

Reintroduction strategies for Southern Pygmy Perch to Gunbower Island wetlands using a metapopulation model

C.R. Todd, H.F. Wootton and J.D. Koehn

December 2023

Arthur Rylah Institute for Environmental Research Technical Report Series No. 374



Acknowledgements

The authors thank North Central Catchment Management Authority for funding this project. The authors gratefully acknowledge support and input from Peter Rose. The authors would also like to thank the attendees of the Southern Pygmy Perch workshop held in Cohuna April 2023: Peter Rose, Matt Crawford, Kathryn Stanislawski, Nick Whiterod, Scott Raymond, Gabriel Cornell, Conner Gervais, Max Smiles-Schmidt, Jian Yen, and Will Honybun. Thanks to Jian Yen and Scott Raymond for their comments on this report.

Authors

Charles R Todd¹, Henry F Wootton¹, John D Koehn^{1,2}

¹ Applied Aquatic Ecology, Arthur Rylah Institute for Environmental Research, Department of Energy, Environment and Climate Action, 123 Brown Street, Heidelberg, Victoria, 3084, Australia.

² Gulbali Institute for Agriculture, Water and Environment, Charles Sturt University, Elizabeth Mitchell Drive Albury, NSW, 2640

Citation

Todd, C. R. Wootton, H. F. and Koehn, J. D. (2023). Reintroduction strategies for Southern Pygmy Perch to Gunbower Island wetlands using a metapopulation model. Arthur Rylah Institute for Environmental Research Technical Report Series No. 374. Arthur Rylah Institute for Environmental Research, Heidelberg.

Editor

Fox Writing Services

Photo credit

Southern Pygmy Perch (source: Michael Hammer)

We acknowledge and respect Victorian Traditional Owners as the original custodians of Victoria's land and waters, their unique ability to care for Country and deep spiritual connection to it.

We honour Elders past and present whose knowledge and wisdom has ensured the continuation of culture and traditional practices.

DEECA is committed to genuinely partnering with Victorian Traditional Owners and Victoria's Aboriginal community to progress their aspirations.



© The State of Victoria Department of Energy, Environment and Climate Action December 2023.

Creative Commons

This work is licensed under a Creative Commons Attribution 4.0 International licence, visit the [Creative Commons website](http://creativecommons.org/licenses/by/4.0/) (<http://creativecommons.org/licenses/by/4.0/>).

You are free to re-use the work under that licence, on the condition that you credit the State of Victoria as author. The licence does not apply to any images, photographs or branding, including the Victorian Coat of Arms, and the Victorian Government and Department logos.

ISSN 1835-3827 (print)

ISSN 1835-3835 (pdf)

Disclaimer

This publication may be of assistance to you but the State of Victoria and its employees do not guarantee that the publication is without flaw of any kind or is wholly appropriate for your particular purposes and therefore disclaims all liability for any error, loss or other consequence which may arise from you relying on any information in this publication.

Accessibility

To receive this document in an alternative format, phone the Customer Service Centre on 136 186, email customer.service@delwp.vic.gov.au, or contact National Relay Service on 133 677. Available at [DEECA website](http://www.deeca.vic.gov.au) (www.deeca.vic.gov.au).

Reintroduction strategies for Southern Pygmy Perch to Gunbower Island wetlands using a metapopulation model

Charles R. Todd¹, Henry F. Wootton¹, John D. Koehn^{1,2}

¹ Applied Aquatic Ecology, Arthur Rylah Institute for Environmental Research, Department of Energy, Environment and Climate Action, 123 Brown Street, Heidelberg, Victoria, 3084, Australia.

² Gulbali Institute for Agriculture, Water and Environment, Charles Sturt University, Elizabeth Mitchell Drive Albury, NSW, 2640.

December 2023

Arthur Rylah Institute for Environmental Research
Technical Report Series No. 374

This page has been left deliberately blank.

Contents

Summary	ix
Recommendations.....	x
Population modelling	x
Reintroduction strategies	x
Monitoring	xi
General recommendations that may improve population establishment	xi
Introduction	1
Project objectives and outcomes.....	1
Methods: model construct, inputs, and analysis	2
Project approach and methodology.....	2
Specialist Southern Pygmy Perch model development workshop	3
Key management questions.....	3
Major threats.....	3
Gunbower Island site description	4
Hydrological history at Gunbower Island	6
Flooding.....	6
Wetland water permanency history	7
Movement	7
Habitat variation	7
Modelling scenarios	7
Model sensitivity to flood effects.....	8
Exploring competition with other species and predation impacts on Southern Pygmy Perch	8
Stocking loss	8
Two stocking strategies were compared alongside two stocking rates	9
Modelling a ‘Leaky Regulator’ population	10
Sensitivity analyses of movement	12
Interpretation of stochastic population model outputs.....	12
Results.....	14
Predicted population dynamics of Southern Pygmy Perch at Gunbower Island to reintroduction strategies: A metapopulation model with eight populations.....	15
Base case population trajectory for the total of all eight populations	15
Modelled scenarios including stocking of 20,000 fish per year for 7 years	15
Modelled scenarios including stocking of 5,000 fish per year for 7 years.....	19
Predicted population dynamics of Southern Pygmy Perch at Gunbower Island to reintroduction strategies including a Leaky Regulator population: A metapopulation model with nine populations	23
Leaky regulator scenarios including stocking of 20,000 fish per year for 8 years.....	23
Leaky Regulator scenarios including stocking of 5,000 fish per year for 8 years	28
Sensitivity to movement assumptions	32

Discussion.....	34
Recommendations.....	36
Population modelling	36
Reintroduction strategies	36
Monitoring	37
General recommendations that may improve population establishment	37
References	39
Appendices	43
Appendix 1. Additional outputs from modelled scenarios	43
Predicted responses of individual populations of Southern Pygmy Perch at Gunbower Island to reintroduction strategies: A metapopulation model with eight populations	43
Stocking 20,000 fish	44
Stocking 5,000 fish	53
Predicted responses of individual populations of Southern Pygmy Perch at Gunbower Island to reintroduction strategies including a Leaky Regulator population: A metapopulation model with nine populations	62
Stocking 20,000 fish	63
Stocking 5,000 fish	73
Appendix 2. Southern Pygmy Perch ecology and the population model.....	83
Southern Pygmy Perch background	83
Ecology	83
Conservation status.....	83
Distribution.....	83
Habitat	83
Movement.....	83
Life cycle	84
Age at maturity	84
Spawning	84
Fecundity	84
Egg development and larvae.....	84
Recruitment	84
Ageing	85
Length-weight relationship	85
Behaviour	85
Sex ratios.....	85
Genetics	85
Habitats	86
Movements	86
Threats	86
Habitat degradation	87
Predation/competition.....	87
Closely related and similar species.....	87
Yarra Pygmy Perch (<i>Nannoperca obscura</i>)	87
Variegated Pygmy Perch (<i>Nannoperca variegata</i>).....	87
Oxleyana Pygmy Perch (<i>Nannoperca oxleyana</i>)	88
Structured population models	88

A general approach to population modelling through a species life cycle	88
Dynamic models	89
Density dependence.....	89
Stochasticity	90
Expressions of risk and scenario ranking.....	90
ESSENTIAL – modelling framework	91
Model development for Southern Pygmy Perch	92
Life history analysis of Southern Pygmy Perch.....	92
Data assessment.....	93
Model construct.....	98
Stochastic population model	98
Mathematical and sensitivity analysis	99
Population model inputs.....	101
Additional information for movement rules within the model	102
New information or worthwhile future projects.....	104
Appendix 3. Specialist Southern Pygmy Perch model development workshop.....	105
Ecology and flows	105
Spawning.....	105
Movement and connectivity	106
Constraints on Southern Pygmy Perch	106
Productivity	106
Sites	106
Blackwater and water quality	106
Lower Lakes reintroduction	106
Stocking decisions	106
Model timeframe	106
Model outputs	107
Project assessment.....	107
Additional resources	107

Tables

Table 1.	Description of the sites chosen for modelling in this study.	5
Table 2.	Population growth rates (with population halving and doubling times) that can be applied to each population depending on habitat quality and expected levels of competition.	7
Table 3.	Assessed factors affecting stocking outcomes for Gunbower wetlands.	9
Table 4.	Southern Pygmy Perch reintroduction scenarios for the eight population metapopulation modelled at Gunbower Island.	10
Table 5.	The expected value (EV) of the distribution of minimum population sizes (risk curves) and the associated standard deviation (s.d.) when data were collected from the 5 th timestep onwards for scenarios where fish were stocked at a rate of 20,000 per year for seven years.	17
Table 6.	The expected value (EV) of the distribution of minimum population sizes (risk curves) and the associated standard deviation (s.d.) when data were collected from the 10 th timestep onwards for scenarios where fish were stocked at a rate of 20,000 per year for seven years..	18
Table 7.	The expected value (EV) of the distribution of minimum population sizes (risk curves) and the associated standard deviation (s.d.) when data were collected from the 5 th timestep onwards for scenarios where fish were stocked at a rate of 5,000 per year for seven years.	20
Table 8.	The expected value (EV) of the distribution of minimum population sizes (risk curves) and the associated standard deviation (s.d.) when data were collected from the 10 th timestep onwards for scenarios where fish were stocked at a rate of 5,000 per year for seven years.	21
Table 9.	The expected value (EV) of the distribution of minimum population sizes (risk curves) and the associated standard deviation (s.d.) for the Leaky Regulator scenario comparison when data were collected from the 5 th timestep onwards. Scenarios here had fish stocked at a rate of 20,000 per year for seven years.	26
Table 10.	The expected value (EV) of the distribution of minimum population sizes (risk curves) and the associated standard deviation (s.d.) for the Leaky Regulator scenario comparison when data were collected from the 10 th timestep onwards. Scenarios here had fish stocked at a rate of 20,000 per year for seven years.	26
Table 11.	The expected value (EV) of the distribution of minimum population sizes (risk curves) and the associated standard deviation (s.d.) for the Leaky Regulator scenario comparison when data were collected from the 5 th timestep onwards. Scenarios here had fish stocked at a rate of 5,000 per year for seven years.	30
Table 12.	The expected value (EV) of the distribution of minimum population sizes (risk curves) and the associated standard deviation (s.d.) for the Leaky Regulator scenario comparison when data were collected from the 10 th timestep onwards. Scenarios here had fish stocked at a rate of 5,000 per year for seven years.	30
Table 13.	Model sensitivity to movement rates, using the expected value of the minimum population size distribution from the default scenario with movement = 0.1, and percentage change in the equivalent expected value for movement = 0 and movement = 0.2 with stocking 20,000 Southern Pygmy Perch.	32
Table 14.	Model sensitivity to movement rates, using the expected value of the minimum population size distribution from the default scenario with movement = 0.1, and percentage change in the equivalent expected value for movement = 0 and movement = 0.2 with stocking 5,000 Southern Pygmy perch.	32

Figures

Figure 1. The site, Reedy Lagoon, showing fringing vegetation, woody habitat and submerged aquatic vegetation indicative of high-quality habitat for Southern Pygmy Perch.....	4
Figure 2. Conceptual diagram of Gunbower Forest habitats/populations included in the metapopulation modelling conducted in this study.....	6
Figure 3. Example of the leaky regulator concept at Reedy Lagoon in September 2023.	11
Figure 4. A conceptual example of the mean Southern Pygmy Perch population trajectories of three illustrative scenarios.....	13
Figure 5. An example of the distributions of minimum Southern Pygmy Perch population sizes for the three hypothetical scenarios in Figure 4.....	14
Figure 6. Modelled adult Southern Pygmy Perch trajectories of the base case scenario (Scenario 1) across the whole eight population metapopulation structure at Gunbower Island.....	15
Figure 7. Predicted adult Southern Pygmy Perch responses to 12 modelled scenarios where fish were stocked at a rate of 20,000 per year for seven years. Lines show mean scenario trajectories through time across all modelled populations at Gunbower Island.	16
Figure 8. Predicted adult Southern Pygmy Perch responses to 12 modelled scenarios where fish were stocked at a rate of 20,000 per year for seven years. Lines show cumulative distributions of the minimum population size (risk curves) for scenarios across all modelled populations at Gunbower Island.....	17
Figure 9. Predicted adult Southern Pygmy Perch responses to 12 modelled scenarios where fish were stocked at a rate of 20,000 per year for seven years. Lines show cumulative distributions of the minimum population size (risk curves) for scenarios across all modelled populations at Gunbower Island.....	18
Figure 10. Predicted adult Southern Pygmy Perch responses to 12 modelled scenarios where fish were stocked at a rate of 5,000 per year for seven years. Lines show mean scenario trajectories through time across all modelled populations at Gunbower Island.	19
Figure 11. Predicted adult Southern Pygmy Perch responses to 12 modelled scenarios where fish were stocked at a rate of 5,000 per year for seven years. Lines show cumulative distributions of the minimum population size (risk curves) for scenarios across all modelled populations at Gunbower Island. Data were collected from the 5 th timestep onwards.	20
Figure 12. Predicted adult Southern Pygmy Perch responses to 12 modelled scenarios where fish were stocked at a rate of 5,000 per year for seven years. Lines show cumulative distributions of the minimum population size (risk curves) for scenarios across all modelled populations at Gunbower Island. Data were collected from the 10 th timestep onwards.	21
Figure 13. Predicted adult Southern Pygmy Perch responses to six scenarios comparing the Leaky Regulator concept under differing combinations of flood impact, competition effects and stocking strategy. Fish were stocked at a rate of 20,000 per year for seven years under these scenarios. Lines show mean scenario trajectories through time across all modelled populations at Gunbower Island.....	24
Figure 14. Predicted adult Southern Pygmy Perch responses to six modelled scenarios comparing the Leaky Regulator concept under differing combinations of flood impact, competition effects and stocking strategy. Fish were stocked at a rate of 20,000 per year for seven years under these scenarios. Lines show cumulative distributions of the minimum population size (risk curves) for scenarios across all modelled populations at Gunbower Island. Data were collected from the 5 th timestep onwards.....	25
Figure 15. Predicted adult Southern Pygmy Perch responses to six modelled scenarios comparing the Leaky Regulator concept under differing combinations of flood impact, competition effects and stocking strategy. Fish were stocked at a rate of 20,000 per year for seven years under these scenarios. Lines show cumulative distributions of the minimum population size (risk curves) for scenarios across all modelled populations at Gunbower Island. Data were collected from the 10 th timestep onwards.....	27
Figure 16. Predicted adult Southern Pygmy Perch responses to six scenarios comparing the Leaky Regulator concept where fish were stocked at a rate of 5,000 per year for seven years. Lines show mean scenario trajectories through time across all modelled populations at Gunbower Island.	28

Figure 17. Predicted adult Southern Pygmy Perch responses to six modelled scenarios comparing the Leaky Regulator concept where fish were stocked at a rate of 5,000 per year for seven years. Lines show cumulative distributions of the minimum population size (risk curves) for scenarios across all modelled populations at Gunbower Island. Data were collected from the 5th timestep onwards.....29

Figure 18. Predicted adult Southern Pygmy Perch responses to six modelled scenarios comparing the Leaky Regulator concept where fish were stocked at a rate of 20,000 per year for seven years. Lines show cumulative distributions of the minimum population size (risk curves) for scenarios across all modelled populations at Gunbower Island. Data were collected from the 10th timestep onwards.....31

Summary

The aim of this project was to develop a metapopulation model to assess strategies for the reintroduction of Southern Pygmy Perch (*Nannoperca australis*) to Gunbower Island, Victoria. The model and relevant management scenarios were developed through a highly inclusive and consultative workshop process that involved modellers, fish ecologists, North Central Catchment Management Authority (CMA) staff, and land and water managers. The workshop identified the following desirable outcomes for the project: identify a suite of wetlands to be considered in the metapopulation construct; quantitatively link population responses to watering regimes, habitat quality, competition with other species, and invasive species impacts; assess likely population outcomes of different reintroduction strategies; and, ultimately, identify management outcomes that are cost-effective, innovative, and able to account for risks and catastrophic event predictions.

Predicted population dynamics of Southern Pygmy Perch at Gunbower Island were investigated for a range of reintroduction strategies using a metapopulation model. An existing, single-population model was considered appropriate following minor updates to knowledge, parameterisation to the Gunbower sites, and conversion into a metapopulation model to accommodate movements between sites. Modelling tested two stocking rates (20,000 and 5,000 fish per annum) and two stocking strategies (spread: stocked fish distributed evenly across all reintroduction sites each year for seven years; or focussed: sequentially stocking all fish at one reintroduction site per year for seven years) at different hypothesised levels of competition with other species and with different levels of flood effects on movement.

Stocking of 20,000 fish each year with no flood impacts and low levels of competition generated the largest predicted population sizes (upwards of 120,000 fish). Competition and flood impacts both imposed strong effects on population trajectories, resulting in weaker population growth and smaller predicted population sizes. High flood effects and high levels of competition produced the smallest population estimates of any scenario, where population trajectories within the target wetlands were close to zero throughout the study. However, it is noted that fish removed from target wetlands due to flooding may contribute to populations or establish occurrences elsewhere (including outside Gunbower Island), and we provide an example of a population only receiving fish through flooding inside Gunbower Island. The relative outcomes of different reintroduction strategies were similar when 5,000 fish were stocked each year, but with lower predicted population sizes. This lower rate of stocking was still predicted to support a successful reintroduction. Preferred stocking strategy (spread or focussed) depended on the stocking rate, with the spread strategy less likely to produce small population sizes for lower stocking rates and the focussed strategy less likely to produce small population sizes for higher stocking rates, particularly under low levels of competition.

An extension of the model assessed whether the introduction of an additional population adjacent to, and watered from, a wetland regulator would improve predicted reintroduction outcomes in this study. This population was modelled as situated in the channel between the lower Gunbower Creek and Reedy Lagoon populations, but could be implemented at other locations at Gunbower Island. This 'Leaky Regulator' concept model predicted substantially larger metapopulation sizes under scenarios with competition and stocking effort spread amongst the populations when compared with the metapopulation model. Although the benefits of the Leaky Regulator were observed primarily within the added population, the Reedy Lagoon and Gunbower Creek populations downstream of Cohuna, which were adjacent to the leaky regulator population, had higher predicted population sizes with some partial benefit to other populations in the lower Gunbower Island.

Recommendations

Several recommendations emerged from both the modelling results and the modelling process (specialist workshop, site analysis, and discussions), including strategies to support reintroductions of Southern Pygmy Perch into wetlands within Gunbower Forest and opportunities and risks associated with these reintroductions. We also provide direction for a program to monitor the progress of reintroduced populations. Detailed recommendations are included in the main text and are summarised here.

Population modelling

- It is recommended that the population model continue to be used as part of an adaptive management cycle; as actions are undertaken and population responses are measured, the model can be updated and used to inform ongoing management strategies and continue to be a basis for management decisions.
- It is recommended that data are collected to reduce uncertainty in key model parameters such as fecundity and survival rates (estimated in this project from Tasmanian Southern Pygmy Perch data), the interaction between density, habitat quality, competition, and the effect floods have on these parameters, acknowledging that collection of detailed life history data may be impractical. Captive breeding programs would improve knowledge of fecundity and early life survival.

Reintroduction strategies

- Stocking more fish per year was consistently associated with larger population sizes, lower likelihoods of population declines, and a lower likelihood of reintroduction failure. Therefore, reintroduction strategies should aim to maximise the number of fish stocked in each year. This may include more 'production' sites or fish from other sources (e.g. Victoria's new conservation hatchery).
- The addition of a population under the Leaky Regulator concept benefits overall population outcomes. The recommended option is to stock this population first in any sequence.
- Flood events had a strong influence on modelled population outcomes, so the risk of floods (and the spatial distribution of flood impacts) should be considered when determining stocking strategies and locations for stocking. Stocked populations should be monitored immediately following any floods.
- Stocking failure (hypothesised to occur due to competition with introduced species) substantially reduced the likelihood of reintroduction success, which suggests that introduced species should be removed from reintroduction sites prior to stocking (acknowledging that such removals may be logistically challenging). An intensive monitoring program is recommended following initial stocking events to determine the fate of stocked fish and the reasons for stocking success or failure. Stocking failure causes reduced population outcomes from reintroductions, and removing competition prior to any releases acts to improve population outcomes even with uncertainty around flood effects.
- A simultaneous spread stocking strategy (spreading the available fish equally among populations each year) is a low-risk strategy, and is recommended if lower numbers of fish are stocked each year (3,000–5,000) or competition is high and cannot be altered. A staggered stocking strategy (targeting one location each year) provides opportunities to implement location-specific interventions (e.g. removing introduced species) and is recommended if higher numbers of fish are stocked each year (10,000 plus).

Monitoring

- A monitoring program should be designed specific to the objectives of the Southern Pygmy Perch reintroduction strategy, in addition to (or added to) existing fish monitoring programs (e.g. Brown and Whiterod 2021; Bloink et al. 2023).
- All populations should be monitored, and data collected on presence, abundance, and annual recruitment. Sampling should use targeted methods (e.g. fyke nets, bait traps and seine netting) at reintroduction sites and other sites across Gunbower Island. Monitoring at spatial scales beyond Gunbower Island should be included in the strategy, especially following flooding because flooding may distribute fish to other locations. Monitoring techniques need to be considered because changed population densities may affect detectability. The experience of Wedderburn et al. (2019) may be useful here and the inclusion of e-DNA may be an option.
- Modelling results should be used to inform monitoring, particularly in exploring the likely population densities over time (numbers and site areas and habitats) because this will help determine the likelihood of detection and can be used to design the appropriate sampling regime and effort. A change in the magnitude of flood effects will also greatly impact fish densities and therefore detection of successful population establishment or even occurrence of Southern Pygmy Perch.

General recommendations that may improve population establishment

- Reintroduction success will be predicted more reliably following an assessment of predation and competition likelihood (fish and birds in conjunction with habitat cover) at each site. This assessment should include lists of all other fish species present at a site.
- As the populations appear sensitive to competition, options to reduce likely impacts at stocking locations should be considered. A key option is the removal of introduced species, especially Carp (*Cyprinus carpio*) and Redfin Perch (*Perca fluviatilis*); removal of Eastern Gambusia (*Gambusia holbrooki*) and Oriental Weatherloach (*Misgurnus anguillicaudatus*) is expected to be difficult.
- Consideration should be given to the use of screens to exclude Carp from reintroduction sites (or areas within these sites).
- The establishment of vegetated habitat plots at reintroductions sites could be beneficial, as demonstrated at some dam stocking sites (e.g., the Harcourt Dog Park, Bendigo).
- There are several projects that could help improve population establishment, which relate to key elements of the model (see Appendix 2: New information or worthwhile future projects).

This page has been left deliberately blank.

Introduction

Several small-bodied, off-channel specialist fish species that would historically have existed in the Gunbower-lower Loddon River system are no longer naturally occurring, including Southern Pygmy Perch, Southern Purple-spotted Gudgeon (*Mogurnda adspersa*), Flat-headed Galaxias (*Galaxias rostratus*) and Murray Hardyhead (*Craterocephalus fluviatilis*). For many years in the region, these species have either not been detected, or detected only in low numbers, and so re-establishing populations in the future will require reintroductions (Mallen-Cooper et al. 2014).

It is important to develop a reintroduction strategy, which is cost-effective and maximises the likelihood that self-sustaining populations of the target species eventually develop. To do so requires accurate information to help predict the likely outcomes of a range of decisions such as:

- How many fish should you reintroduce? This is important because there are likely to be critical population sizes that are required for populations to become viable.
- When should fish be reintroduced? This is important because reintroductions at different times of the year might have various outcomes. Also, in some instances, single releases may lead to adequate population outcomes, whereas in other circumstances, multiple releases over time might be required.
- For species that exist as metapopulations (i.e. connected sub-populations in the same area), where should fish be released to maximise regional persistence?

Threatening processes impacting on the species include habitat alteration (such as loss of aquatic vegetation), seasonal flow changes/reductions, floodplain alienation, and predation (Lintermans 2023). Assessing the viability of remnant populations is an essential prerequisite for determining conservation priorities, for assigning effort and resources in the form of management actions, and for projecting and evaluating the results of recovery plans (Todd et al. 2004; Koehn and Todd 2012; Saddler et al. 2014; Todd et al. 2017).

To aid decision making about where best to assign limited resources and effort, different processes can be examined through the application of population modelling where numerous scenarios may be examined methodically to identify suitable management options. In the Gunbower-lower Loddon River system, numerous wetlands have been identified as potential receiving habitats for the reintroduction of Southern Pygmy Perch. A single population model has been developed for Southern Pygmy Perch (Todd et al. 2017). This model can be updated to a metapopulation construct to accommodate movement between different populations (stocking sites), and therefore is suitable for the exploration of reintroduction strategies for Southern Pygmy Perch into wetlands in the Gunbower-lower Loddon River system and in particular with application to Gunbower Forest.

Project objectives and outcomes

The main objective of this project was to develop a stochastic (meta)population model to guide reintroductions of Southern Pygmy Perch into waters of the Gunbower islands (wetlands and connecting channels) by North Central CMA. The model was based on the existing Southern Pygmy Perch model (Todd et al. 2017), but expanded to a metapopulation structure model to reflect the likely movements of this species within Gunbower Forest and into connecting waterbodies such as Gunbower Creek and Cameron's Creek.

Initially, the model was intended to be used to examine questions like:

- What is the optimal number of fish to stock?

- Into which permanent wetlands or connecting waterbodies should fish be stocked?
- How frequently should fish be stocked?
- When should fish be stocked?

These initial questions were further developed at a specialist workshop held at Cohuna with fish ecologists, North Central CMA staff, and waterway managers (see Methods below and Appendix 3). Outcomes of this workshop included:

- A revision of the current population model (including conversion to a metapopulation construct) and its application to this project
- Development of stocking scenarios and identification of key model sensitivities to be tested (see below)
- Definition of key knowledge gaps in the ecology of Southern Pygmy Perch relevant to the population model (see Discussion)
- Definition of criteria for success of the overall project (i.e. against what overall objectives should the model outputs be judged?).

An overall goal of the reintroduction program, success, was defined as the establishment of at least one stable population of Southern Pygmy Perch in the upper and the lower sections of Gunbower Island. The populations should be able to survive a large drought event. A long-term timeframe (> 10 years) was seen as acceptable to achieve this. Detection of Southern Pygmy Perch at additional sites would also be seen as a measure of success.

Methods: model construct, inputs, and analysis

Project approach and methodology

Previous research and the development of a Southern Pygmy Perch model (Todd et al. 2017) was used as the basis for this project. Specifics of this process and some of its outcomes are included in this report, including details of the model development and consultation processes, Southern Pygmy Perch ecology (Koehn et al. 2020, Appendix 2), and the model itself (Appendix 2). This information provides important context for the use of this model and its application to Gunbower Island.

Existing techniques for population modelling in aquatic and terrestrial environments were used to develop a stochastic population model for Southern Pygmy Perch (see Todd et al. 2001, 2004, 2017; Todd and Koehn 2009, for detailed methodology). Population models summarise life history processes such as recruitment and survival, population size, sex ratio, and genetics, and use age structures to provide the underlying structure to the model. This requires analysis of available data or, where no data are available, information on similar species may be used. The purpose of the model was to improve understanding about the viability of Southern Pygmy Perch, to provide the supporting analysis to prioritise remnant populations for conservation, and to identify management actions to secure or expand viable populations.

The previous work and existing population model (Todd et al. 2017) were reviewed and updated to ensure their applicability to the Gunbower Island reintroduction project, and as the basis of a metapopulation model. This included a literature review to identify all new information published on the biology and ecology of Southern Pygmy Perch (post Todd et al. 2017 and Koehn et al. 2020) and related species. In addition, site inspections and a local workshop were held to provide relevant site details and to refine the model and

modelling scenarios to be undertaken to achieve the management objectives. This review found the existing population model would be suitable following minor updates to knowledge, parameterisation to the Gunbower sites, and conversion into a metapopulation model to accommodate movements between sites.

Specialist Southern Pygmy Perch model development workshop

A specialist Southern Pygmy Perch modelling workshop that involved fish ecologists, North Central CMA staff and waterway managers was held in Cohuna on the 19 April 2023 to: 1) explain the population viability modelling process, including requirements of model building; 2) review the biology and ecology of Southern Pygmy Perch used in the existing model; 3) determine what to include in a model: fecundity; survival; movement; dispersal; habitat; flows; predation; invasive species; genetics; density dependence; and 4) determine possible model structure; parameters; data; model output; and management options for this particular reintroduction project. The aim of the workshop was to bring together a range of experts in small-bodied fish, and in particular Southern Pygmy Perch expertise, to discuss the above points and reach agreement on both the approach and outcomes. The workshop was attended by: Peter Rose, Matt Crawford, Kathryn Stanislawski, Nick Whiterod, Scott Raymond, Gabriel Cornell, Conner Gervais, Max Smiles-Schmidt, Jian Yen, Will Honybun, Charles Todd, Henry Wootton and John Koehn. Further details of the workshop are provided below and in Appendix 3.

Key management questions

The workshop identified several important management issues, of which the following were considered relevant to this project:

1. How best to link disparate populations;
2. Modelling the impacts on populations of different environmental variables and processes (e.g. flows and floods, movements, and connectivity);
3. Modelling population size and introductions into certain sized areas, implying density dependence;
4. How to manage small, fragmented populations; and
5. Management outcomes and guiding principles:
 - The most cost-effective reintroduction program;
 - New ideas that may improve reintroduction effectiveness and likelihood of success;
 - Monitoring of outcomes;
 - Risks and catastrophic event predictions;
 - Additional knowledge that may refine the program into the future.

Major threats

Several major threats to Southern Pygmy Perch were identified: lack of water; habitat loss; sedimentation; lack of connectivity; introduced species; lack of flows; hypoxic blackwater; fire; run-off – nutrients (and blue-green algae) that may result in reduced dissolved oxygen levels; land use changes – water availability, chemicals; sand slugs; climate change; weed infestation. The specific threat of predation was discussed, and the following predators identified: native: River Blackfish (*Gadopsis marmoratus*) and Two-spined Blackfish (*Gadopsis bispinosus*), *Galaxias* species (various), birds (not major); introduced: Redfin Perch, Carp, Rainbow Trout

(*Oncorhynchus mykiss*) and Brown Trout (*Salmo trutta*), Oriental Weatherloach, and Eastern Gambusia. Introduced species also compete for resources (Carp and Eastern Gambusia) and degrade habitats (Carp).



Figure 1. The site, Reedy Lagoon, showing fringing vegetation, woody habitat and submerged aquatic vegetation indicative of high-quality habitat for Southern Pygmy Perch.

Gunbower Island site description

Gunbower Island is in north-central Victoria, adjoining the Murray River. Several potential sites within the broader Gunbower Island area were discussed at the workshop for the reintroduction of Southern Pygmy Perch. Of these sites, eight locations (interchangeably called ‘populations’) were selected for inclusion in modelling (Table 1; Figure 1; Figure 2) after consideration of the quality of habitat (i.e. quantity and quality of macrophyte cover), the community of competitors and/or predators present, the ability to manage hydrology (e.g. does the wetland permanently hold water? Can water be delivered?) and its location within the broader metapopulation structure (i.e. does it provide connection pathways). At the workshop, each site was discussed and awarded a value out of three for two habitat characteristics: macrophyte habitat quality and the competitor/predator assemblage (Table 1), with higher values indicating better habitat for Southern Pygmy

Perch. These values were used to capture stocking failure variation as well as habitat variation for each population (see sections Stocking loss and Habitat variation).

Table 1. Description of the sites chosen for modelling in this study. Each site is modelled as a discrete population where life history processes (e.g. spawning, mortality) occur within yearly timesteps. Movement among populations is recorded as a proportion of each population moving at the end of each yearly timestep. Macrophyte habitat quality and competitor/predator assemblage values are scored on a scale of 1–3, with higher values indicating better habitat for Southern Pygmy Perch.

Population number	Site name	Macrophyte habitat quality	Competitor predator assemblage value	Area at full
1	Cameron's Creek	2	3	3.3 ha
2	Black Charlie Lagoon	1	2	6.8 ha
3	Gunbower Creek upstream of Cohuna township	1	2	293 ha
4	Green Swamp	1	1	12 ha
5	Reedy Lagoon	3	2	34 ha
6	Black Swamp	2	1	37 ha
7	Little Gunbower Wetland Complex	1	1	47 ha
8	Gunbower Creek downstream of Cohuna township	3	2	288 ha
9	Leaky regulator population	3	3	0.2-1 ha

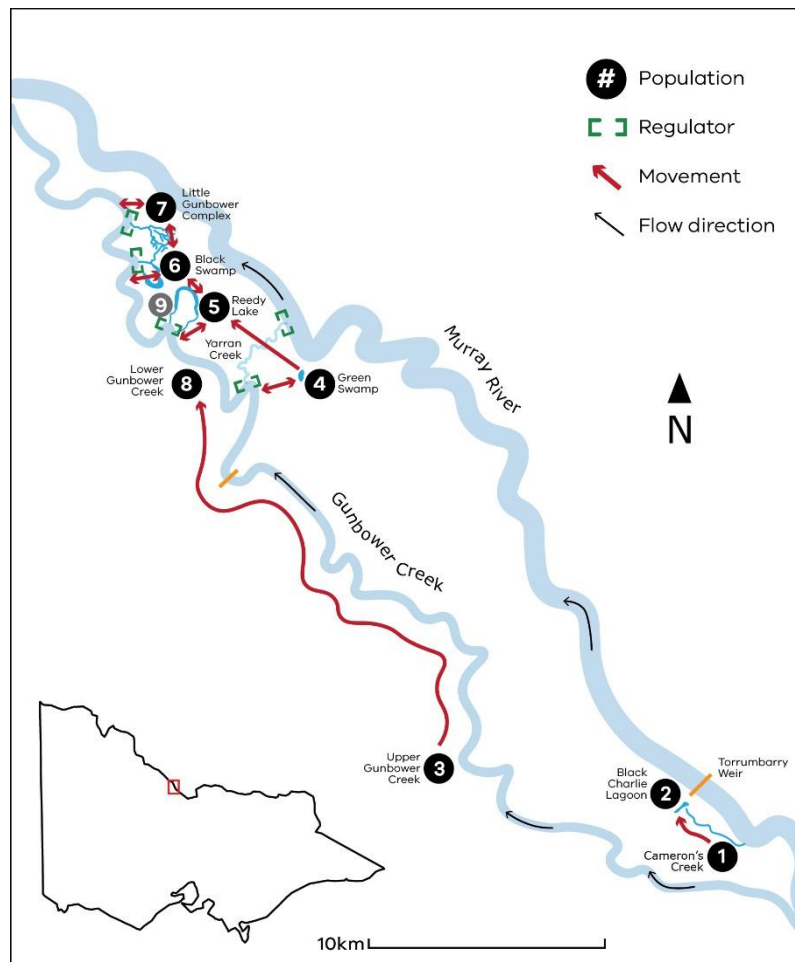


Figure 2. Conceptual diagram of Gunbower Forest habitats/populations (shown with black circles) included in the metapopulation modelling conducted in this study. Populations in the Gunbower Creek are assumed to be evenly distributed along the length of the creek. Possible movements between populations are shown with red arrows. Note that population number 9 (indicated by the grey circle) shows the location of the ‘Leaky Regulator’ population, which was only modelled in specific scenarios (see description below). Large barriers are shown with orange bars.

Hydrological history at Gunbower Island

The hydrological history at Gunbower Island was used to determine movement and flooding sequences in the population model. Historical hydrological data sets were supplied to the modelling team by North Central CMA collaborators for use in this project. These included a watering regime history and an operational history assessment and contained a complete record of all data from the 2006-2007 watering year to the 2021-2022 watering year (hereafter referred to as 2007–2022 for this period). This 16-year period forms the temporal extent of modelling in this project. Hydrological data were used to inform the modelling of Southern Pygmy Perch reintroduction strategies as described below.

Flooding

The operational history dataset was used to create a flood schedule for modelling (Figure A-48). In any given year, if the ‘river level’ was recorded as ‘overbank’ for one or more months then a flood was recorded as occurring in that year and flood impacts were included in the model in this year (see below for description of impacts).

Wetland water permanency history

The watering regime history dataset was used to inform the hydrological status of wetland sites (populations) through time within the model (Figure A-49). For each population, the status of the wetland in a given year determined the habitat quality (carrying capacity) of that population for that year. If a site was recorded as 'dry', the carry capacity was reduced by a factor of 20 in that year. When sites were recorded as 'drying', the carrying capacity was reduced by a factor of 2 in that year. Finally, a habitat status of 'water present' meant that the carry capacity for the wetland remained unchanged in that site and year.

Movement

Movement rates among populations were estimated from the operational history dataset (Figure A-50 for scenario's S1–S12 and Figure A-51 for Leaky Regulator scenario's S13–S24) (see section Modelling scenarios). The specific movement rate between populations was determined annually by the number of months that the relevant regulator was open in that year. The number of months with an open regulator was converted to an annual proportion (divided by 12) and multiplied by the underlying movement rate (default value of 10%) to estimate the proportion of the population that moved in a timestep. Appendix 2 contains further information on the estimation of movement rates.

Habitat variation

Different population growth rates were specified to capture differing habitat quality at different wetlands. Depending on the connectivity history, baseline estimates of habitat quality may decline or improve according to the wetland watering history. The baseline population growth rates used in the metapopulation model are listed in Table 2. The allocation of growth rate to population was based on expert opinion from the Southern Pygmy Perch specialist workshop (Appendix 3. Specialist Southern Pygmy Perch model development workshop).

Table 2. Population growth rates (with population halving and doubling times) that can be applied to each population depending on habitat quality and expected levels of competition.

Habitat type.	Population no. (see Table 1)	Population growth rate	Years to halve	Years to double
1	3	0.9298815	10	-
2	2; 4; 7	0.9695973	22	-
3	1; 6	1.052905	-	14
4	5; 8	1.156944	-	5

Modelling scenarios

We developed and tested several scenarios with the population model to investigate:

1. the relative success of different Southern Pygmy Perch stocking strategies
2. the sensitivity of model outputs to key sources of uncertainty in the model construct, such as the effects of floods and competition.

The modelled scenarios were all combinations of three factors (flood effects, competition, and stocking strategy) that were defined at the specialist workshop as factors likely to affect population outcomes (Table 4).

The scenarios were applied over 16 years and assumed all other drivers of the population model were constant or a stochastic sequence repeated exactly (e.g. movement rate, survival).

Model sensitivity to flood effects

Specialists at the workshop indicated a strong belief that floods would influence Southern Pygmy Perch populations, but the level of this effect was uncertain. A consensus decision was to model three levels of flood effects to assess the sensitivity of reintroduction success to uncertainty in this model parameter. Modelled flood effects were: no effect (0% loss to each population in each flood year), low effect (10% loss), and high effect (40% loss). The sequence of flood events across the modelled period was determined from the hydrological record at Gunbower Island (see above).

An important caveat is that 'loss' of individuals due to floods refers only to target wetlands because the model only tracks fish in these populations. Specialists at the workshop indicated that the mechanism of loss was likely to be in the form of large dispersal events rather than mortality. Given that floods flow through lowland waterways (such as those in Gunbower Forest) at a relatively slow rate, mortalities due to high velocity or severe habitat scouring (e.g. as reported by Pearce 2014) are not thought to occur in these systems. Therefore, any modelled loss in the present study relates to downstream movements of fish (either between sites or out of the study area), and could benefit surrounding areas. Furthermore, modelled flood effects provided a small contribution to downstream populations (where a connection is likely), with one twentieth of the fish lost from the upstream population contributing to a downstream population.

Exploring competition with other species and predation impacts on Southern Pygmy Perch

Competition and predation are known to affect Southern Pygmy Perch, including influencing the stocking success of small farm dams (see Appendix 3). Anecdotal observations indicate that carp gudgeons (*Hypseleotris* species) and Oriental Weatherloach may prevent population establishment or reduce abundances of established, isolated populations. There is, however, uncertainty around the mechanisms of competition with other species and the life-history stages affected, and whether these processes would occur in the larger wetland sites on Gunbower Island (compared with smaller systems where existing breeding projects have occurred). Competition and predation impacts were discussed at the workshop, and included in the model as changes in stocking success in each year of stocking. Two scenarios of competition were considered: 1) low competition where a 20% chance of stocking failure was applied across all stocked populations; and 2) high competition where the chance of stocking failure was based on the competitor/predator assemblage for each population (three levels defined in Table 1 and quantified in Table 3 referred to as competition effects).

Stocking loss

Each population had two factors affecting stocking outcomes: 1) the probability of stocking failure due to competition described in the section above; and 2) the proportion of stocked fish lost due to habitat and wetland characteristics (stocking penalty). At the Southern Pygmy Perch specialist workshop (Appendix 3. Specialist Southern Pygmy Perch model development workshop), each wetland was assessed for its quality and level of competition (low-medium-high levels defined in Table 1 and quantified in Table 3). The higher the level of competition, the greater the likelihood of stocking failure. If stocking failure occurred, the outcome from the

stocking event was zero; whereas if stocking failure did not occur, then the outcome from the stocking event depended on the proportion of stocked fish that survived the stocking event (one minus the stocking penalty).

Table 3. Assessed factors affecting stocking outcomes for Gunbower wetlands.

Wetland	Competition effects	Stocking penalty
Cameron's Creek	0.2	0.5
Black Charlie Lagoon	0.5	0.8
Gunbower Creek upstream of Cohuna	NA	NA
Green Swamp	0.8	0.8
Reedy Lagoon	0.8	0.2
Black Swamp	0.8	0.5
Little Gunbower Creek	0.8	0.8
Gunbower Creek downstream of Cohuna	0.8	0.2

Two stocking strategies were compared alongside two stocking rates

We applied two stocking strategies to investigate whether alternate stocking strategies would alter the likelihood of reintroduction success: stocking strategy 1 (SS = 1), releasing all available stock into one location in one year then a different location the following year for seven years (seven reintroduction locations – focussed strategy); and stocking strategy 2 (SS = 2), spreading all available stock equally among all populations (excluding Gunbower Creek upstream of Cohuna) every year for seven years (equivalent in total stocked fish to strategy 1 – spread strategy). We assessed two rates of stocking for each strategy, representing the estimated lower (5,000 fish stocked each year) and higher bounds (20,000 fish stocked each year) on the possible supply of fish from surrogate sites in the North Central CMA's breeding program. The focussed strategy stocked fish into the 'best' wetlands first in the order of population number 8, 5, 1, 4, 7, 6, 2 (Table 1).

We tested competition effects set at 0.2 for all populations (low – Table 4) or at the individual population level quantified in Table 3 (high setting – Table 4), as well as the effects of floods distributing fish downstream, where the probability of movement (0 = zero, 0.1 = low, and 0.4 = high) determines the number of fish moving from a population and 5% of this number move to downstream wetlands (e.g. fish moving on a flood from Green Swamp will be distributed to Reedy Lagoon, Black Swamp, Little Gunbower Creek, and Gunbower Creek downstream of Cohuna, with the balance lost from the metapopulation model, but potentially retained between sites or beyond the study area). The rate of movement in the absence of a flood was defined by the operational history (see Movement, above). All scenarios were tested sequentially (Table 4).

Table 4. Southern Pygmy Perch reintroduction scenarios for the eight population metapopulation modelled at Gunbower Island. Leaky Regulator (nine populations) scenarios are indicated in brackets. Descriptions of each factor (column headings) can be found above.

Scenario no.	Flood impact level	Competition level	Stocking strategy	Stocking rate (pa)
S1 (LR S13)	Zero	Low	SS=1	5,000 20,000
S2 (LR S14)	Zero	Low	SS=2	5,000 20,000
S3 (LR S15)	Zero	High	SS=1	5,000 20,000
S4 (LR S16)	Zero	High	SS=2	5,000 20,000
S5 (LR S17)	Low	Low	SS=1	5,000 20,000
S6 (LR S18)	Low	Low	SS=2	5,000 20,000
S7 (LR S19)	Low	High	SS=1	5,000 20,000
S8 (LR S20)	Low	High	SS=2	5,000 20,000
S9 (LR S21)	High	Low	SS=1	5,000 20,000
S10 (LR S22)	High	Low	SS=2	5,000 20,000
S11 (LR S23)	High	High	SS=1	5,000 20,000
S12 (LR S24)	High	High	SS=2	5,000 20,000

Modelling a 'Leaky Regulator' population

The model was extended to test whether the introduction of an additional population (called the 'Leaky Regulator' population) situated between the lower Gunbower Creek population (population 5) and the Reedy Lagoon population (population 8) (Figure 2) would improve outcomes for the reintroduction of Southern Pygmy Perch into the Gunbower Island site. The Leaky Regulator concept was suggested at the expert workshop and derived from observations of small wetland habitats occurring on the floodplain side of regulators along the Gunbower Creek (see Figure 3). These locations were characterised by good macrophyte cover, low competitor/predator occurrence, and are easily manipulated hydrologically via the regulator itself. The channel

that connects the lower Gunbower Creek and Reedy Lagoon presents an opportunity for easy hydrological manipulation as it can be watered from the Gunbower Creek and also drawn down easily for local removal of competitors or predators. The Leaky Regulator concept may provide benefits to the broader metapopulation structure in the form of a central node operating as a source of individuals via small movement opportunities.

The Leaky Regulator concept was assessed in terms of its impacts on reintroduction outcomes in adjoining populations and in the metapopulation overall. All population characteristics were decided at a second smaller workshop with North Central CMA staff. We therefore modelled a scenario where a Leaky Regulator population was included adjacent to Reedy Lagoon (population 5) and assumed high-quality habitat and low competitor/predator impacts at this site (population growth rate 4: Table 2; competition effect 0.2 ~ Cameron's Creek: Table 3; stocking penalty 0.2 ~ Reedy Lagoon: Table 3). The carrying capacity of this population was set at 20,000 fish and it was assumed that this location did not dry out. Stocking of the Leaky Regulator population occurred in the first timestep. As this was an additional population added to the metapopulation construct, the Leaky Regulator construct represents an increase to the overall carrying capacity of the metapopulation.



Figure 3. Example of the leaky regulator concept at Reedy Lagoon in September 2023. The photo shows the habitat provided by 'leaking' water from the regulator (shown bottom right) into the channel connecting the Gunbower Creek with Reedy Lagoon. This photo was taken following extensive flooding in 2022, which caused the growth of surface-dwelling aquatic plants that degraded the usually diverse aquatic vegetation at the site.

This scenario was run separately to scenario's 1–12, and therefore had differing possible movement pathways (Figure 2) where the leaky regulator population is located between the lower Gunbower Creek population (population 5) and the Reedy Lagoon population (population 8). This means that movement between population's 5 and 8 cannot occur directly because fish are constrained to adjacent populations in a single timestep. Movement between population's 5 and 9 and between 8 and 9 was possible in years when Reedy Lagoon is connected to the Gunbower Creek via the regulator (see Figure 2). The impacts of a Leaky Regulator

population were considered across scenario's 1–12 (Table 4), renamed as scenario's S13–S24 when the Leaky Regulator population was included. The leaky regulator includes an additional population relative to scenario's S1–S12 (nine populations in total). Therefore, 8 years of stocking was modelled for all Leaky Regulator scenarios (rather than the 7 years of stocking for scenario's S1–S12) to ensure that all populations were stocked in sequential scenarios. The Leaky Regulator was stocked in the first year for the focussed stocking strategy (SS = 1) and stocked fish were spread evenly among all populations each year for 8 years under the spread stocking strategy (SS = 2). The focussed strategy stocked fish into the Leaky Regulator first and then the same order was followed with the next 'best' wetlands stocked in the order of population number 8, 5, 1, 4, 7, 6, 2 (Table 1). The consequence in output from applying this stocking method is that comparisons between focussed standard scenarios and focussed Leaky Regulator scenarios was that the individual population trajectories of the Leaky Regulator scenarios were one timestep behind the standard equivalent scenarios.

