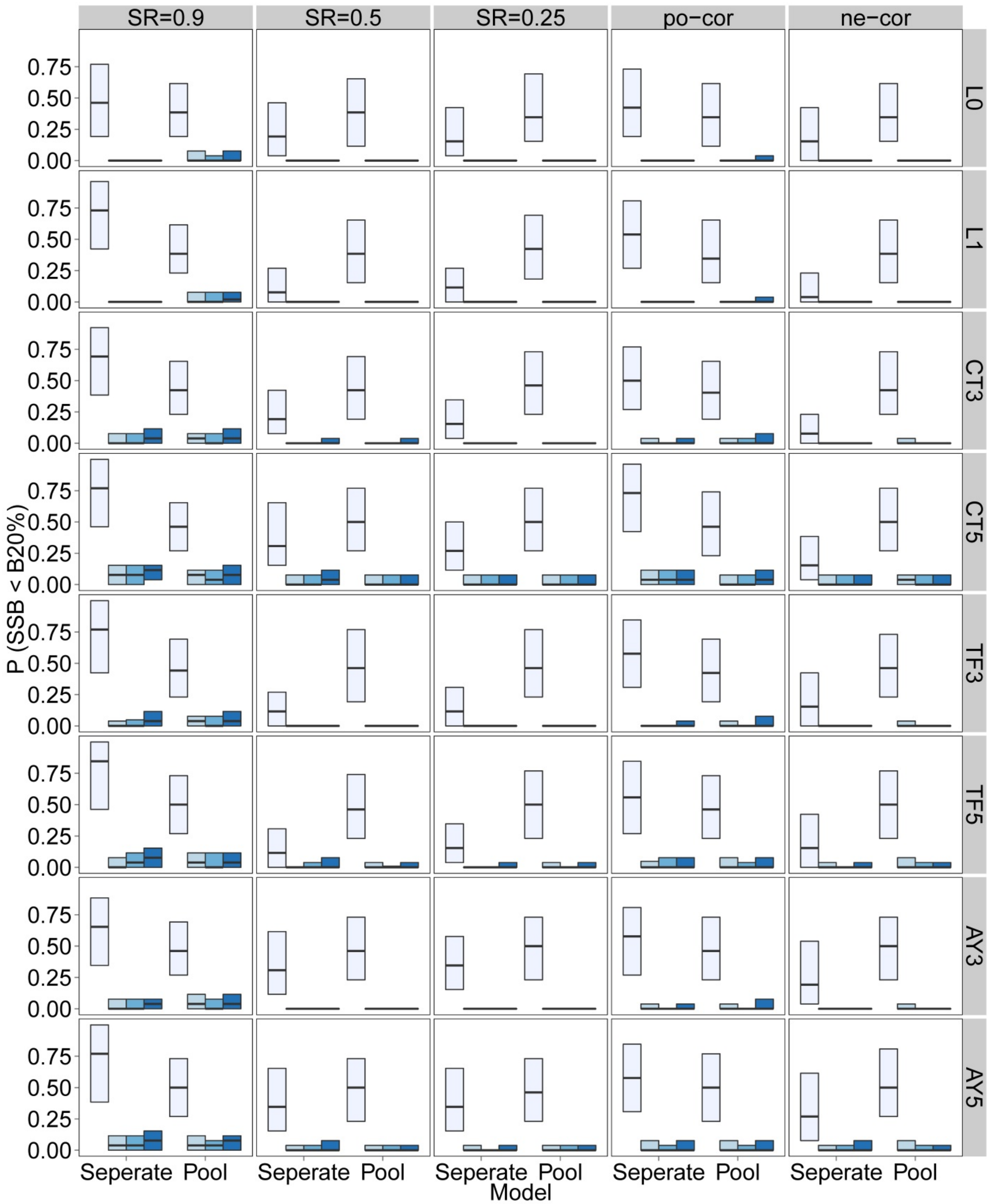


Figure 3.3: As for Figure 3.1, except y-axis is probability of SSB for each population being less than 20% of the unfished SSB level.

Figure 3.4: As for Figure 3.1, except y-axis is mean inter-annual percent variation in fishery yield.