Sensitivity analyses of movement

A comprehensive sensitivity analysis was previously undertaken on the single-population model for Southern Pygmy Perch (Todd et al. 2017). Here, we assessed the sensitivity of the model to the description of connectivity and movement among populations, which is the feature that distinguishes metapopulation models from single-population models. For the default scenarios, we assumed a maximum annual movement rate between connected populations of 0.1 (a maximum of 10% of the population can move to a connected population), rescaled by the proportion of months in a year for which the connection is open. The scenarios above include tests of different levels of movement due to floods. As an additional exploration of the model, we tested the sensitivity of the model to the annual maximum movement rate and compared the expected value of the minimum population size distribution between the default movement rate and two alternative levels of movement: maximum annual movement = 0 (M0) and maximum annual movement = 0.2 (M2).

Interpretation of stochastic population model outputs

To aid in the interpretation of the modelling results in the next section, we provide some examples of common population model outputs and their interpretation.

Southern Pygmy Perch population (abundance) trajectories can be plotted (see Figure 4 for a plot of three conceptual scenario examples). Average trajectories enable comparisons of population outcomes through time between different floodplain regulation scenarios. Specific aspects of the modelled Southern Pygmy Perch populations (e.g. age classes; numbers of adults or recruits) can be examined in this way.

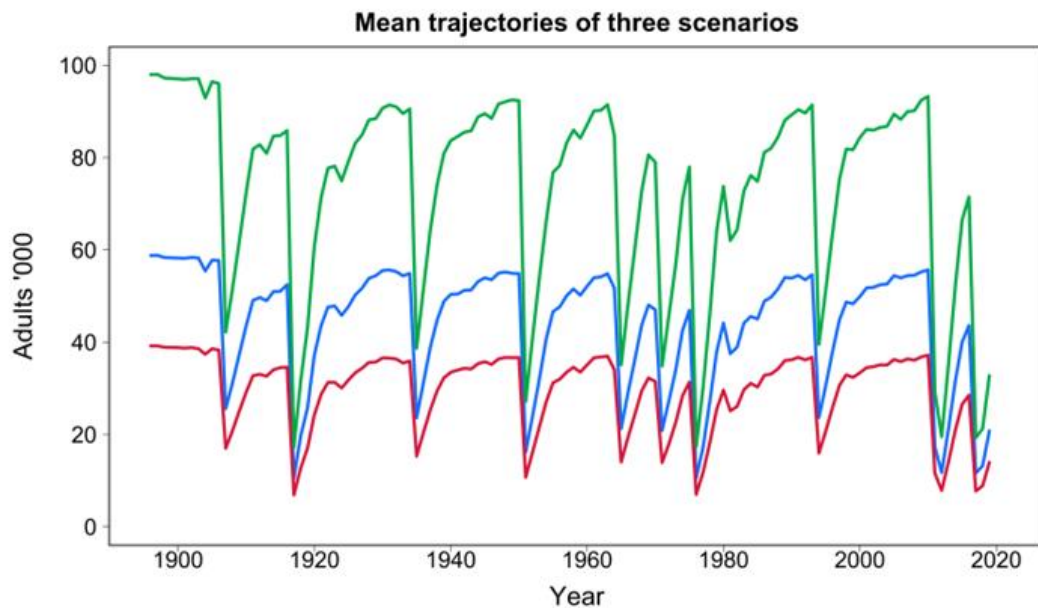


Figure 4. A conceptual example of the mean Southern Pygmy Perch population trajectories of three illustrative scenarios. Note that each line represents an average scenario trajectory, each of which are calculated from many model runs (usually ≥ 1000) that encompass variation from demographic and environmental stochasticity.

While plotting the average trajectory for each scenario provides useful comparative information of average trajectories, this approach does not provide information on the risk of populations declining to low abundances, nor on the variation in model runs of each modelled scenario stemming from random variation around demographic and environmental processes. A common approach to compare various scenarios in terms of risk and variation is to compile the distribution of minimum population sizes for each scenario. The minimum population size from each model run trajectory can be recorded and converted into a cumulative distribution, forming the distribution of the minimum population sizes (see Figure 5 for examples plotted from the conceptual scenarios in Figure 4 above). Graphing these distributions allows a visual comparison of each scenario that provides information on the difference between scenarios in their average minimum population sizes (i.e. the midpoint or expected value of each curve), but also in the distributions of minimum population sizes across all model runs for each scenario (i.e. the shape of each distribution curve). A distribution of minimum population sizes closer to zero represents a higher likelihood of the population declining to a low abundance compared with a distribution further from zero (Figure 5). Moreover, any overlap in minimum population size distribution curves would indicate similarity between scenarios.

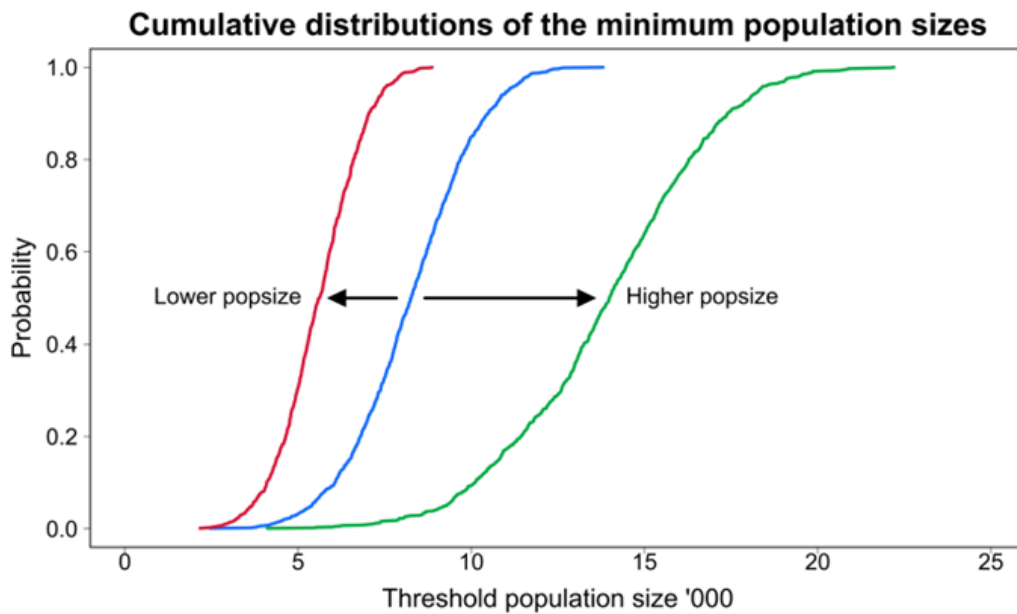


Figure 5. An example of the distributions of minimum Southern Pygmy Perch population sizes for the three hypothetical scenarios in Figure 4. The green line indicates the population outcome with best management outcomes, the blue line the population outcome with management addressing some threats, and the red line the worst population outcome. These distributions represent the likelihood of the population falling below an identified minimum threshold, with theoretical extinction occurring when this falls to zero.

Results

Results of metapopulation modelling conducted in this project are presented in four sections: the first section shows model predictions for a base case scenario, the second and third sections present results for the two levels of stocked fish available (20,000 and 5,000), respectively, and the fourth section presents the Leaky Regulator scenario results. Each section (apart from the base case scenario) contains figures of the mean trajectories of each scenario through time for the total population (summed over eight individual populations), and two figures of risk curves (cumulative distributions of the minimum population size of each trajectory), where the minimum population size is collected from the 5th timestep onwards, and from the 10th timestep onwards for assessing scenario efficacy. Collating responses from the 5th timestep includes some years where stocking is still occurring, which provides some information during this initial phase. Collation of results from the 10th timestep onwards only includes information from the post-stocking period and therefore characterises reintroduction success following cessation of stocking. Each section also contains tables of the expected values and standard deviations of the risk curves for two data collection timeframes. These tables summarise the risk curves for simple comparison. Finally, predicted responses to reintroduction scenarios for each individual population are presented in Appendix 1.

Predicted population dynamics of Southern Pygmy Perch at Gunbower Island to reintroduction strategies: A metapopulation model with eight populations

Base case population trajectory for the total of all eight populations

To predict the dynamics of Southern Pygmy Perch under conditions that would likely provide the best population growth and therefore a good comparison for all other modelling, a base case scenario was run with no flood impacts, low competition, and a focussed stocking strategy of 20,000 individuals for the first 7 years (called Scenario 1 or the base case scenario). Between 2007 and 2022, the predicted number of adult Southern Pygmy Perch increased significantly through time to reach a predicted mean population size of ~110,000 by the end of the study period (Figure 6).

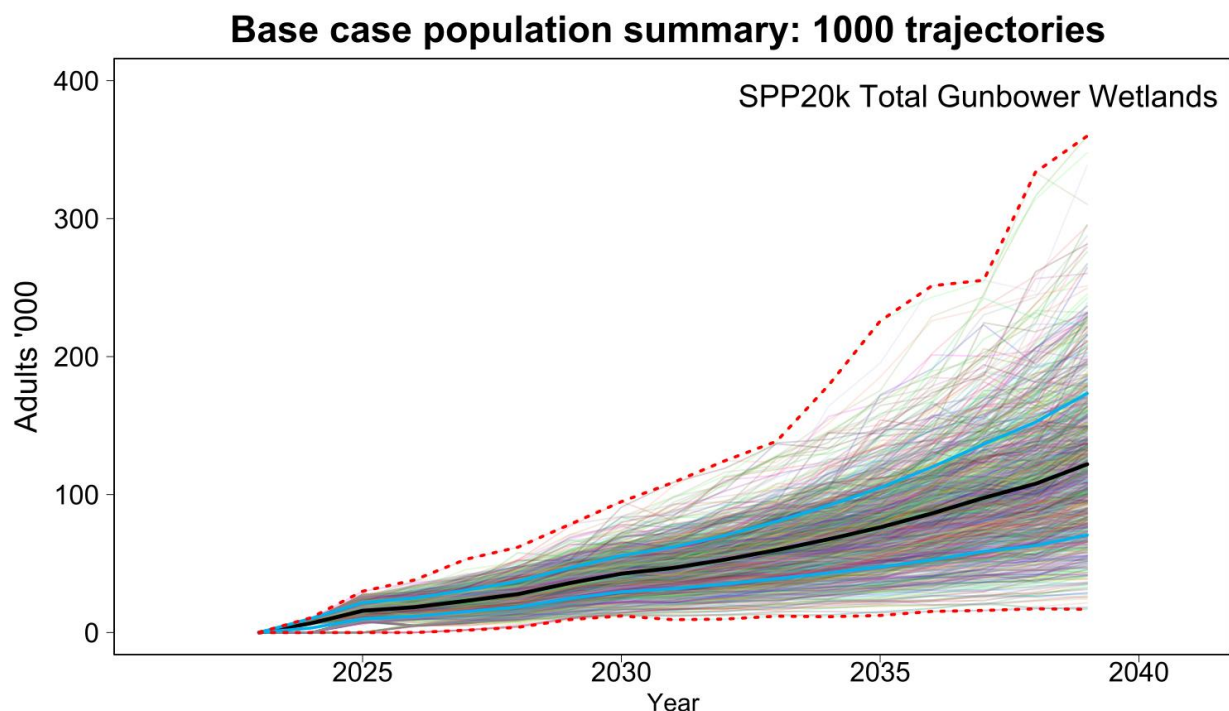


Figure 6. Modelled adult Southern Pygmy Perch trajectories of the base case scenario (Scenario 1) across the whole eight population metapopulation structure at Gunbower Island. The black line shows the mean adult population trajectory of 1000 model runs (each shown with smaller coloured lines), with the associated ± 1 standard deviation as blue lines and the maximum and minimum values as red dashed lines. Here there is no flooding impact modelled, as well as low competition effects and a focussed stocking strategy at 20,000 individuals per year. Note that the black line shown here represents the average scenario trajectory and is conceptually equivalent to one of the lines shown in Figure 4.

Modelled scenarios including stocking of 20,000 fish per year for 7 years

Stocking of 20,000 fish each year produced varied predicted population trajectories depending on the scenario applied (Figure 7; Figure 9). Scenarios with no flood impacts and low competition had the highest predicted population sizes at the end of the study, with upwards of 120,000 fish (Figure 7). Competition and flood impacts both imposed strong effects on population trajectories, with weaker population growth and smaller predicted population sizes at the end of the study (Figure 7). Combinations of these disturbances also caused additive impacts on the populations, with smaller predicted population responses due to increasing flood impacts and

competition. High flood effects and high competition produced the smallest population estimates of any scenario, with population trajectories close to zero throughout the study (Figure 7).

The expected value of the minimum population size (this is the average of the smallest population size of each of the 1,000 model runs for each scenario) compares each scenario directly in terms of the risk of population decline. When 20,000 fish were stocked in each year for seven years and we collate results for the period including stocking (5th timestep onwards), stocking one population at a time produced only slightly higher expected values compared to spreading stocking effort among all populations (compare S1 to S2, and S5 to S6 and so forth, Figure 8, Table 5). This pattern, however, flips when flood impacts are high (compare scenario's S9 to S10 and then S11 to S12 in Table 5; Figure 8).

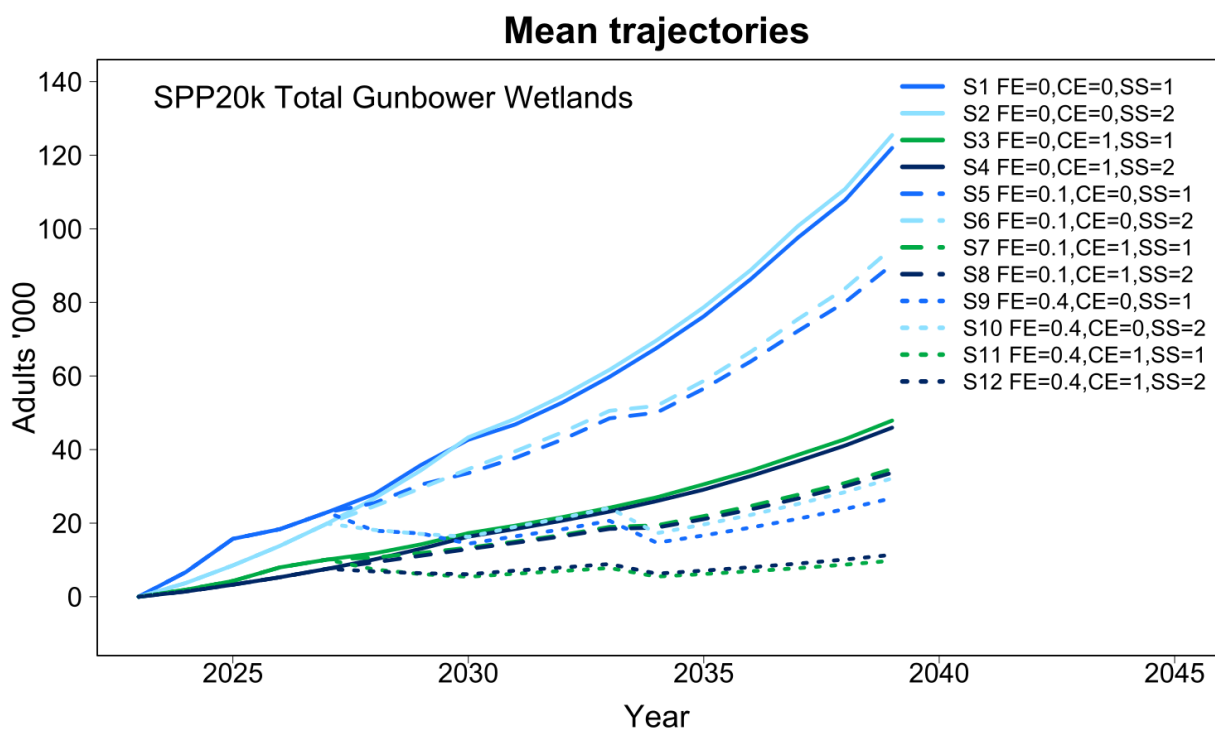


Figure 7. Predicted adult Southern Pygmy Perch responses to 12 modelled scenarios where fish were stocked at a rate of 20,000 per year for seven years. Lines show mean scenario trajectories through time across all modelled populations at Gunbower Island. FE = flood effect (0=none; 1=flood), CE = competition effect (0=none, 1=Competition), and SS = stocking strategy. Stocking strategy 1 denotes focussed strategy and stocking strategy 2 denotes spread strategy.

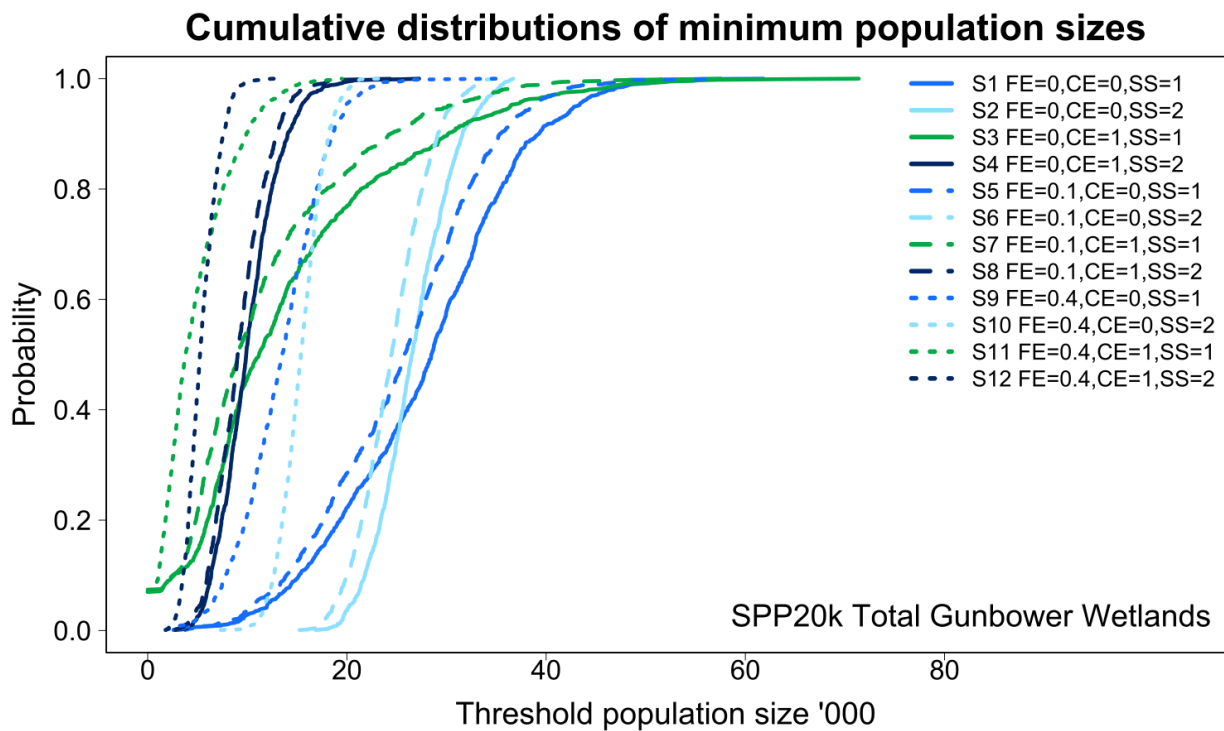


Figure 8. Predicted adult Southern Pygmy Perch responses to 12 modelled scenarios where fish were stocked at a rate of 20,000 per year for seven years. Lines show cumulative distributions of the minimum population size (risk curves) for scenarios across all modelled populations at Gunbower Island. Data were collected from the 5th timestep onwards as a measure of reintroduction success, which includes some years of stocking. FE = flood effect (0=none; 1=flood); CE = competition effect (0=none, 1=competition), and SS = stocking strategy. Stocking strategy 1 denotes focussed strategy and stocking strategy 2 denotes spread strategy.

Table 5. The expected value (EV) of the distribution of minimum population sizes (risk curves) and the associated standard deviation (s.d.) when data were collected from the 5th timestep onwards for scenarios where fish were stocked at a rate of 20,000 per year for seven years. Blue cells denote focussed strategy (SS=1: all effort in one population each year) and white cells denote spread strategy (SS=2).

Scenarios						
Competition effects = 0						
Flood effects	Zero		Low		High	
Scenario	S1	S2	S5	S6	S9	S10
EV	27,833	26,702	25,266	24,573	13,423	15,417
s.d.	9,273	3,799	8,444	3,514	4,223	2,179
Competition effects = 1						
Scenario	S3	S4	S7	S8	S11	S12
EV	14,152	10,126	11,583	9,298	4,755	5,443
s.d.	11,028	3,089	9,050	2,809	3,581	1,582

These patterns change if we collate predicted population responses from the 10th timestep onwards (i.e. after stocking was ceased, Table 6; Figure 9). For this period, the slightly better stocking strategy was to spread stocking effort when competition is low (lower rate of stocking failure), but to concentrate stocking effort when

competition impacts are high (compare the higher rows with the lower rows, Figure 9, Table 6). Again, it was best to spread stocking efforts equally among populations if flood impacts were high (compare scenario's S9 to S10, and compare scenario's S11 to S12, Table 6; Figure 9).

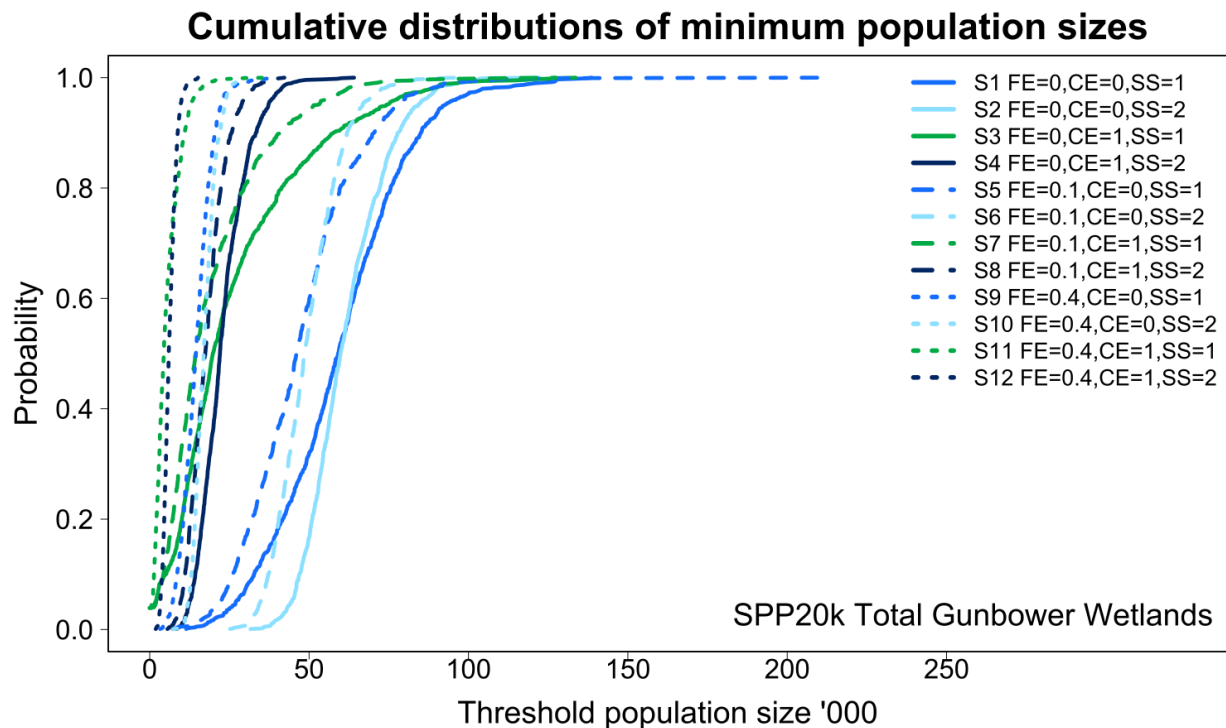


Figure 9. Predicted adult Southern Pygmy Perch responses to 12 modelled scenarios where fish were stocked at a rate of 20,000 per year for seven years. Lines show cumulative distributions of the minimum population size (risk curves) for scenarios across all modelled populations at Gunbower Island. Data were collected from the 10th timestep onwards as a measure of reintroduction success, which does not include any stocking years. FE = flood effect (0=none; 1=flood), CE = competition effect (0=none, 1=Competition), and SS = stocking strategy. Stocking strategy 1 denotes focussed strategy and stocking strategy 2 denotes spread strategy.

Table 6. The expected value (EV) of the distribution of minimum population sizes (risk curves) and the associated standard deviation (s.d.) when data were collected from the 10th timestep onwards for scenarios where fish were stocked at a rate of 20,000 per year for seven years. Blue cells denote focussed strategy (SS=1: all effort in one population each year) and white cells denote spread strategy (SS=2).

Scenarios						
Competition effects = 0						
Flood effects	Zero		Low		High	
Scenario	S1	S2	S5	S6	S9	S10
EV	59,587	61,560	47,274	49,414	14,645	17,227
s.d.	20,634	12,371	17,901	10,020	4,880	3,449
Competition effects = 1						
Scenario	S3	S4	S7	S8	S11	S12
EV	26,760	23,061	19,194	17,956	5,434	6,260
s.d.	22,129	7,600	15,945	5,831	4,106	2,013

Modelled scenarios including stocking of 5,000 fish per year for 7 years

Population trajectories and cumulative distributions of expected minimum population sizes showed similar patterns when 5,000 fish were stocked each year for 7 years when compared to when 20,000 fish were stocked in each year, but the predicted population sizes were much lower (Figure 10; Figure 12: note the differing horizontal axes).

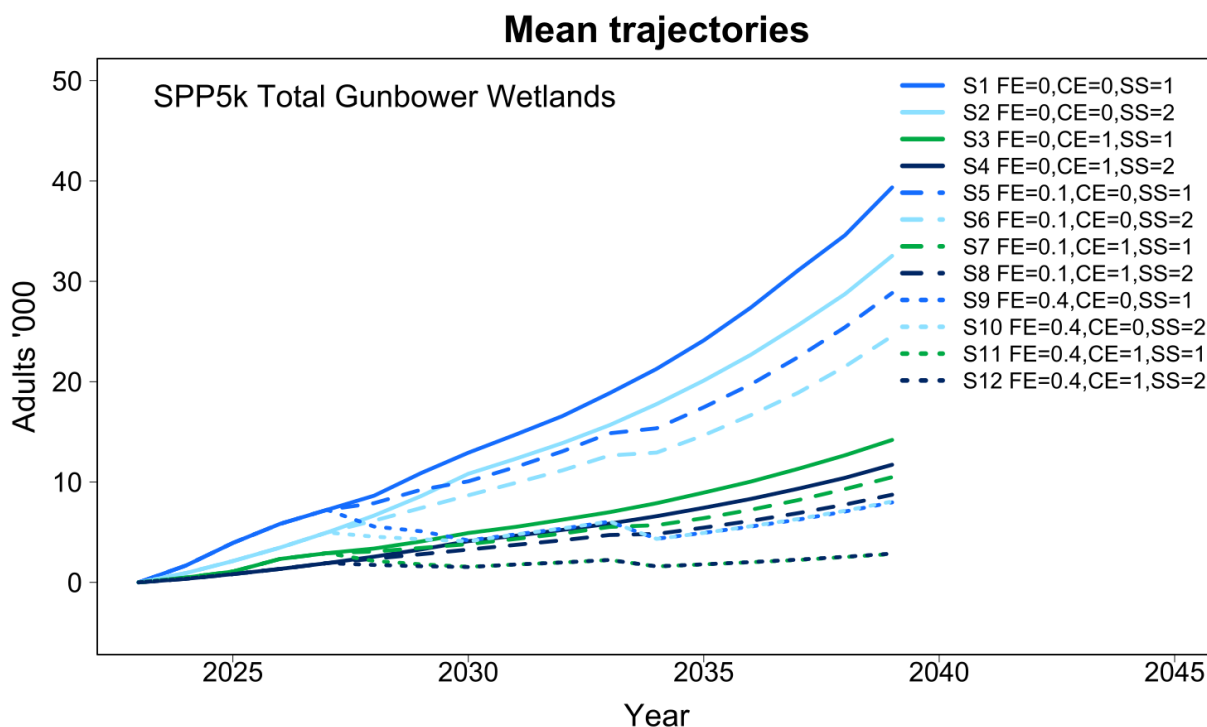


Figure 10. Predicted adult Southern Pygmy Perch responses to 12 modelled scenarios where fish were stocked at a rate of 5,000 per year for seven years. Lines show mean scenario trajectories through time across all modelled populations at Gunbower Island, where FE = flood effect, CE = competition effect and SS = stocking strategy. Stocking strategy 1 denotes focussed strategy and stocking strategy 2 denotes spread strategy.

When fish were stocked at the lower rate (5,000 fish per year), the emergent patterns from among scenario comparisons of the minimum population sizes were also similar to when stocking numbers were higher (i.e. focussed stocking was better), but the relative magnitude of the differences increased (Table 7; Figure 11). There was very little difference between either stocking strategy at low or high competition rates when flood impacts were largest (compare S9 to S10 and S11 to S12, Table 7; Figure 11).

Collating population responses from the 10th timestep onwards when 5,000 fish were stocked each year produced similar patterns among scenarios when compared to responses collated from the earlier 5th timestep (Table 8; Figure 12). The expected values were, however, larger due to the populations increasing in size over time (and therefore collating from the later period increased the average population size). There was also a slightly larger impact of floods on expected values relative to the same scenarios when collating from the earlier 5th timestep (Figure 11-Figure 12, Table 7-Table 8).

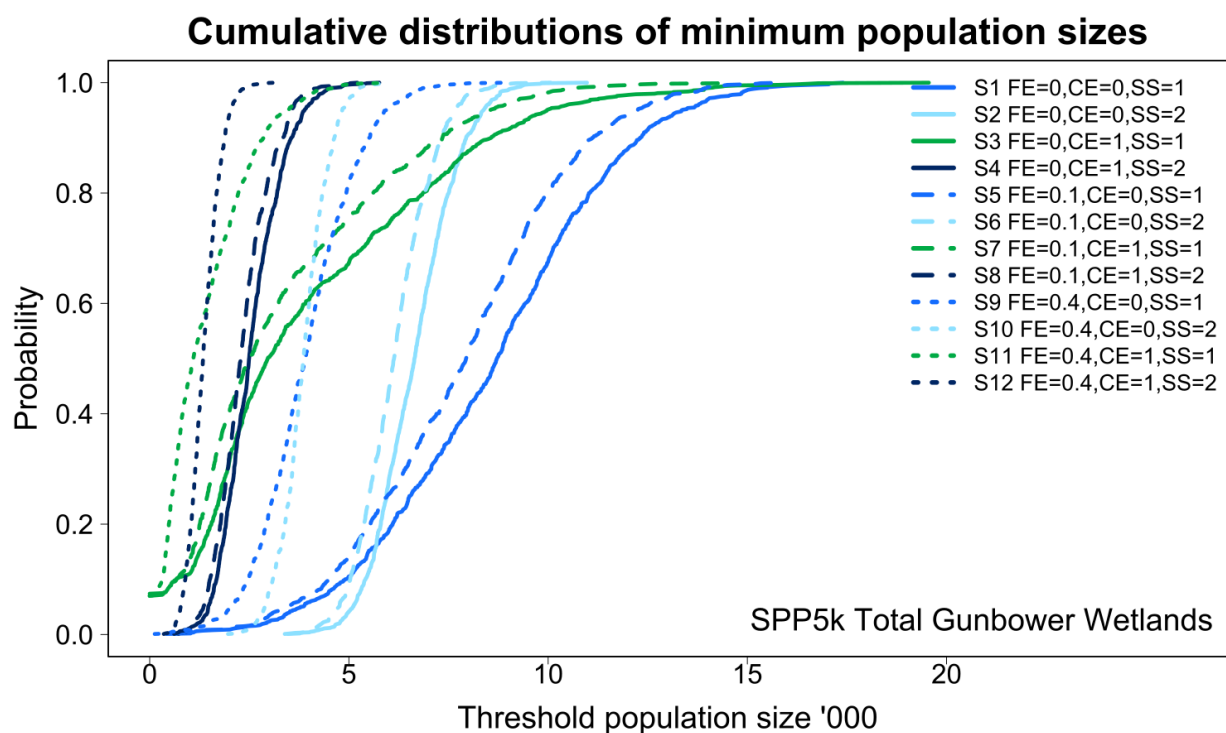


Figure 11. Predicted adult Southern Pygmy Perch responses to 12 modelled scenarios where fish were stocked at a rate of 5,000 per year for seven years. Lines show cumulative distributions of the minimum population size (risk curves) for scenarios across all modelled populations at Gunbower Island. Data were collected from the 5th timestep onwards as a measure of reintroduction success, which includes some years of stocking. FE = flood effect, CE = competition effect and SS = stocking strategy. Stocking strategy 1 denotes focussed strategy and stocking strategy 2 denotes spread strategy.

Table 7. The expected value (EV) of the distribution of minimum population sizes (risk curves) and the associated standard deviation (s.d.) when data were collected from the 5th timestep onwards for scenarios where fish were stocked at a rate of 5,000 per year for seven years. Blue cells denote focussed strategy (SS=1: all effort in one population each year) and white cells denote spread strategy (SS=2).

Scenarios						
Competition effects = 0						
Flood effects	Low		Medium		High	
Scenario	S1	S2	S5	S6	S9	S10
EV	8,634	6,660	7,836	6,148	3,930	3,866
s.d.	2,895	1,012	2,619	905	1,211	592
Competition effects = 1						
Scenario	S3	S4	S7	S8	S11	S12
EV	4,052	2,561	3,351	2,349	1,375	1,369
s.d.	3,215	755	2,633	694	1,056	388

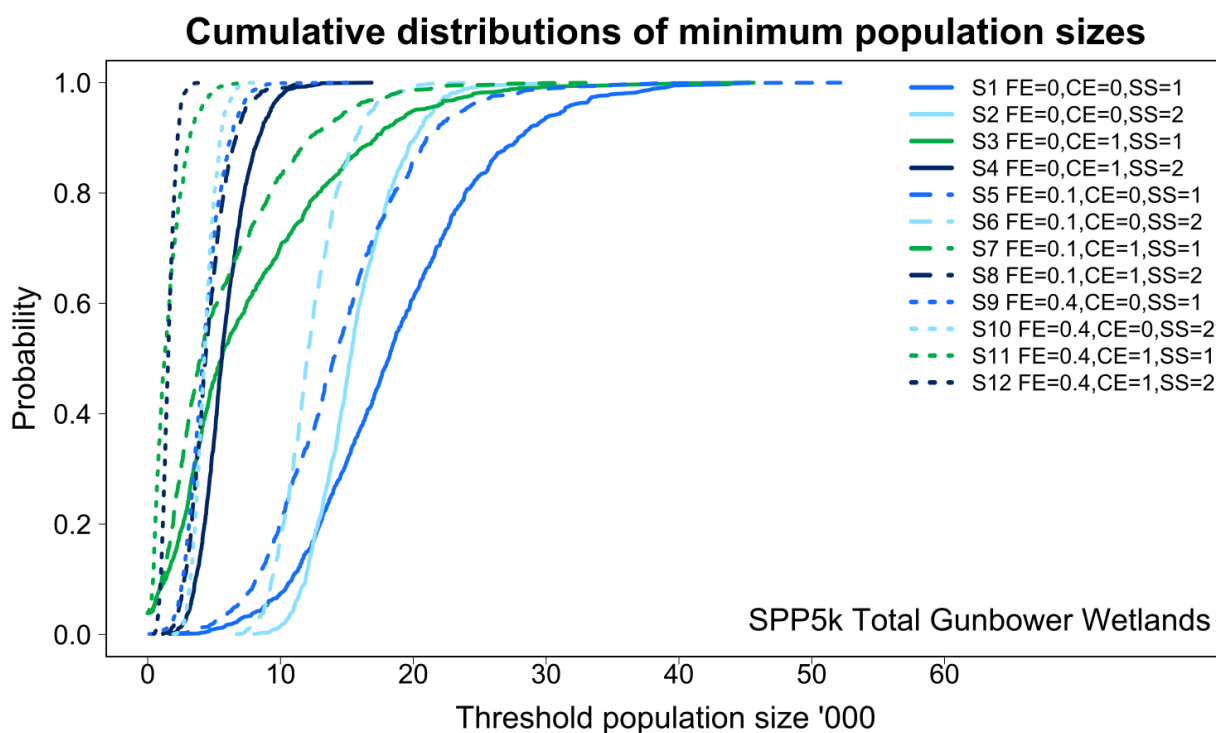


Figure 12. Predicted adult Southern Pygmy Perch responses to 12 modelled scenarios where fish were stocked at a rate of 5,000 per year for seven years. Lines show cumulative distributions of the minimum population size (risk curves) for scenarios across all modelled populations at Gunbower Island. Data were collected from the 10th timestep onwards as a measure of reintroduction success, which does not include any stocking years. FE = flood effect, CE = competition effect and SS = stocking strategy. Stocking strategy 1 denotes focussed strategy and stocking strategy 2 denotes spread strategy.

Table 8. The expected value (EV) of the distribution of minimum population sizes (risk curves) and the associated standard deviation (s.d.) when data were collected from the 10th timestep onwards for scenarios where fish were stocked at a rate of 5,000 per year for seven years. Blue cells denote focussed strategy (SS=1: all effort in one population each year) and white cells denote spread strategy (SS=2).

Scenarios						
Competition effects = 0						
Flood effects	Low		Medium		High	
Scenario	S1	S2	S5	S6	S9	S10
EV	18,792	15,648	14,499	12,347	4,328	4,322
s.d.	6,886	3,241	5,470	2,503	1,477	894
Competition effects = 1						
Scenario	S3	S4	S7	S8	S11	S12
EV	7,819	5,836	5,629	4,588	1,574	1,586
s.d.	6,634	1,878	4,826	1,588	1,189	511

Comparisons of variation around the expected minimum population sizes for almost all scenarios show higher variation when a focussed stocking strategy was implemented than when stocking efforts were spread amongst populations (Table 5 and Table 8). This is due to competition effects affecting stocking success in a given population, and highlights the risk of placing all available fish in one location.

Predicted population dynamics of Southern Pygmy Perch at Gunbower Island to reintroduction strategies including a Leaky Regulator population: A metapopulation model with nine populations

We applied a range of reintroduction scenarios to the nine population, Leaky Regulator metapopulation construct (extra Leaky Regulator population; see section Modelling a 'Leaky Regulator' population), where stocking occurred over 8 years to compare expected outcomes while ensuring appropriate comparisons with base case scenarios.

Leaky regulator scenarios including stocking of 20,000 fish per year for 8 years.

The Leaky Regulator concept modelled produces higher population outcomes in all scenarios tested (Figure 13), where a total of 140,000 fish stocked for the standard eight population metapopulation model and 160,000 fish stocked for the Leaky Regulator nine population metapopulation model. In general, the Leaky Regulator produced no benefit to wetlands upstream (Cameron's Creek, Black Charlie Lagoon and Gunbower Creel upstream of Cohuna – Figure A-19 – Figure A-21); however, there were benefits to both the adjacent wetlands in Reedy Lagoon and Gunbower Creek downstream of Cohuna (Figure A-23 and Figure A-26) and there were partial benefits to the other wetlands in the lower Gunbower Island (Figure A-22; Figure A-24; Figure A-25) depending on the stocking strategy.

The use of a spread stocking strategy together with an extra population meant that the overall number of fish stocked per population was decreased under the Leaky Regulator construct (from ~2860 to 2500 per population). The consequence of fewer stocked fish per population is lower abundances in each individual population (with the exception of the adjacent populations in Reedy Lagoon and Gunbower Creek downstream of Cohuna), with an overall increase in overall metapopulation outcomes in the modelled Leaky Regulator for the spread strategy (see Figure A-19 to Figure A-29).

For the focussed strategy, there were benefits to both the adjacent wetlands in Reedy Lagoon and Gunbower Creek downstream of Cohuna (Figure A-23 and Figure A-26) and smaller benefits to the other wetlands in the lower Gunbower Island (Figure A-22; Figure A-24; Figure A-25). It should be noted that, for the focussed strategies, the Leaky Regulator mean trajectories are one timestep out of sync with the equivalent standard trajectories due to the stocking of the Leaky Regulator first and then the rest of the populations (see for example Figure A-19 a and e).

With 20,000 fish stocked each year for 8 years, the expected values were collated for the period including the stocking period (5th timestep onwards) in Figure 14 and Table 9. The expected values with the added population were substantially higher than those for the scenarios without the added population. The patterns observed in Table 9 are reinforced in

Table 10, where observations are recorded from the 10th timestep, with scenarios including the Leaky Regulator population producing higher expected values (

Table 10; Figure 15).

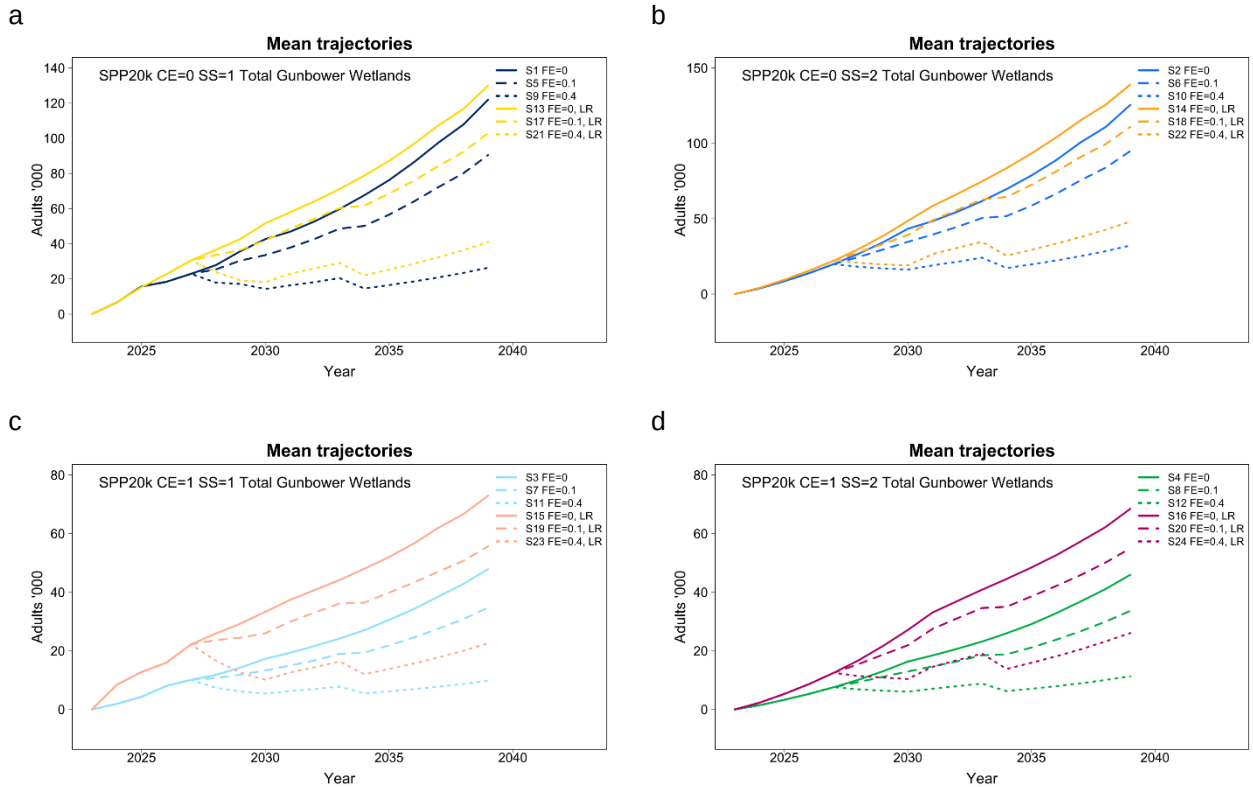


Figure 13. Predicted adult Southern Pygmy Perch responses to six scenarios comparing the Leaky Regulator concept under differing combinations of flood impact, competition effects and stocking strategy. Fish were stocked at a rate of 20,000 per year for seven years under these scenarios. Lines show mean scenario trajectories through time across all modelled populations at Gunbower Island, where FE = flood effect, CE = competition effect and SS = stocking strategy. Stocking strategy 1 denotes focussed strategy and stocking strategy 2 denotes spread strategy.

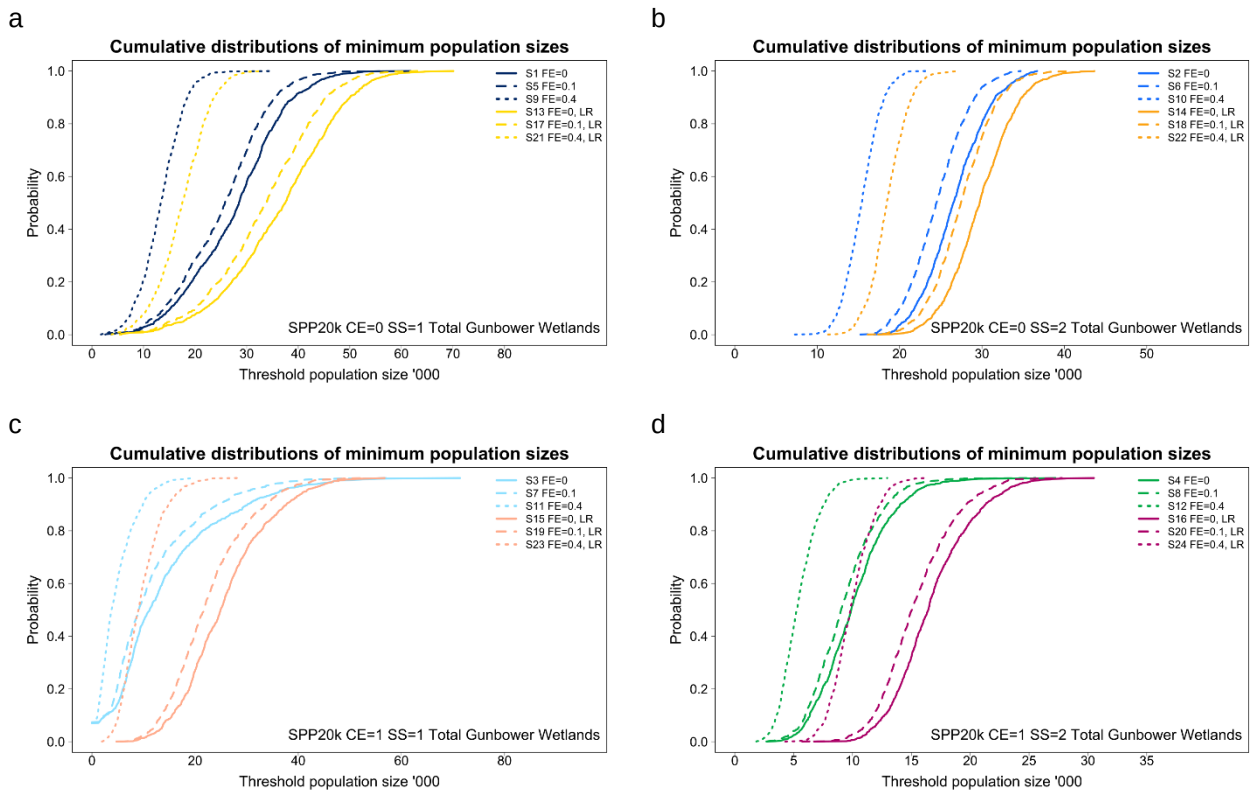


Figure 14. Predicted adult Southern Pygmy Perch responses to six modelled scenarios comparing the Leaky Regulator concept under differing combinations of flood impact, competition effects and stocking strategy. Fish were stocked at a rate of 20,000 per year for seven years under these scenarios. Lines show cumulative distributions of the minimum population size (risk curves) for scenarios across all modelled populations at Gunbower Island. Data were collected from the 5th timestep onwards as a measure of reintroduction success, which includes some years of stocking. FE = flood effect, CE = competition effect and SS = stocking strategy. Stocking strategy 1 denotes focussed strategy and stocking strategy 2 denotes spread strategy.

Table 9. The expected value (EV) of the distribution of minimum population sizes (risk curves) and the associated standard deviation (s.d.) for the Leaky Regulator scenario comparison when data were collected from the 5th timestep onwards. Scenarios here had fish stocked at a rate of 20,000 per year for seven years. Blue cells denote the Leaky Regulator scenarios and white cells show scenarios without the Leaky Regulator population for comparison.

Flood effects							
Zero			Low		High		
Scenario		S1	S13	S5	S17	S9	S21
CE=0, SS=1	EV	27832	36549	25257	33211	13355	17439
	s.d.	9272	10958	8438	10031	4178	5038
Scenario		S2	S14	S6	S18	S10	S22
CE=0, SS=2	EV	26701	29814	24570	27562	15398	18561
	s.d.	3799	4026	3513	3686	2167	2302
Scenario		S3	S15	S7	S19	S11	S23
CE=1, SS=1	EV	10126	16734	9295	15437	5427	9939
	s.d.	3088	3361	2808	3136	1585	1779
Scenario		S4	S16	S8	S20	S12	S24
CE=1, SS=2	EV	14151	25746	11572	22638	4738	9555
	s.d.	11027	8523	9062	7753	3577	3935

Table 10. The expected value (EV) of the distribution of minimum population sizes (risk curves) and the associated standard deviation (s.d.) for the Leaky Regulator scenario comparison when data were collected from the 10th timestep onwards. Scenarios here had fish stocked at a rate of 20,000 per year for seven years. Blue cells denote the Leaky Regulator scenarios and white cells show scenarios without the Leaky Regulator population for comparison.

Flood effects							
Zero			Low		High		
Scenario		S1	S13	S5	S17	S9	S21
CE=0, SS=1	EV	59587.38	70969.45	47397.31	58978.94	14562.24	21964.98
	s.d.	20634.38	21349.33	17938.32	17128.85	4840.19	6423.65
Scenario		S2	S14	S6	S18	S10	S22
CE=0, SS=2	EV	61560.07	74635.96	49290.54	61653.02	17222.52	25451.72
	s.d.	12370.68	12298.71	10159.33	10208.02	3456.08	4365.63
Scenario		S3	S15	S7	S19	S11	S23
CE=1, SS=1	EV	26760.29	43891.91	19153.65	34946.43	5419.33	11992.87
	s.d.	22128.69	15522.38	15950.96	12965.19	4106.76	5327.72
Scenario		S4	S16	S8	S20	S12	S24
CE=1, SS=2	EV	23060.91	40710.51	17969.56	33724.42	6215.84	13774.4
	s.d.	7599.67	7718.82	5832.18	6812.11	1988.94	3298.02

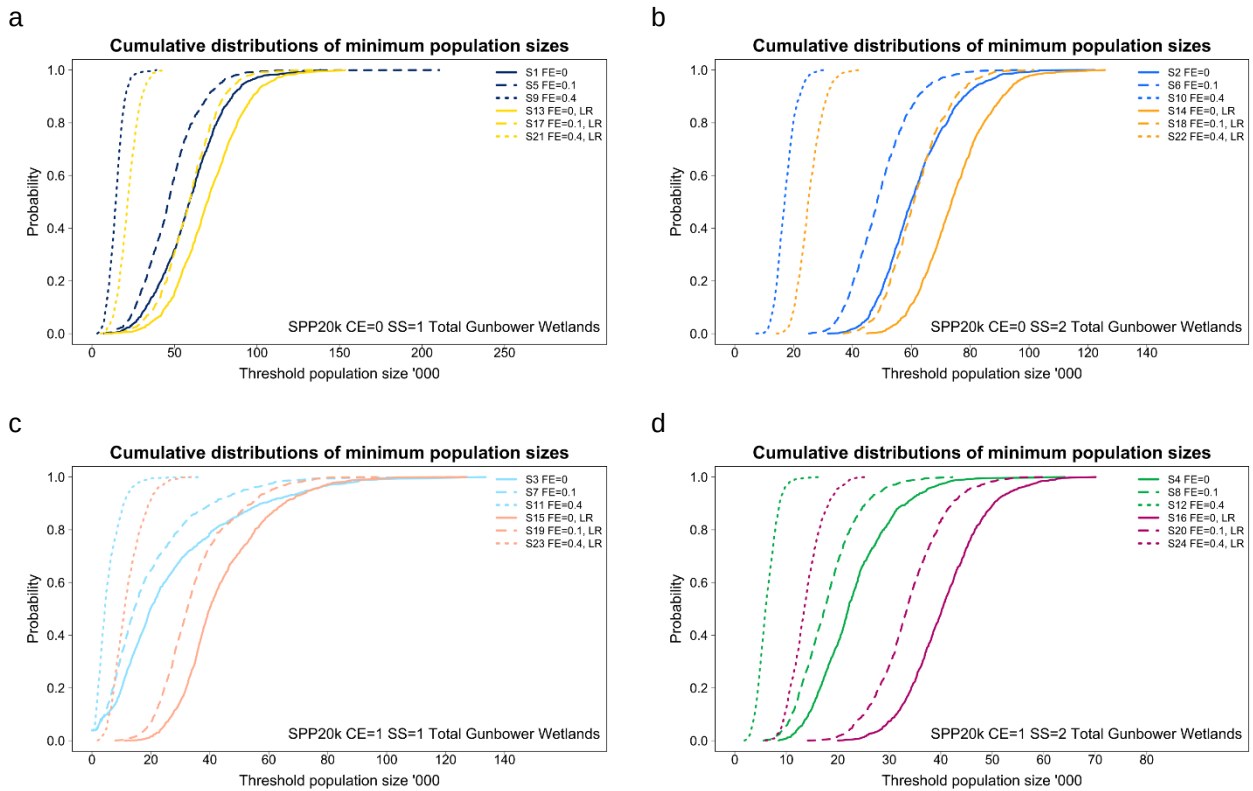


Figure 15. Predicted adult Southern Pygmy Perch responses to six modelled scenarios comparing the Leaky Regulator concept under differing combinations of flood impact, competition effects and stocking strategy. Fish were stocked at a rate of 20,000 per year for seven years under these scenarios. Lines show cumulative distributions of the minimum population size (risk curves) for scenarios across all modelled populations at Gunbower Island. Data were collected from the 10th timestep onwards as a measure of reintroduction success, which does not include any stocking years. FE = flood effect, CE = competition effect and SS = stocking strategy. Stocking strategy 1 denotes focussed strategy and stocking strategy 2 denotes spread strategy.

Leaky Regulator scenarios including stocking of 5,000 fish per year for 8 years

Population trajectories and cumulative distributions of expected minimum population sizes showed similar patterns for the Leaky Regulator concept involving 5,000 fish being stocked each year for 8 years when compared with the scenarios involving 20,000 fish being stocked each year. It should be noted that under the Leaky Regulator nine population metapopulation model a total of 40,000 fish were stocked compared with a total of 35,000 fish stocked for the standard eight population metapopulation model in the previous section.

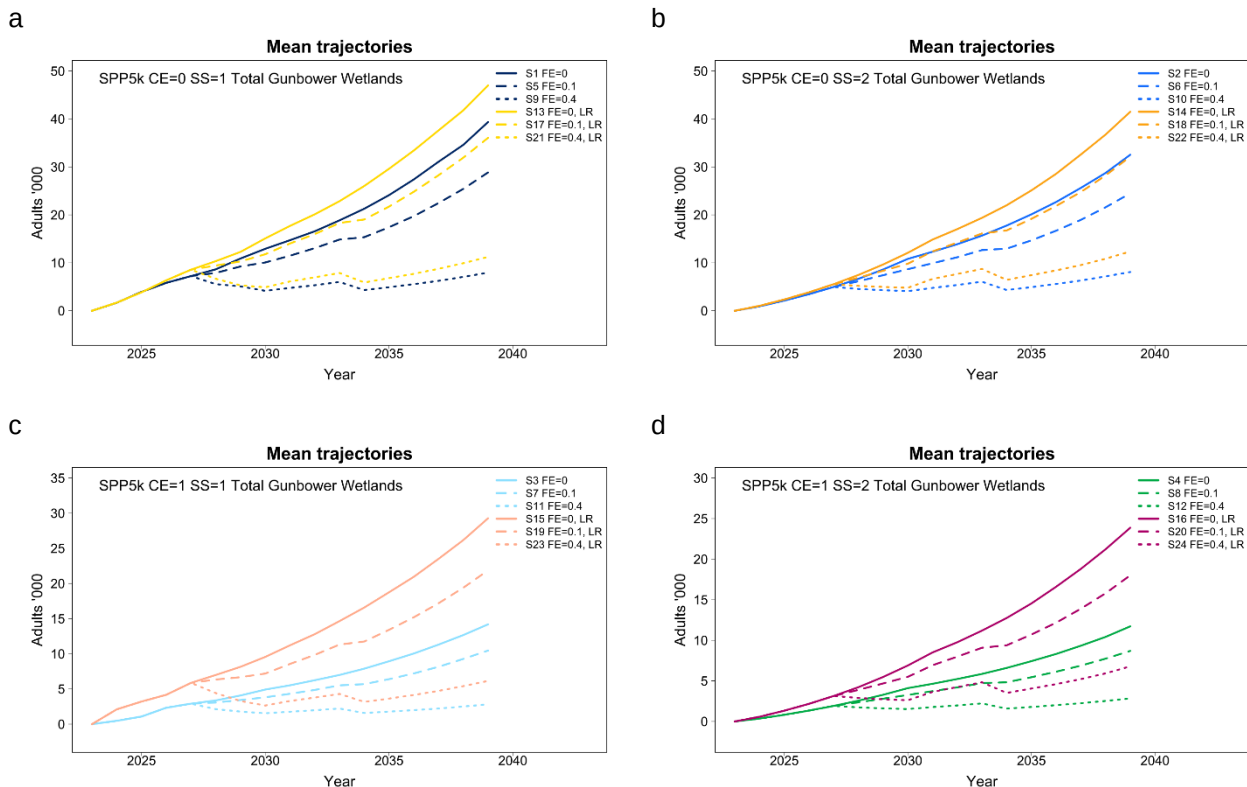


Figure 16. Predicted adult Southern Pygmy Perch responses to six scenarios comparing the Leaky Regulator concept where fish were stocked at a rate of 5,000 per year for seven years. Lines show mean scenario trajectories through time across all modelled populations at Gunbower Island, where FE = flood effect, CE = competition effect and SS = stocking strategy.

Stocking at the lower rate produced population sizes that were much lower than for the higher stocking rate, but scenarios with the added Leaky Regulator modelled still produced higher population sizes than those without the added population (Figure 16 – Figure 18: note the differing horizontal axes). The use of a spread stocking strategy together with an extra population meant that the overall number of fish stocked per population was decreased under the Leaky Regulator construct (from ~715 to ~625 per population). The consequence of fewer stocked fish per population is lower abundances in each individual population (with the exception of the added population of the Leaky Regulator), despite an overall increase in overall metapopulation outcomes in the modelled Leaky Regulator concept (see Figure A-29 to Figure A-38). There are some difference in the focussed strategy when stocking 5,000 fish per population compared with stocking 20,000 fish per population where the Leaky Regulator scenario FE=0, CE=0 produces a lower population size in adjacent populations

(Figure A-33 and Figure A-36) and produces little or no benefit to other lower Gunbower Island populations (Figure A-32; Figure A-34 and Figure A-35).

When only 5,000 fish were stocked in each year for 8 years, the added population produces higher expected values, corresponding with the associated cumulative distributions shifted further to the right, compared with the scenarios without the added population, which is a similar finding to when 20,000 fish were stocked (Table 11 and Table 12).

Comparisons of variation around the expected minimum population sizes for all scenarios show lower variation with an added population (Table 9, Table 10, Table 11 and Table 12).

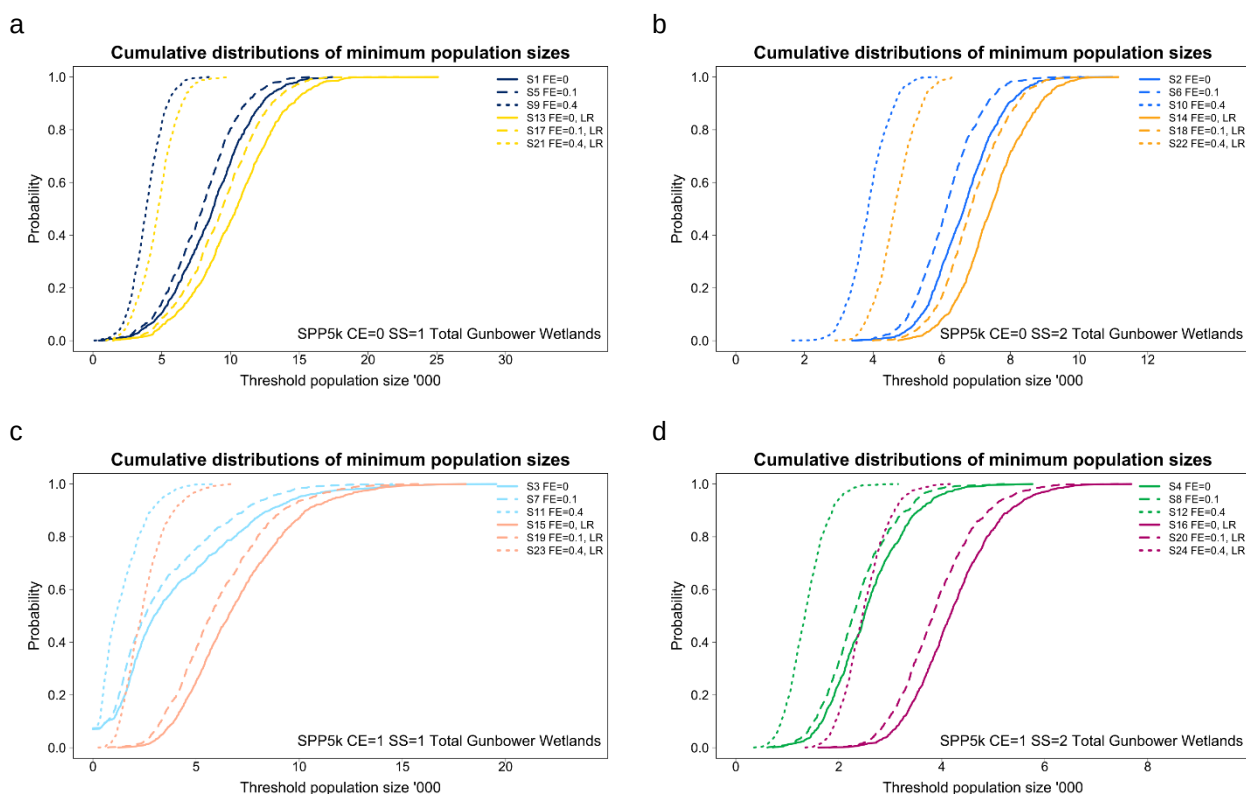


Figure 17. Predicted adult Southern Pygmy Perch responses to six modelled scenarios comparing the Leaky Regulator concept where fish were stocked at a rate of 5,000 per year for seven years. Lines show cumulative distributions of the minimum population size (risk curves) for scenarios across all modelled populations at Gunbower Island. Data were collected from the 5th timestep onwards as a measure of reintroduction success, which includes some years of stocking. FE = flood effect, CE = competition effect and SS = stocking strategy. Stocking strategy 1 denotes focussed strategy and stocking strategy 2 denotes spread strategy.

Table 11. The expected value (EV) of the distribution of minimum population sizes (risk curves) and the associated standard deviation (s.d.) for the Leaky Regulator scenario comparison when data were collected from the 5th timestep onwards. Scenarios here had fish stocked at a rate of 5,000 per year for seven years. Blue cells denote the Leaky Regulator scenarios and white cells show scenarios without the Leaky Regulator population for comparison.

Flood effects							
Zero			Low		High		
Scenario		S1	S13	S5	S17	S9	S21
CE=0, SS=1	EV	8634.46	10335.17	7837.47	9319.51	3914.23	4718.51
	s.d.	2894.93	3245.47	2618.33	2935.54	1207.95	1399.83
Scenario		S2	S14	S6	S18	S10	S22
CE=0, SS=2	EV	6660.08	7467.4	6146.6	6897.33	3862.91	4654.04
	s.d.	1012.18	1044.87	905.06	967.3	582.54	592.38
Scenario		S3	S15	S7	S19	S11	S23
CE=1, SS=1	EV	4051.57	6958.28	3351.23	6075.9	1372.15	2494.53
	s.d.	3215.23	2647.05	2632.43	2390.17	1052.02	1073.79
Scenario		S4	S16	S8	S20	S12	S24
CE=1, SS=2	EV	2560.67	4222	2348.72	3886.65	1364.19	2493.64
	s.d.	755.08	837.66	693.56	783.78	388.77	446.67

Table 12. The expected value (EV) of the distribution of minimum population sizes (risk curves) and the associated standard deviation (s.d.) for the Leaky Regulator scenario comparison when data were collected from the 10th timestep onwards. Scenarios here had fish stocked at a rate of 5,000 per year for seven years. Blue cells denote the Leaky Regulator scenarios and white cells show scenarios without the Leaky Regulator population for comparison.

Flood effects							
Zero			Low		High		
Scenario		S1	S13	S5	S17	S9	S21
CE=0, SS=1	EV	18792	22807	14490	17980	4301	5886
	s.d.	6885	7683	5495	6102	1432	1770
Scenario		S2	S14	S6	S18	S10	S22
CE=0, SS=2	EV	15648	19348	12353	15877	4309	6439
	s.d.	3241	3609	2516	2980	886	1183
Scenario		S3	S15	S7	S19	S11	S23
CE=1, SS=1	EV	7819	14545	5623	10964	1567	3154
	s.d.	6634	6363	4782	5043	1181	1472
Scenario		S4	S16	S8	S20	S12	S24
CE=1, SS=2	EV	5835	11153	4588	8862	1575	3505
	s.d.	1877	2759	1591	2170	498	856

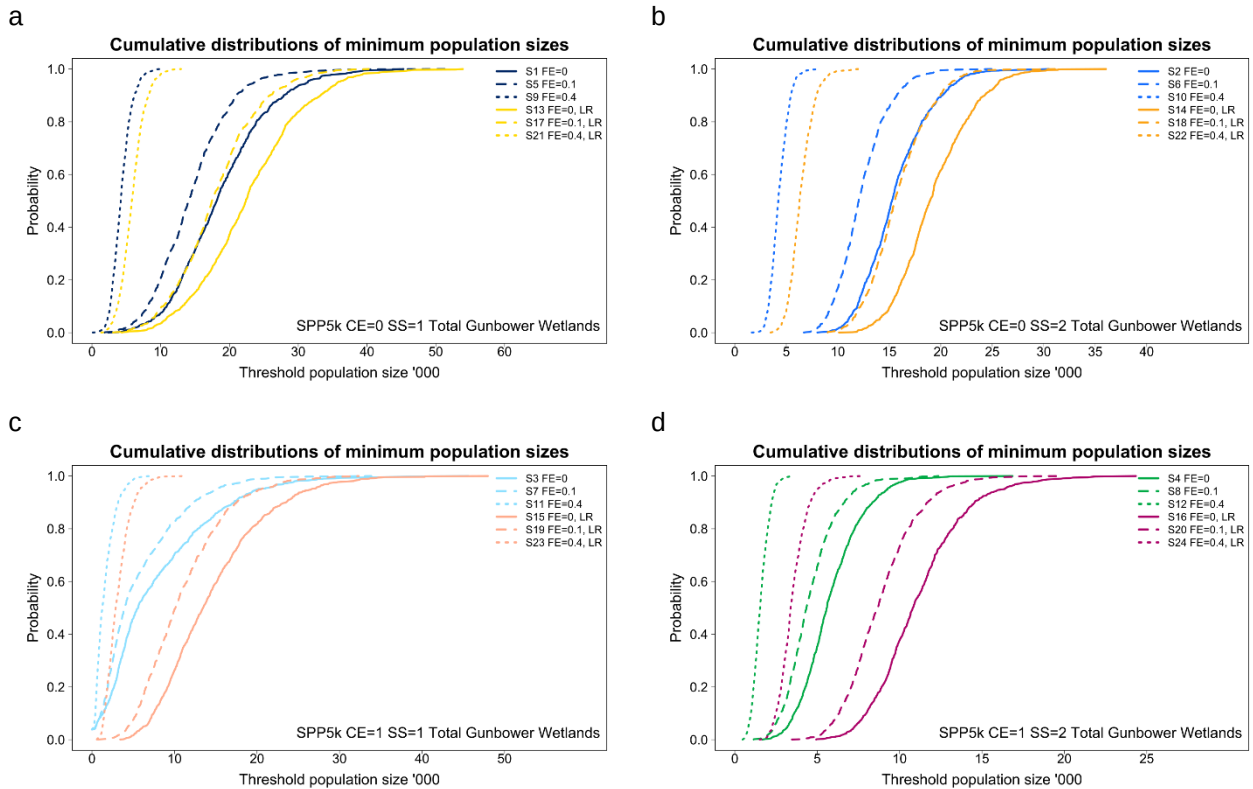


Figure 18. Predicted adult Southern Pygmy Perch responses to six modelled scenarios comparing the Leaky Regulator concept where fish were stocked at a rate of 20,000 per year for seven years. Lines show cumulative distributions of the minimum population size (risk curves) for scenarios across all modelled populations at Gunbower Island. Data were collected from the 10th timestep onwards as a measure of reintroduction success, which does not include any stocking years. FE = flood effect, CE = competition effect and SS = stocking strategy. Stocking strategy 1 denotes focussed strategy and stocking strategy 2 denotes spread strategy.

Sensitivity to movement assumptions

Table 13. Model sensitivity to movement rates, using the expected value of the minimum population size distribution from the default scenario with movement = 0.1, and percentage change in the equivalent expected value for movement = 0 and movement = 0.2 with stocking 20,000 Southern Pygmy Perch.

Scenarios						
Competition effects = 0						
Flood effects	Low		Medium		High	
Scenario	S1	S2	S5	S6	S9	S10
M=0.1	59,587	61,560	47,274	49,414	14,645	17,227
M=0	4%	2%	0%	0%	-1%	1%
M=0.2	-3%	-3%	-1%	-1%	1%	0%
Competition effects = 1						
Scenario	S3	S4	S7	S8	S11	S12
M=0.1	26,760	23,061	19,194	17,956	5,434	6,260
M=0	-2%	3%	-6%	3%	-4%	1%
M=0.2	-5%	-2%	-2%	-1%	0%	-1%

Table 14. Model sensitivity to movement rates, using the expected value of the minimum population size distribution from the default scenario with movement = 0.1, and percentage change in the equivalent expected value for movement = 0 and movement = 0.2 with stocking 5,000 Southern Pygmy perch.

Scenarios						
Competition effects = 0						
Flood effects	Low		Medium		High	
Scenario	S1	S2	S5	S6	S9	S10
M=0.1	18,792	15,648	14,499	12,347	4,328	4,322
M=0	0%	2%	-2%	1%	-2%	1%
M=0.2	-1%	-1%	0%	1%	-1%	1%
Competition effects = 1						
Scenario	S3	S4	S7	S8	S11	S12
M=0.1	7,819	5,836	5,629	4,588	1,574	1,586
M=0	-4%	2%	-7%	0%	-5%	1%
M=0.2	-4%	-2%	-2%	-1%	-2%	0%

Changing the maximum annual rate of movement from the default value of 0.1 to 0 (no movement) or 0.2 (doubling the maximum annual movement rate) led to only minor changes in total estimated population abundances (ranging from a 7% reduction to a 4% increase) (Table 13 and Table 14). When stocking 20,000 Southern Pygmy Perch per year, the impacts of altered movement were greatest under low flood effects or when competition occurred (Table 13). In general, doubling the maximum rate of movement reduced population abundances, whereas allowing no movement (except on flood events) led to both increases and decreases in population abundances (Table 13). The proportional effects of altered movement were similar when stocking 5,000 Southern Pygmy Perch per year (Table 14). These results suggest that metapopulation projections are relatively insensitive to uncertainty in the rate of movement.

Discussion

An existing population model for Southern Pygmy Perch (Todd et al. 2017), which was developed with the best available data and knowledge, was reviewed and found to be suitable to inform the stocking of this species into sites on Gunbower Island as part of a reintroduction project. There were minor updates to knowledge, parameterisation specific to the Gunbower sites, and conversion into a metapopulation model construct to accommodate movements between sites. Two sets of modelling were completed in this project. The first tested two alternative stocking rates (20,000 and 5,000 fish per annum, totals of 140,000 and 35,000, respectively). The second tested two stocking strategies: strategy 1 that spread stocked fish across all populations each year, and strategy 2 that focussed on stocking one population per year in a sequential manner. Both stocking rates and stocking strategies were tested at multiple hypothesised levels of competition with other species, and with different levels of flood effects on movement. Sensitivity analysis was used to determine the influence on model outcomes of uncertainty in connectivity and movement rates between populations. We also tested a 'Leaky Regulator' concept, repeating the annual stocking rates, stocking strategies, competition and flood effects with the exception that the Leaky Regulator model received a total of 160,000 stocked fish (20,000 fish per annum) and 40,000 stocked fish (5,000 per annum), and with an added smaller population (the Leaky Regulator).

The modelling results indicate that reintroducing Southern Pygmy Perch to the Gunbower Island will be successful; however, the results were sensitive to the number of fish available for stocking, key assumptions around competition, flood effects, and the timeframes over which reintroduction success is assessed. This suite of modelling provides a solid scientific basis and key results from which informed decisions can be made to enhance the success of this introduction program:

- Modelled outcomes (abundances and risks of declines) were highly sensitive to the number of fish available for stocking. The values of 5,000 and 20,000 fish stocked are plausible lower and upper bounds on the number of fish available for stocking per year, and model outputs at these two levels highlighted significant benefits of stocking more fish (larger population sizes, lower likelihoods of population declines, and a lower likelihood of reintroduction failure). However, stocking at the lower rate of 5,000 fish per year was still predicted to support a successful reintroduction, albeit with higher risks of population declines and an increased likelihood of reintroduction failure.
- Stocking strategies (spread: across all populations each year; or focussed: sequentially one population per year) produced different outcomes depending on the level of competition, flood effect and the number of fish stocked. Generally, the spread strategy produced higher expected values than the focussed strategy when stocking 5,000 fish per annum. However, when stocking the higher 20,000 fish per annum, the focussed strategy produced higher expected values at low competition levels and also when competition was high and flood effects were high. The spread strategy highlights the potential benefits of spreading risks at lower stocking rates; however, there is some benefit in considering a focussed strategy at higher stocking rates particularly if competition can be removed prior to a stocking event. Reducing competition for the spread strategy may not be feasible if managers aim to remove competing species (e.g. Carp, Eastern Gambusia and Redfin Perch) from wetlands prior to stocking due to the logistical challenge of conducting species removals across all locations every year for 7 years. Whereas reducing competition one population at a time may be achievable, and if higher stocking rates are also achievable, the modelling

indicates that the focussed strategy is likely to produce higher expected values and therefore less likely to fail. It is also worth noting that competition effects the variation in the expected value, with higher variation from competition effects for the focussed strategy, an indicator that some trajectories produce lower population sizes. This highlights the risk of placing all available fish in one location if competition cannot be removed.

- A change in the magnitude of flood effects from 0 to 0.1 to 0.4 led to reductions in total population abundances. The intensity of this effect depends on both the magnitude of flood impacts and the frequency of floods. All scenarios included three flooding events. It should be noted that flooding may remove some fish from stocked sites, but these fish may contribute to populations or establish occurrences elsewhere, including outside Gunbower Island. The addition of the Gunbower Creek upstream of Cohuna population demonstrates this possible outcome; this population is only connected through flood and is not stocked; however, a population becomes established following flood connections.
- Modelled outcomes for Southern Pygmy Perch were sensitive to stocking failure, with stocking failure hypothesised to occur due to competition with other species (within individual wetlands). Characterised in this way, the occurrence of stocking failure (competition effects = 1 in the results) substantially reduced expected population abundances and therefore increases the risk of reintroduction failure particularly at lower stocking rates. Stocking failure causes reduced population outcomes from reintroductions, and removing competition (the hypothesised cause of stocking failure) prior to any releases acts to improve population outcomes even with uncertainty around flood effects.
- Modelled outcomes for Southern Pygmy Perch were relatively insensitive to uncertainty in the maximum annual rate of movement, a parameter that was not known with certainty. Changing this parameter from its default value (0.1) to values of 0 (no movement) or 0.2 (doubled maximum rate of movement) resulted in average population abundances within 7% of the default scenario, with differences often near 0 or 1%. The lack of sensitivity is due to the generally low rates of movement specified by Southern Pygmy Perch experts at the workshop and low rates of connectivity between populations. This low connectivity is caused by the existence of regulators between many populations, which are often closed most months of each year – therefore limiting total movement even when movement rates were doubled.

Including an additional small Leaky Regulator population was predicted to benefit the reintroduction program. Although this population did not significantly contribute to populations either side of the regulator, the total population size was substantially higher, with lower risks of the population being small when a Leaky Regulator population was included. The added population supports the reintroduction outcome, as predicted by the metapopulation theory that adding more populations lowers risk (Burgman et al.1993). Also, the hypothesised absence of competition in the added population allows this population to perform better than the other modelled wetlands, which experience higher levels of competition. Consequently, the outcomes for fish stocked into the Leaky Regulator are generally better than if those same fish were stocked into other populations (as would occur in a scenario without the Leaky Regulator population). Nonetheless, the Leaky Regulator outcomes may depend on whether the small pool was totally dried beforehand removing all competition. If remnant pools remain prior to the introduction of Southern Pygmy Perch into Leaky Regulator habitats, they may contain alien fish and therefore affect reintroduction outcomes.

- The Leaky Regulator concept was predicted to be effective in improving metapopulation outcomes, but not via the hypothesised mechanism of contributing more fish to adjacent populations (which does occur

but at low levels). Rather, the predicted benefits of the Leaky Regulator population can be attributed to the addition of a wetland with no competition effects. This finding supports a general metapopulation concept that adding more populations reduces the overall risk of extinction.

- Population outcomes for Southern Pygmy Perch were sensitive to flood impacts under scenarios with and without a Leaky Regulator population. However, the inclusion of the Leaky Regulator population buffered these negative flood effects, such that the expected minimum population size under a high flood impact ($FE = 0.4$) and with a Leaky Regulator population was more than double that of an equivalent scenario without this added population.

Recommendations

Several recommendations emerge from both the modelling results and the modelling process (specialist workshop, site analysis and discussions) that would be likely to improve the outcomes of the reintroduction of Southern Pygmy Perch on Gunbower Island. We identify several strategies to support reintroductions of Southern Pygmy Perch into wetlands within Gunbower Forest and highlight several opportunities and potential risks associated with these reintroductions. Modelled outcomes for Southern Pygmy Perch were highly sensitive to the number of fish stocked per year and the risk of stocking failure (hypothesised to occur due to competition with other species), and moderately sensitive to the magnitude of flood effects and stocking strategy (spread versus focussed reintroductions). Importantly, the benefits of each stocking strategy were dependent on the magnitude of flood effects, with spread reintroductions performing best at low stocking rates and focussed reintroductions performing best (mostly) at high stocking rates, but in particular with low competition. We also provide direction for a program to monitor the progress of introduced populations. Based on these findings, we provide the following recommendation:

Population modelling

- It is recommended that the population model continue to be used as part of an adaptive management cycle. As actions are undertaken, and population responses measured, the model can be updated and used to inform ongoing management strategies and continue to be a basis for management decisions.
- It is recommended that data are collected to reduce uncertainty in key model parameters such as fecundity and survival rates (estimated from Tasmanian fish) and the interaction between density, habitat quality, competition, and floods have on these parameters, acknowledging that collection of detailed life history data may be impractical. Captive breeding programs would improve knowledge of fecundity and early life survival.

Reintroduction strategies

- Stocking more fish per year was consistently associated with larger population sizes, lower likelihoods of population declines, and a lower likelihood of reintroduction failure. Therefore, reintroduction strategies should aim to maximise the number of fish stocked in each year. This may include more 'production' sites or fish from other sources (e.g. Victoria's new conservation hatchery).
- The addition of a population under the Leaky Regulator concept benefits overall population outcomes. The recommended option is to stock this population first in any sequence.

- Flood events had a strong influence on modelled population outcomes, so the risk of floods (and the spatial distribution of flood impacts) should be considered when determining stocking strategies and locations for stocking. Stocked populations should be monitored immediately following any floods.
- Stocking failure (hypothesised to occur due to competition with introduced species) substantially reduced the likelihood of reintroduction success, which suggests that introduced species should be removed from reintroduction sites prior to stocking (acknowledging that such removals may be logistically challenging). An intensive monitoring program is recommended following initial stocking events to determine the fate of stocked fish and the reasons for stocking success or failure.
- A simultaneous stocking strategy (spreading the available fish equally among populations each year) is a low-risk strategy and is recommended if lower numbers of fish are stocked each year or competition is high and cannot be altered. A staggered stocking strategy (targeting one location each year) provides opportunities to implement location-specific interventions (e.g. removing introduced species) and is recommended if higher numbers of fish are stocked each year.

Monitoring

- A monitoring program should be designed specific to the objectives of the Southern Pygmy Perch reintroduction strategy, in addition to (or added to) existing fish monitoring programs (e.g. Brown and Whiterod 2021; Bloink et al. 2023).
- All populations should be monitored, and data collected on occurrence, abundance, and annual recruitment. Sampling should use targeted methods (e.g. fyke nets, bait traps and seine netting) at reintroduction sites and other sites across Gunbower Island. Monitoring at spatial scales beyond Gunbower should be included in the strategy, especially following flooding, because flooding may distribute fish to other locations. Monitoring techniques need to be considered, because changed population densities may affect detectability. The experience of Wedderburn et al. (2019) may be useful here, and the inclusion of e-DNA may be an option.
- Modelling results should be used to inform monitoring, particularly in exploring the likely population densities over time (numbers and site areas and habitats), because this will help determine the likelihood of detection and can be used to design the appropriate sampling regime and effort. A change in the magnitude of flood effects will also greatly impact fish densities, and therefore the detection of successful population establishment or even occurrence of Southern Pygmy Perch.

General recommendations that may improve population establishment

- Reintroduction success will be predicted more reliably following an assessment of predation and competition likelihood (fish and birds in conjunction with habitat cover) at each site. This assessment should include lists of all other fish species present at a site.
- As Southern Pygmy Perch populations appear sensitive to competition, options to reduce likely impacts at stocking locations should be considered. A key option is the removal of introduced species, especially Carp and Redfin perch; the removal of Eastern Gambusia and Oriental Weatherloach is expected to be difficult.
- Consideration should be given to the use of screens to exclude Carp from reintroduction sites (or areas within these sites).

- The establishment of vegetated habitat plots at reintroductions sites could be beneficial, as demonstrated at some dam stocking sites (e.g. the dog park).
- There are several projects that could help improve population establishment, which relate to key elements of the model (see Appendix 2: New information or worthwhile future projects).

References

- Akçakaya, H. R. (1991). A method for simulating demographic stochasticity. *Ecological Modelling* **54**, 133–136.
- Allee, W. C. (1931). *Animal Aggregations. A study in General Sociology*. University of Chicago Press, Chicago, USA.
- Berry, D. A. and Lindgren, B. W. (1996). *Statistics: Theory and Methods, Second Edition*. Wadsworth Publishing Company, Belmont, California, USA.
- Bice, C. and Ye, Q. (2007). *Monitoring threatened fish communities on Hindmarsh Island, in the Lower Lakes of the River Murray, South Australia, in the summers of 2006 and 2007 with reference to baseline data from 2005*. SARDI Publication No. F2007/000551-2, South Australian Research and Development Institute (Aquatic Sciences), Adelaide, SA.
- Bloink, C., Halliday, B.T., Linn, M., Walker, G. and Lewis, S. (2023). *The Living Murray: Gunbower Icon Site Fish Condition Monitoring 2023*. Report to North Central CMA, Ecology Australia Pty. Ltd., Fairfield, Victoria.
- Brown, P. and Whiterod, N. (2021). *Fish Monitoring at Gunbower Island 2020-21*. Draft Final report prepared in conjunction with North Central CMA by Fisheries and Wetlands Consulting and Aquasave-Nature Glenelg Trust, FWC Publication 01/2021, September.
- Burgman, M. A., Ferson, S. and Akçakaya, H. R. (1993). *Risk Assessment in Conservation Biology*. Chapman and Hall, London, UK.
- Cadwallader, P. L. and Backhouse, G. N. (1983). *A Guide to the Freshwater Fishes of Victoria*. Government Printer, Melbourne, Victoria.
- Caswell, H. (2001). *Matrix Population Models, Second Edition*. Sinauer Associates: Sunderland, Massachusetts, USA.
- Chessman, B. C. (2013). Identifying species at risk from climate change: Traits predict the drought vulnerability of freshwater fishes. *Biological Conservation* **160**, 40–49
doi:10.1016/j.biocon.2012.12.032
- Chessman, B. C. and Williams, W. D. (1974). Distribution of fish in inland saline waters in Victoria, Australia. *Australian Journal of Marine and Freshwater Research* **25**, 167–172.
- Cole, T. L., Hammer, M. P., Unmack, P. J., Teske, P. R., Brauer, C. J., Adams, M. and Beheregaray, L. B. (2016). Range-wide fragmentation in a threatened fish associated with post-European settlement modification in the Murray–Darling Basin, Australia. *Conservation Genetics* **17**, 1377–1391
doi:10.1007/s10592-016-0868-8
- Cook, B. D., Bunn, S. E. and Hughes, J. M. (2007). Molecular genetic and stable isotope signatures reveal complementary patterns of population connectivity in the regionally vulnerable southern pygmy perch (*Nannoperca australis*). *Biological Conservation* **138**, 60–72.
- Crook, D. A., Reich, P., Bond, N. R., McMaster, D., Koehn, J. D. and Lake, P. S. (2010). Using biological information to support proactive strategies for managing freshwater fish during drought. *Marine and Freshwater Research* **61**, 379–387 doi:10.1071/MF09209
- Dexter, T., Bond, N., Hale, R. and Reich, P. (2014). Dispersal and recruitment of fish in an intermittent stream network. *Austral Ecology* **39**, 225–235 doi:10.1111/aec.12064
- Evans, M., Hastings, N. and Peacock, B. (1993). *Statistical Distributions, Second Edition*. John Wiley and Sons, New York, USA.
- Ferson, S., Ginzburg, L. R. and Silvers, A. (1989). Extreme event risk analysis for age-structured populations. *Ecological Modelling* **47**, 175–187.
- Gaston, K. J. and Lawton, J. H. (1987). A test of statistical techniques for detecting density dependence in sequential censuses of animal populations. *Oecologia* **74**, 404–410.
- Gompertz, B. (1825). On the nature of the function expressive of the law of human mortality, and on a new mode of determining the value of life contingencies. *Philosophical Transactions of the Royal Society* **115**, 515–585.

- Hammer, M., Doube, J. and Roberts, M. (2000). *Conservation of the variegated pygmy perch: Freshwater fish survey of lower south eastern South Australia*. Report to National Parks and Wildlife SA and the South Eastern Water Conservation and Drainage Board, Adelaide.
- Hammer, M. (2001). *Molecular systematics and conservation biology of the southern pygmy perch Nannoperca australis (Günther, 1861) (Teleostei: Percichthyidae) in south-eastern Australia*. Honours Thesis, Adelaide University, Adelaide.
- Hammer, M. (2002). *Recovery outline for the Southern Pygmy Perch in the Mount Lofty Ranges, South Australia*. Department of Environment and Biology, University of Adelaide and Native Fish Australia (SA) Inc.
- Hammer, M. P., Unmack, P.J., Adams, M., Johnson, J. B. and Walker, K. F. (2010). Phylogeographic structure in the threatened Yarra pygmy perch *Nannoperca obscura* (Teleostei: Percichthyidae) has major implications for declining populations. *Conservation Genetics* **11**, 213–223.
- Hassell, M.P. (1986). Detecting density-dependence. *Trends in Ecology and Evolution* **1**, 90–93.
- Higham, J., Ye, Q. and Smith, B. (2005). *Murray–Darling Basin drought monitoring: Monitoring small-bodied fish in the lower Murray during and after drought conditions in 2003-2004*. SARDI Research Report Series No. 73. SARDI Aquatic Sciences, Adelaide.
- Hilborn, R. and Walters, C.J. (1992). *Quantitative Fisheries Stock Assessment: Choice, Dynamics and Uncertainty*. Chapman and Hall, New York, USA.
- Humphries, P. (1995). Life history, food and habitat of southern pygmy perch, *Nannoperca australis*, in the Macquarie River, Tasmania. *Marine and Freshwater Research* **46**, 1159–1169.
- Jones, M., Tinkler, P., Lindeman, M., Hackett, G. and Pickworth, A. (2008). *Threats, distribution and abundance of Yarra Pygmy Perch in Victoria during a drought period*. Arthur Rylah Institute for Environmental Research Technical Report Series No. 184. Department of Sustainability and Environment, Heidelberg, Victoria.
- Kuiter, R. H. and Allen, G. R. (1986). A synopsis of the Australian pygmy perches (Percichthyidae), with the description of a new species. *Revue française d'aquariologie (Nancy)* **12**, 109–116.
- Kuiter, R. H., Humphries, P. and Arthington, A. H. (1996). Pygmy perches: Family Nannopercidae. In: McDowall, R.M. (Ed.) *Freshwater Fishes of South-Eastern Australia*, 2nd edition, pp 168–175. Reed Books, Chatswood, NSW.
- Knight, J. T., Butler, G. L., Smith, P. S. and Wager, R. N. E. (2007). Reproductive biology of the endangered Oxleyan pygmy perch *Nannoperca oxleyana* Whitley. *Journal of Fish Biology* **71**, 1494–1511.
- Koehn, J. D. and O'Connor, W. G. (1990). *Biological information for management of native freshwater fish in Victoria*. Department of Conservation and Environment: Government Printer, Melbourne, Victoria.
- Koehn, J. D. and Todd, C. R. (2012). Balancing conservation and recreational fishery objectives for a threatened fish species, the Murray cod, *Maccullochella peelii*. *Fisheries Management and Ecology* **19**, 410–425.
- Koehn, J.D., Raymond, S.A., Stuart, I., Todd, C.R., Balcombe, S.R., Zampatti, B.P., Bamford, H., Ingram, B.A., Bice, C., Burndred, K., Butler, G., Baumgartner, L., Clunie, P., Ellis, I., Forbes, J., Hutchison, M., Koster, W., Lintermans, Lyon, J.P., M., Mallen-Cooper, M., McLellan, M., Pearce, L., Ryall, J., Sharpe, C., Stoessel, D.J., Thiem, J.D., Tonkin, Z., Townsend, A. and Ye, Q. (2020). A compendium of ecological knowledge for restoration of freshwater fishes in Australia's Murray–Darling Basin. *Marine and Freshwater Research* **71**, 1391–1463.
- Lake, J. S. (1967). *Freshwater fish of the Murray Darling River System*. State Fisheries Research Bulletin Number 7, Chief Secretary's Department, New South Wales.
- Lintermans, M. (2023). *Fishes of the Murray-Darling Basin*. Murray–Darling Basin Commission, Canberra, ACT.
- Llewellyn, L. C. (1974). Spawning, development and distribution of the Southern Pygmy Perch *Nannoperca australis* Günther from inland waters in Eastern Australia. *Australian Journal of Marine and Freshwater Research* **25**, 121–149.
- Llewellyn, L. C. (1980). Pygmy perches: Family Nannopercidae. In: McDowall, R.M. (Ed.) *Freshwater Fishes of South-Eastern Australia*, 1st edition, pp 153–155. Reed Books, Chatswood, NSW.

- Lyon, J., Stuart, I., Ramsey, D. and O'Mahony, J. (2010). The effect of water level on lateral movements of fish between river and off-channel habitats and implications for management. *Marine and Freshwater Research* **61**, 271–278 doi:10.1071/mf08246
- Macdonald, J. and Tonkin, Z. (2008). *A review of the impact of eastern gambusia on native fishes of the Murray–Darling Basin*. Arthur Rylah Institute for Environmental Research, Department of Sustainability and Environment, Heidelberg, Victoria.
- Mallen-Cooper M, Stuart I.G. and Sharpe C. (2014). *The Native Fish Recovery Plan – Gunbower and Lower Loddon*. Report prepared for the North Central Catchment Management Authority.
- Manly, B.F.J. (1990). *Stage-Structured Populations: Sampling, Analysis and Simulation*. Chapman and Hall, London, UK.
- McCarthy, M. A. (1995). *Stochastic population models for wildlife management*. PhD thesis, The University of Melbourne, Parkville, Victoria.
- McCarthy, M. A. and Thompson, C. (2001). Expected minimum population size as a measure of threat. *Animal Conservation* **4**, 351–355.
- McNeil, D. G. and Closs, G. P. (2007). Behavioural responses of a south-east Australian floodplain fish community to gradual hypoxia. *Freshwater Biology* **52**, 412–420.
- Mills, L. S. and Lindberg, M. S. (2002). Sensitivity analysis to evaluate the consequences of conservation actions. In: Beissinger, S. R. and McCullough, D. R. (Eds.) *Population Viability Analysis*, pp. 338–366. University of Chicago Press, Chicago, Illinois, USA.
- Mitchell, P. A. (1976). *A study of the behaviour and breeding biology of the southern pygmy perch, Nannoperca australis australis (Günther)(Teleostei: Nannopercidae)*. Honours Thesis, University of Melbourne, Parkville, Victoria.
- Morrongiello, J. R., Bond, N. R., Crook, D. A. and Wong, B. B. M. (2010). Nuptial coloration varies with ambient light environment in a freshwater fish. *Journal of Evolutionary Biology* **23**, 2718–2725.
- Morrongiello, J. R. (2011). *Life history variation along environmental gradients in a freshwater fish, the southern pygmy perch Nannoperca australis*. PhD Thesis, School of Biological Sciences, Monash University, Victoria.
- Morrongiello, J. R., Bond, N. R., Crook, D. A. and Wong, B. B. M. (2012). Spatial variation in egg size and egg number reflects trade-offs and bet-hedging in a freshwater fish. *Journal of Animal Ecology* **81**, 806–817.
- NSW Department of Primary Industries (2014). *Southern Pygmy Perch Nannoperca australis, Primefact 190, Second Edition*. Fisheries Ecosystems Unit, Port Stephens Fisheries Institute, Port Stephens, NSW.
- Pearce, L. K. (2014). *Conservation management of southern pygmy perch (Nannoperca australis) in NSW, in the context of climatic extremes and alien species*. Masters Thesis, Charles Sturt University, Albury, NSW.
- Pearce, L., Humphries, P. and Watts, R. (2013). *Where have all the fishes gone: Distribution and population trends of southern pygmy perch through climatic extremes*. The Australian Society for Limnology 52nd Annual Congress: 2–5th December 2013, Ann Harding Centre, University of Canberra, Bruce ACT, Delegate Handbook.
- Pearce, L., Bice, C., Whiterod, N. and Raadik, T. (2019). *Nannoperca australis*. The IUCN Red List of Threatened Species 2019: e.T123358579A123382811. <http://dx.doi.org/10.2305/IUCN.UK.2019-3.RLTS.T123358579A123382811.en> (accessed 13 April 2020).
- Ricker, W. E. (1975). *Computation and interpretation of biological statistics of fish populations*. Bulletin 191, Fisheries Research Board of Canada, Ottawa, Canada.
- Rose, K. A. and Cowan, J. H. (2000). Predicting fish population dynamics: Compensation and the importance of site-specific considerations. *Environmental Science and Policy* **3**, S433–S443.
- Saddler, S. Koehn, J. D. and Hammer M. P. (2013). Let's not forget the small fishes – two threatened species of pygmy perch in south-eastern Australia. *Marine and Freshwater Research* **64**(9), 874–886.
- Saila, S., Martin, B., Ferson, S., Ginzburg, L. and Millstein, J. (1991). *Demographic modeling of selected fish species with RAMAS*. Electric Power Research Institute Report EN-7178. Electric Power Research Institute, Palo Alto, USA.

- Sanger, A. C. (1978). *Aspects of the ecology and evolution of the pigmy perches (Teleostei: Kuhlidae)*. Honours Thesis, University of Melbourne, Parkville, Victoria.
- Thompson, V. J. and Bray, D. J. (2011). Southern Pygmy Perch, *Nannoperca australis*, in *Fishes of Australia*. <http://www.fishesofaustralia.net.au/home/species/1828> (accessed 14 Jan 2014).
- Todd, C. R. and Ng, M. P. (2001). Generating unbiased correlated random survival rates for stochastic population models. *Ecological Modelling* **144**, 1–11.
- Todd, C. R., Jenkins, S. and Bearlin, A. R. (2002). Lessons about extinction and translocation: Models for the eastern barred bandicoots (*Perameles gunnii*) at Woodlands Historic Park, Victoria, Australia. *Biological Conservation* **106**, 211–223.
- Todd, C. R. and Lovelace, P. R. (2008). Essential, version 2.12. Freeware: <http://livinglogic.com.au/Essential.html> 3 August 2010.
- Todd, C. R., Nicol, S. J. and Koehn, J. D. (2004). Density-dependence uncertainty in population models for the conservation management of trout cod, *Maccullochella macquariensis*. *Ecological Modelling* **171**, 359–380.
- Todd, C. R., Ryan, T., Nicol, S. J. and Bearlin, A. R. (2005). The impact of cold water releases on the critical period of post-spawning survival and its implications for Murray cod (*Maccullochella peelii peelii*): A case study of the Mitta Mitta River southeastern Australia. *River Research Applications* **21**, 1035–1052.
- Todd, C.R. and Koehn, J.D. (2009). *Murray cod management model: User manual*. Arthur Rylah Institute for Environmental Research, Victoria.
- Todd, C. R., Sharley, D. J., Koehn, J. D. and Stuart, I. (2011). *Assessment of priority species in the MDB for the potential development of population models: Final report for project MD1179*. Arthur Rylah Institute for Environmental Research Client Report to the Murray–Darling Basin Authority. Department of Sustainability and Environment, Heidelberg, Victoria.
- Todd, C. R., Koehn, J. D., Pearce, L., Dodd, L., Humphries, P. and Morrongiello, J. R. (2017). Forgotten fishes: What is the future for small threatened freshwater fish? Population risk assessment for southern pygmy perch, *Nannoperca australis*. *Aquatic Conservation: Marine and Freshwater Ecosystems* **27**, 1290–1300 doi:10.1002/aqc.2808
- Tonkin, Z., King, A. J., and Mahoney, J. (2008). Effects of flooding on recruitment and dispersal of the southern pygmy perch (*Nannoperca australis*) at a Murray River floodplain wetland. *Ecological Management and Restoration* **9**, 196–201.
- Unmack, P. J. (2001). Biogeography of Australian freshwater fishes. *Journal of Biogeography* **28**, 1053–1089.
- Wedderburn, S. D., Barnes, T. C. and Hillyard, K. A. (2014). Shifts in fish assemblages indicate failed recovery of threatened species following prolonged drought in terminating lakes of the Murray–Darling Basin, Australia. *Hydrobiologia* **730**, 179–190 doi:10.1007/s10750-014-1836-2
- Wharton, J. C. F. (1973). Spawning induction, artificial fertilisation and pond culture of the Macquarie Perch (*Macquaria australasica* [Cuvier, 1830]). *Australian Society for Limnology Bulletin* **5**, 43–65.
- Wedderburn, S., Furst, D. and Barnes, T. (2019). *Responses of threatened fish populations to environmental management scenarios for Lake Alexandrina determined with Generalised Additive Models*. The University of Adelaide and the Department for Environment and Water, Adelaide, SA
- Wittwer, J. W. (2004). *Monte Carlo Simulation Basics*, Vertex42.com. <http://vertex42.com/ExcelArticles/mc/MonteCarloSimulation.html> (accessed April 2008).
- Woodward, G. M. A. (2005). *Factors influencing the distribution and abundance of Nannoperca obscura (Yarra pygmy perch) and Nannoperca australis (southern pygmy perch)*. PhD Thesis, La Trobe University, Melbourne, Victoria.
- Woodward, G. M. A. and Malone, B. S. (2002). Patterns of abundance and habitat use by *Nannoperca obscura* (Yarra Pygmy Perch) and *Nannoperca australis* (Southern Pygmy Perch). *Proceedings of the Royal Society of Victoria* **114**, 61–72.
- Yearsley, J. M., Fletcher, D. and Hunter, C. (2003). Sensitivity analysis of equilibrium population size in a density-dependent model for Short-tailed Shearwaters. *Ecological Modelling* **163**, 119–129.

Appendices

Appendix 1. Additional outputs from modelled scenarios

Predicted responses of individual populations of Southern Pygmy Perch at Gunbower Island to reintroduction strategies: A metapopulation model with eight populations

Stocking 20,000 fish

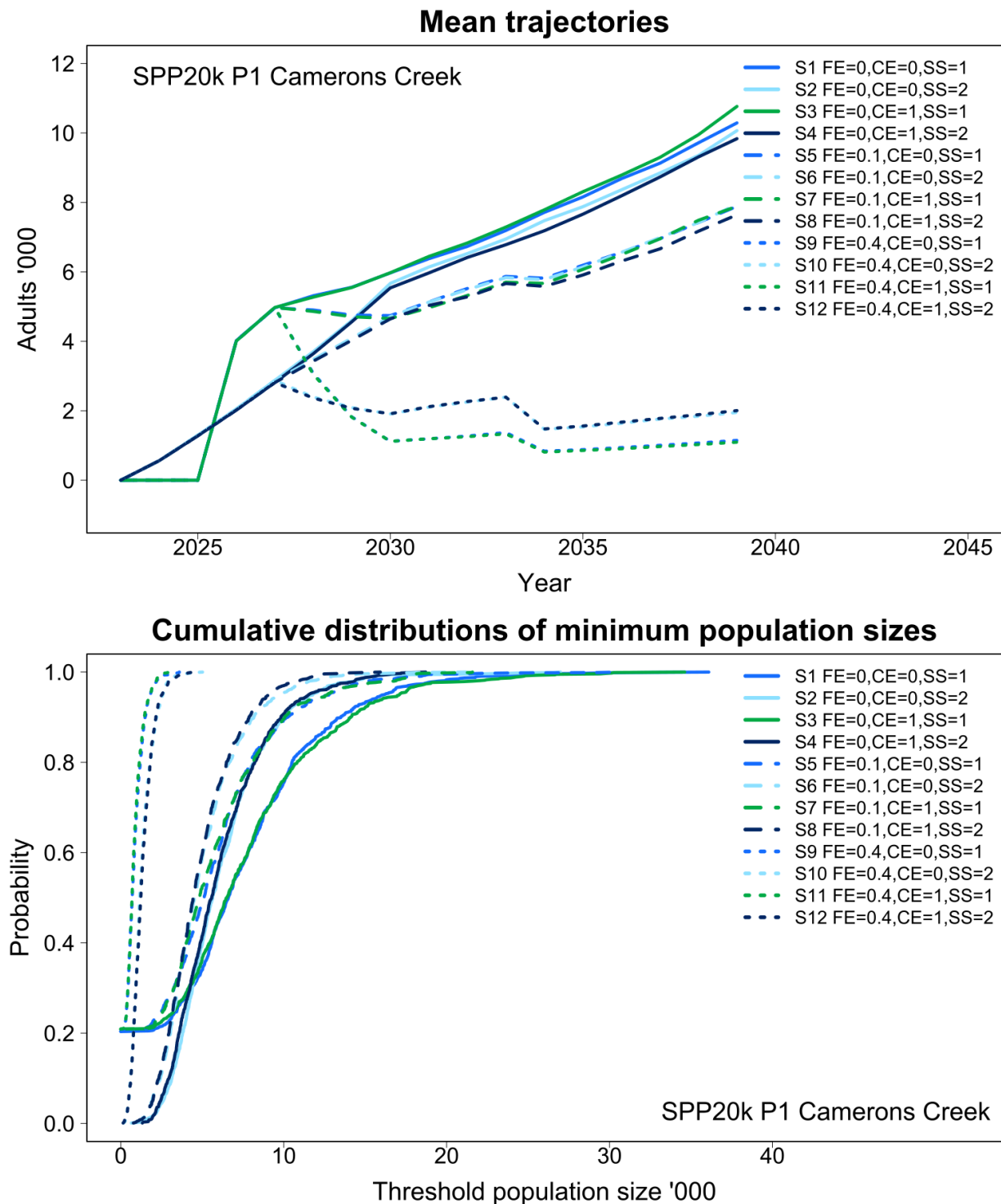


Figure A-1. Predicted adult Southern Pygmy Perch responses to 12 modelled scenarios for the Cameron's Creek population where fish were stocked at a rate of 20,000 per year for seven years. Top panel shows mean scenario trajectories through time and the bottom panel shows the distributions of the minimum population size for each scenario collected from the 10th timestep onwards. FE = flood effect, CE = competition effect and SS = stocking strategy. Stocking strategy 1 denotes stocking one population per year and stocking strategy 2 denotes stocking evenly across all populations.

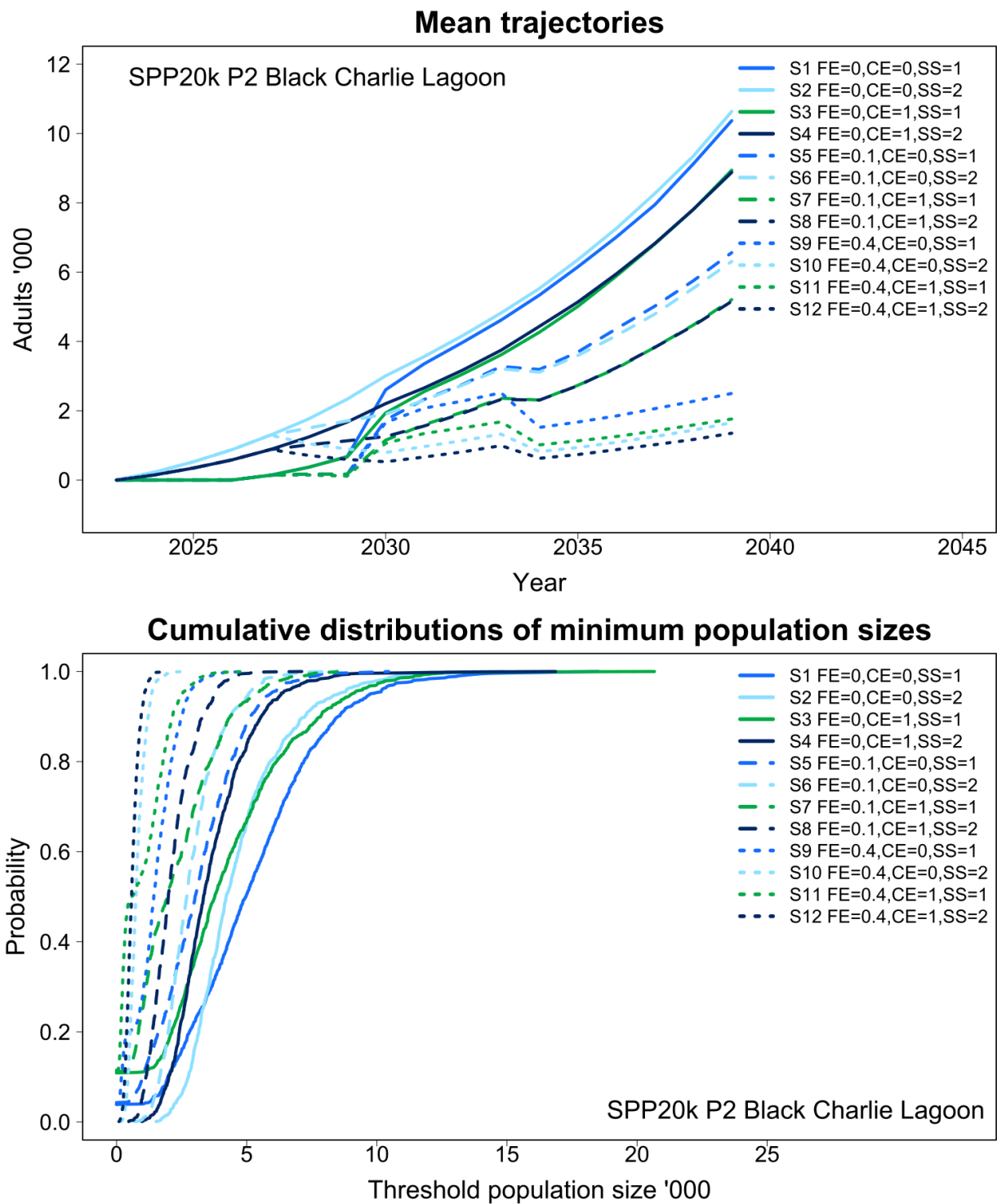


Figure A-2. Predicted adult Southern Pygmy Perch responses to 12 modelled scenarios for the Black Charlie Lagoon population where fish were stocked at a rate of 20,000 per year for seven years. Top panel shows mean scenario trajectories through time and the bottom panel shows the distributions of the minimum population size for each scenario collected from the 10th timestep onwards. FE = flood effect, CE = competition effect and SS = stocking strategy. Stocking strategy 1 denotes stocking one population per year and stocking strategy 2 denotes stocking evenly across all populations.

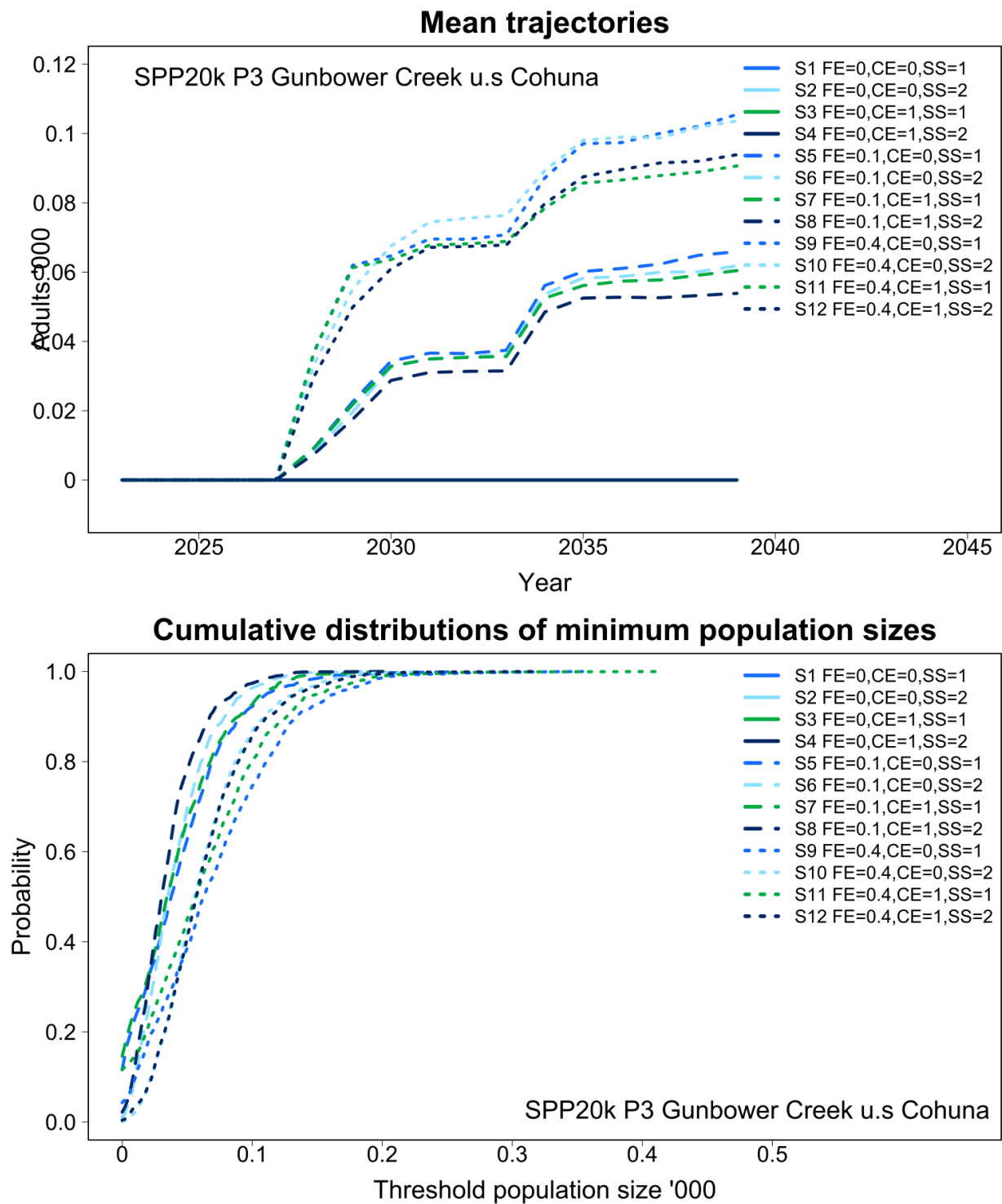


Figure A-3. Predicted adult Southern Pygmy Perch responses to 12 modelled scenarios for the Gunbower Creek upstream of Cohuna population where fish were stocked at a rate of 20,000 per year for seven years. Top panel shows mean scenario trajectories through time and the bottom panel shows the distributions of the minimum population size for each scenario collected from the 10th timestep onwards. FE = flood effect, CE = competition effect and SS = stocking strategy. Stocking strategy 1 denotes stocking one population per year and stocking strategy 2 denotes stocking evenly across all populations.

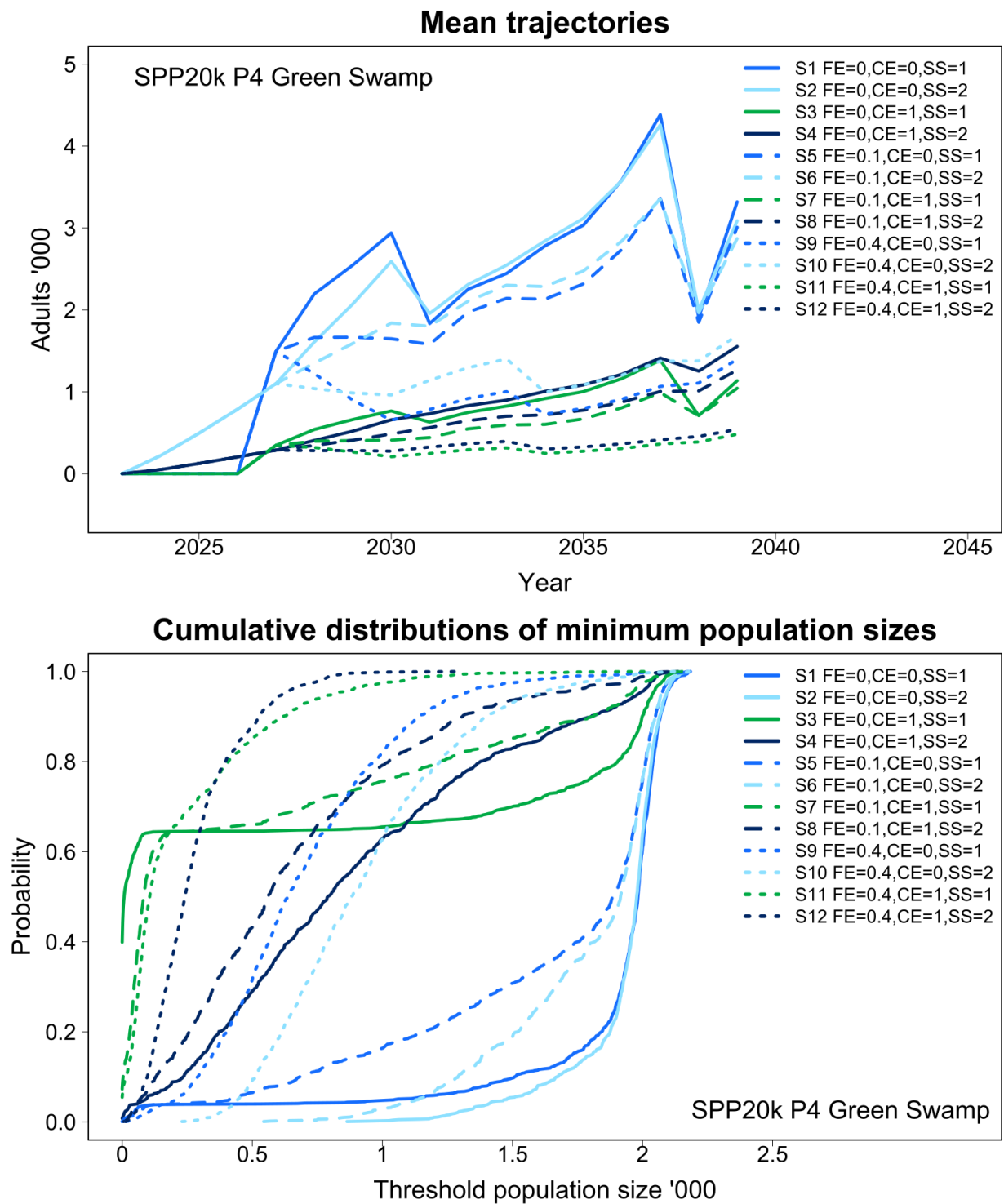


Figure A-4. Predicted adult Southern Pygmy Perch responses to 12 modelled scenarios for the Green Swamp population where fish were stocked at a rate of 20,000 per year for seven years. Top panel shows mean scenario trajectories through time and the bottom panel shows the distributions of the minimum population size for each scenario collected from the 10th timestep onwards. FE = flood effect, CE = competition effect and SS = stocking strategy. Stocking strategy 1 denotes stocking one population per year and stocking strategy 2 denotes stocking evenly across all populations.

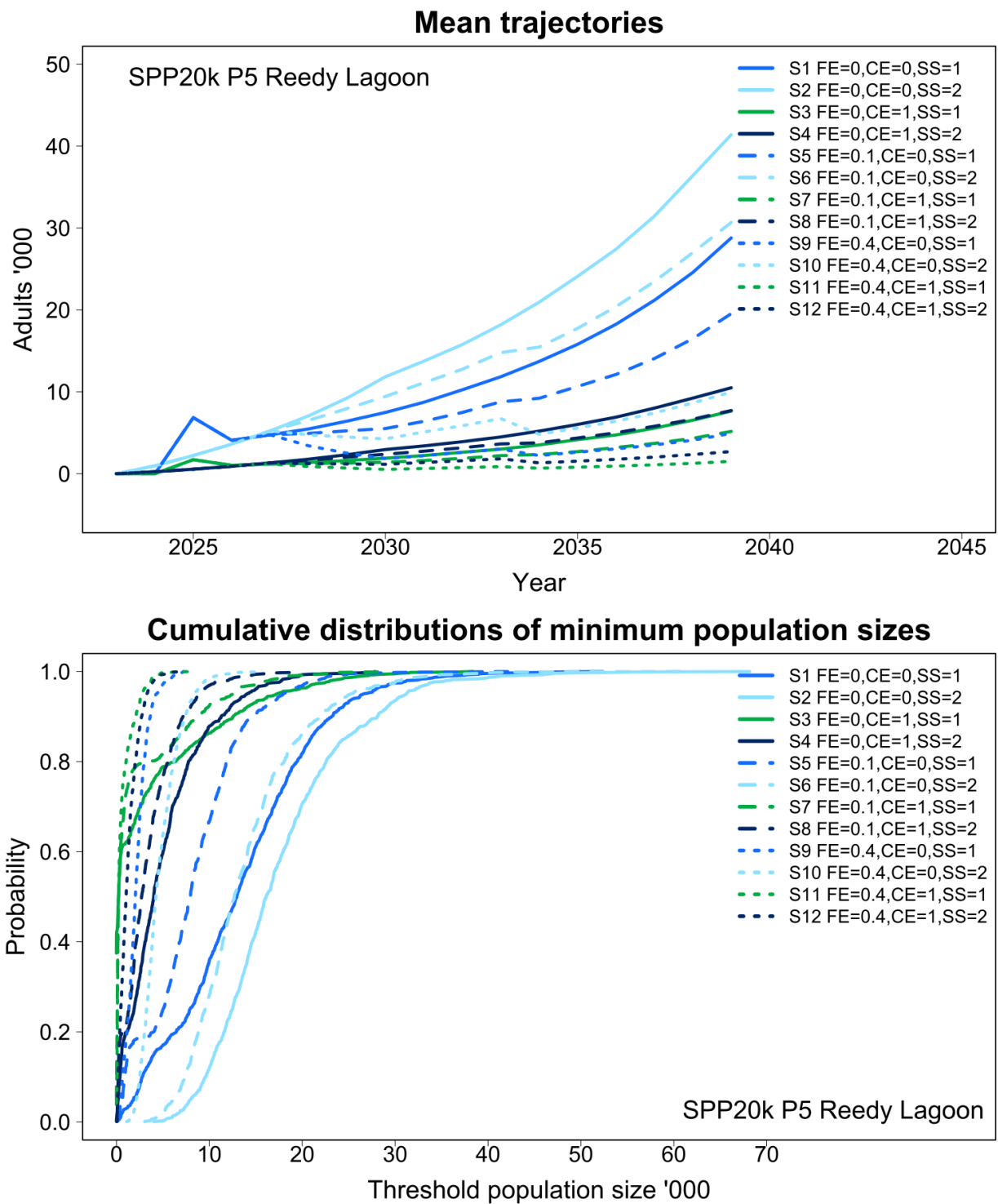


Figure A-5. Predicted adult Southern Pygmy Perch responses to 12 modelled scenarios for the Reedy Lagoon population where fish were stocked at a rate of 20,000 per year for seven years. Top panel shows mean scenario trajectories through time and the bottom panel shows the distributions of the minimum population size for each scenario collected from the 10th timestep onwards. FE = flood effect, CE = competition effect and SS = stocking strategy. Stocking strategy 1 denotes stocking one population per year and stocking strategy 2 denotes stocking evenly across all populations.

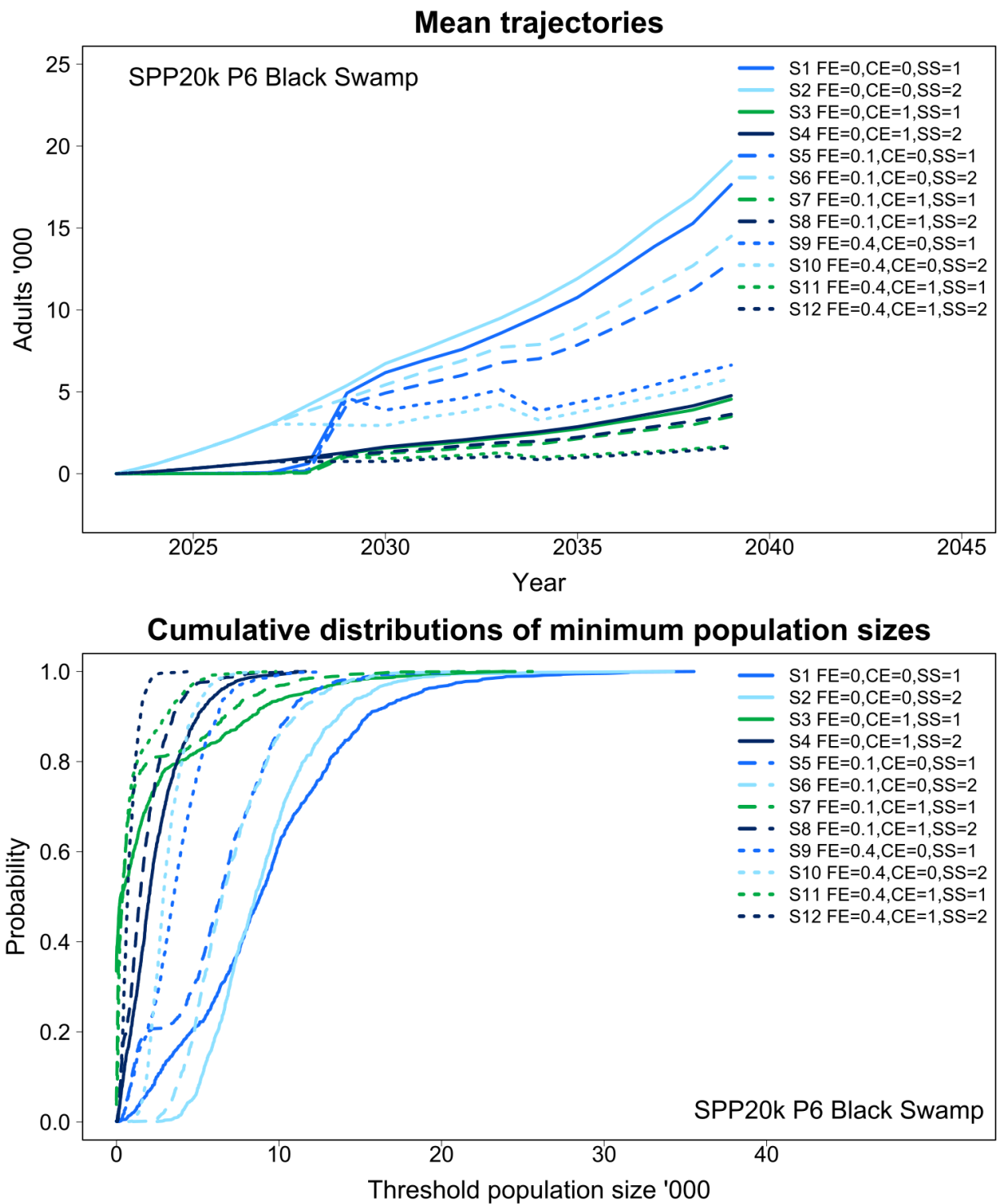


Figure A-6. Predicted adult Southern Pygmy Perch responses to 12 modelled scenarios for the Black Swamp population where fish were stocked at a rate of 20,000 per year for seven years. Top panel shows mean scenario trajectories through time and the bottom panel shows the distributions of the minimum population size for each scenario collected from the 10th timestep onwards. FE = flood effect, CE = competition effect and SS = stocking strategy. Stocking strategy 1 denotes stocking one population per year and stocking strategy 2 denotes stocking evenly across all populations.

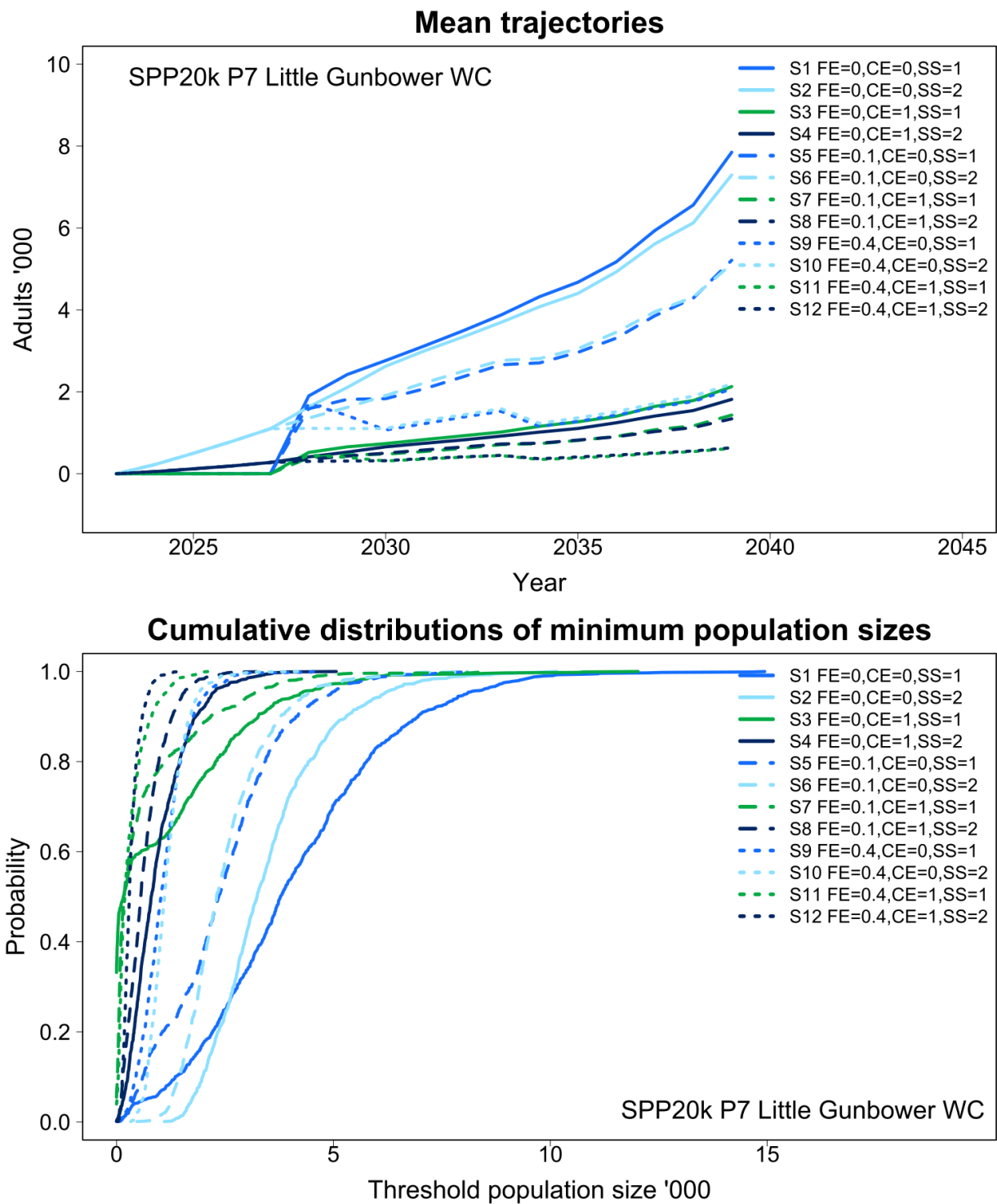


Figure A-7. Predicted adult Southern Pygmy Perch responses to 12 modelled scenarios for the Little Gunbower Wetland Complex population where fish were stocked at a rate of 20,000 per year for seven years. Top panel shows mean scenario trajectories through time and the bottom panel shows the distributions of the minimum population size for each scenario collected from the 10th timestep onwards. FE = flood effect, CE = competition effect and SS = stocking strategy. Stocking strategy 1 denotes stocking one population per year and stocking strategy 2 denotes stocking evenly across all populations.

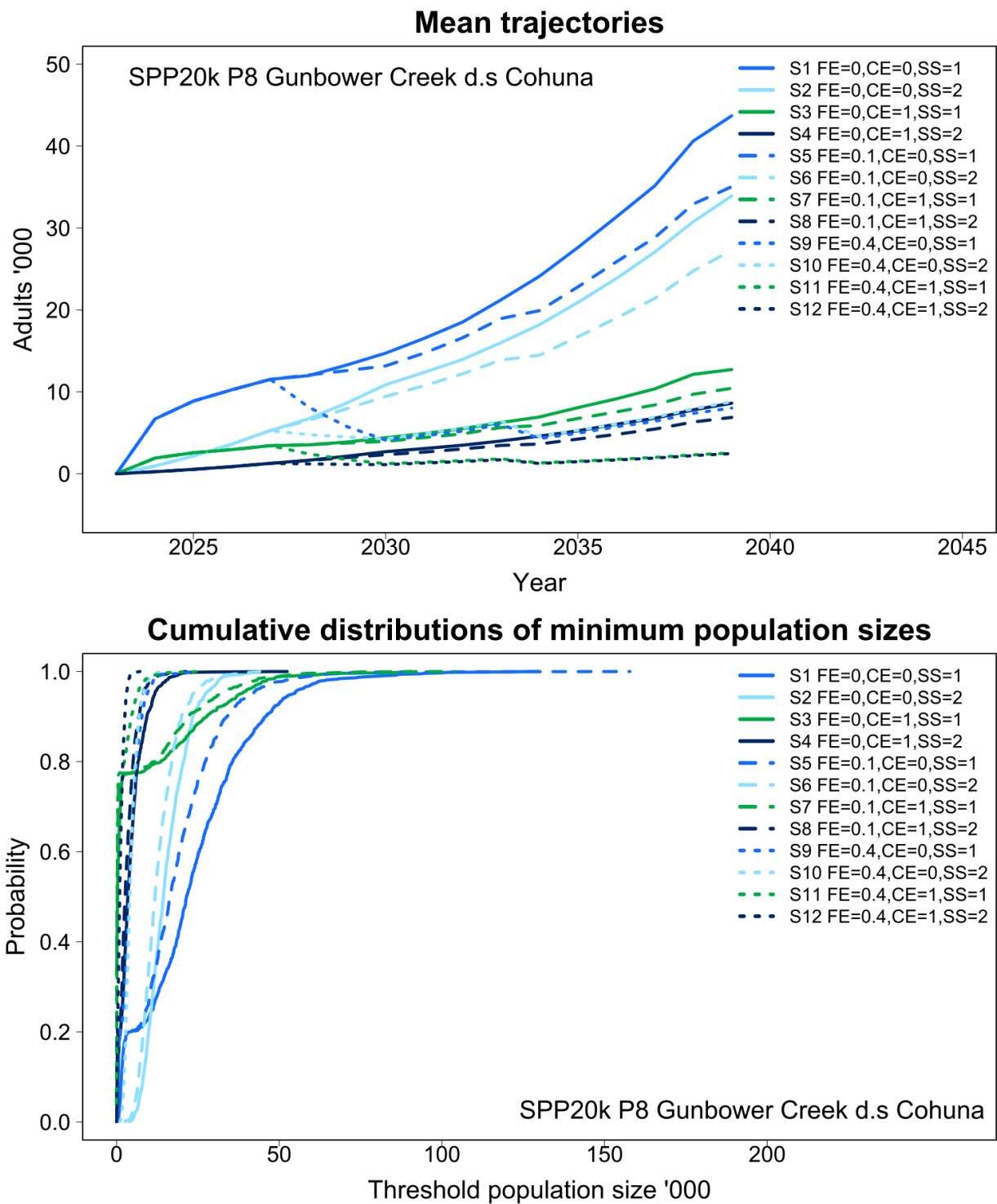


Figure A-8. Predicted adult Southern Pygmy Perch responses to 12 modelled scenarios for the Little Gunbower Creek downstream of Cohuna population where fish were stocked at a rate of 20,000 per year for seven years. Top panel shows mean scenario trajectories through time and the bottom panel shows the distributions of the minimum population size for each scenario collected from the 10th timestep onwards. FE = flood effect, CE = competition effect and SS = stocking strategy. Stocking strategy 1 denotes stocking one population per year and stocking strategy 2 denotes stocking evenly across all populations.

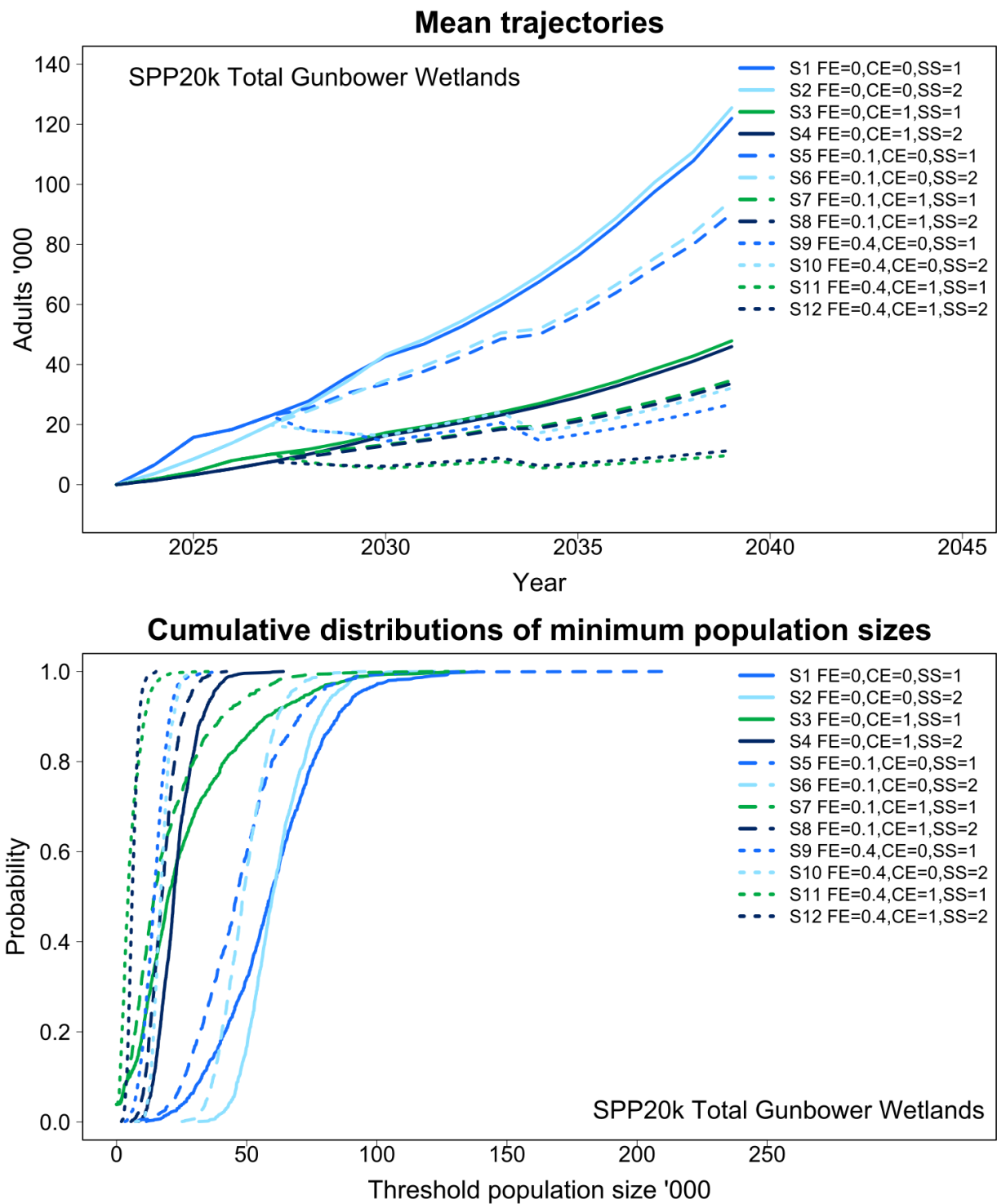


Figure A-9. Predicted adult Southern Pygmy Perch responses to 12 modelled scenarios for all populations modelled at Gunbower Island where fish were stocked at a rate of 20,000 per year for seven years. Top panel shows mean scenario trajectories through time and the bottom panel shows the distributions of the minimum population size for each scenario collected from the 10th timestep onwards. FE = flood effect, CE = competition effect and SS = stocking strategy. Stocking strategy 1 denotes stocking one population per year and stocking strategy 2 denotes stocking evenly across all populations.

Stocking 5,000 fish

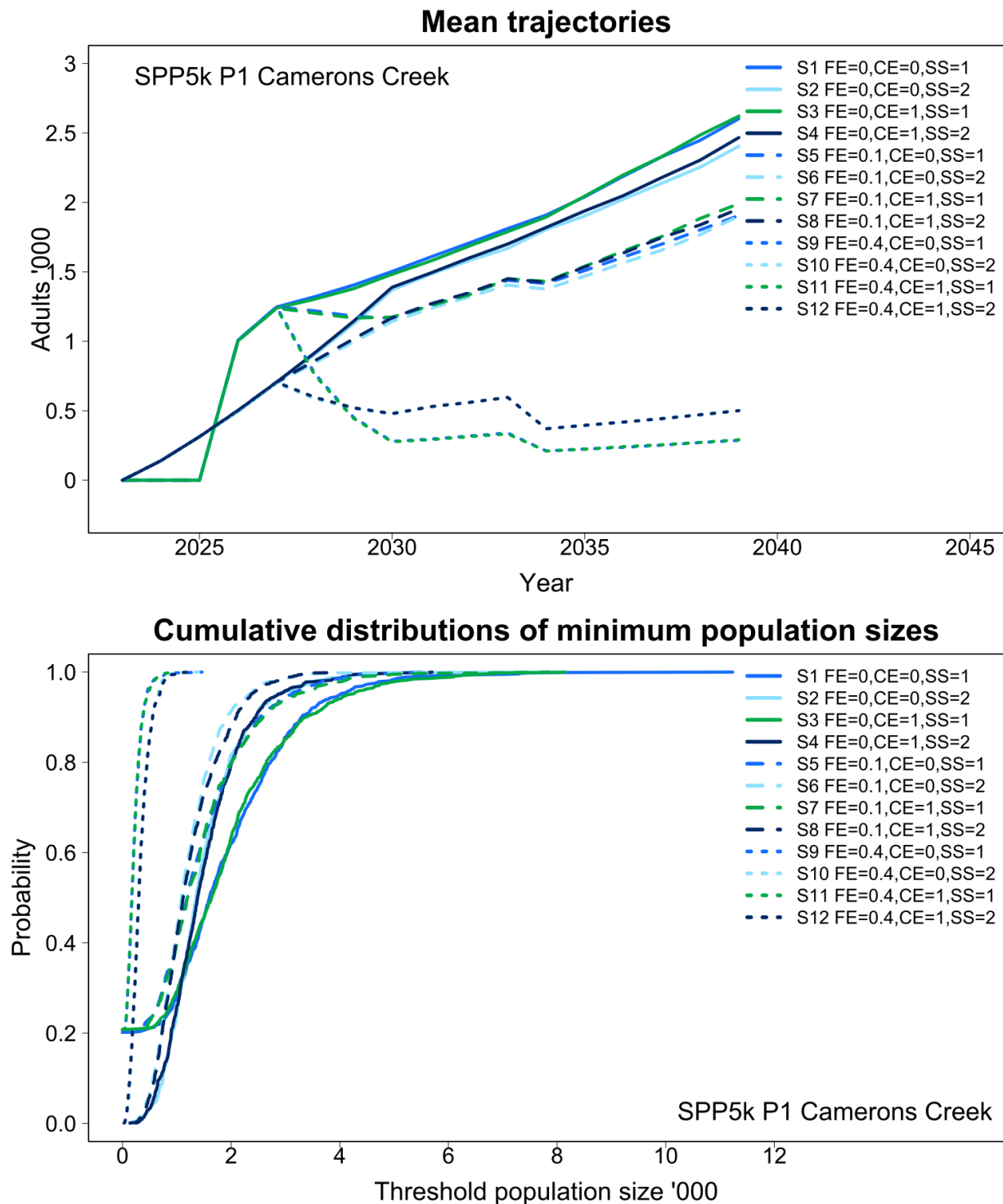


Figure A-10. Predicted adult Southern Pygmy Perch responses to 12 modelled scenarios for the Cameron's Creek population where fish were stocked at a rate of 5,000 per year for seven years. Top panel shows mean scenario trajectories through time and the bottom panel shows the distributions of the minimum population size for each scenario collected from the 10th timestep onwards. FE = flood effect, CE = competition effect and SS = stocking strategy. Stocking strategy 1 denotes stocking one population per year and stocking strategy 2 denotes stocking evenly across all populations.

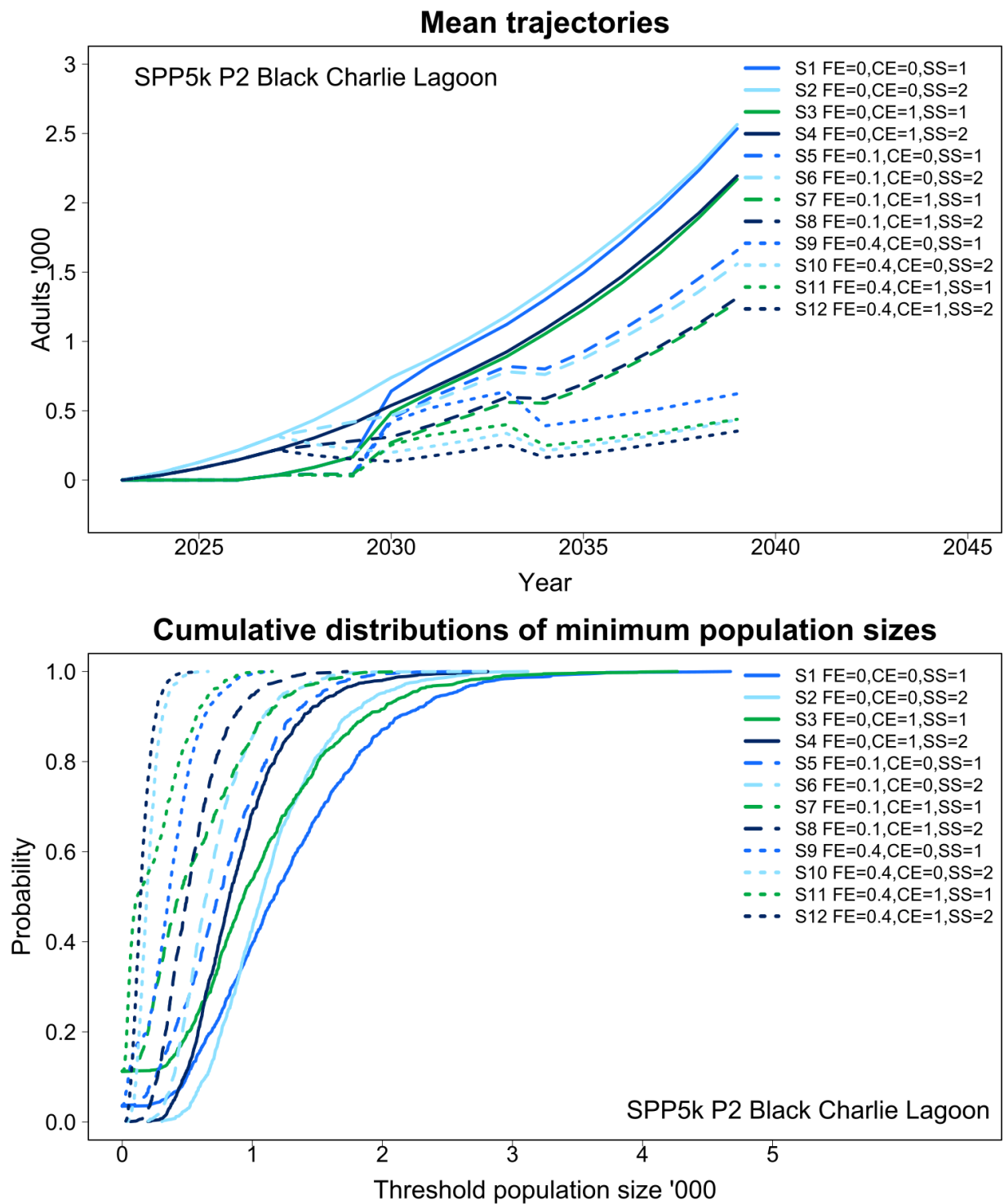


Figure A-11. Predicted adult Southern Pygmy Perch responses to 12 modelled scenarios for the Black Charlie Lagoon population where fish were stocked at a rate of 5,000 per year for seven years. Top panel shows mean scenario trajectories through time and the bottom panel shows the distributions of the minimum population size for each scenario collected from the 10th timestep onwards. FE = flood effect, CE = competition effect and SS = stocking strategy. Stocking strategy 1 denotes stocking one population per year and stocking strategy 2 denotes stocking evenly across all populations.

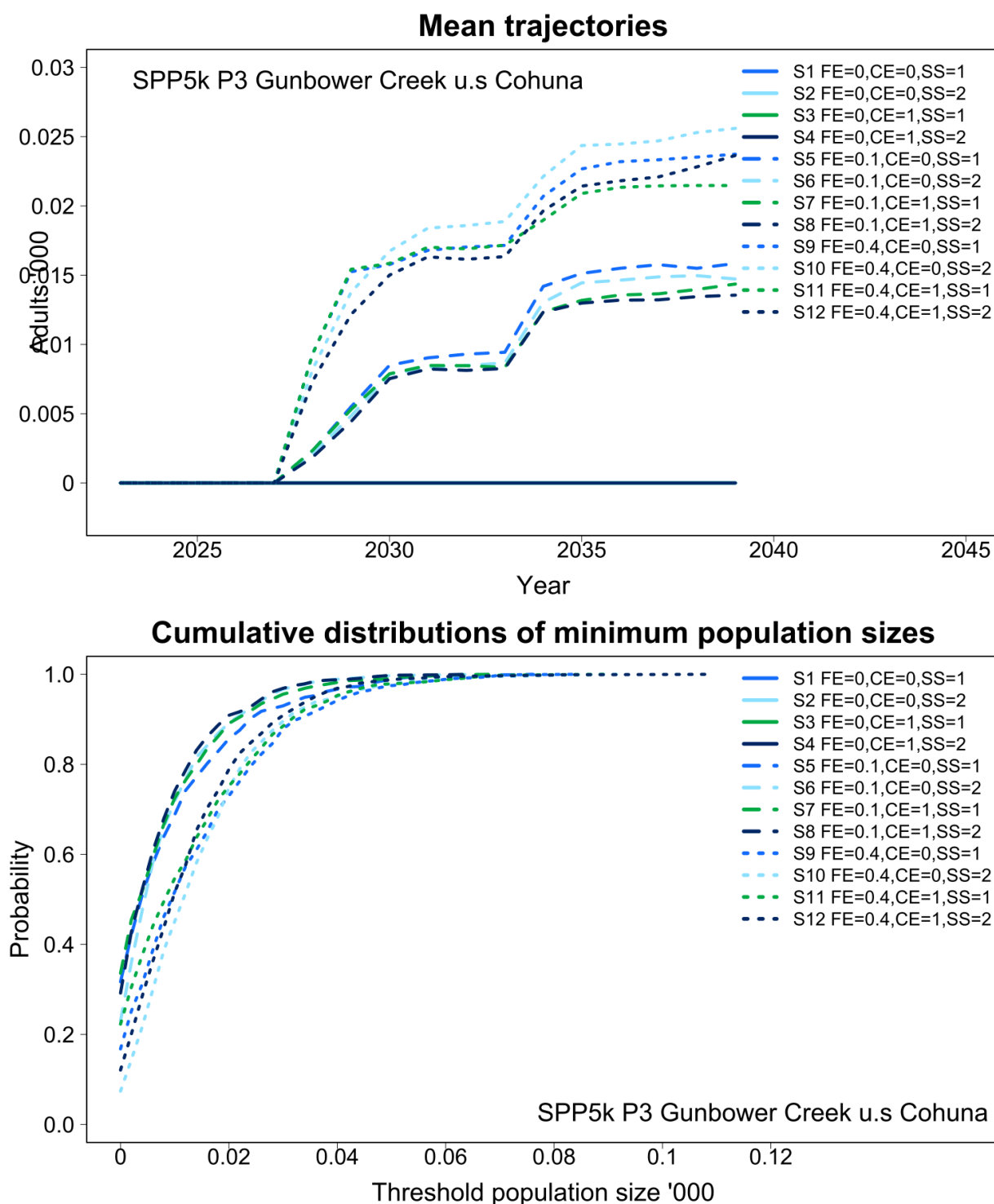


Figure A-12. Predicted adult Southern Pygmy Perch responses to 12 modelled scenarios for the Gunbower Creek upstream of Cohuna population where fish were stocked at a rate of 5,000 per year for seven years. Top panel shows mean scenario trajectories through time and the bottom panel shows the distributions of the minimum population size for each scenario collected from the 10th timestep onwards. FE = flood effect, CE = competition effect and SS = stocking strategy. Stocking strategy 1 denotes stocking one population per year and stocking strategy 2 denotes stocking evenly across all populations.

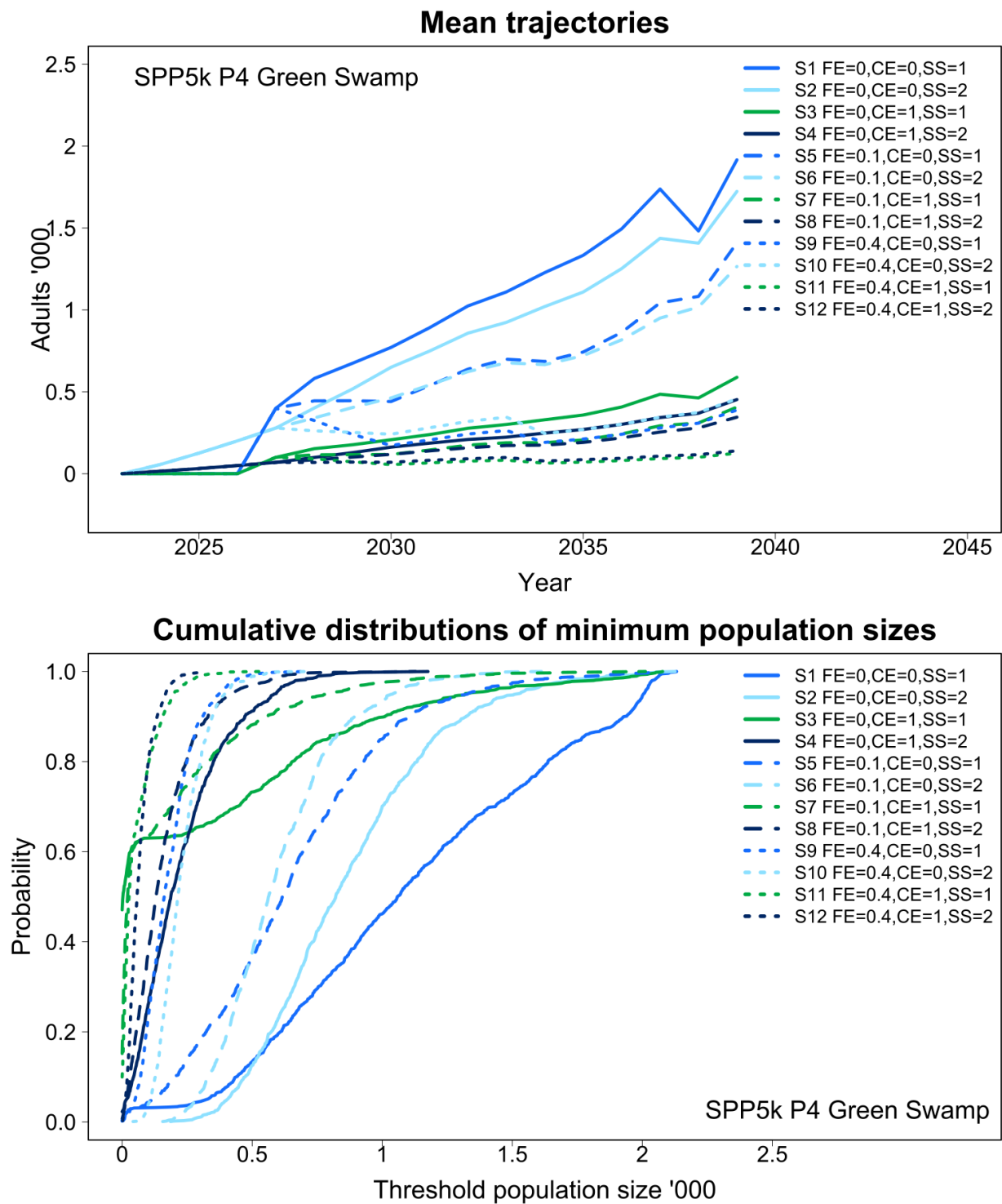


Figure A-13. Predicted adult Southern Pygmy Perch responses to 12 modelled scenarios for the Green Swamp population where fish were stocked at a rate of 5,000 per year for seven years. Top panel shows mean scenario trajectories through time and the bottom panel shows the distributions of the minimum population size for each scenario collected from the 10th timestep onwards. FE = flood effect, CE = competition effect and SS = stocking strategy. Stocking strategy 1 denotes stocking one population per year and stocking strategy 2 denotes stocking evenly across all populations.

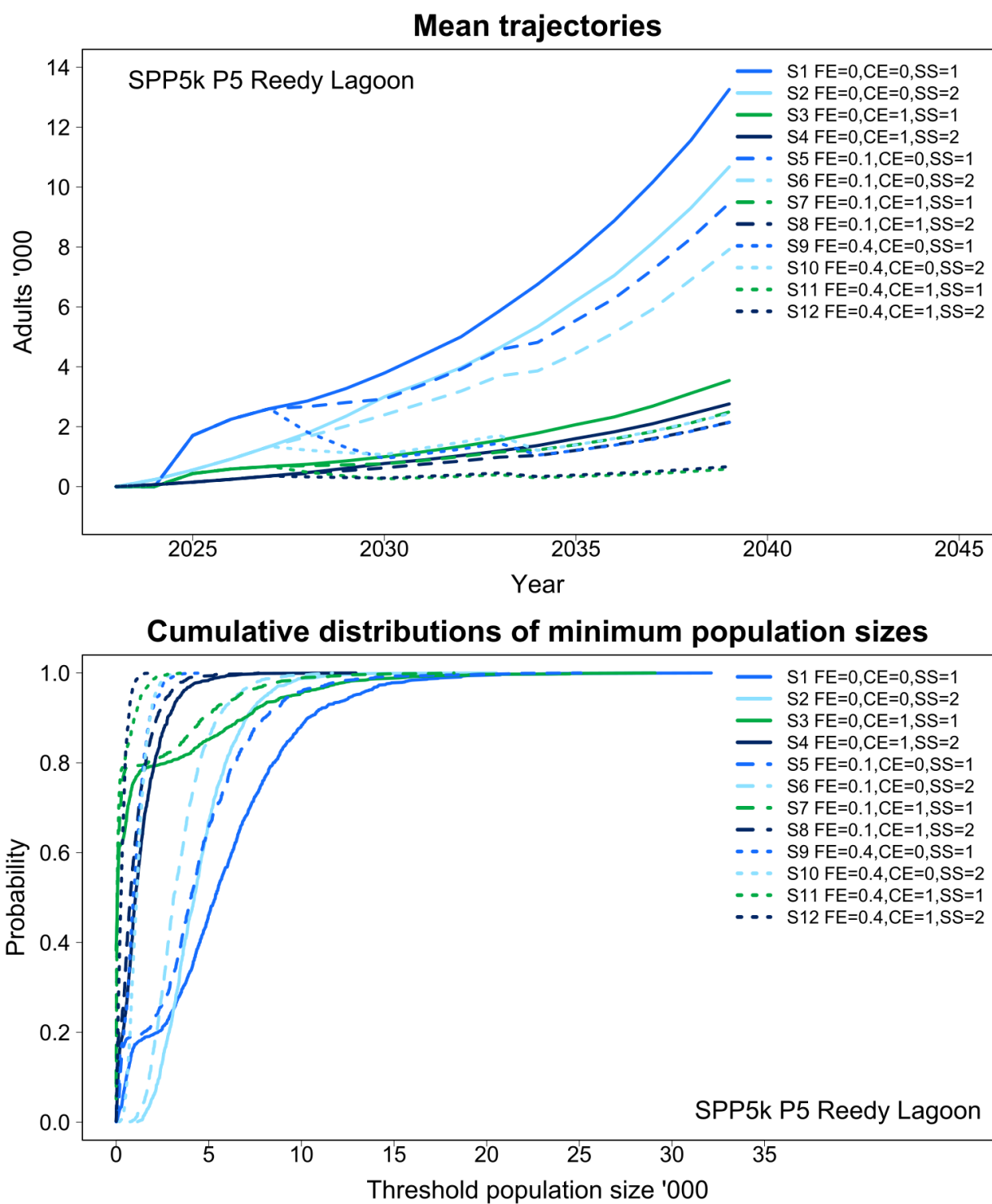


Figure A-14. Predicted adult Southern Pygmy Perch responses to 12 modelled scenarios for the Reedy Lagoon population where fish were stocked at a rate of 5,000 per year for seven years. Top panel shows mean scenario trajectories through time and the bottom panel shows the distributions of the minimum population size for each scenario collected from the 10th timestep onwards. FE = flood effect, CE = competition effect and SS = stocking strategy. Stocking strategy 1 denotes stocking one population per year and stocking strategy 2 denotes stocking evenly across all populations.

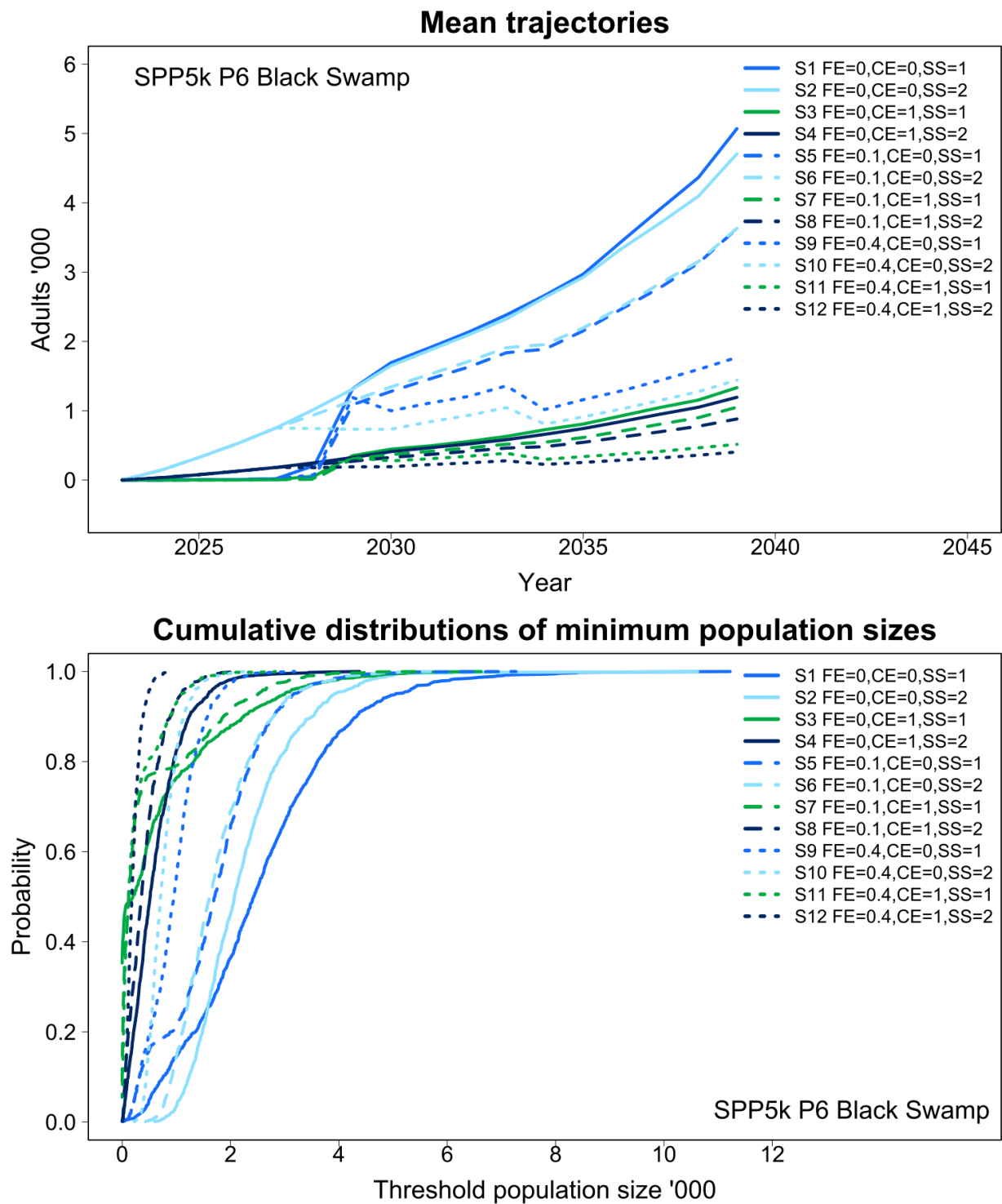


Figure A-15. Predicted adult Southern Pygmy Perch responses to 12 modelled scenarios for the Black Swamp population where fish were stocked at a rate of 5,000 per year for seven years. Top panel shows mean scenario trajectories through time and the bottom panel shows the distributions of the minimum population size for each scenario collected from the 10th timestep onwards. FE = flood effect, CE = competition effect and SS = stocking strategy. Stocking strategy 1 denotes stocking one population per year and stocking strategy 2 denotes stocking evenly across all populations.

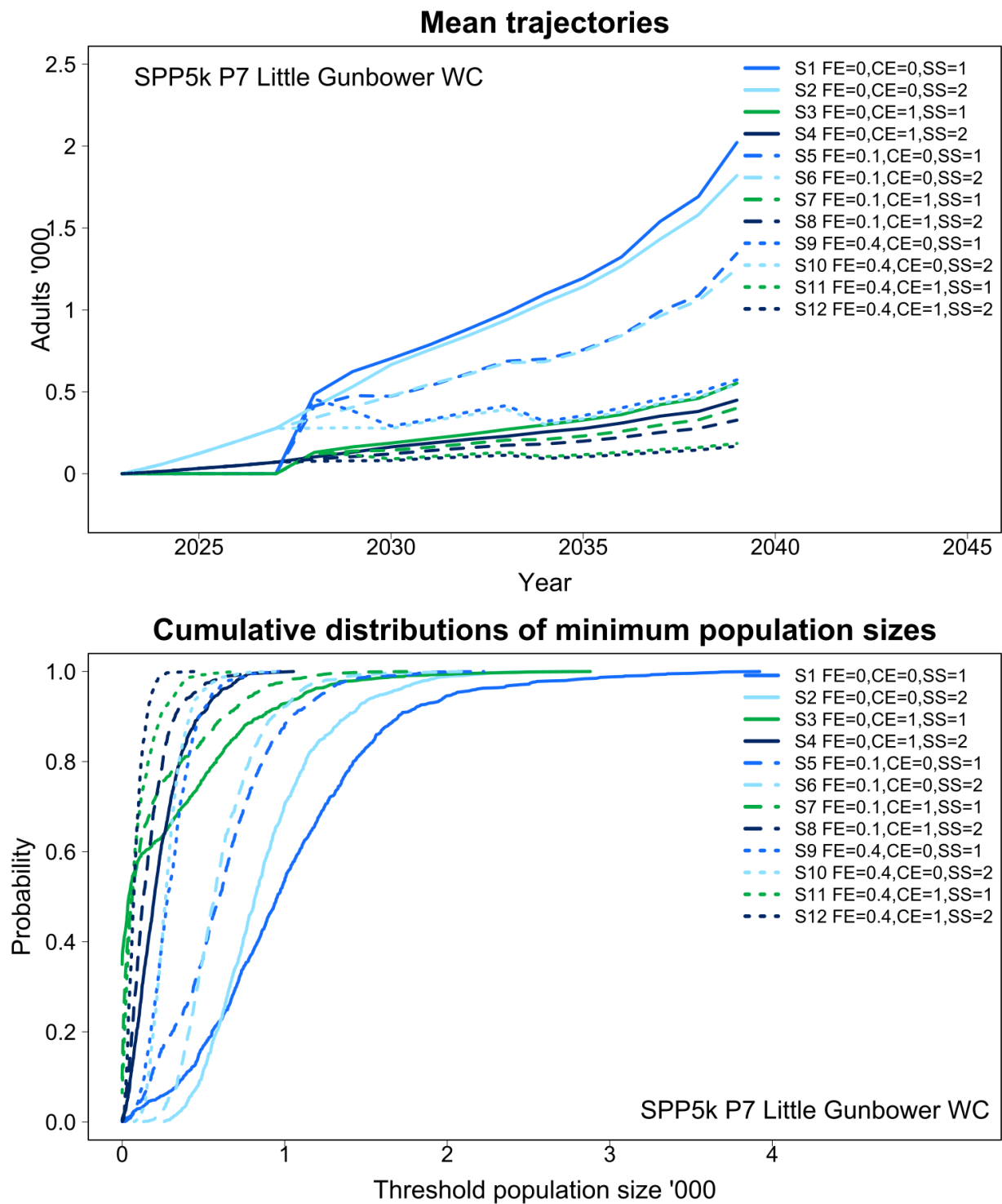


Figure A-16. Predicted adult Southern Pygmy Perch responses to 12 modelled scenarios for the Little Gunbower Wetland Complex population where fish were stocked at a rate of 5,000 per year for seven years. Top panel shows mean scenario trajectories through time and the bottom panel shows the distributions of the minimum population size for each scenario collected from the 10th timestep onwards. FE = flood effect, CE = competition effect and SS = stocking strategy. Stocking strategy 1 denotes stocking one population per year and stocking strategy 2 denotes stocking evenly across all populations.

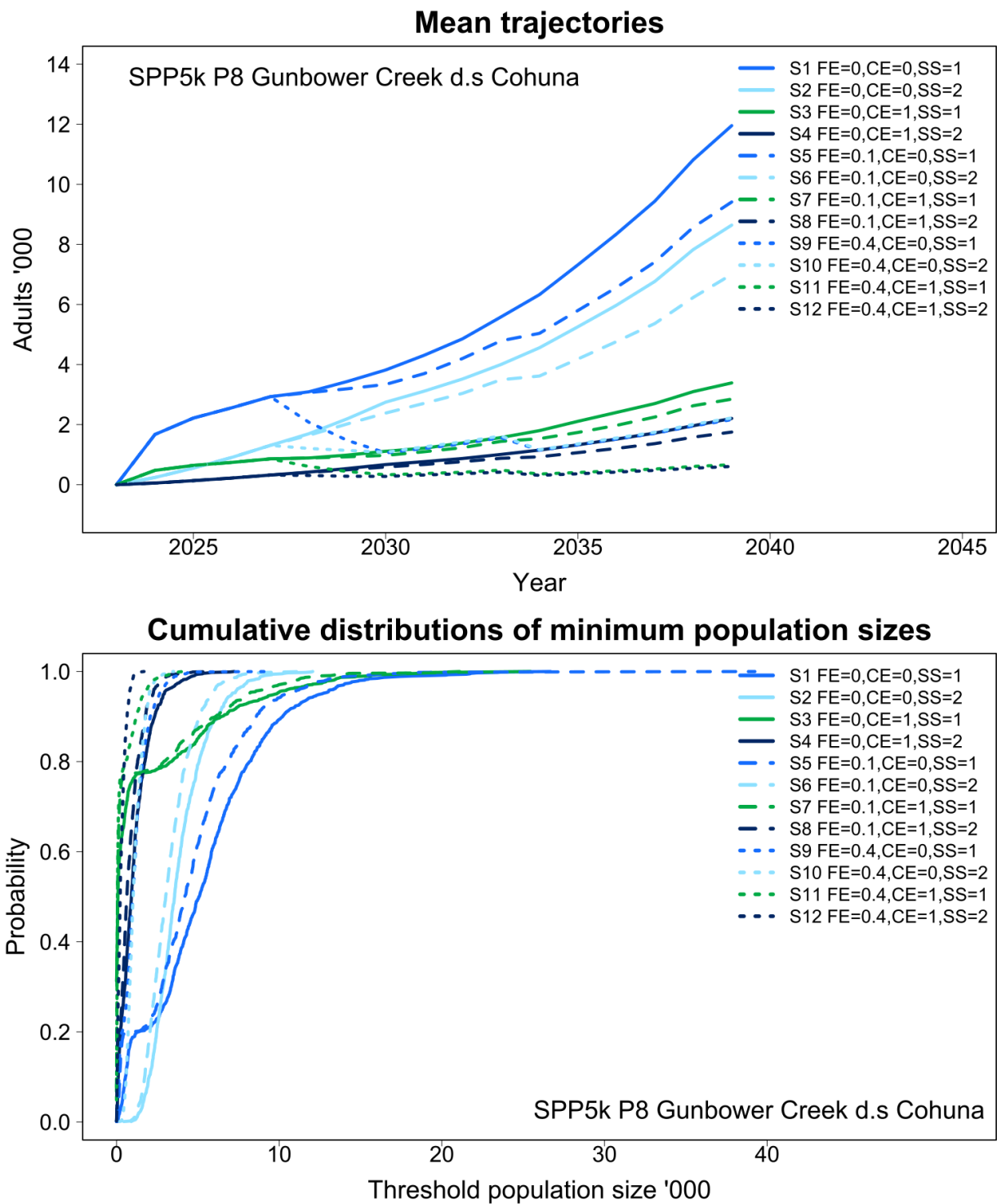


Figure A-17. Predicted adult Southern Pygmy Perch responses to 12 modelled scenarios for the Gunbower Creek downstream of Cohuna population where fish were stocked at a rate of 5,000 per year for seven years. Top panel shows mean scenario trajectories through time and the bottom panel shows the distributions of the minimum population size for each scenario collected from the 10th timestep onwards. FE = flood effect, CE = competition effect and SS = stocking strategy. Stocking strategy 1 denotes stocking one population per year and stocking strategy 2 denotes stocking evenly across all populations.

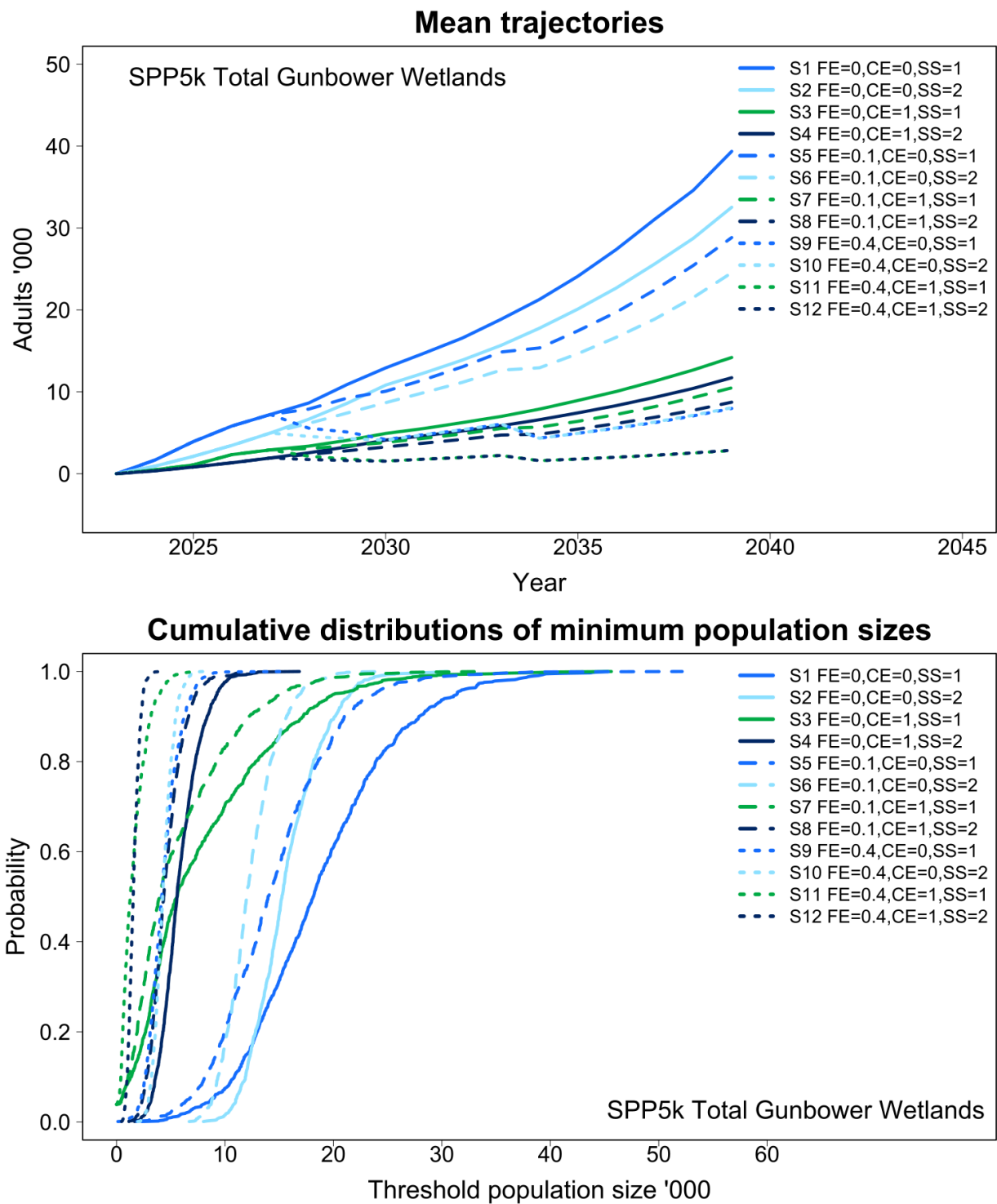


Figure A-18. Predicted adult Southern Pygmy Perch responses to 12 modelled scenarios for all populations modelled at Gunbower Island where fish were stocked at a rate of 5,000 per year for seven years. Top panel shows mean scenario trajectories through time and the bottom panel shows the distributions of the minimum population size for each scenario collected from the 10th timestep onwards. FE = flood effect, CE = competition effect and SS = stocking strategy. Stocking strategy 1 denotes stocking one population per year and stocking strategy 2 denotes stocking evenly across all populations.

Predicted responses of individual populations of Southern Pygmy Perch at Gunbower Island to reintroduction strategies including a Leaky Regulator population: A metapopulation model with nine populations

Stocking 20,000 fish

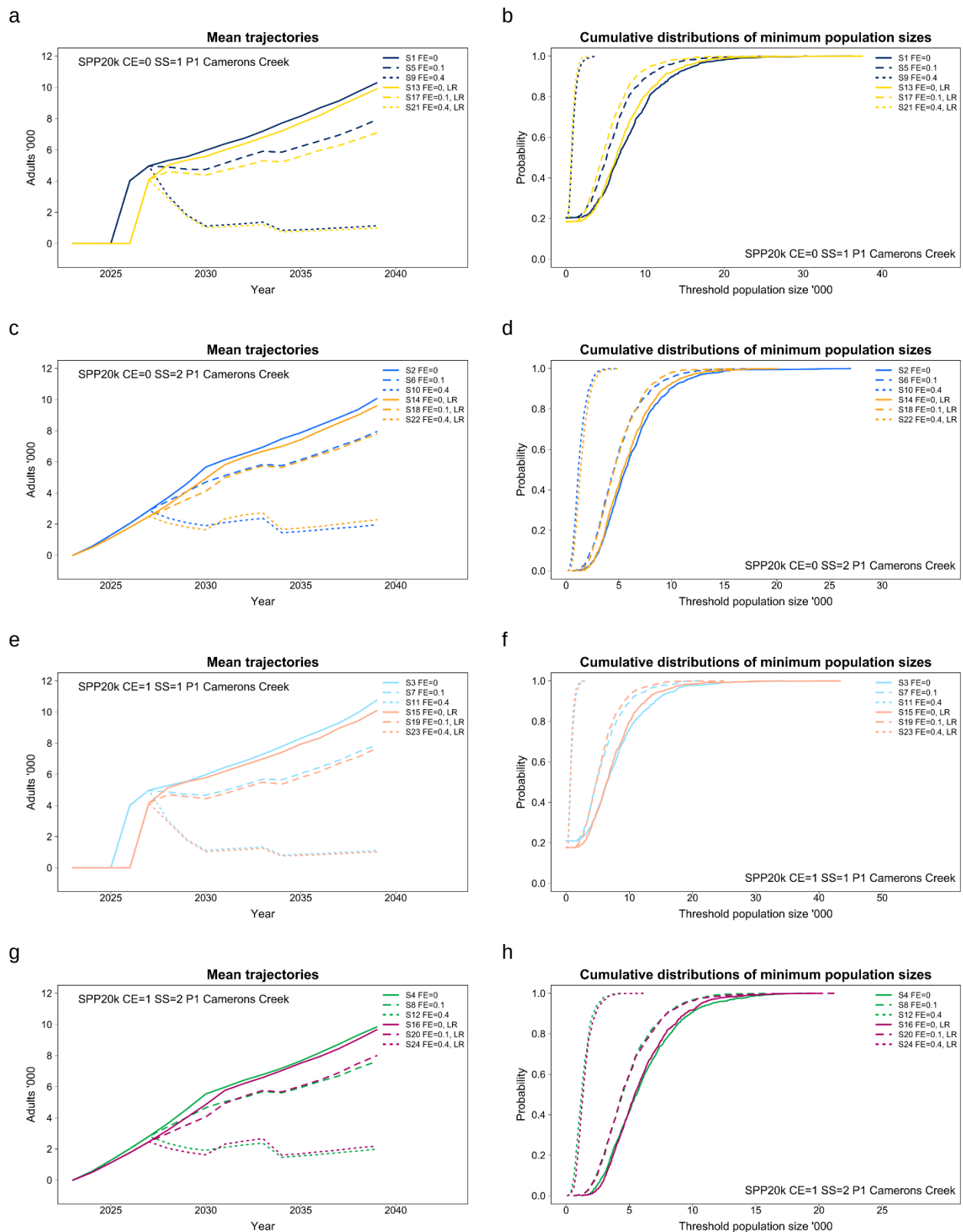


Figure A-19. Predicted adult Southern Pygmy Perch responses to six scenarios comparing the Leaky Regulator concept for the Cameron's Creek population. Fish were stocked at a rate of 20,000 per year. Top panel shows mean scenario trajectories through time and the bottom panel shows the distributions of the minimum population size for each scenario collected from the 10th timestep onwards. FE = flood effect, CE = competition effect and SS = stocking strategy.

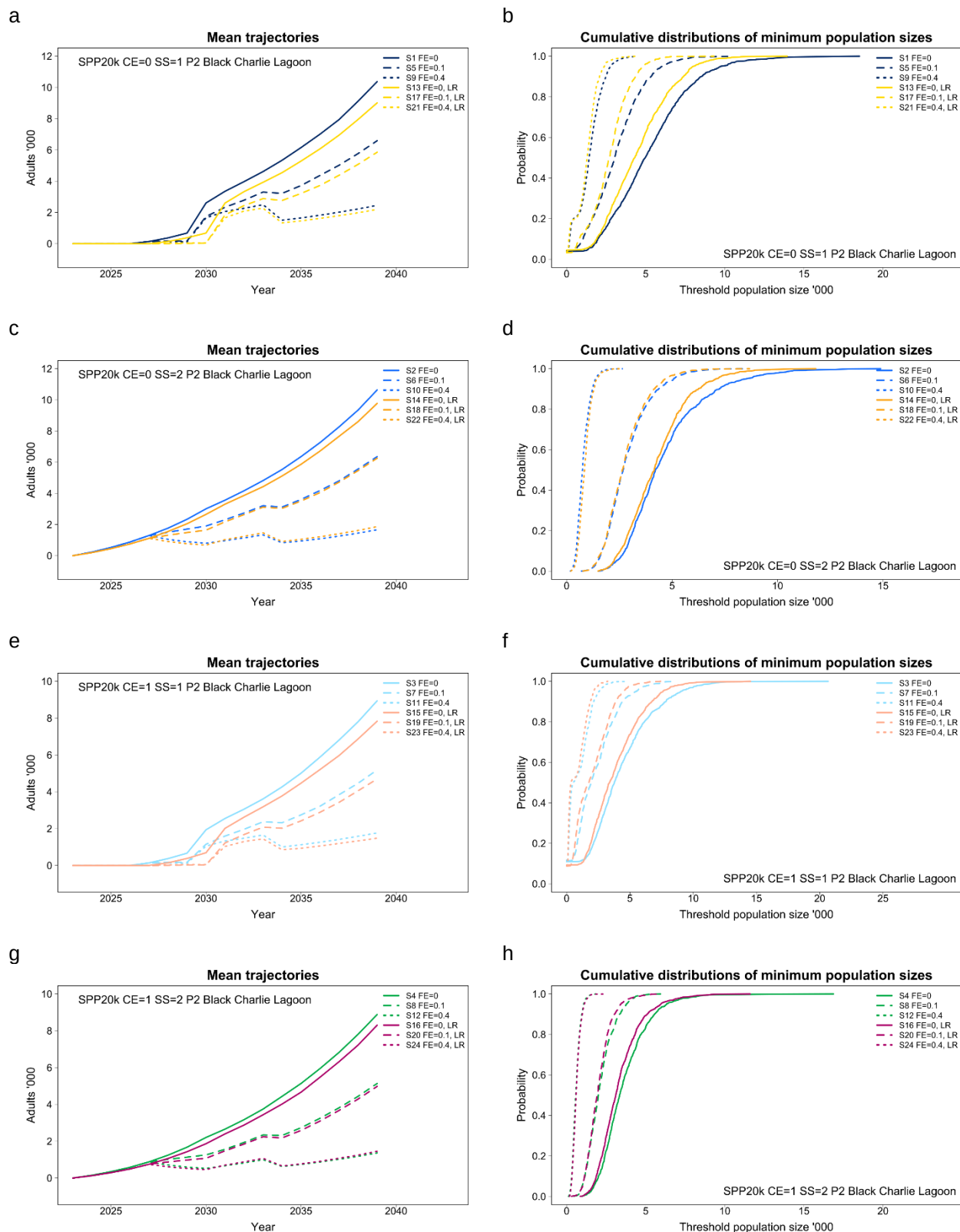


Figure A-20. Predicted adult Southern Pygmy Perch responses to six scenarios comparing the Leaky Regulator concept for the Black Charlie Lagoon population. Fish were stocked at a rate of 20,000 per year. Top panel shows mean scenario trajectories through time and the bottom panel shows the distributions of the minimum population size for each scenario collected from the 10th timestep onwards. FE = flood effect, CE = competition effect and SS = stocking strategy.

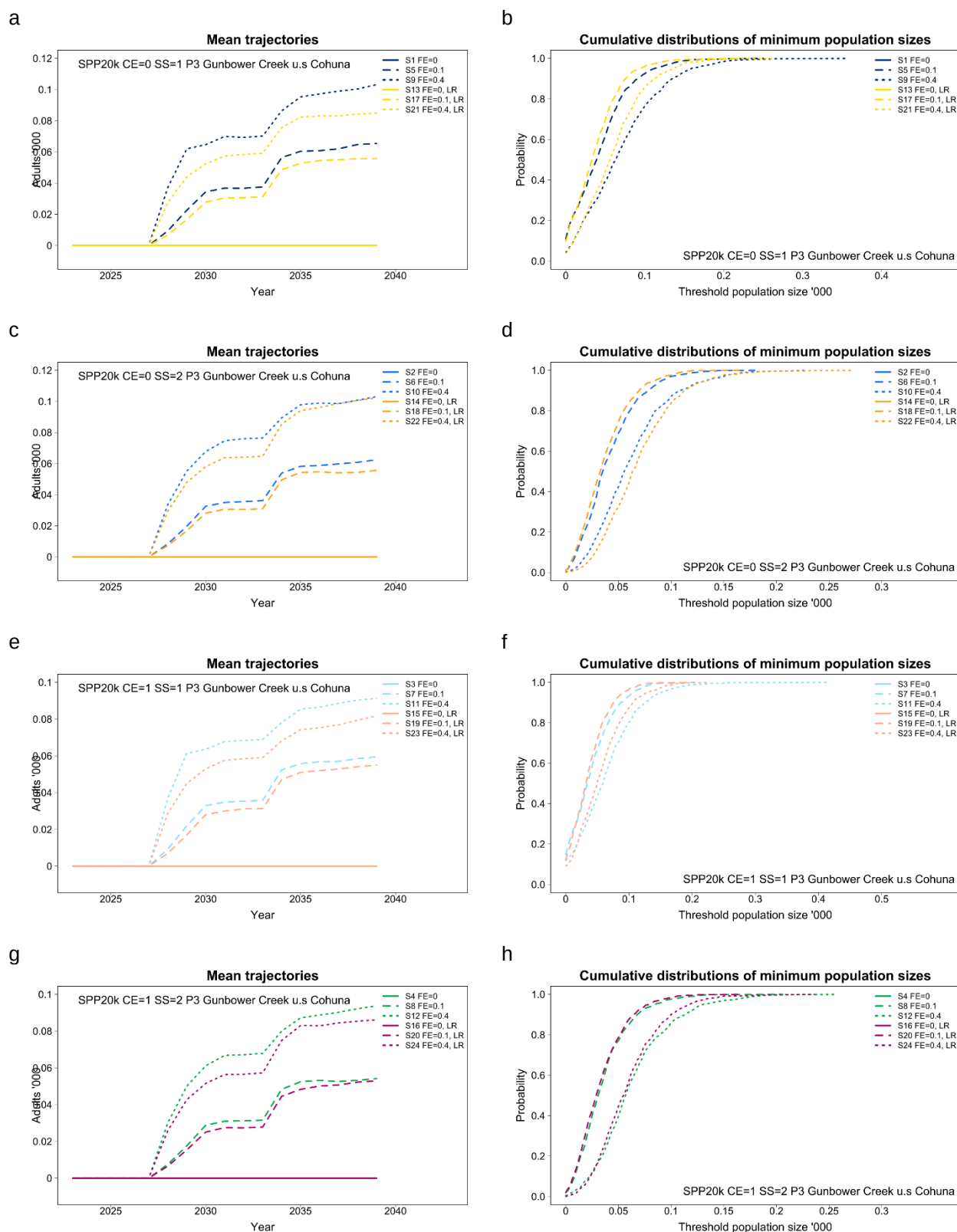


Figure A-21. Predicted adult Southern Pygmy Perch responses to six scenarios comparing the Leaky Regulator concept for the Gunbower Creek upstream of Cohuna population. Fish were stocked at a rate of 20,000 per year. Top panel shows mean scenario trajectories through time and the bottom panel shows the distributions of the minimum population size for each scenario collected from the 10th timestep onwards. FE = flood effect, CE = competition effect and SS = stocking strategy.

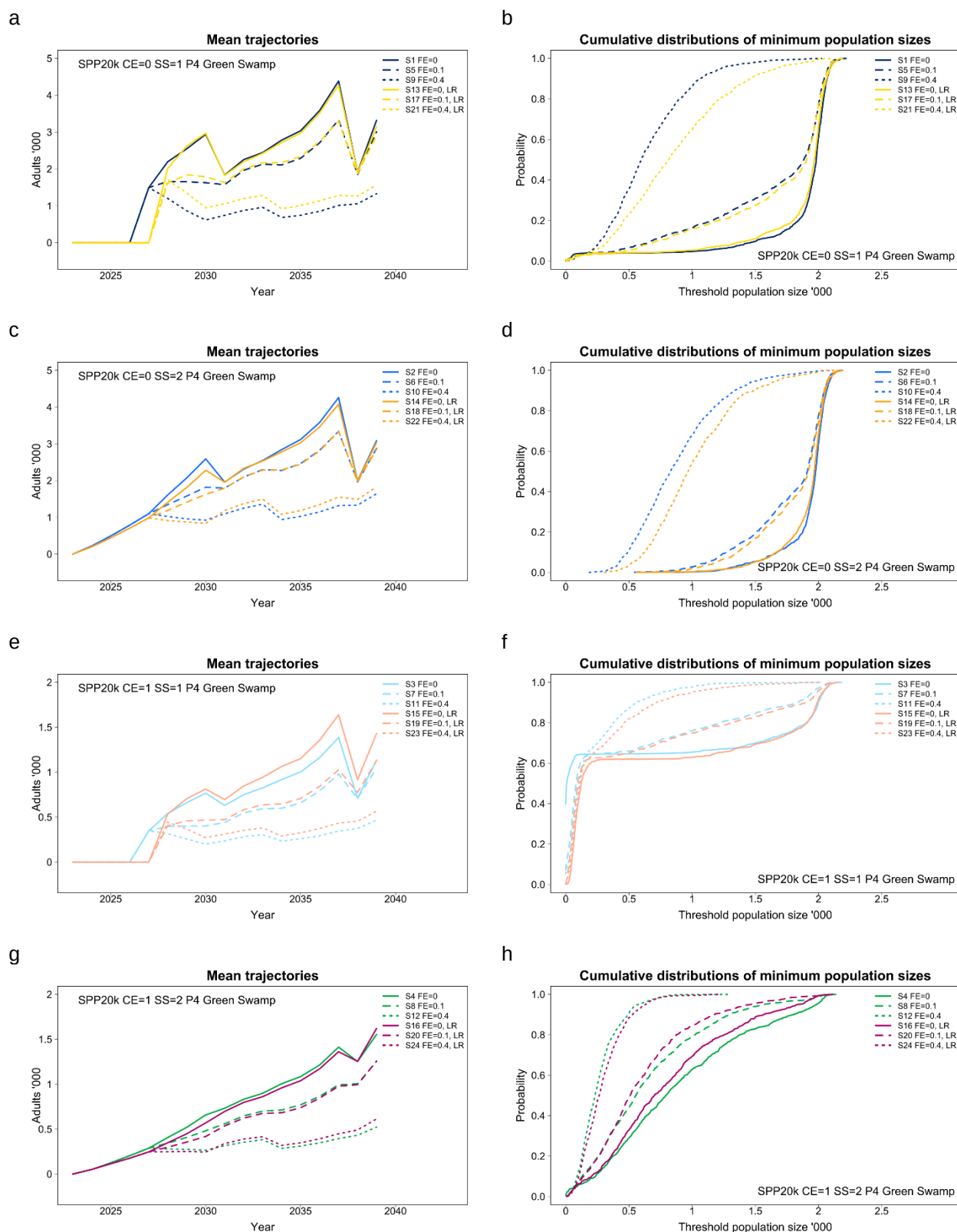


Figure A-22. Predicted adult Southern Pygmy Perch responses to six scenarios comparing the Leaky Regulator concept for the Green Swamp population. Fish were stocked at a rate of 20,000 per year. Top panel shows mean scenario trajectories through time and the bottom panel shows the distributions of the minimum population size for each scenario collected from the 10th timestep onwards. FE = flood effect, CE = competition effect and SS = stocking strategy.

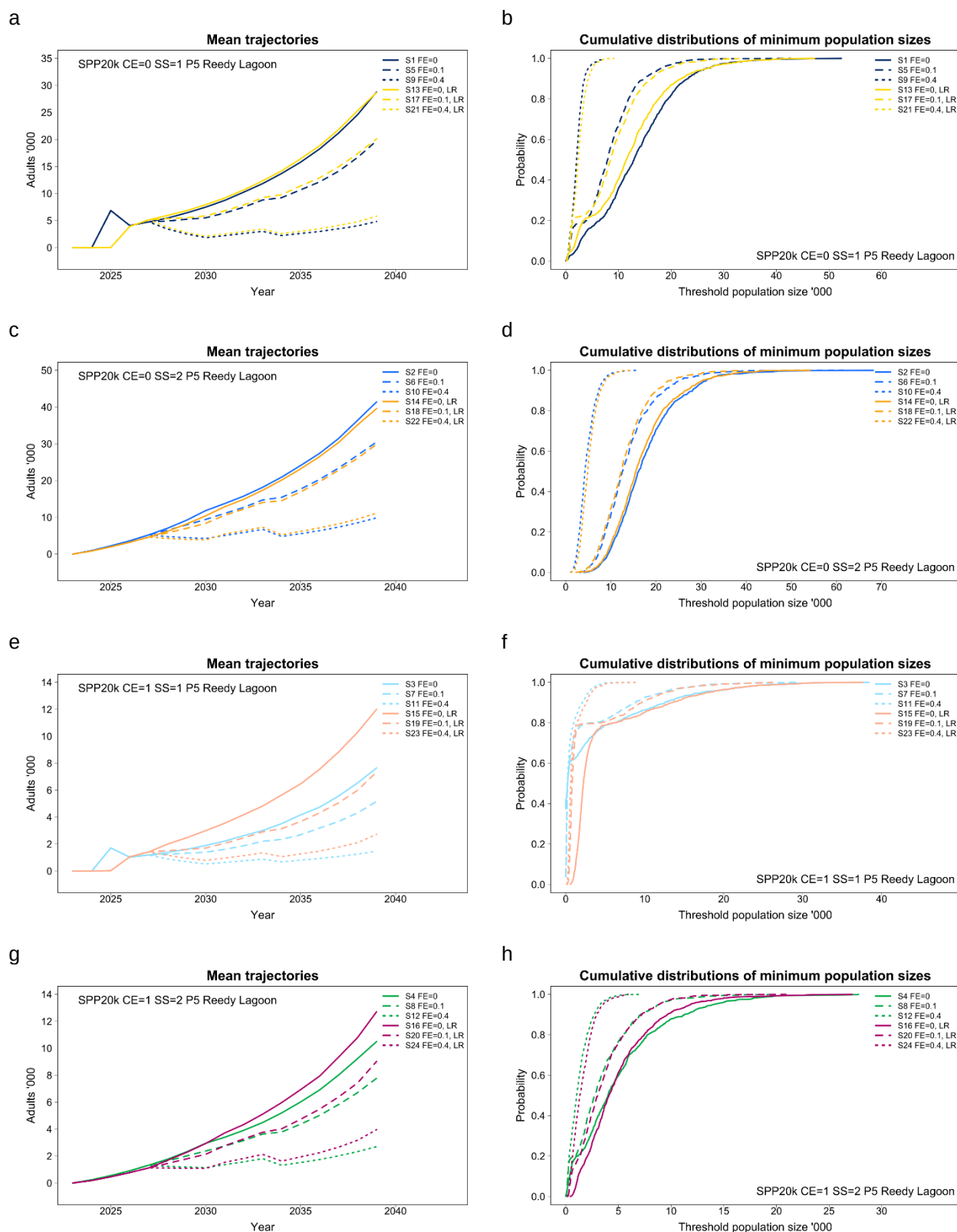


Figure A-23. Predicted adult Southern Pygmy Perch responses to six scenarios comparing the Leaky Regulator concept for the Reedy Lagoon population. Fish were stocked at a rate of 20,000 per year. Top panel shows mean scenario trajectories through time and the bottom panel shows the distributions of the minimum population size for each scenario collected from the 10th timestep onwards. FE = flood effect, CE = competition effect and SS = stocking strategy.

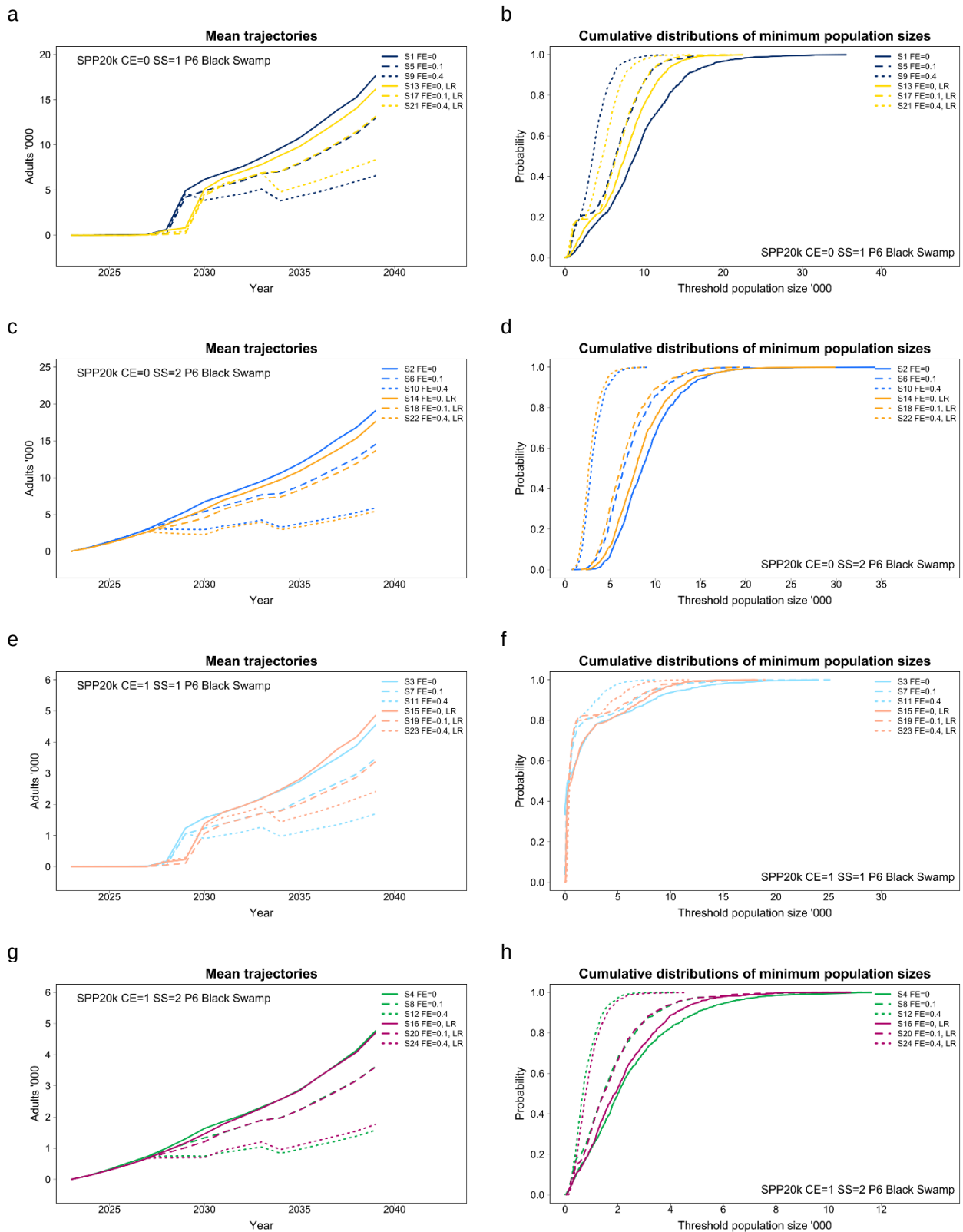


Figure A-24. Predicted adult Southern Pygmy Perch responses to six scenarios comparing the Leaky Regulator concept for the Black Swamp population. Fish were stocked at a rate of 20,000 per year. Top panel shows mean scenario trajectories through time and the bottom panel shows the distributions of the minimum population size for each scenario collected from the 10th timestep onwards. FE = flood effect, CE = competition effect and SS = stocking strategy.

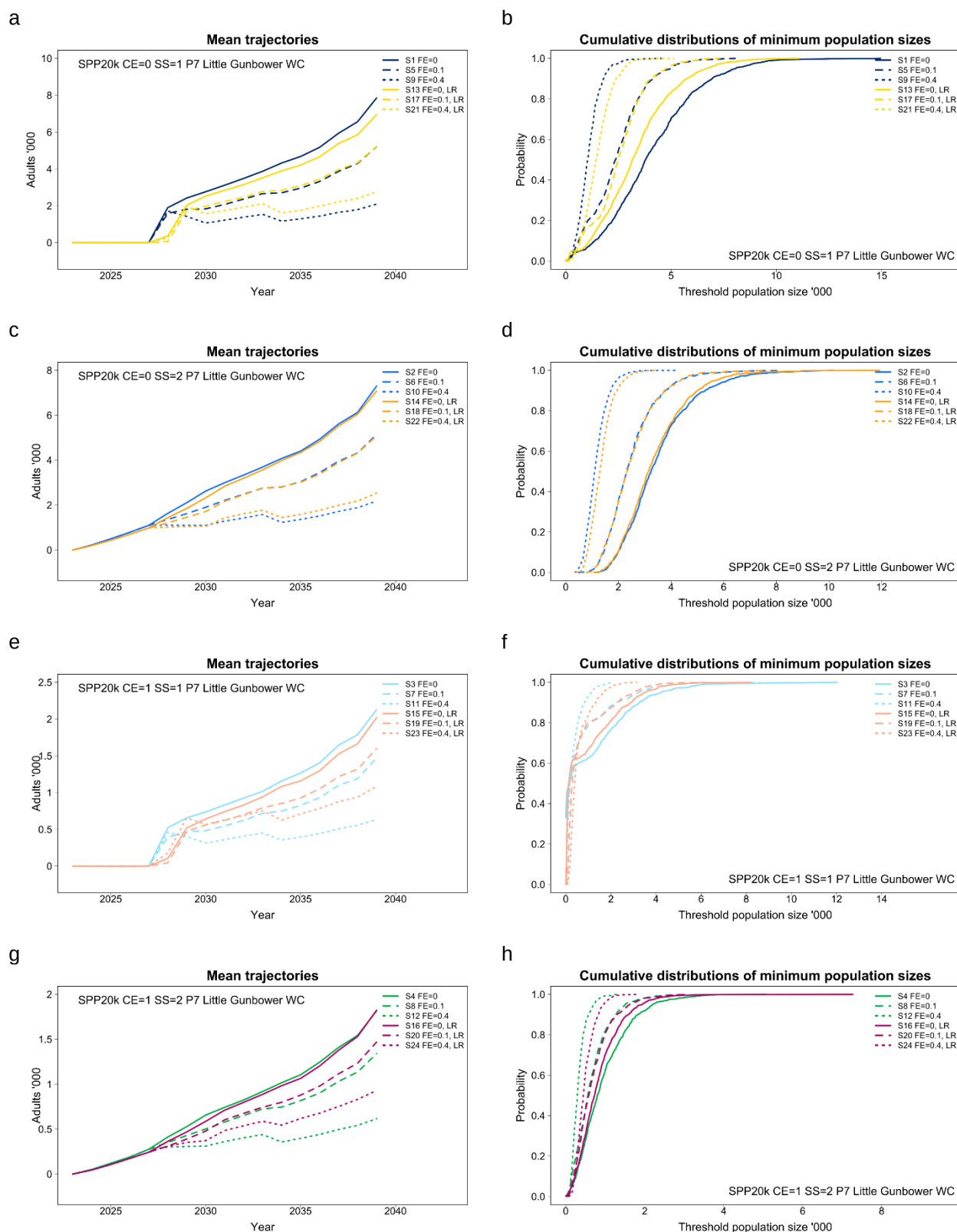


Figure A-25. Predicted adult Southern Pygmy Perch responses to six scenarios comparing the Leaky Regulator concept for the Little Gunbower Wetland Complex population. Fish were stocked at a rate of 20,000 per year. Top panel shows mean scenario trajectories through time and the bottom panel shows the distributions of the minimum population size for each scenario collected from the 10th timestep onwards. FE = flood effect, CE = competition effect and SS = stocking strategy.

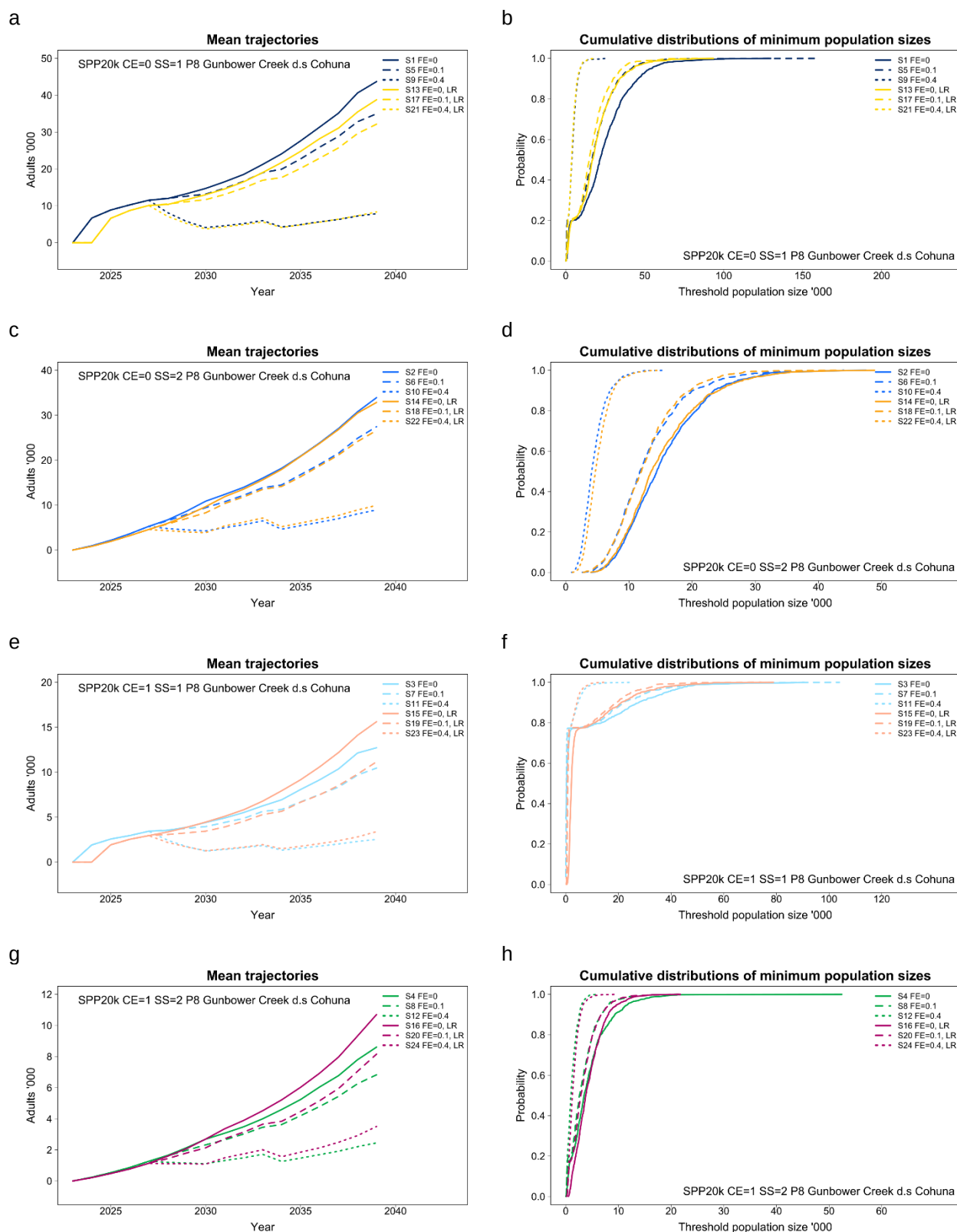


Figure A-26. Predicted adult Southern Pygmy Perch responses to six scenarios comparing the Leaky Regulator concept for the Gunbower Creek downstream of Cohuna population. Fish were stocked at a rate of 20,000 per year. Top panel shows mean scenario trajectories through time and the bottom panel shows the distributions of the minimum population size for each scenario collected from the 10th timestep onwards. FE = flood effect, CE = competition effect and SS = stocking strategy.

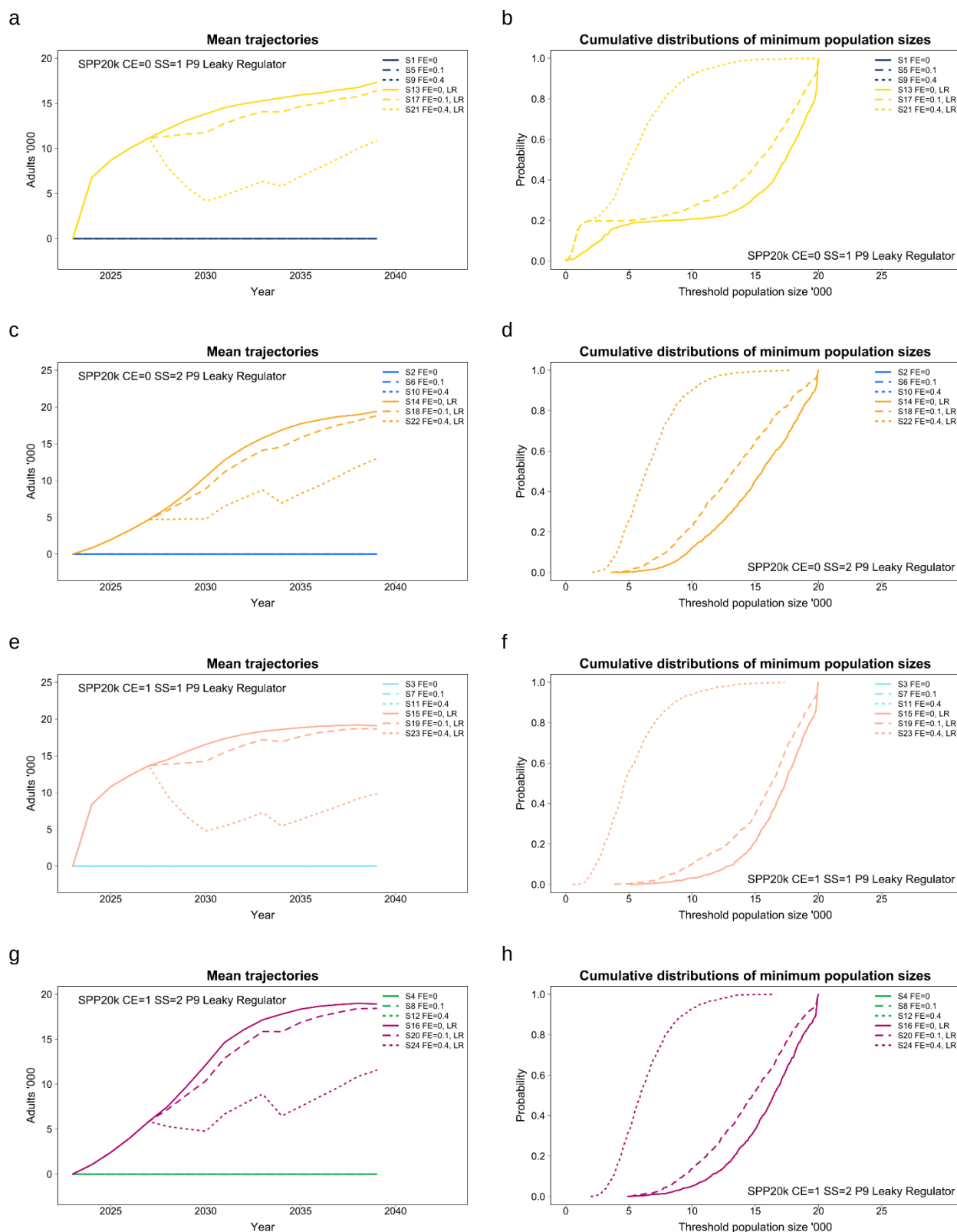


Figure A-27. Predicted adult Southern Pygmy Perch responses to six scenarios comparing the Leaky Regulator concept for the Leaky Regulator population. Fish were stocked at a rate of 20,000 per year. Top panel shows mean scenario trajectories through time and the bottom panel shows the distributions of the minimum population size for each scenario collected from the 10th timestep onwards. FE = flood effect, CE = competition effect and SS = stocking strategy. Note outcomes from scenarios S1 to S12 are zero as there is no 9th population in these scenarios.

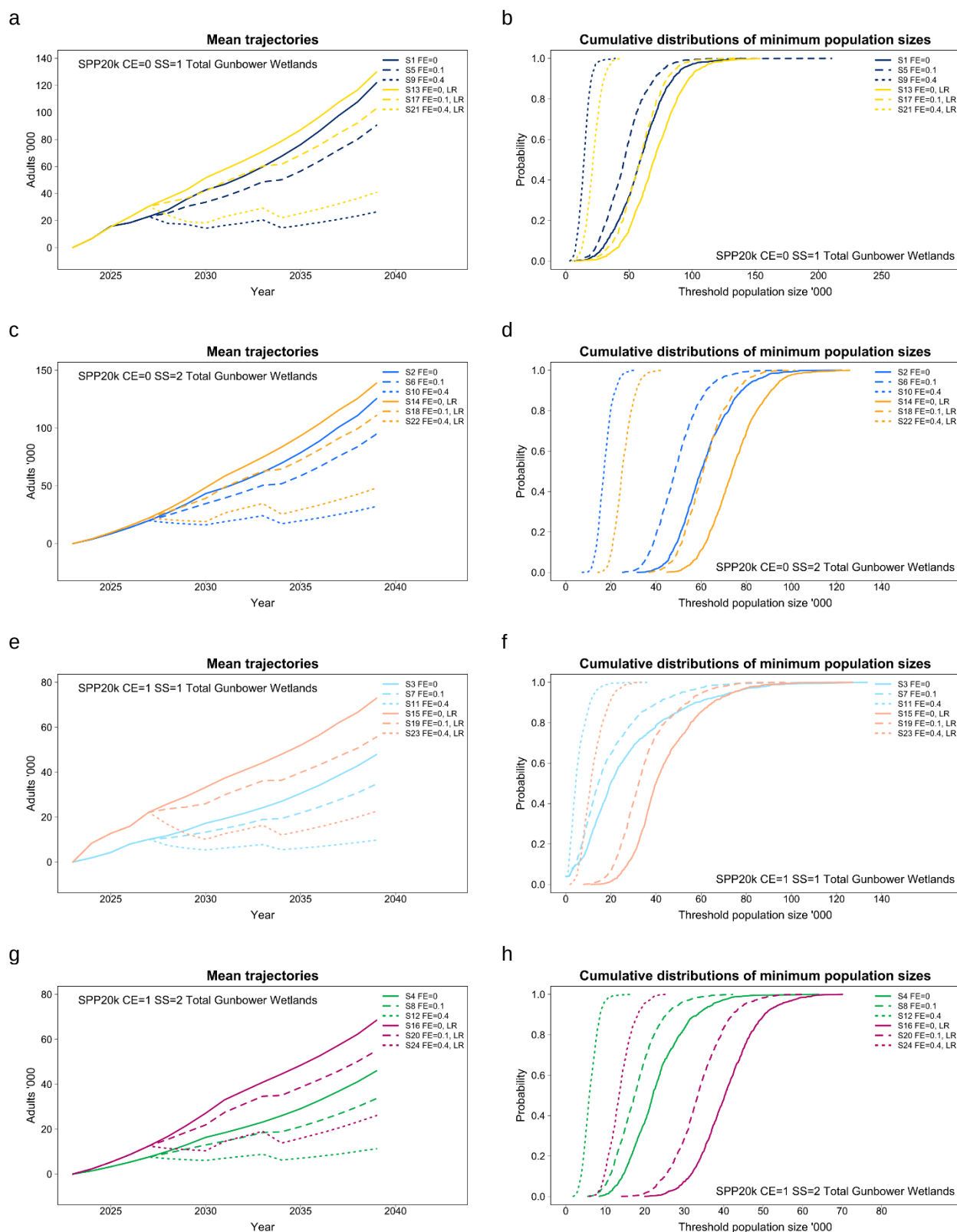


Figure A-28. Predicted adult Southern Pygmy Perch responses to six scenarios comparing the Leaky Regulator concept for all populations modelled at Gunbower Island. Fish were stocked at a rate of 20,000 per year. Top panel shows mean scenario trajectories through time and the bottom panel shows the distributions of the minimum population size for each scenario collected from the 10th timestep onwards. FE = flood effect, CE = competition effect and SS = stocking strategy.

Stocking 5,000 fish

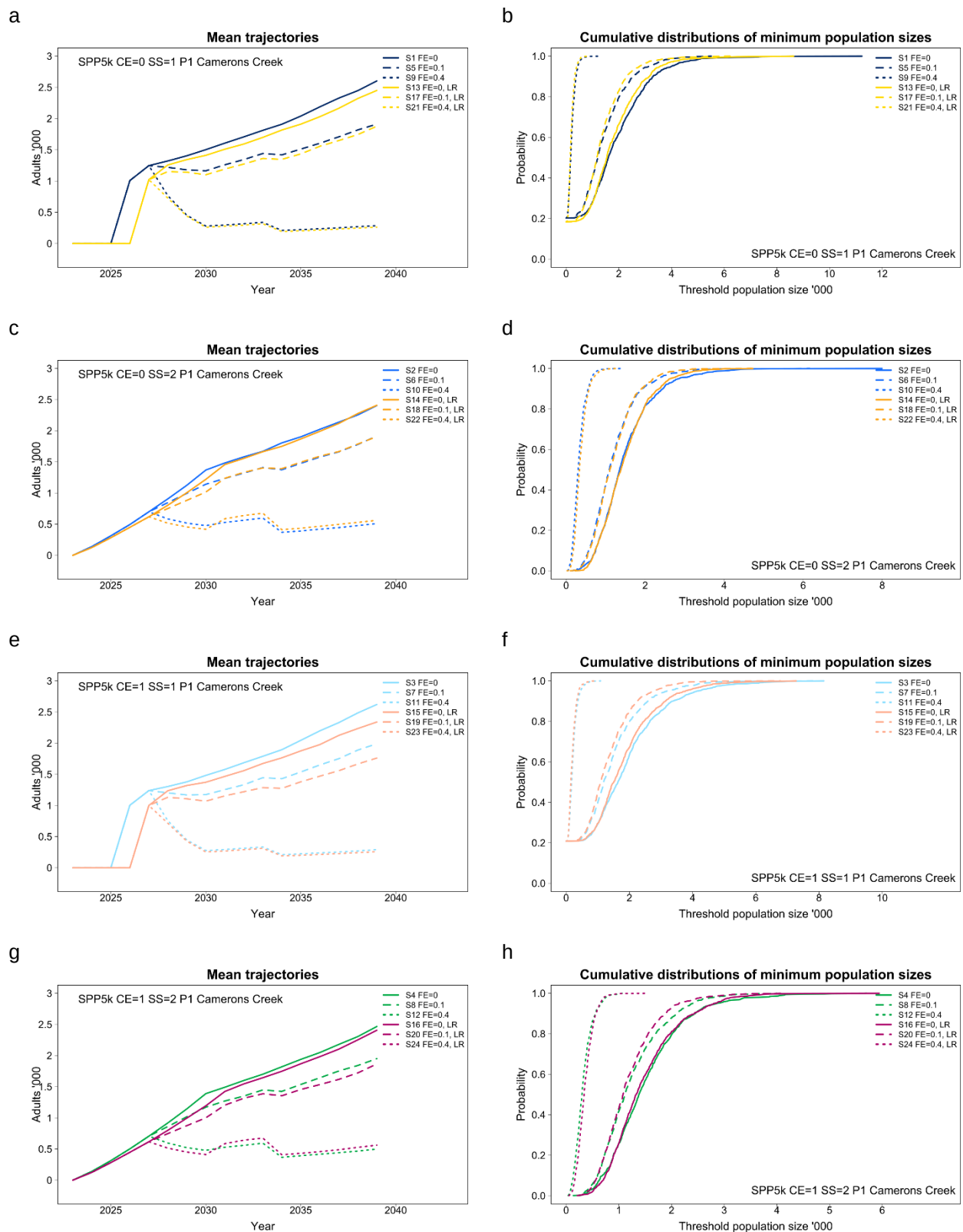


Figure A-29. Predicted adult Southern Pygmy Perch responses to six scenarios comparing the Leaky Regulator concept for the Cameron's Creek population. Fish were stocked at a rate of 5,000 per year. Top panel shows mean scenario trajectories through time and the bottom panel shows the distributions of the minimum population size for each scenario collected from the 10th timestep onwards. FE = flood effect, CE = competition effect and SS = stocking strategy.

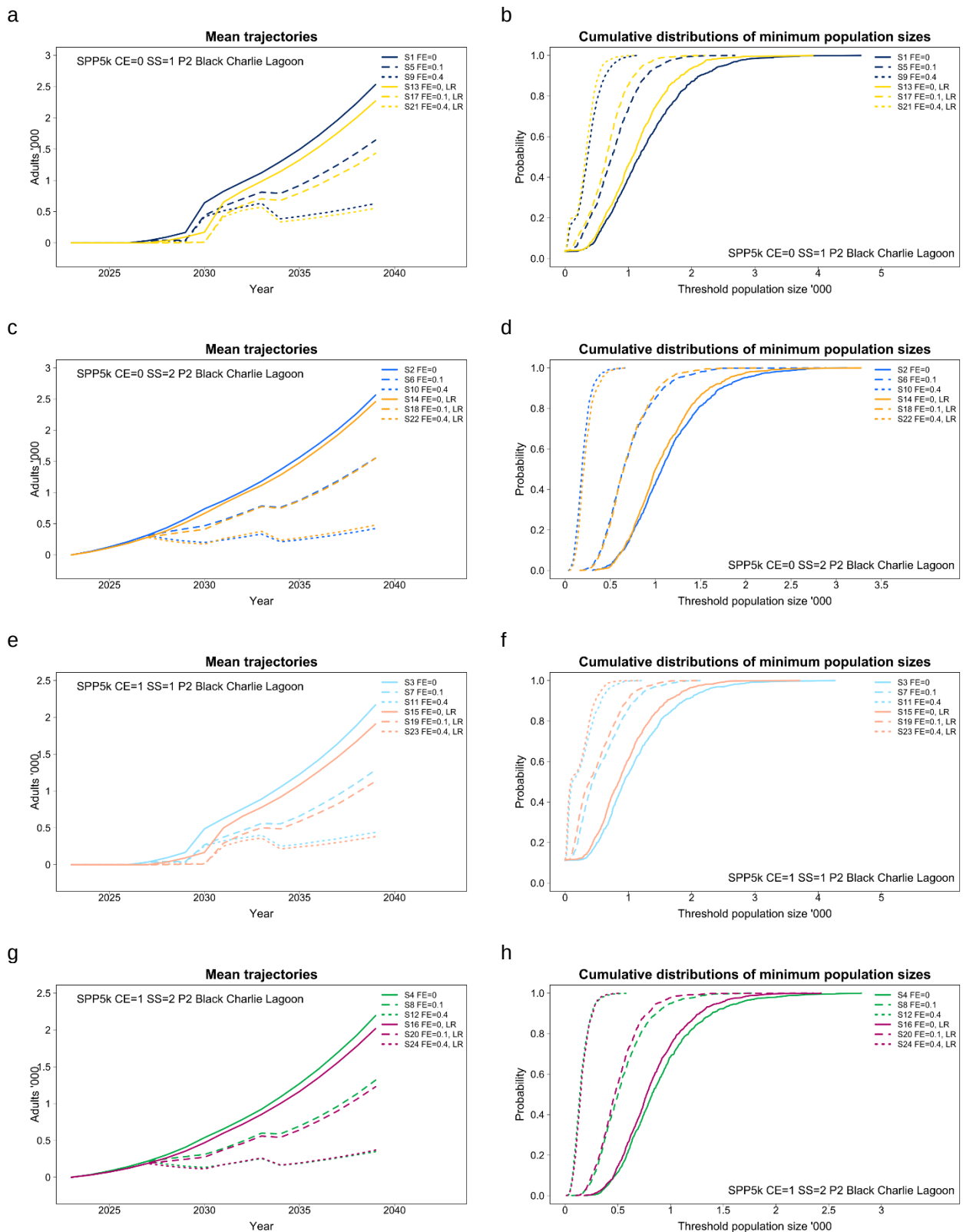


Figure A-30. Predicted adult Southern Pygmy Perch responses to six scenarios comparing the Leaky Regulator concept for the Black Charlie Lagoon population. Fish were stocked at a rate of 5,000 per year. Top panel shows mean scenario trajectories through time and the bottom panel shows the distributions of the minimum population size for each scenario collected from the 10th timestep onwards. FE = flood effect, CE = competition effect and SS = stocking strategy.

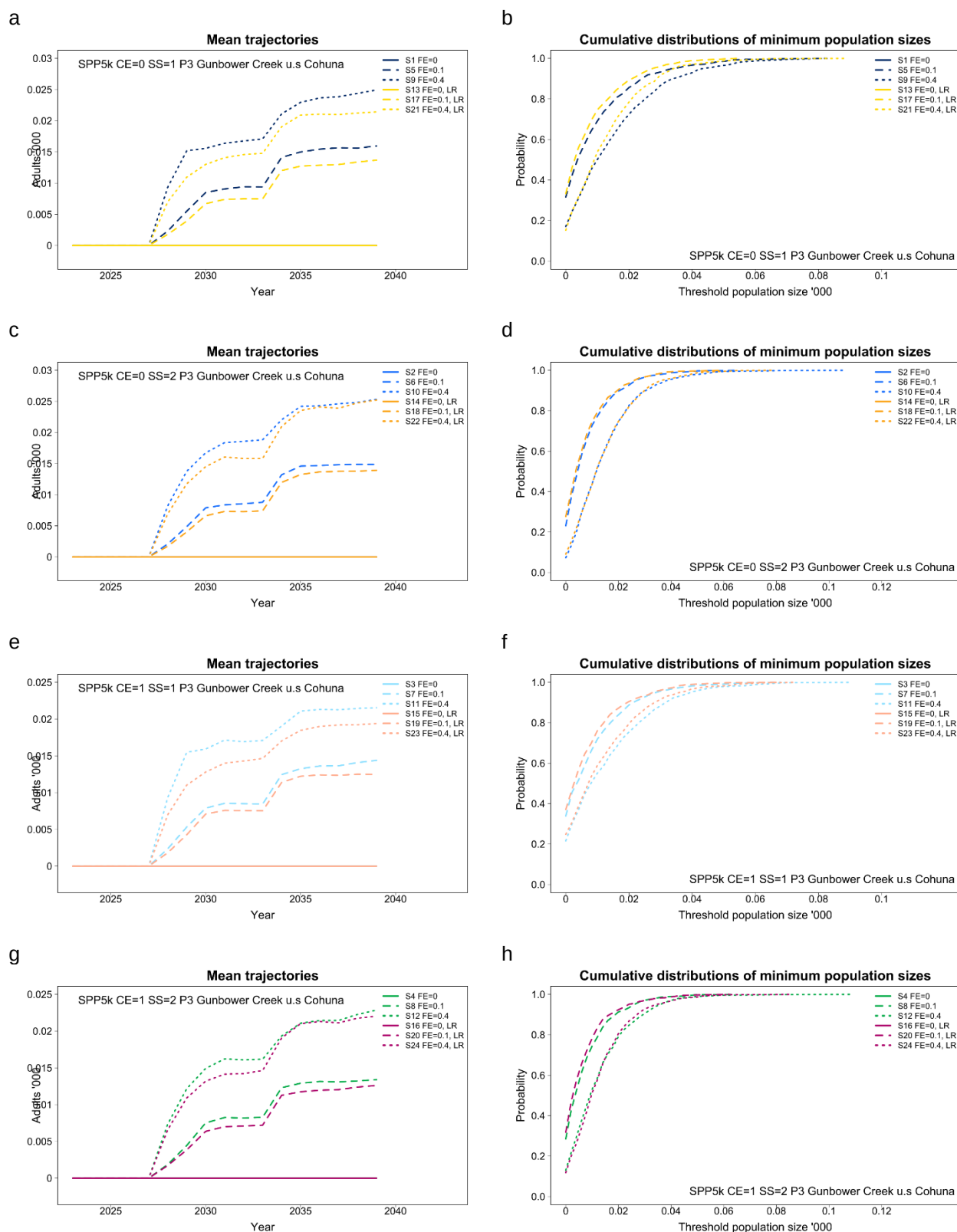


Figure A-31. Predicted adult Southern Pygmy Perch responses to six scenarios comparing the Leaky Regulator concept for the Gunbower Creek upstream of Cohuna population. Fish were stocked at a rate of 5,000 per year. Top panel shows mean scenario trajectories through time and the bottom panel shows the distributions of the minimum population size for each scenario collected from the 10th timestep onwards. FE = flood effect, CE = competition effect and SS = stocking strategy.

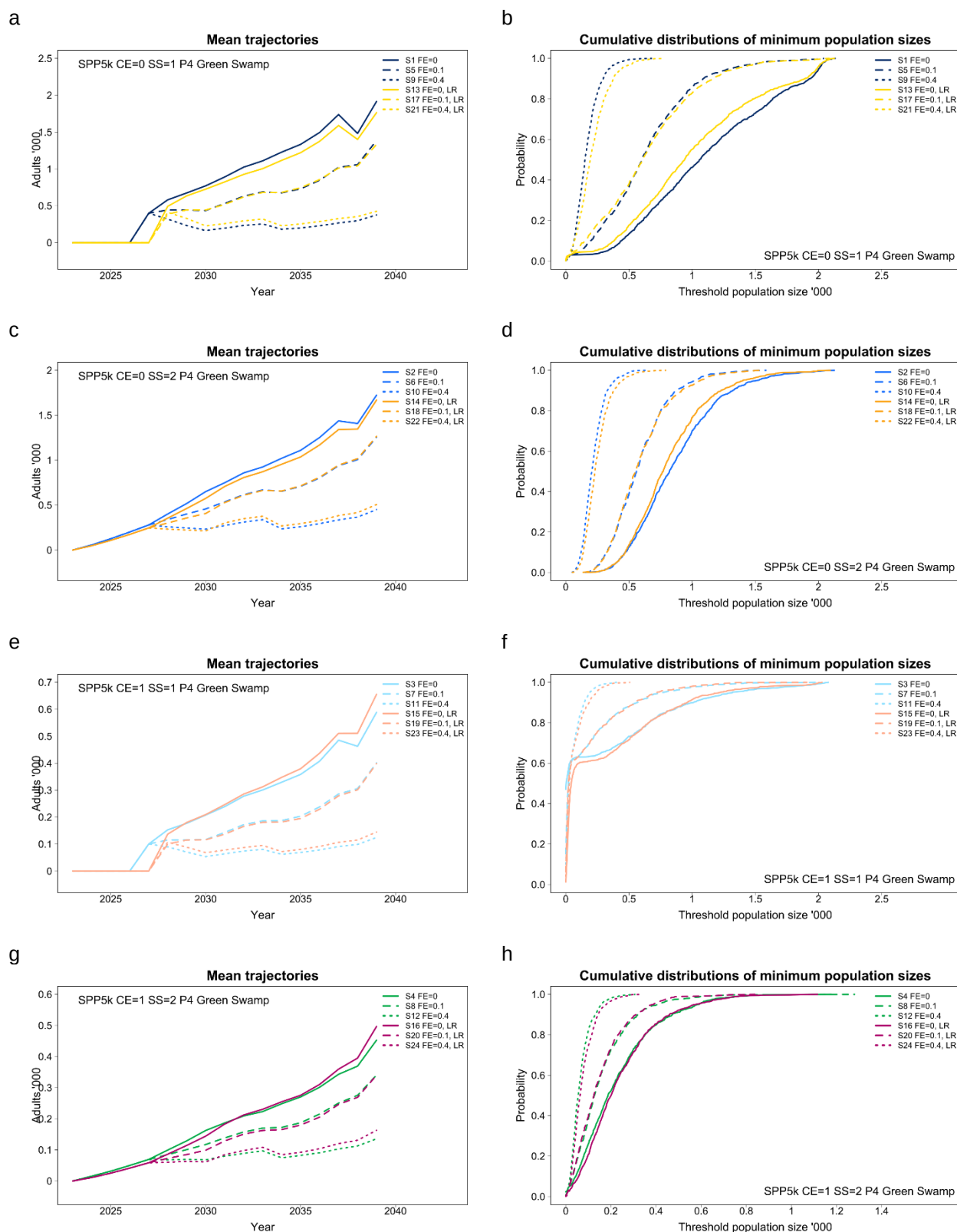


Figure A-32. Predicted adult Southern Pygmy Perch responses to six scenarios comparing the Leaky Regulator concept for the Green Swamp population. Fish were stocked at a rate of 5,000 per year. Top panel shows mean scenario trajectories through time and the bottom panel shows the distributions of the minimum population size for each scenario collected from the 10th timestep onwards. FE = flood effect, CE = competition effect and SS = stocking strategy.

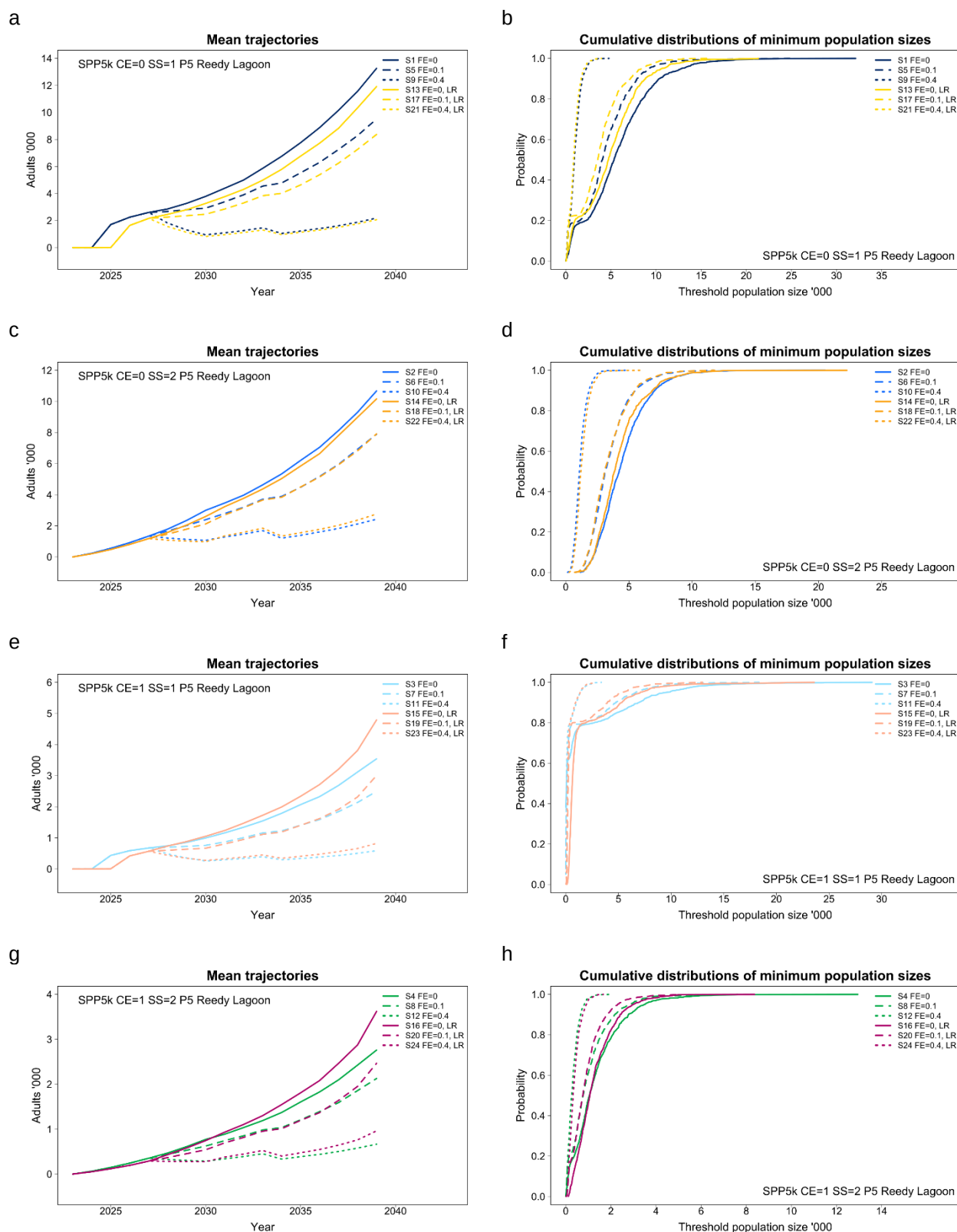


Figure A-33. Predicted adult Southern Pygmy Perch responses to six scenarios comparing the Leaky Regulator concept for the Reedy Lagoon population. Fish were stocked at a rate of 5,000 per year. Top panel shows mean scenario trajectories through time and the bottom panel shows the distributions of the minimum population size for each scenario collected from the 10th timestep onwards. FE = flood effect, CE = competition effect and SS = stocking strategy.

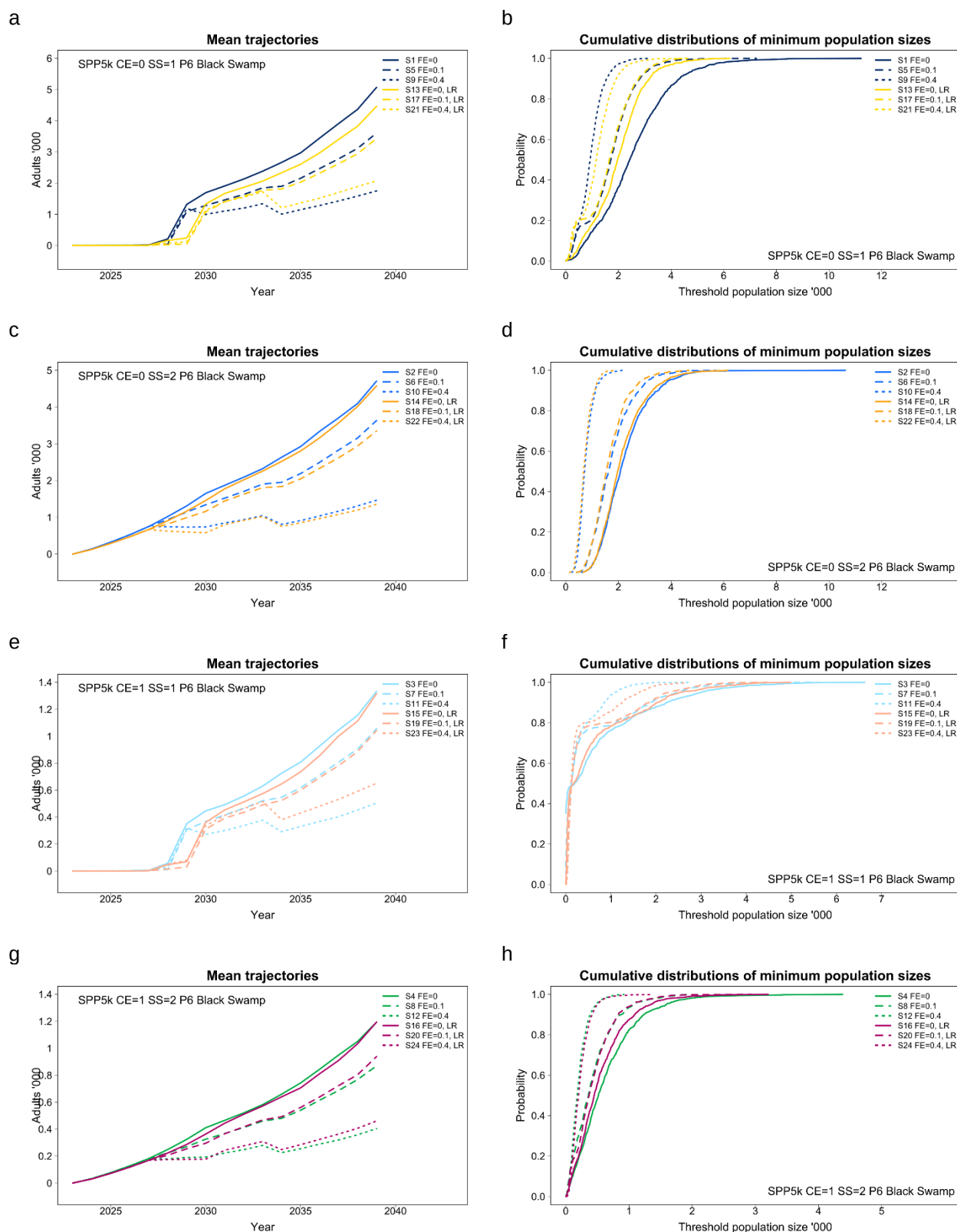


Figure A-34. Predicted adult Southern Pygmy Perch responses to six scenarios comparing the Leaky Regulator concept for the Black Swamp population. Fish were stocked at a rate of 5,000 per year. Top panel shows mean scenario trajectories through time and the bottom panel shows the distributions of the minimum population size for each scenario collected from the 10th timestep onwards. FE = flood effect, CE = competition effect and SS = stocking strategy.

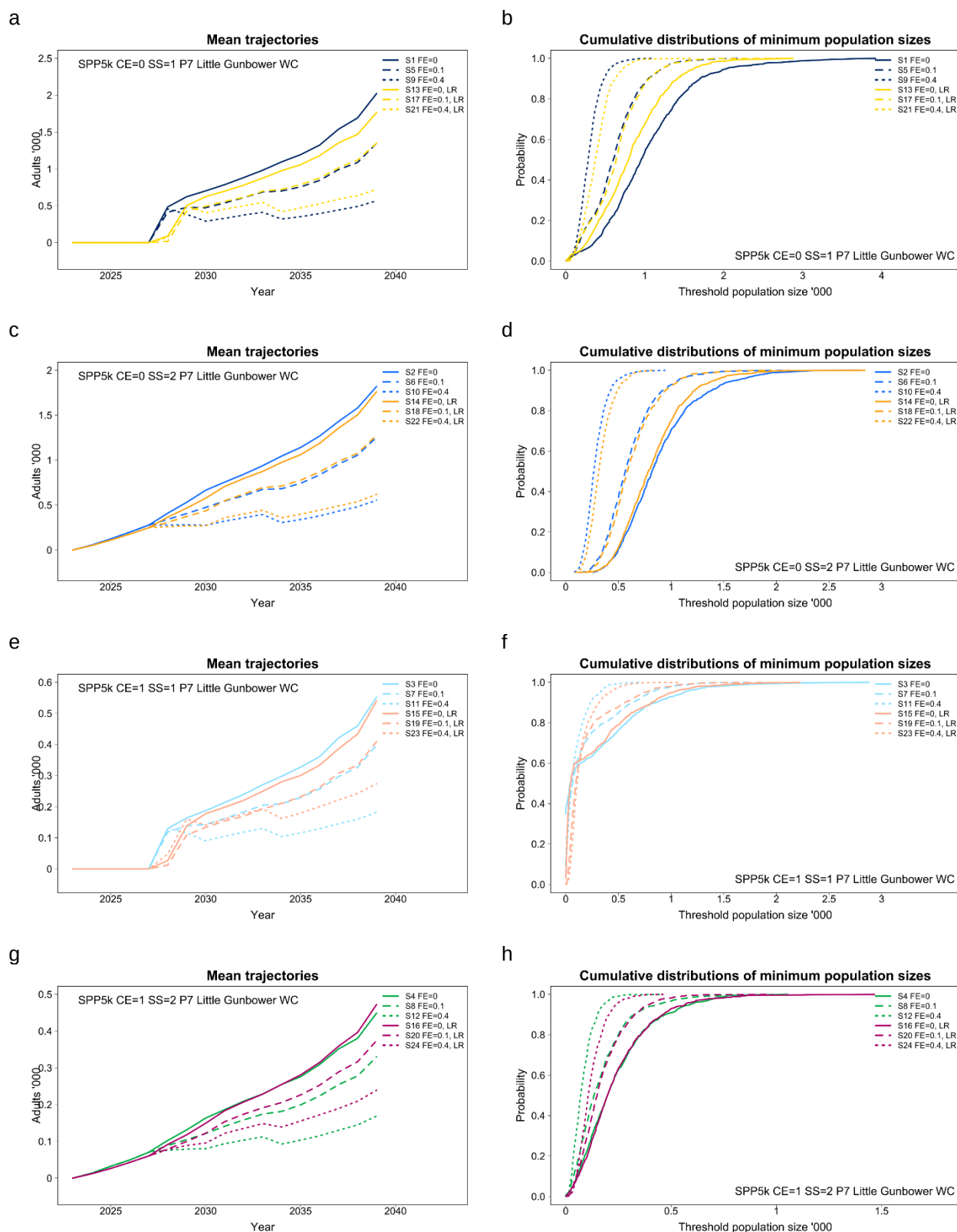


Figure A-35. Predicted adult Southern Pygmy Perch responses to six scenarios comparing the Leaky Regulator concept for the Little Gunbower Wetland Complex population. Fish were stocked at a rate of 5,000 per year. Top panel shows mean scenario trajectories through time and the bottom panel shows the distributions of the minimum population size for each scenario collected from the 10th timestep onwards. FE = flood effect, CE = competition effect and SS = stocking strategy.

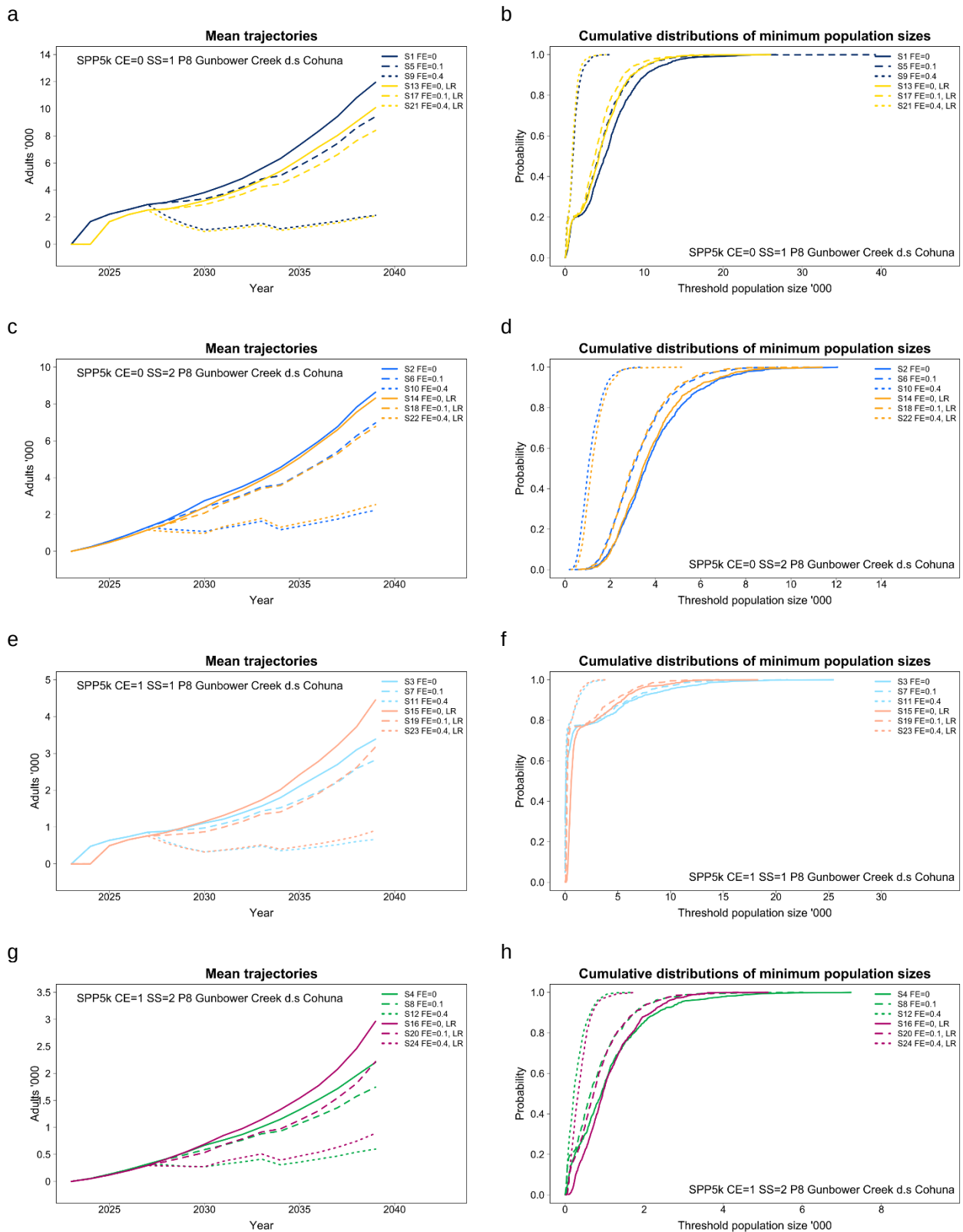


Figure A-36. Predicted adult Southern Pygmy Perch responses to six scenarios comparing the Leaky Regulator concept for the Gunbower Creek downstream of Cohuna population. Fish were stocked at a rate of 5,000 per year. Top panel shows mean scenario trajectories through time and the bottom panel shows the distributions of the minimum population size for each scenario collected from the 10th timestep onwards. FE = flood effect, CE = competition effect and SS = stocking strategy.

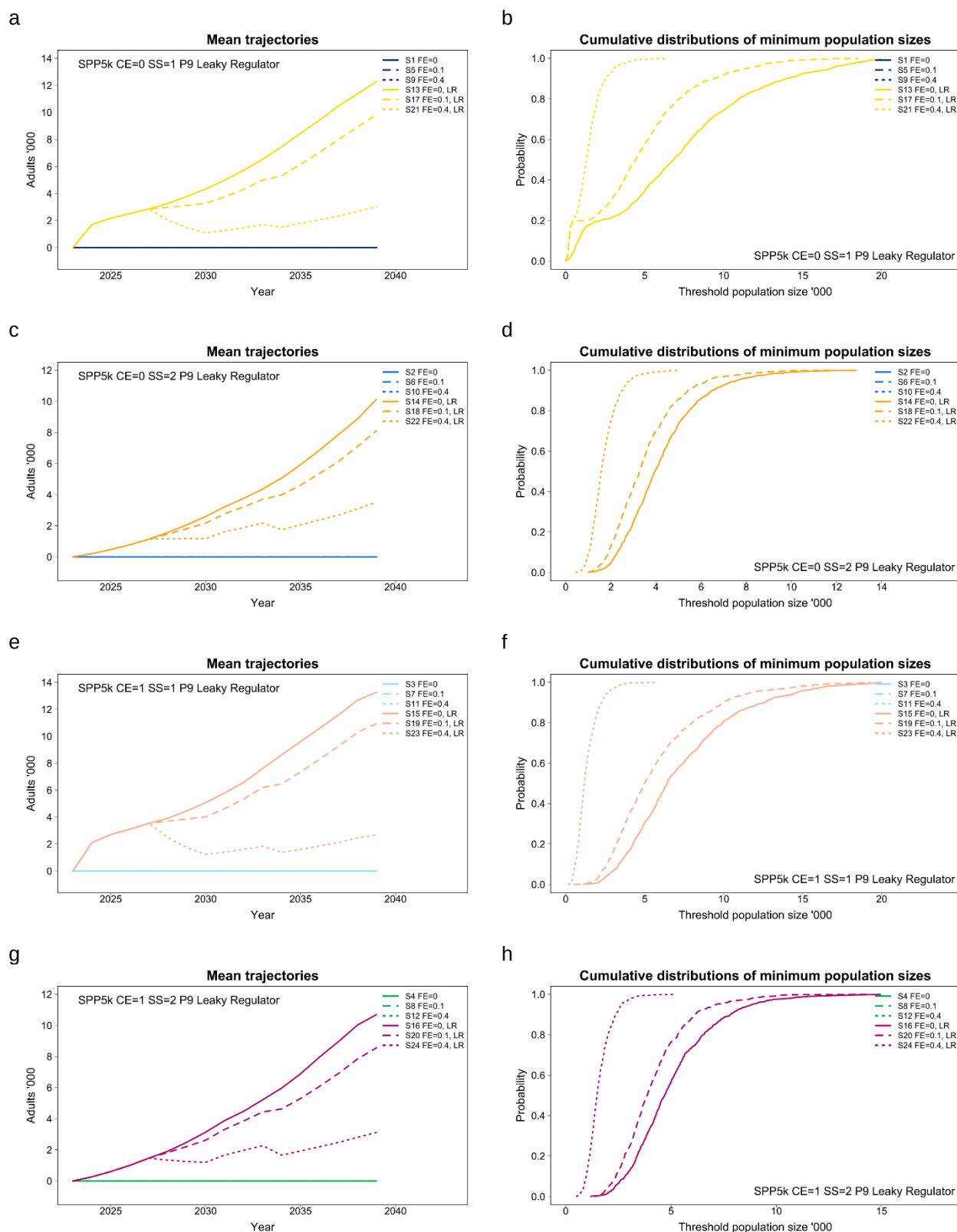


Figure A-37. Predicted adult Southern Pygmy Perch responses to six scenarios comparing the Leaky Regulator concept for the Leaky Regulator population. Fish were stocked at a rate of 5,000 per year. Top panel shows mean scenario trajectories through time and the bottom panel shows the distributions of the minimum population size for each scenario collected from the 10th timestep onwards. FE = flood effect, CE = competition effect and SS = stocking strategy. Note outcomes from scenarios S1 to S12 are zero as there is no 9th population in these scenarios.

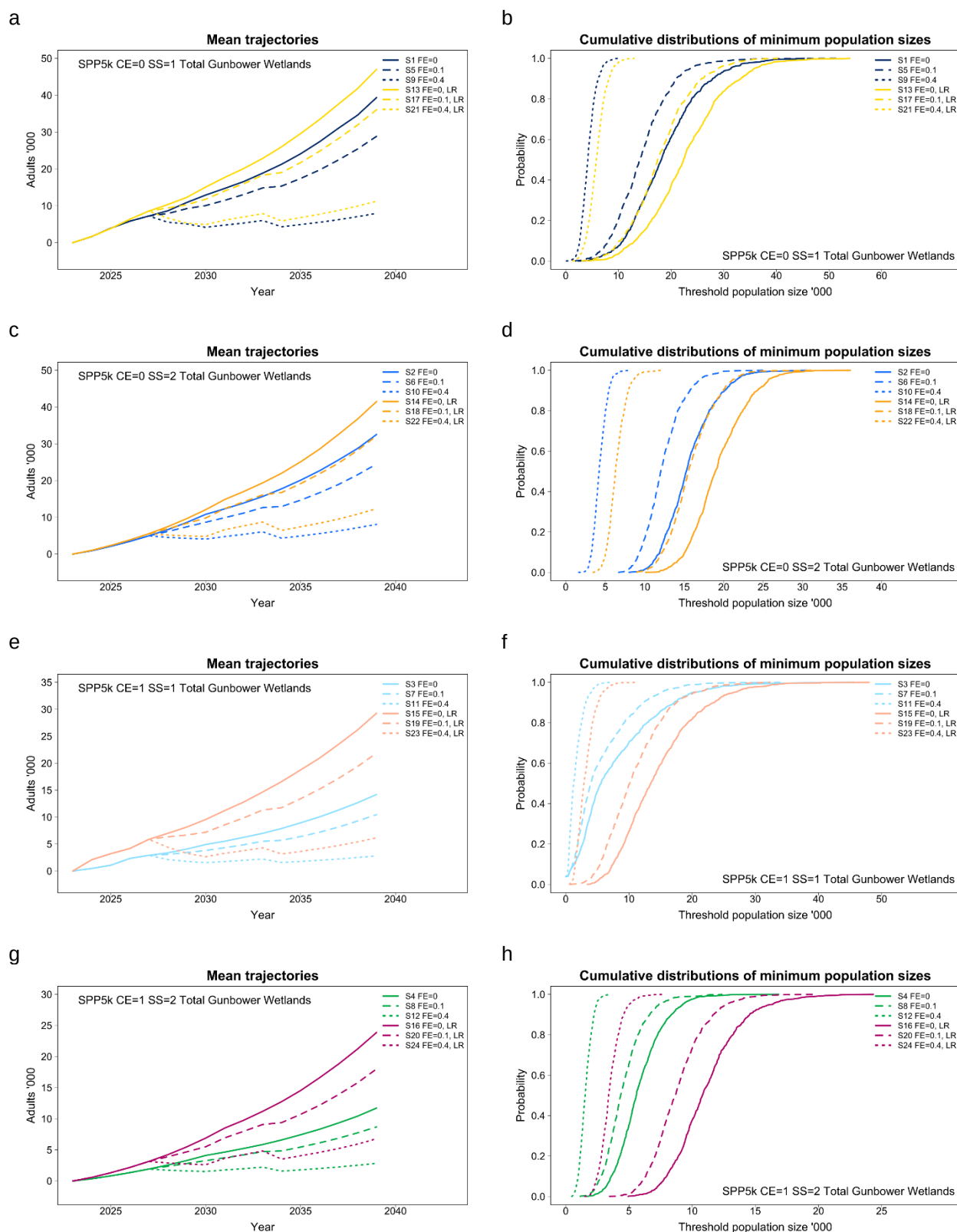


Figure A-38. Predicted adult Southern Pygmy Perch responses to six scenarios comparing the Leaky Regulator concept for all populations modelled at Gunbower Island. Fish were stocked at a rate of 5,000 per year. Top panel shows mean scenario trajectories through time and the bottom panel shows the distributions of the minimum population size for each scenario collected from the 10th timestep onwards. FE = flood effect, CE = competition effect and SS = stocking strategy.

Appendix 2. Southern Pygmy Perch ecology and the population model

Southern Pygmy Perch background

Ecology

The Southern Pygmy Perch, *Nannoperca australis*, is a small carnivorous fish, growing to 65–85 mm in length (Sanger, 1978; Llewellyn 1980; Jones et al. 2008), with a small mouth reaching to just below the eye and a rounded tail. The species is deep bodied and varies in colour from pale cream to dark olive with a darker back and lighter belly (DPI NSW 2014). It is relatively short lived, with the oldest being recorded at 3+ years of age, and most individuals only living for one to two years after their first spawning season (Humphries 1995; Hammer 2002). The species breeds during spring when water temperatures increase, with egg numbers ranging from hundreds to thousands depending on body size.

Conservation status

Southern Pygmy Perch are listed as endangered under three different Acts:

- 7a of the NSW Fisheries Management Act 1994.
- Commonwealth Environmental Protection and Biodiversity Conservation Act 1999.
- South Australia National Parks and Wildlife Act 1972.

Distribution

Historically, the species was widely distributed throughout the Lachlan, Murrumbidgee and Murray river systems, as well as coastal streams in South Australia, Victoria, north-eastern Tasmania and King and Flinders islands in Bass Strait (Llewellyn 1974). It is still relatively common in coastal Victoria; however, overall its population numbers and distribution have both declined, particularly in inland regions (Thomson et al. 2011).

Habitat

Southern Pygmy Perch are found in a wide range of lentic and lotic environments, but prefer vegetated slow flowing water associated with backwaters and the fringes of small streams, and within wetland, lake, billabong and drainage systems (Llewellyn 1974; Lintermans 2023; Cook 2007; NSW DPI 2014). The species forms small groups amongst aquatic vegetation and woody debris where they feed, spawn and seek refuge (Thomson and Bray 2011). They can tolerate a broad range of temperatures and extremely low dissolved oxygen levels (McNeil and Closs 2007), which are often associated with their preferred habitat.

Movement

The species has been found to be very poor at dispersing (Hammer 2002), with main river channels acting as the primary means of dispersal and recolonisation (Llewellyn 1974). Flooding of these main river channels can provide new habitats, favouring high spawning productivity and a fresh input of new recruits, which influences the population structure and viability (Humphries 1995; Tonkin et al. 2008).

Life cycle

Age at maturity

Both sexes become sexually mature and spawn at the end of their first year of life, when males reach 30 mm and females reach 33 mm in length (Humphries 1995; Hammer 2002; NSW DPI 2014).

Spawning

Spawning is protracted and typically occurs between September and December (or January in Tasmania), with eggs scattered over aquatic vegetation woody debris or rocks (Llewellyn 1974) or the benthos within male territories (Mitchell 1976). Spawning typically occurs in slow-flowing habitats with complex physical habitat (Tonkin 2008) including available floodplains (Woodward and Malone 2002). It is not linked to hydrology (Llewellyn 1980), but rather to circa-annual cues, particularly water temperatures of 15–20.5 °C (Llewellyn 1974, 1980; Humphries 1995; Woodward 2005; Tonkin et al. 2008; NSW DPI 2014).

Fecundity

Fecundity and egg size vary within and among populations, depending on body size, age and environmental conditions (Humphries 1995; Woodward and Malone 2002; Morrongiello et al. 2012). Fecundity estimates range from 40–4000 eggs per female (mean 451.19 ± 359.82 SD) (Cadwallader and Backhouse 1983; Kuiter et al. 1996; Morrongiello et al. 2012). There is a relationship between fecundity and length: $F = 20.096L - 597.220$ (Humphries 1995). Kuiter et al. (1996) state variable fecundity from 100 to 2000, with over 600 eggs recorded in a 63 mm fish. Morrongiello et al. (2012) recorded 40 to 2651 in fish ranging from lengths of 33–85 mm. Combined with data from Morrongiello et al. (2012), fecundity has been modelled as $F = \exp(0.05068 \times Length + 3.2043)$ or $F_{Age} = \exp(0.05068 \times \exp(0.1933 \times Age + 3.4597) + 3.2043)$ (Todd et al. 2017). Eggs are small (0.91–1.55 mm; Morrongiello et al. 2012), round, transparent, non-adhesive and demersal (Llewellyn 1974; Humphries 1995). Morrongiello (2011) showed that the average egg size decreased and egg number increased with increasing environmental variability and decreasing environmental quality.

Egg development and larvae

Eggs are scattered over vegetation or rocks on the substrate and, at 15–18 °C, and take 2–4 days to hatch (Llewellyn 1974). Larvae are 3–4 mm once hatched, and start foraging at the age of 5 days once the yolk sack has been used up (Llewellyn 1974).

Paternal protection of eggs and larvae is potentially weak, because they are scattered within male territories (Knight et al. 2007).

Recruitment

Given the short longevity, population persistence is largely reliant on annual recruitment. Populations have been found to be highly variable in their interannual recruitment, and dependant on fecundity and larval survival rates (Humphries 1995). Increases in local population abundance are typically observed in November following juvenile recruitment, but recruitment strength may vary between years (Woodard and Malone 2002). Enhanced recruitment has been associated with flooding and elevated water levels in spring in the mid-Murray and Lower Lakes, presumably due to greater productivity and access to nursery habitats (Bice and Ye 2007; Tonkin et al. 2008). Conversely, in small highly altered upland streams, large flood events can cause catastrophic declines because major erosive flooding events can destroy preferred habitats of aquatic vegetation and result in the

adults, larvae and eggs being washed downstream, causing mortalities and stranding fish or washing them into unsuitable habitats (Woodward 2005; Pearce 2014). Dry conditions and low water levels during or following the spawning season have been associated with diminished recruitment. Adults may persist within remnant pools, but prolonged dry conditions and an associated lack of connectivity, reduced habitat quality (e.g. loss of submerged macrophytes and increased salinity) and limited productivity can all cause consecutive recruitment failures and ultimately local populations losses (Tonkin et al. 2008; Wedderburn et al. 2014). Flooding may support recruitment and movements in wetland areas (EO). Populations are typically dominated by 0+ and 1+ fish, suggesting only a small proportion of fish survive to 2+ (Humphries 1995).

Ageing

The microstructure of sagittal otoliths of early juvenile Southern Pygmy Perch possesses clear banding, although daily increment deposition has not been validated for the species (Tonkin et al. 2008). No attempt has been made to assess the age structure of older fish due to the difficulties of annuli interpretation (Humphries 1995). Southern Pygmy Perch at 30 mm in length are around 70 days old (Tonkin et al. 2008), at 45 mm in length are approximately one year old, and at 52 mm in length are approximately 1.5 years old (Humphries 1995). A fish captured at 76 mm was aged at 3+ years (Humphries 1995). An age-length relationship was established by Humphries (1995) for both female and male fish:

$Lf_t = 64.12(1 - \exp(-0.994(t+0.309)))$ for females and $Lm_t = 61.39(1 - \exp(-0.989(t+0.326)))$ for males.

Length-weight relationship

There is a positive relationship between length and weight for Southern Pygmy Perch (i.e. as length increases, weight increases), with flattening of the curve in the upper size-classes (Jones et al. 2008). The largest fish record was 83 mm in length and weighed 6.6 g, from a sample size of 469 measured Southern Pygmy Perch (Jones et al. 2008).

Behaviour

During breeding season, males have bright red fins with black edges and display territorial behaviour (Llewellyn 1974). These colouration patterns in males are associated with lighting conditions, body size and spawning condition. It has been suggested that the colouration can potentially increase camouflage and convey information about male dominance status and quality to potential mates and other males (Morrongiello et al. 2010). Males exhibit territorial behaviour mainly during the breeding season and changes in colour can occur at this time (Mitchell 1976).

Sex ratios

In one study, when the samples of fish from all sites were combined, the sex ratios in each month did not differ significantly from 1:1 (χ^2 , $p > 0.05$) (Humphries 1995).

Genetics

There is significant genetic differentiation between the populations located north and south of the Great Dividing Range, which acts as a major biogeographic barrier (Unmack 2001). The species has also displayed localised and large-scale genetic differentiation (Hammer 2001; Cook et al. 2007), and in some cases this is despite hydrologic connectivity via major rivers, indicating that major rivers may represent barriers to population connectivity and recovery (Cook et al. 2007). Isolation of waterways during dry periods has also

been implicated in driving local genetic structuring of populations, with effective population size being related to greater population connectivity and therefore higher diversity via genetic rescue effect (Cook et al. 2007).

Another closely related species, Yarra Pygmy Perch (*Nannoperca obscura*) co-occurs with Southern Pygmy Perch at several locations, and hybrids have been confirmed (Kuitert et al. 1996; Woodward and Malone 2002; Hammer et al. 2010). Southern Pygmy Perch generally had greater mtDNA diversity than that reported for other endangered freshwater fish (Cook et al. 2007), indicating genetic inbreeding to be of less concern compared with other endangered freshwater fish.

Habitats

Southern Pygmy Perch occur in a wide range of lentic and lotic habitats (Cook et al. 2007), including small creeks, shallow wetlands and lakes nearby to large rivers (Humphries 1995). In the Murray–Darling Basin (MDB), they are most commonly found in off-channel habitats or in creeks preferring slow-flowing or still waters associated with macrophytes and woody debris (Llewellyn 1974; Tonkin et al. 2008; NSW DPI 2014). Southern Pygmy Perch favour shallow littoral habitats, but individuals may be observed at greater depths in areas with macrophytes not exposed to substantial currents (Humphries 1995). They are reliant on the presence of perennial refuge pools during cease-to-flow periods to avoid localised population losses (Dexter et al. 2014), but are able to tolerate a broad range of temperatures (3.4–29.5 °C; Llewellyn 1974), salinities (to 10 ppt; Chessman and Williams 1974), and extremely low DO levels (< 1.0 mgL⁻¹) for short periods of time (McNeil and Closs 2007).

Movements

Southern Pygmy Perch are considered to be non-migratory, exhibiting limited dispersal ability (Hammer 2002; Dexter et al. 2014). Surveys after high flow years and floodplain inundation reported local colonisation at a greater number of sites (Tonkin et al. 2008). Flooding may provide new habitats, promote productivity and facilitate the movement of the species (Humphries 1995; Tonkin et al. 2008). Genetic analyses indicate a lack of contemporary gene flow among remnant populations in the MDB in concurrence with a largely sedentary life history and limited dispersal ability (Cole et al. 2016). The species has exhibited slow upstream dispersal from translocations into a small creek (a total of 528 fish), with fish detected 3 km upstream of the stocking site after 9 years (L. Pearce, NSW DPI, pers. comm.).

Threats

Southern Pygmy Perch generally live within small and sometimes isolated populations in fragmented, patchy and variable habitats. A reduction in seasonal flooding, which creates habitat linkages, highlights the species' poor dispersal ability and the species' short life span, greatly reducing its ability to recolonise new habitats, leaving them at increased risk from a number of different threats (Higham et al. 2005; Jones et al. 2008; Lintermans 2023). Threats include but are not limited to: predation by alien species; habitat alteration; floodplain disconnection; water abstraction; cold-water pollution; seasonal flow changes/reductions; disturbance from alien species. The species is considered highly vulnerable to drought (Crook et al. 2010) (particularly in small streams with refuge pools that will dry with prolonged drought), and climate change impacts (Chessman, 2013)

Habitat degradation

The Southern Pygmy Perch's preferred habitat is often at risk of the degrading effects of urbanisation, farming, wetland drainage and modification of natural flows through river regulation. These threats can cause a loss of riparian and aquatic vegetation, an increase in turbidity, and fragmentation of populations. Carp (*Cyprinus carpio*) are destructive in their feeding habits, which can affect the density of aquatic vegetation and turbidity levels which has an adverse impact on Southern Pygmy Perch populations (Jones et al. 2008; Pearce et al. 2013). Livestock access to areas where Southern Pygmy Perch occur creates an increase in turbidity and a loss of aquatic habitat (Jones et al. 2008). Decreased frequency of floodplain inundation has led to a decrease in wetland habitat diversity (many wetlands are now either 'wet' or 'dry') and this has potentially affected dispersal (NSW DPI 2014). Lowland, shallow, fragmented freshwater habitats where populations persist are particularly susceptible to habitat degradation and unnatural cycles of drying and loss of refuge habitats (Saddler et al. 2013; Dexter et al. 2014). Catastrophic flooding in some upland streams can be detrimental due to extensive erosion and habitat (macrophyte) destruction (Pearce 2014).

Predation/competition

A major threat to this small fish is predation from the introduced fish species, Redfin Perch (*Perca fluviatilis*), trout (mainly Brown Trout, *Salmo trutta*) and Eastern Gambusia (*Gambusia holbrooki*) (Humphries 1995; Jones et al. 2008; NSW DPI 2014). The nipping of Southern Pygmy Perch fins by Eastern Gambusia has been witnessed in a number of studies (Jones et al. 2008; Macdonald and Tonkin 2008), as well as the predation of Southern Pygmy Perch eggs and larvae (Woodward and Malone 2002). Southern Pygmy Perch have also been recognised as an important prey species for Redfin Perch (Humphries 1995). Carp may impact habitat quality, by for instance, causing an increase in turbidity (Jones et al. 2008) and/or a loss of aquatic macrophytes; and Southern Pygmy Perch do not appear to persist when Carp are in high densities (Koehn et al. 2020).

Closely related and similar species

Yarra Pygmy Perch (*Nannoperca obscura*)

- Overlaps with Southern Pygmy Perch distribution within Victoria and South Australia
- The species is classified as 'near threatened' in Victoria (DSE 2007) and listed as threatened in Victoria under the *Flora and Fauna Guarantee Act 1998* (Vic.) and vulnerable nationally under the *Environment Protection and Biodiversity Conservation Act 1999* (Commonwealth).
- Their distribution often overlaps with that of Southern Pygmy Perch (Woodward and Malone, 2002).
- Their relative abundance has been found to be lower in the absence of a floodplain (Woodward and Malone 2002).
- Yarra Pygmy Perch are often restricted to shallow habitat adjacent to the stream margins due to competition with Southern Pygmy Perch for habitat and space (Woodward and Malone 2002).

Variegated Pygmy Perch (*Nannoperca variegata*)

- Located in South Australia and the Glenelg River, Victoria

- Variegated Pygmy Perch are usually found in small groups, often mixed with Southern Pygmy Perch and Yarra Pygmy Perch, although the Variegated Pygmy Perch prefers faster water velocities than the other two species (Kuitert and Allen 1986; Hammer et al. 2000).

Oxleyana Pygmy Perch (*Nannoperca oxleyana*)

- Located in northern New South Wales and southern Queensland
- Mean total and batch fecundities of captive females were 1323 eggs per fish and 7.8 eggs per fish per day, respectively, and relative fecundity was 587 eggs g⁻¹ of body mass (Knight et al. 2007).

Structured population models

A general approach to population modelling through a species life cycle

Individual organisms are born, grow, mature, reproduce and ultimately die. The likelihood that any one of these events occurs within a particular period depends upon the environment that the individual inhabits and the evolutionary adaptation of the individual to its environment. Life cycle analysis descriptively translates the individual to the population level. The likelihoods that determine the population-level rates of birth, growth, maturation, fertility and mortality, are collectively described as the vital rates, and it is these vital rates that determine the dynamics of a population. Structured population models provide a quantitative link between the individual and the population, built around a simple description of the life cycle.

The population projection matrix is a $k \times k$ matrix **A** (also called a square matrix) whose elements are made up of the vital rates described in the population projection matrix. The state of the population at time t is described by the vector **n**(t) (a single column matrix), whose entries $n_i(t)$ give the numbers of individuals in each age or stage class described by the life cycle graph. If the elements of the projection matrix **A** do not change with time, then the population dynamics can be simply represented by the linear model:

$$\mathbf{n}(t+1) = \mathbf{A}\mathbf{n}(t) \quad (1)$$

If the population dynamics vary with time (environmental and demographic variation) and with the population itself (density dependence or negative feedback through overuse of a resource), then the population dynamics are represented by a system of inhomogeneous nonlinear equations, for which no analytic solution may exist:

$$\mathbf{n}(t+1) = \mathbf{A}_{n,t}\mathbf{n}(t) \quad (2)$$

However, the analytic solutions to Equation (1) provide useful information about some of the population dynamics arising from Equation (2). Eigenvalues provide the complete dynamic information from the solution to a set of static, algebraic equations, such as Equation (1). Given the $k \times k$ matrix **A** and a non-zero population vector **n**(t), then there exists a scalar λ such that:

$$\mathbf{A}\mathbf{n}(t) = \lambda\mathbf{n}(t)$$

Where λ is known as the eigenvalue. As the matrix **A** is a $k \times k$ matrix, then there exist k values for λ , of which the largest positive value is equivalent to the finite rate of increase (growth rate) of the population model. The characteristic equation of the matrix **A** is:

$$\det(\mathbf{A} - \lambda \mathbf{I}) = 0 \quad (3)$$

See Manly (1990), Saila et al. (1991), Burgman et al. (1993), and Caswell (2001) for greater detail on population modelling using matrix modelling techniques particularly for wildlife management.

Equations (1) and (2) provide the basis upon which to construct population models for Southern Pygmy Perch.

Dynamic models

Models of the form found in Equation (2) are considered dynamic when components are time varying. That is, when the population-level rates, such as survival, fecundity, and growth change through time. While there is likely to be a strong relationship with how these rates vary with age in any given year, circumstances may vary due to changes in the environment (year to year variation in rainfall, temperature, etc.) or individual variation (demographic variation) in fecundity and survival. Environmental and demographic variation are known as stochasticity. Populations cannot increase *ad infinitum*, populations are regulated through predation or limiting resources (or both). This regulation is known as density-dependence and its influence may impact at any point in a species life history.

Density dependence

There are difficulties in detecting density-dependent relationships (Hassell 1986; Gaston and Lawton 1987; Rose and Cowan, 2000; Yearsley et al. 2003) even when appropriate data are available (Hilborn and Walters 1992; Burgman et al. 1993; for example, long time series data), let alone when appropriate data are limited or non-existent. However, the effects of density-dependence may still be included in the model through exploration of the species' life history (Gaston and Lawton 1987; Hilborn and Walters 1992; Burgman et al. 1993; Rose and Cowan 2000). Todd et al. (2004) explored a number of density dependent constructs for Trout Cod (*Maccullochella macquariensis*). Contest competition (the unequal division of resources) is typically modelled by the Beverton–Holt function (Ricker 1975; Table A-2) and is compensatory in that rates of increase in recruitment will diminish as the population increases and will always allow some recruitment. Scramble competition (the equal division of resources) is typically modelled by the Ricker function (Ricker 1975; Table A-2); however, it is over compensatory, and may lead to recruitment failure for large population sizes. Scramble competition is likely to be the incorrect mechanism in which to model recruitment, particularly as larvae are the most vulnerable life stage with little mobility and are unlikely to be able to access resources equally in a heterogeneous environment. Todd et al. (2004) also explored a 'top down' construct where an adult carrying capacity was specified and older (and larger) fish were allocated a place. This continued on to younger fish until all places were allocated and any remaining fish removed from the population. Another form of density-dependence is the Allee effect (Allee 1931). The Allee effect is depensatory, where a decrease in the breeding population leads to further decreases in the production of eggs or offspring, typically due to the inability in finding a mate.

The density-dependence mechanism used for Southern Pygmy Perch was to specify an adult carrying capacity and proportionally decrease all age classes by the amount the total adult population was above the carrying capacity. This mechanism does not attribute any advantage to any particular age class (or size). The construct does not constrain the number of juveniles in the model and may not capture other levels of density-dependence relating to juveniles such as food limitation for larvae. Applying this proportional construct to all

adult fish produces sufficient negative feedback to constrain population growth. Without accounting for any other affects, recruitment to one-year-olds is unconstrained.

If density dependence is thought to act on other aspects of the life history, then other mechanisms may be required to capture this process.

Stochasticity

Stochasticity in population modelling uses the process known as Monte Carlo simulation where random numbers are generated from distributions describing variation in population parameters. The purpose is to determine how random variation, lack of knowledge, or error affects the sensitivity, performance, or reliability of the predictions (Wittwer 2004). Monte Carlo simulation is categorised as a sampling method, because the inputs are randomly generated from probability distributions to simulate the process of sampling from an actual population (Wittwer 2004). Including mechanistic descriptions of demographic and environmental variation into an underlying projection matrix construct produces a stochastic population model. Demographic stochasticity is modelled by allowing for variation in the survival and reproduction of individuals (Akçakaya 1991), and is incorporated by using a binomial distribution to model the number of individuals surviving between consecutive timesteps, and a Poisson distribution to model recruitment (Todd et al. 2005). Environmental stochasticity is modelled by randomly selecting survival and fecundity rates from specified distributions for each timestep (Todd and Ng 2001).

Expressions of risk and scenario ranking

The model uses a Monte Carlo simulation technique where the user determines the number of iterations produced. Typically, in order to examine the consequences of a potential management action, each scenario is run a minimum of 1000 times (iterations). The purpose of the large number of iterations is to sample sufficiently from the parameter distributions so that a full exploration of the variation of the distribution is undertaken and the likelihood of extreme events can be examined (Ferson et al. 1989; Burgman et al. 1993). The data generated from the simulation can be represented as probability distributions (or histograms) or converted to error bars, reliability predictions, tolerance zones, and confidence intervals (Wittwer 2004).

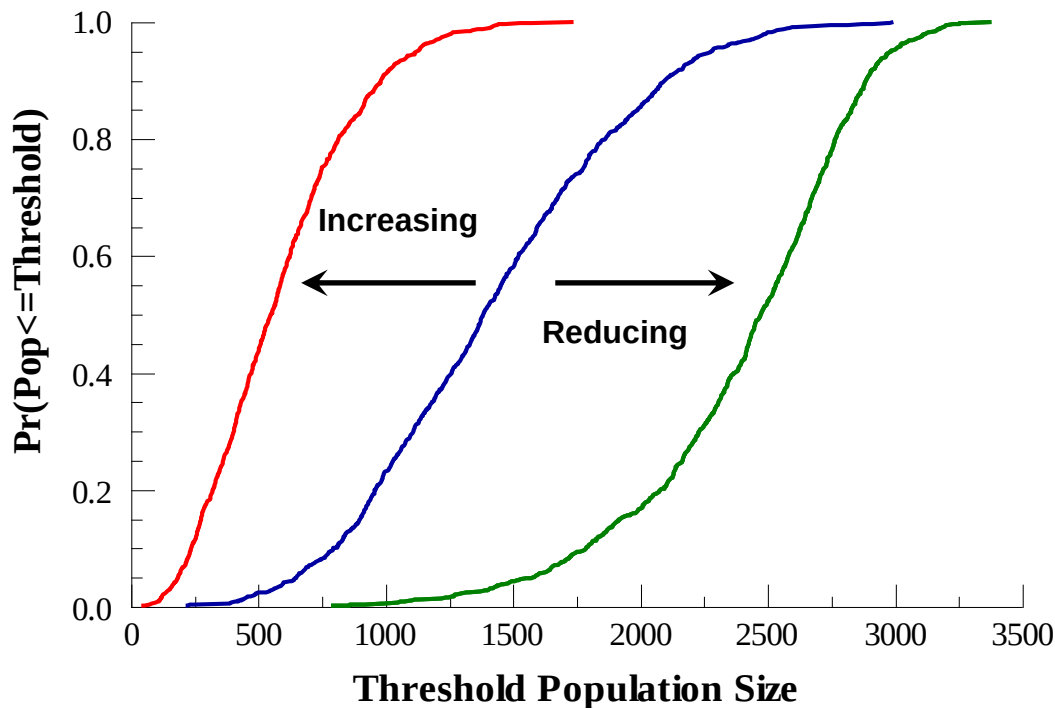


Figure A-39. Minimum population size risk curves (risk increases as the risk curve shifts to the left and risk decreases as risk curves shift to the right).

Recording the minimum population size from each iteration or trajectory and then graphing the associated normalised cumulative frequency distribution produces a graph of probabilities versus population size, the minimum population size risk curve. These represent both the chances of extinction (probability of falling to zero), and the chances of falling below some non-zero population threshold (Burgman et al. 1993: quasi-extinction risk). Additionally, risk curves can be readily compared and assessed in terms of increasing or decreasing risk by a shift to the left or right, respectively, of the minimum population size risk curve (Figure A-39). A method for quantifying changes in risks is to calculate the expected minimum population size for each curve and compare these values (McCarthy 1995; McCarthy and Thompson 2001; Todd et al. 2002; 2004; Koehn and Todd 2012).

Given that one of the objectives of the project was to compare several management scenarios, it was useful to report on the statistics of:

- risk curves associated with the distribution of the minimum population size (these may focus on specific elements of the population, such as adult fish or recruitment)
- the expected minimum population size of the above statistics
- the absolute difference in the expected minimum population size
- the percentage change in expected minimum population size.

ESSENTIAL – modelling framework

The construction of all models and modelling of all scenarios was undertaken using the software package *Essential* (Todd and Lovelace 2008). *Essential* is a highly flexible stochastic modelling platform that allows both expert model development as well as general use by way of access to a limited suite of parameters. Data

generated can be accessed for all parameters over all timesteps and iterations. Specific applications of *Essential* have been developed to provide a standalone Southern Pygmy Perch population model.

Model development for Southern Pygmy Perch

Life history analysis of Southern Pygmy Perch

Southern Pygmy Perch have an estimated life span of approximately 5 years, maturing by the end of their first year of life, and approach a maximum size of around 85 mm after about 4 years. Females produce from a few hundred to several thousand small transparent non-adhesive eggs (Llewellyn 1974; Cadwallader and Backhouse 1983; Humphries 1995), which can vary depending on age, body size, predator abundance/intensity and environmental conditions such as water quality (Humphries 1995; Woodward and Malone 2002, Morrongiello 2011). Eggs are scattered over vegetation or rocks on the substrate and, at 15–18 °C, take 2–4 days to hatch into larvae, which start foraging at around 5 days of age (Llewellyn 1974). Southern Pygmy Perch at 30 mm in length are around 70 days old (Tonkin et al. 2008), at 45 mm in length are approximately one year old, and at 52 mm in length are approximately 1.5 years old (Humphries, 1995). A fish captured at 76 mm was aged at 4 years (Humphries 1995).

There are four life stages of Southern Pygmy Perch, as shown in the life cycle in Figure A-40.

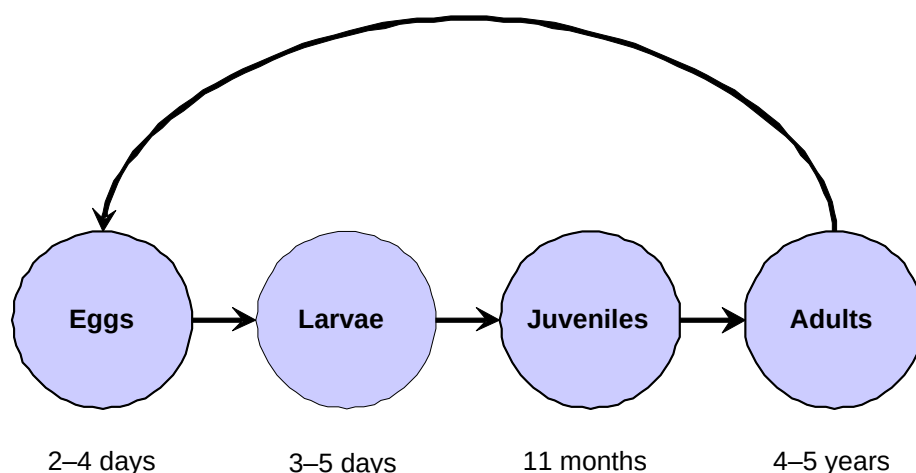


Figure A-40. Life history cycle of female Southern Pygmy Perch, with associated estimated time transitions for each stage of development.

Transforming the stage-based life history into an age-based life history allows an age-based model to be constructed for Southern Pygmy Perch. Having an age-based model fits more easily into management time scales (annual timesteps) and is analytically more straightforward.

To ensure complete capture of the birth and death process, it was decided to construct a 4-age class model where fish in the final age class do not survive to become any older. It was thought that while it was plausible that some Southern Pygmy Perch may live to 5-plus years, it was unlikely that fish would live longer than 4 years. Furthermore, the only age data available for adult fish had no 5-year-old fish represented in the data. Therefore a 4-age class model would sufficiently encapsulate the dynamics of Southern Pygmy Perch with the following projection matrix:

$$\begin{pmatrix} s_0 \times f_1 & s_0 \times f_2 & s_0 \times f_3 & s_0 \times f_4 \\ s_1 & 0 & 0 & 0 \\ 0 & s_2 & 0 & 0 \\ 0 & 0 & s_3 & 0 \end{pmatrix} \dots(4)$$

The age-structured matrix requires estimates of age-based survival rates and age-based fecundity and recruitment to one-year-olds.

Data assessment

Survival rates

Age data obtained through analysing otoliths can be used to generate estimates of age-specific survival. One-hundred-and-forty-eight (148) female Southern Pygmy Perch were aged from otoliths of fish sampled from the Macquarie River, Tasmania (Paul Humphries, CSU, pers. comm.). An age class may be considered to be fully represented when the number of fish in the subsequent age class is less than the age class in question (Ricker 1975, Todd et al. 2004). The age frequency data reveal that all age class are fully represented in the data (Figure A-41). The ratio between age classes were then taken as the 'average' or mean survival rate (Ricker 1975, Todd et al. 2004) for the Southern Pygmy Perch population model (Table A-1). Variation around the mean estimates in Table A-1 remains unknown, although it was assumed that the coefficient of variation in survival rates decreases with age (Todd et al. 2004).

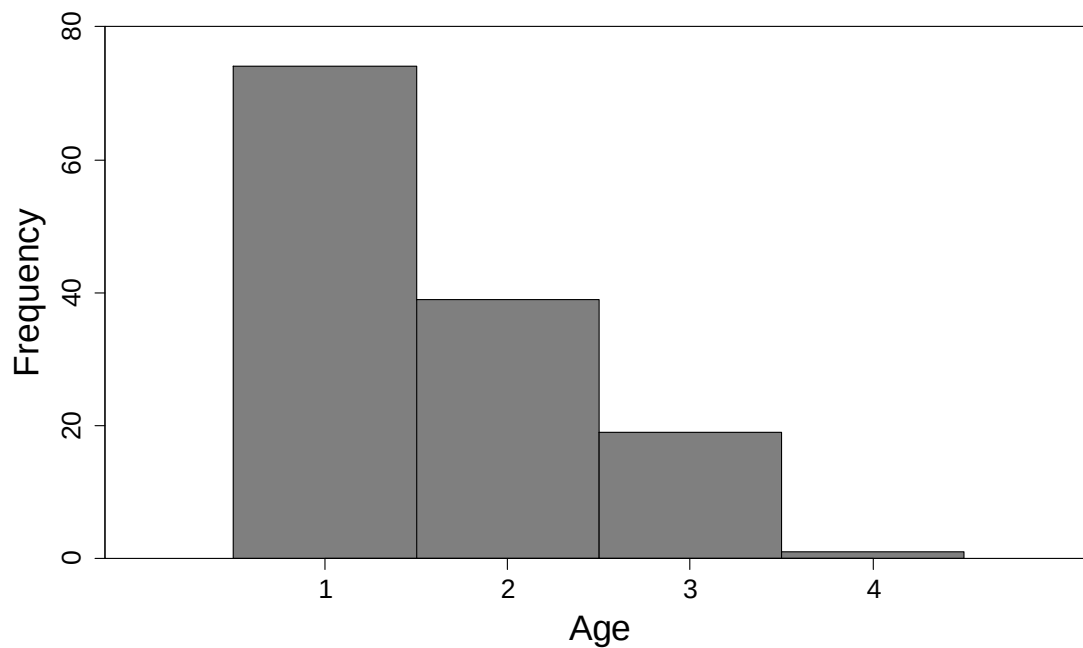


Figure A-41. Southern Pygmy Perch age frequency data from aged otoliths. The data were considered to be fully representative of all age classes.

Table A-1. Age-specific survival rates with estimated coefficient of variations (CVs).

Survival parameter	Survival mean	Survival S.D.	Survival CV
S_1	0.5270	0.0527	0.1
S_2	0.4872	0.0487	0.1
S_3	0.0526	0.0053	0.1

Fecundity rates

Reported fecundity of Southern Pygmy Perch in the literature indicates highly variable fecundity based upon both size of the female and environmental conditions. There were three studies from which fecundity data were available for Southern Pygmy Perch: Llewellyn (1974) nine females with mean 2261.22 and standard deviation 1085.47; Paul Humphries (pers. comm.) 20 females with mean 345.30 and standard deviation 167.34; and John Morrongiello (pers. comm.) 185 females with mean 460.23 and 373.79 standard deviation.

The fecundity data found in Llewellyn (1974) is much higher in comparison to the other two datasets, particularly when length is also considered; for example, a 55 mm female with 3045 eggs and a 57 mm female with 4217 eggs. Consequently, the Llewellyn (1974) data were not used in the analysis of fecundity due to the unusually high estimates of fecundity. The other datasets of Paul Humphries and John Morrongiello had egg counts that ranged 65 and 2651 eggs, with a mean of 451.19 and a standard deviation of 359.82, and unknown ages ranging in size from 33–84 mm. Upon examination, it was found that a log-linear relationship best described the data, with $R^2 = 99.99$ (Figure A-42): $\text{Fecundity} = \exp(0.05068 \times \text{Length} + 3.2043)$.

Table A-2. Length (mm) fecundity data (Paul Humphries pers. comm. and John Morrongiello pers. comm.)

Length	Fecundity	Length	Fecundity	Length	Fecundity	Length	Fecundity
33	87	46	340	52	539	58	477
36	139	46	227	52	495	58	427
37	78	46	182	52	467	59	638
37	108	46	118	52	435	59	538
38	270	46	117	52	316	59	320
38	190	47	332	52	310	59	307
39	244	47	489	52	267	60	949
39	242	47	374	52	259	60	547
39	321	47	329	52	183	60	543
39	292	47	313	53	612	60	406
39	133	47	261	53	605	60	371
40	220	47	261	53	569	60	339
40	191	47	233	53	482	60	337
40	143	47	221	53	442	60	313
40	65	47	208	53	348	61	770
41	207	47	206	53	348	61	737
41	318	48	285	53	212	61	404

Length	Fecundity	Length	Fecundity	Length	Fecundity	Length	Fecundity
41	266	48	227	54	635	62	822
41	195	48	106	54	386	62	757
41	184	49	473	54	319	62	417
41	155	49	562	54	290	62	401
41	98	49	552	54	167	63	679
42	342	49	462	55	592	63	659
42	219	49	385	55	575	63	487
42	193	49	326	55	469	64	809
42	159	49	293	55	466	64	433
42	144	49	264	55	461	64	200
42	136	49	259	55	360	65	1416
42	99	49	253	55	349	65	950
43	487	49	220	55	314	65	595
43	417	50	546	55	288	65	543
43	290	50	581	55	176	65	424
43	250	50	416	56	632	66	730
44	371	50	396	56	591	68	1112
44	372	50	313	56	558	68	951
44	247	50	288	56	527	70	1715
44	166	50	288	56	492	72	1046
44	146	50	252	56	441	72	1038
44	86	50	248	56	384	73	974
45	202	50	214	56	361	74	1307
45	354	51	425	56	118	74	871
45	165	51	470	57	693	75	1334
45	416	51	430	57	481	75	729
45	359	51	372	57	453	77	1227
45	354	51	332	57	445	77	739
45	293	51	322	57	413	78	1272
45	265	51	235	57	363	82	1434
45	242	51	211	57	329	84	2651
45	237	52	330	57	197	84	2411
45	205	52	258	58	504	84	1321

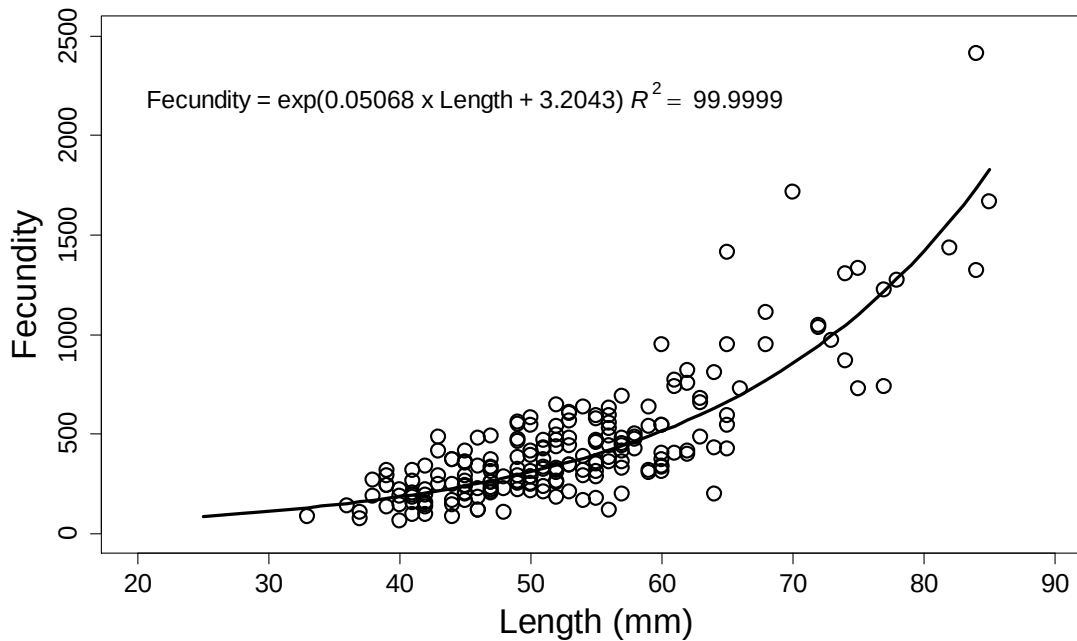


Figure A-42. Southern Pygmy Perch fecundity length data and regression line.

As no ages were recorded with the fecundity data, and as the population model is age structured, an age fecundity relationship must be established for Southern Pygmy Perch.

Using fecundity data in Table A-2, we regressed fecundity against length (mm) (Figure A-43) and regressed length (mm) against age (Figure A-44) and combined these to establish an age-fecundity relationship:

$$\text{Fecundity} = \exp(0.05068 \times \exp(0.1933 \times \text{Age} + 3.4597) + 3.2043) \quad \dots(5)$$

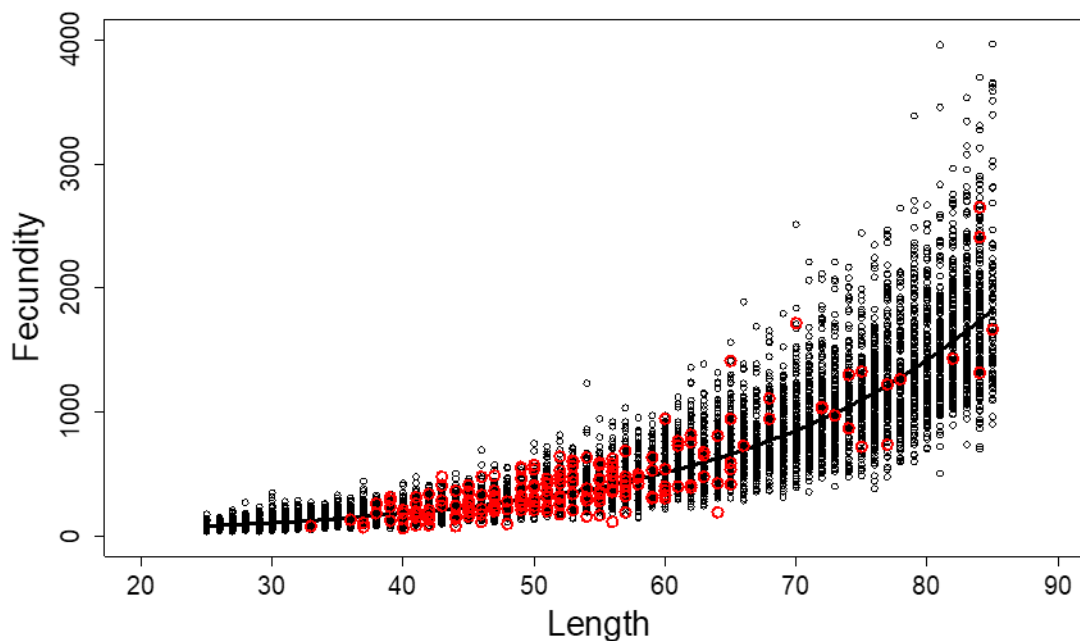


Figure A-43. Generated Southern Pygmy Perch fecundity data given length, 10000 samples (red circles are observed data) (Table A-2). The line is $\text{Fecundity} = \exp(0.05068 \times \text{Length} + 3.2043)$.

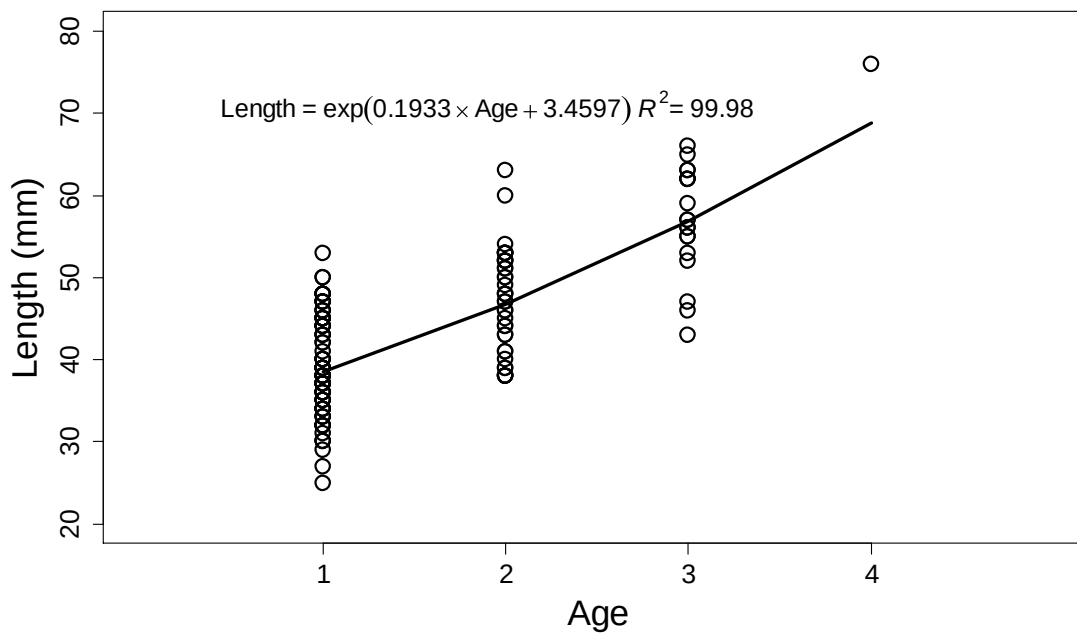


Figure A-44. Southern Pygmy Perch age-length data.

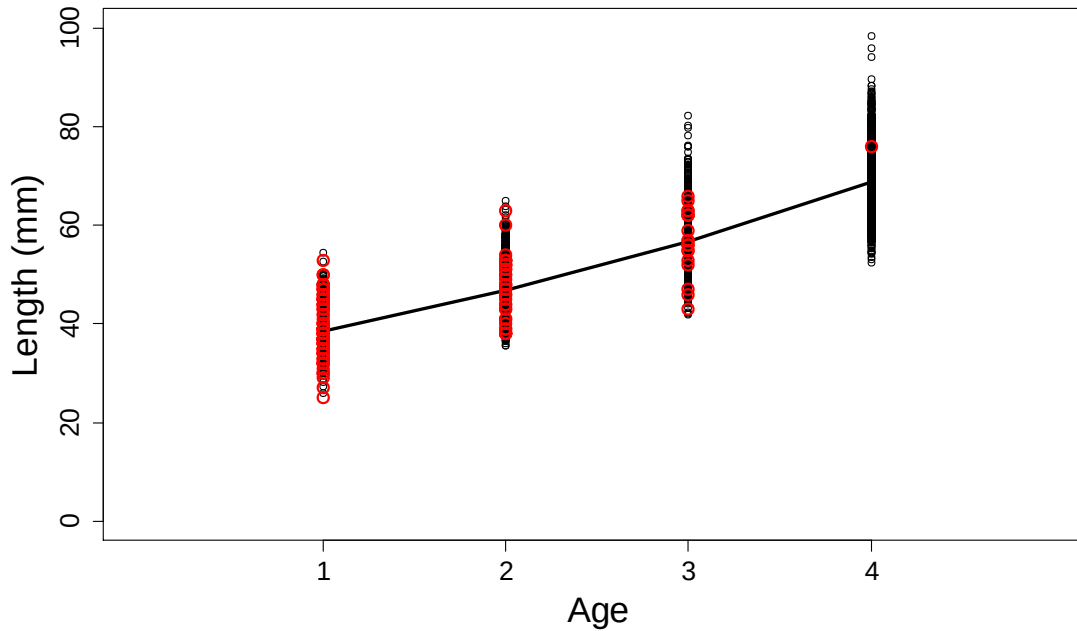


Figure A-45. Generated Southern Pygmy Perch length data given age, 10000 samples (red circles are observed data). The line is $\text{Length} = \exp(0.1933 \times \text{Age} + 3.4597)$.

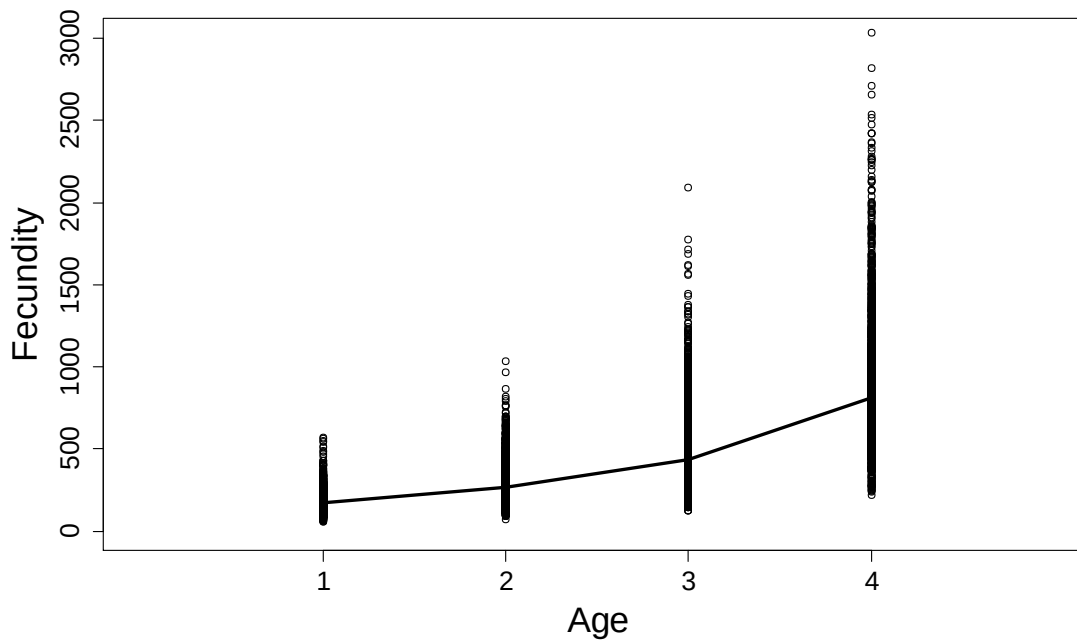


Figure A-46. Southern Pygmy Perch generated age-fecundity data from the inferred age-fecundity relationship, 10000 samples, with combined regressions of Equation (5). Note that the estimated maximum number of eggs per female is within the range reported in the literature.

It is desirable to use variation in the data to inform the model parameters describing environmental variability of fecundity. The age-length data indicates that length varies within age classes (Figure A-43) and varying one coefficient of the fitted curve, $\text{Length} = \exp(0.1933 \times \text{Age} + y_1)$: $y_1 \sim Y_1 = N(3.4597, sd_1)$, to explore variability in growth. Selecting $sd_1 = 0.09$ provides a reasonable description of variation in growth given age (Figure A-44). Variation in fecundity was similarly explored, $\text{Fecundity} = \exp(0.05068 \times \text{Length} + y_2)$: $y_2 = Y_2 \sim N(3.2043, sd_2)$. Selecting $sd_2 = 0.3$ returned estimates of fecundity with variance similar to that observed (Fig. 7). Using the specified distributions above in Equation (5) provides a variety of fecundity estimates for a given age (see Figure A-46).

Model construct

Stochastic population model

A female-only Southern Pygmy Perch population (males are thought not to be limiting) is represented by the following equations:

$$\begin{aligned}
N_i(t+1) &= \text{Bin}(N_{i-1}(t), \text{dens}(t) \times s_{i-1}(t)), & i = 1, \dots, 4 \\
N_1(t+1) &= \text{Poisson}(\text{dens}(t) \times s_0(t) \times 0.5 \times \text{EggNum}(t)), \\
\text{EggNum}(t) &= c \times \sum_{i=1}^4 F_i(t) \times N_i(t) \times N_f \\
\text{dens}(t) &= \begin{cases} CC / \sum_{i=1}^4 N_i(t), & \text{when } \sum_{i=1}^4 N_i(t) > CC \\ 1, & \text{when } \sum_{i=1}^4 N_i(t) \leq CC \end{cases} \\
F_i(t) &= \exp\left(f_c \times \left(\exp(l_c \times i + y_1(t))\right) + y_2(t)\right)
\end{aligned} \tag{6}$$

Where t is an annual time interval; $N_i(t)$ is the number of fish in the i^{th} age class; $s_i(t)$ is a random variate describing environmental variation in survival rates of fish in the i^{th} age class drawn from normal distributions transformed to the unit interval (Todd and Ng 2001) with specified means and standard deviations in Table A-1; $s_0(t)$, is a random variate describing environmental variation in survival from hatching to one year old; $\text{dens}(t)$ is the density-dependence factor for adults; $\text{EggNum}(t)$ the total number of eggs produced at time t ; c is the catastrophe factor affecting recruitment; $F_i(t)$ is the fecundity rate of the i^{th} age class; N_f is the proportion of females contributing to population; dens is the density dependence factor; CC the carrying capacity; f_c is a parameter estimated from length-fecundity data; l_c is the estimated parameter from the age-length data; y_1 , and y_2 , are random variates describing environmental variation in fecundity; $\text{Bin}(n, s)$ is a random variate representing demographic variation in transition from one age class to the next with a binomial distribution $\text{Bin}(n, s) = X \sim \text{Binom}(n, s)$; and $\text{Poisson}(m)$ is a random variate representing demographic variation in recruitment with a Poisson distribution $\text{Poisson}(m) = Y \sim \text{Poi}(m)$.

Mathematical and sensitivity analysis

The growth rate for the matrix in Equation 4 can be obtained mathematically by solving Equation 3 to generate the characteristic equation:

$$\lambda^4 - s_0 f_1 \lambda^3 - s_0 s_1 f_2 \lambda^2 - s_0 s_1 s_2 f_3 \lambda - s_0 s_1 s_2 s_3 f_4 = 0 \tag{7}$$

Solving for λ establishes the deterministic growth rate of a population if all parameters are known. There are estimates for all parameters except s_0 , the proportion of eggs that hatch and survive to become one-year-old female fish. Rearranging Equation 7 to solve for s_0 when $\lambda = 1$ gives the proportion of eggs that survive to become one-year-old female fish necessary for a stable population, $s_0 = 0.0046$. If $s_0 > 0.0046$ the population will increase and if $s_0 < 0.0046$ then the population will decline. It is unknown what the growth rate of Southern Pygmy Perch might be when conditions are good; however, it is expected to be higher than 1. Setting $s_0 = 0.006$ generates a growth rate of 1.16, a sufficiently high growth rate for the population to double every 5 years.

Table A-3. A range of growth rates for specified values of s_0 . λ denotes the asymptotic population growth rate.

s_0	λ
0.004	0.9326
0.004578	1.0000
0.005	1.0477
0.006	1.1570

It is important to examine the sensitivity of the model to parameter estimation and as such, two types of perturbations analysis were considered: sensitivity analysis, measuring the absolute change in the growth rate given a small change in a vital rate; and elasticity analysis, measuring the proportional change in the growth rate given a small change in a vital rate (Caswell 2001). Elasticities are proportional sensitivities that account for the magnitude of the growth rate and the vital rate (Mills and Lindberg 2002). In addition to perturbation analysis, reproductive values were also reported. Reproductive values measure the contribution of an age class to future generations and summarise reproduction, survival and timing (Caswell 2001).

Small changes were observed in the sensitivity analysis depending on the value of s_0 ; however, the pattern was largely the same. Setting $s_0 = 0.006$, the sensitivity analysis indicated that small changes in survival rates of age 1 have a greater impact on the growth rate than the other age classes (Figure A-47). Also, changes to survival have a greater impact on the growth rate than comparative changes to fecundity (Figure A-47). When the sensitivities were rescaled, the corresponding survival elasticities indicated that age 1 survival contributed most to a change in the growth rate, whereas recruitment elasticities indicated age 1 and 2 to be comparable in their contributions to the growth rate (Figure A-47). There is a dip in the reproductive value for age 3; however, age's 2–4 have a higher reproductive value than age 1.

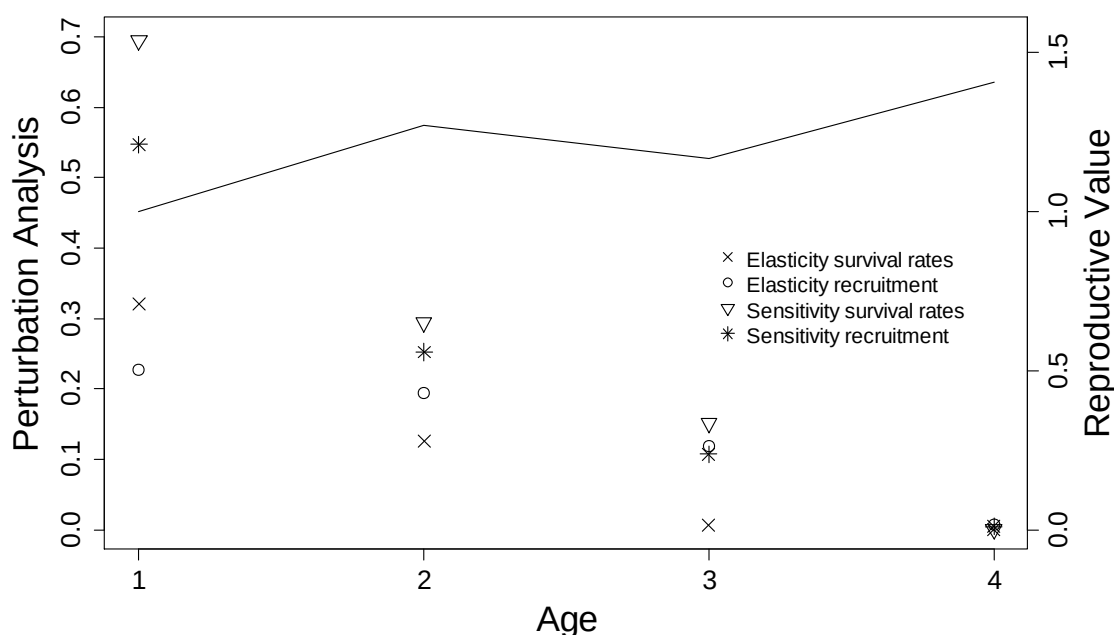


Figure A-47. Southern Pygmy Perch sensitivity analysis when $s_0 = 0.005$.

Population model inputs

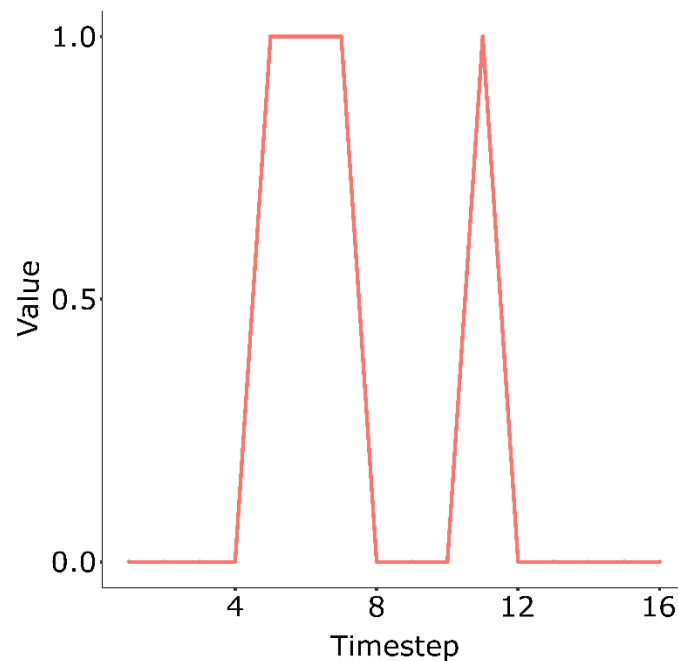


Figure A-48: Flood level input for the Southern Pygmy Perch population model. A value of 1 indicates a timestep (year) where flooding of Gunbower Forest occurred. This causes various impacts on populations according to the flood level impact scenario applied (see Methods). This input was generated from the operational history document supplied by North Central CMA, where any month given an ‘overbank’ flood level designation triggered a flood value in that year.

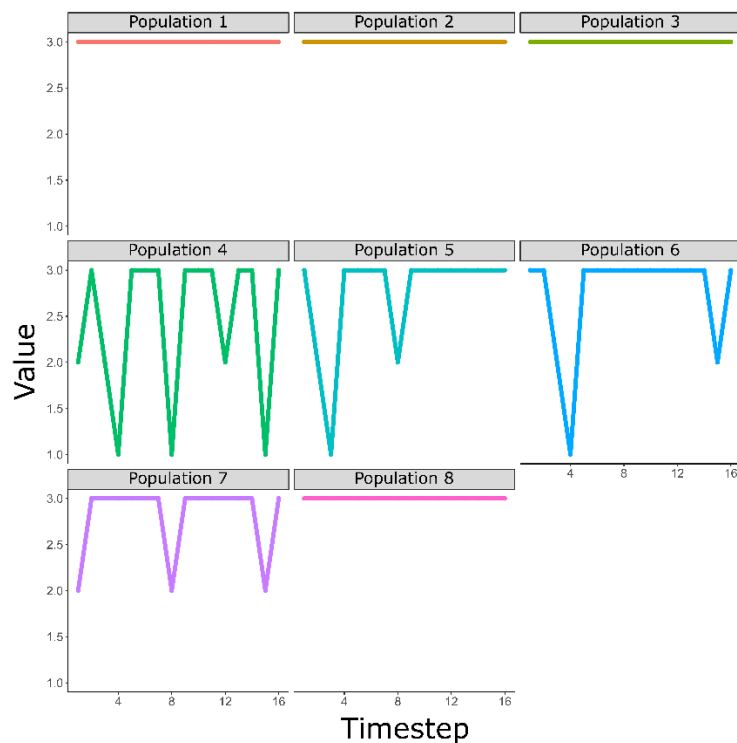


Figure A-49. Habitat status as a population model input for each Southern Pygmy Perch population in Gunbower Forest. A value of 3 = a wet habitat status, a value of 2 = a drying habitat status and a value of 1 = dry habitat status. Habitat status values influence the population growth rate of each population through timesteps (years) in the model. These model inputs were generated from the Gunbower watering regime history document supplied by North Central CMA.

Additional information for movement rules within the model

Movement between connected populations was dictated within the model via the operational history assessment dataset supplied by North Central CMA. The rate of movement calculation is described in the Methods, and here we provide some more specific information on the calculation of movement between connected populations. Movements from singular populations to another population were dictated by the operation of specific regulators within a given year (e.g. movements between populations 7 and 8 were dictated by operation of the Little Gunbower regulator within that year).

Operation of the Hipwell regulator caused upstream and downstream connections between population's 4, 5, 6 and 7 (the same rate of movement was used for all connections). Additionally, operation of all of the Reedy, Black, Little Gunbower and Yarran regulators (LLR's) within the same month caused upstream and downstream connection between population's 5, 6 and 7. The rate of movement for both of these connections was again dictated by the number of months that the regulator was open (as described in the Methods – note that the Hipwell-driven movement is overridden for 5–6–7 movements if the LLR's are all operated at once for more months than Hipwell). These connection events may also cause some loss of fish back into the Murray River (not modelled) within the model (population's 4, 5, 6 and 7 for Hipwell regulator opening, and population's 5, 6 and 7 for all LLR's opening in a year) due to the required drainage phase from wetlands after these operations occur.

Movement between population's 4 and 8 was dictated by Yarran regulator operation. This movement is also supplemented by 2 months in each year that the Yarran regulator is operated due to the operation of a fishway at this regulator. Movement values (the number of months that connections occurred) can be seen in Figure A-50.

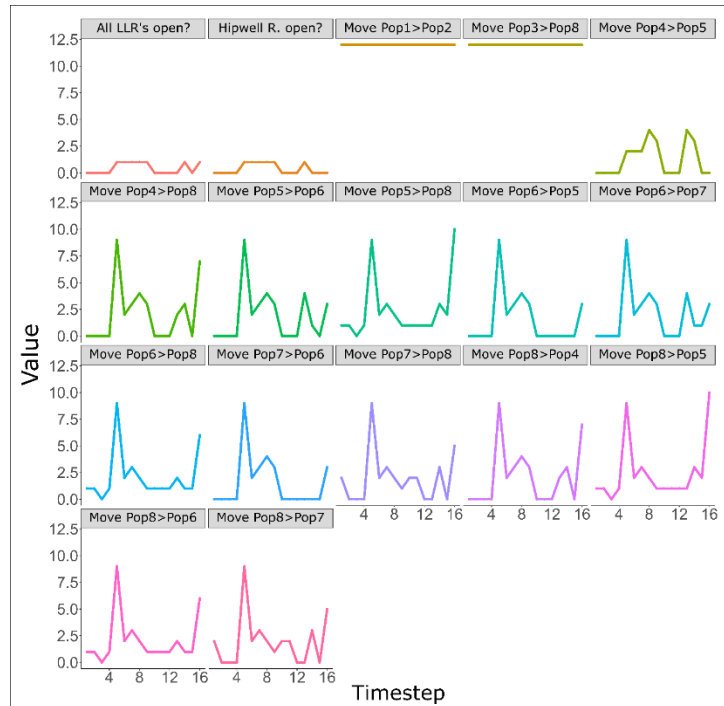


Figure A-50. Movement values for connected habitats of Southern Pygmy Perch for population modelling in Gunbower Forest. Values indicate the number of months within each timestep that populations were connected (e.g. via opened regulators). These values were divided by 12 and then multiplied by the underlying movement rate to generate the movement rate (the proportion of fish that moved in a timestep) for use in population model runs. If the Hipwell regulator was open, it caused upstream and downstream connections between population's 4, 5, 6 and 7, and if all of the LLR regulators were open simultaneously, it caused upstream and downstream connection between population's 5, 6 and 7. The 'All LLR's open?' and 'Hipwell R. open?' panels indicate whether all of the lower regulators were open simultaneously for at least 1 month, and whether the Hipwell regulator was open for at least 1 month, respectively. These parameters were given a value of 1 if this requirement was met in a timestep, and caused a loss of fish from populations (population's 5, 6 and 7 for 'All LLR's open?' and 4, 5, 6 and 7 for 'Hipwell R. open?') due to the required drainage phase from wetlands after these operations occur. These model inputs were generated from the operational history document supplied by North Central CMA.

Movement for the Leaky Regulator scenario is unchanged from Scenarios 1–12, except that the Leaky Regulator population (population 9) slots in-between the lower Gunbower Creek population (population 8) and the Reedy Lagoon population (population 5). Movement between population's 5 and 9, and 8 and 9 was modelled to occur in years when Reedy Lagoon is connected to the Gunbower Creek via the regulator. This movement can be seen in Figure A-51.

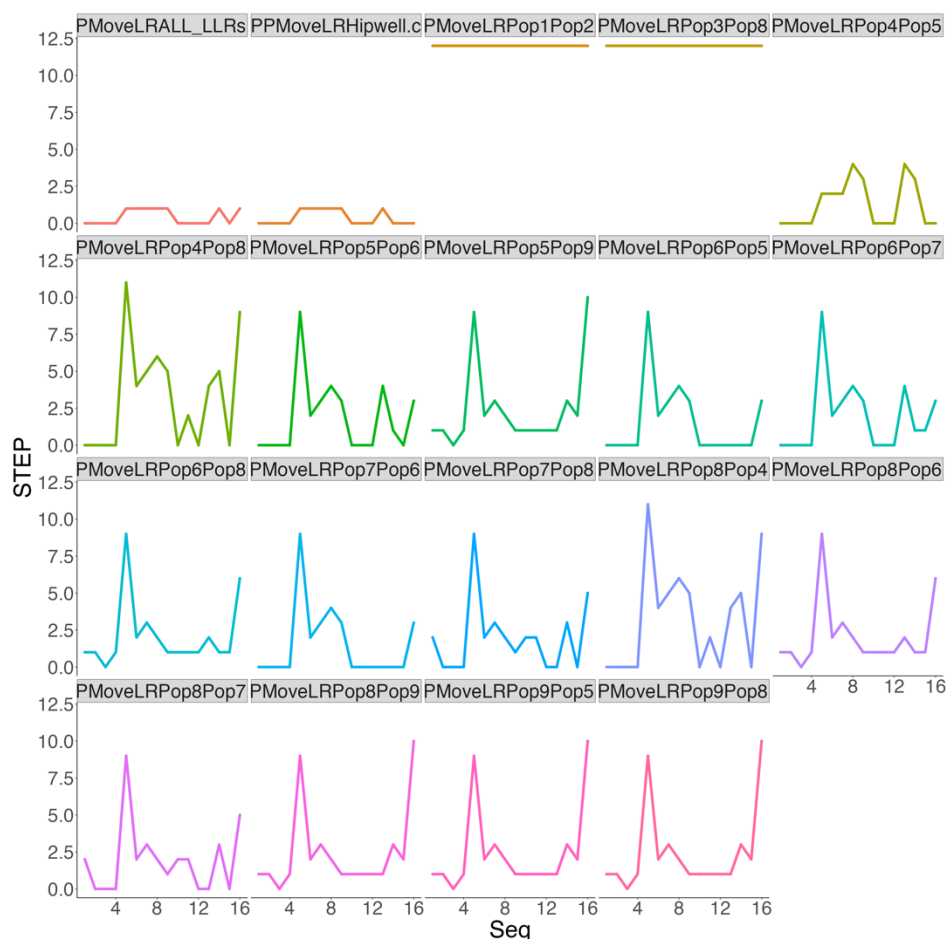


Figure A-51. Movement values for the Leaky Regulator scenario used in population modelling of Southern Pygmy Perch in Gunbower Forest. Inputs presented here are the same as in Supplementary figure 3 above, except for an additional population (population 9) that represents the Leaky Regulator population. Note also that movement for population's 5 and 8 are also modified due to the inclusion of population 9 (i.e. population 9 slots in between population's 5 and 8 meaning that direct movement between population's 5 and 8 is not possible as fish can only move one population in a year). Movement between population's 5 and 9, and 8 and 9 was modelled to occur in years when Reedy Lagoon is connected to the Gunbower Creek via the regulator.

New information or worthwhile future projects

- Small fish previously classified as 'wetland specialists', such as carp gudgeons (*Hypseleotris* spp.), have more flexible movement and life-history strategies than previously considered (and include riverine habitation). There is a high degree of lateral movement, which indicates the importance of habitat connectivity for this species. Carp gudgeons were by far the most numerous of the fish species studied for this type of movement into wetlands (Lyon et al. 2010). Understanding upstream, downstream and lateral movements – relating to dispersal (see Lyon et al. 2010).
- Investigation of productivity levels and their impact on recruitment and reintroduction success.
- This assessment would be undertaken for all potential stocking sites and also for the dam sites. For the dams sites, fish numbers stocked and removed should be added and any analyses undertaken to determine more successful sites and also to group similar sites based on their characteristics.
- Species interactions of Southern Pygmy Perch populations with carp gudgeons and Oriental Weatherloach (*Misgurnus anguillicaudatus*).

Appendix 3. Specialist Southern Pygmy Perch model development workshop

The specialist Southern Pygmy Perch model development workshop was held in Cohuna on 19 April 2023. It was attended by Charles Todd, Henry Wootton, John Koehn, Peter Rose, Matt Crawford, Kathryn Stanislowski, Nick Whiterod, Scott Raymond, Gabriel Cornell, Connor Gervais, Max Smiles-Schmidt, Jian Yen, and Will Honybun.



Figure A-52. Southern Pygmy Perch workshop in Cohuna.

Discussion around the following headings generated the following decisions regarding modelling scenarios:

Ecology and flows

The decision was made to not model scouring floods or mortality at the Gunbower sites because this is not thought to occur (this is more prevalent at upland sites). North Central CMA was to develop a historic watering/connectivity schedule with which to run the model.

Spawning

Despite some evidence of multiple spawning events occurring in farm or hatchery sites (Peter Rose, NCCMA, pers. comm.), there was consensus among experts that only one yearly spawning event would occur in the wild due to sub-optimal conditions. Accordingly, it was decided to model a single Spring spawning event in each year.

Movement and connectivity

Some fish are likely to move and some will be lost from the site upon connection events. Upstream movement during connection events is minimal. Nick Whiterod suggested the Lower Lakes reintroduction took 10 years for the population to take off, but that detections of fish occurred straight away. Nick Whiterod also suggested that the level of Spring inundation linked to recruitment in the Lower Lakes. Populations are stronger in tributaries. When no flows occur in creeks there are drops in abundance.

The group suggested that high flows see fish get pushed out of habitats. It was decided that the modelling team should do sensitivity testing on the movement rates, because little is known about Southern Pygmy Perch movement rates. Aquatic vegetation was suggested to help with retention. No event-driven dispersal was noted in Gunbower creek, despite higher through flows. There was not much connectivity from Cameron's and Black Charlie's lagoons downstream. Any transfer between sites would occur on high flows > 45K ML/day.

Therefore, it was decided that movement rates for Southern Pygmy Perch are low, and that this would likely represent 1–5% proportional movement among Gunbower Island populations upon connection events.

Constraints on Southern Pygmy Perch

Decision: A competition and predation mechanism was to be developed by the modelling team including North Central CMA members (CT, HW, PR and WH).

Productivity

Decision: Inclusion of a productivity mechanism was considered, and suggested as a future inclusion to the model, but that at this stage it was outside the scope for the current project.

Sites

Decision: Model eight sites/populations with connectivity rules. It was decided that a habitat characterisation at each site and the risk of a catastrophic event (e.g. drying out) would be developed by the modelling team in consultation with North Central CMA staff.

Blackwater and water quality

Decision: Blackwater nor poor water quality were not considered to be significant issues for Southern Pygmy Perch within the Gunbower Island context, so it was decided not to model these factors.

Lower Lakes reintroduction

Decision: Use Lower Lakes information to guide development of the model.

Stocking decisions

Decision: Model stocking in July only as this was considered the best option for stocking success and the approach that North Central CMA would take in future.

Model timeframe

Decision: Ideally modelled outputs would be generated for approximately 20 years depending on the availability of input data to the model.

Model outputs

Decision: Adult abundance and risk curves.

Project assessment

Decision: In terms of an overall goal of the reintroduction program, success was deemed to be defined by the establishment of at least one stable population of Southern Pygmy Perch in the upper and the lower sections of Gunbower Island. The populations should also be able to survive a large drought event. A long-term timeframe (> 10 years) was seen as acceptable to achieve this. Detection of Southern Pygmy Perch at other additional sites was also seen as a determinant of success.

Additional resources

These were identified as additional knowledge or data that could further assist the model and modelling outcomes. These may not necessarily be immediately incorporated in the project, but should be recognised and obtained (if possible) for future iterations.

- Scott Wedderburn (and maybe Nick Whiterod) has fish age data from the Lower Lakes as well as lake level and recruitment relationships – Who to approach for these data?
- Scott Wedderburn – Length-weight relationships in different habitats.
- Nick Whiterod – Has written a strategy document prescribing translocation of small-bodied fish.
- Nick Whiterod – Any information on predation impacts on Southern Pygmy Perch populations.
- Nick Whiterod and Gabriel Cornell – Have information on competition with other species (e.g. gudgeons) and perhaps other population data for the Lower Lakes and Corangamite, respectively.
- Peter Rose – Information on species composition at sites in Gunbower Forest. Also pre- and post-flood CPUE data to assist with dispersal densities. This will help inform densities in the model.
- Ben Phillips – May have information on Eastern Gambusia impacts on micro/macroinvertebrate species.
- Scott Raymond – information regarding Carp gudgeon populations and possible correlations with the lack of population establishment, of Southern Pygmy Perch populations or population crashes.
- Check Jarod Lyon small fishes movement paper and also check with Native Fish Australia (NFA) for information regarding Carp gudgeon or Oriental Weatherloach interactions with Southern Pygmy Perch.

www.deeca.vic.gov.au

www.ari.vic.gov.au