RESEARCH **2**

2018-120

WILL CARP VIRUS BIOCONTROL BE EFFECTIVE?

NATIONAL CARP CONTROL PLAN

Population dynamics and carp biomass estimates for Australia

This suite of documents contains those listed below.

NCCP TECHNICAL PAPERS

1. Carp biocontrol background
2. Epidemiology and release strategies
3. Carp biocontrol and water quality
4. Carp virus species specificity
5. Potential socio-economic impacts of carp biocontrol
6. NCCP implementation
7. NCCP engagement report
8. NCCP Murray and Murrumbidgee case study
9. NCCP Lachlan case study

NCCP RESEARCH (peer reviewed)

Will carp virus biocontrol be effective?

1. 2016-153: Preparing for Cyprinid herpesvirus 3: A carp biomass estimate for eastern Australia
2. 2018-120: Population dynamics and carp biomass estimates for Australia
3. 2017-148: Exploring genetic biocontrol options that could work synergistically with the carp virus
4. 2016-170: Development of hydrological, ecological and epidemiological modelling
5. 2017-135: Essential studies on Cyprinid herpesvirus 3 (CyHV-3) prior to release of the virus in Australian waters
6. 2020-104: Evaluating the role of direct fish-to-fish contact on horizontal transmission of koi herpesvirus
7. 2019-163 Understanding the genetics and genomics of carp strains and susceptibility to CyHV-3
8. 2017-094: Review of carp control via commercial exploitation

What are the carp virus biocontrol risks and how can they be managed?

9. 2017-055 and 2017-056: Water-quality risk assessment of carp biocontrol for Australian waterways
10. 2016-183: Cyprinid herpesvirus 3 and its relevance to humans
11. 2017-127: Defining best practice for viral susceptibility testing of non-target species to Cyprinid herpesvirus 3
12. 2019-176: Determination of the susceptibility of Silver Perch, Murray Cod and Rainbow Trout to infection with CyHV-3
13. 2016-152 and 2018-189: The socio-economic impact assessment and stakeholder engagement
    Appendix 1: Getting the National Carp Control Plan right: Ensuring the plan addresses community and stakeholder needs, interests and concerns
    Appendix 2: Findings of community attitude surveys
    Appendix 3: Socio-economic impact assessment — commercial carp fishers
    Appendix 4: Socio-economic impact assessment — tourism sector
    Appendix 5: Stakeholder interviews
    Appendix 6: Socio-economic impact assessment — native fish breeders and growers
    Appendix 7: Socio-economic impact assessment — recreational fishing sector
    Appendix 8: Socio-economic impact assessment — koi hobbyists and businesses
    Appendix 9: Engaging with the NCCP: Summary of a stakeholder workshop
14. 2017-237: Risks, costs and water industry response
15. 2017-054: Social, economic and ecological risk assessment for use of Cyprinid herpesvirus 3 (CyHV-3) for carp biocontrol in Australia
    Volume 1: Review of the literature, outbreak scenarios, exposure pathways and case studies
    Volume 2: Assessment of risks to Matters of National Environmental Significance
    Volume 3: Assessment of social risks
16. 2016-158: Development of strategies to optimise release and clean-up strategies
17. 2016-180: Assessment of options for utilisation of virus-infected carp
18. 2017-104: The likely medium- to long-term ecological outcomes of major carp population reductions
19. 2016-132: Expected benefits and costs associated with carp control in the Murray-Darling Basin

NCCP PLANNING INVESTIGATIONS

1. 2018-112: Carp questionnaire survey and community mapping tool
2. 2018-190: Biosecurity strategy for the koi (*Cyprinus carpio*) industry
3. 2017-222: Engineering options for the NCCP
4. NCCP Lachlan case study (in house) (refer to Technical Paper 9)
5. 2018-209: Various NCCP operations case studies for the Murray and Murrumbidgee river systems (refer to Technical Paper 8)

Modelling Carp Biomass: Estimates for the Year 2023.

C.R. Todd, J.D. Koehn, T.R. Brown, B. Fanson, S. Brooks and I. Stuart

October 2019

Arthur Rylah Institute for Environmental Research
Unpublished Client Report

Modelling Carp Biomass: Estimates for the Year 2023

Charles R. Todd, John D. Koehn, Tim R. Brown, Ben Fanson, Shane Brooks and Ivor Stuart

October 2019

Arthur Rylah Institute for Environmental Research Department of Environment, Land, Water and Planning

Acknowledgements

The authors wish to thank all of the participants in the Carp biomass project for their work. Thanks to Jennifer Marshall (FRDC) and Jarod Lyon (ARI) for supporting this project and to Rob Hale (ARI) and anonymous reviewers for their useful comments on this report.

Arthur Rylah Institute for Environmental Research
Department of Environment, Land, Water and Planning
PO Box 137
Heidelberg, Victoria 3084
Phone (03) 9450 8600
Website: www.ari.vic.gov.au

Citation**:** Citation**: Todd, C.R., Koehn, J.D., Brown, T.R. Fanson, B., Brooks, S., and Stuart, I. (2019). Modelling Carp Biomass: Estimates for the Year 2023.** Arthur Rylah Institute for Environmental Research, Department of Environment, Land, Water and Planning, Heidelberg, Victoria. CC by 3.0

Front cover photos : Ivor Stuart

Contents

Summary

Background

Carp (*Cyprinus carpio*) is Australia's most invasive pest fish. To facilitate more effective management, the Australian Government is considering release of a Carp herpesvirus (CyHV-3) ('Carp virus'), as a potential biological control agent. This required an estimation of Carp biomass across Australia. This Carp biomass estimate provided static 'points-in-time' (for May 2011 and May 2018) derived from available historic catch data collected over the past 20-years. As Carp populations can respond rapidly to hydrological conditions, especially flood events that provide access to preferred spawning habitats and can lead to significant recruitment, there is a need to consider likely population outcomes from subsequent hydrological conditions. Multiple wet years can lead to large population growth and multiple dry years leading to population stagnation or decline. Hence, the static 2011 and 2018 biomass estimates cannot specifically be applied to future scenarios when the Carp virus may be released. The use of a dynamic Carp population model was recognised as a method that could provide future estimates of biomass, taking into account likely several possible hydrological scenarios for the time of future virus release.

Aim

The aim of this project was to modify and apply the existing Carp population model to provide forward temporal estimates of likely Carp biomass and numbers for a range of hydrological scenarios for the year 2023, using the static estimate for 2018 provided from the Carp biomass project.

Methods

A stochastic Carp population model has developed for use in the southern Murray-Darling Basin (SMDB) and was used to predict Carp population dynamics based on a variety of hydrological scenarios. Whilst developed for the SMDB, it was modified for use in the for the northern Murray-Darling Basin (NMDB) and coastal catchments. The structure and parameterisation of the model was modified to be congruent with the static biomass estimate project. Hence, this 28-age class stochastic population model was used to take the existing Carp biomass estimates and generate estimates of Carp biomass and numbers for 2023 in the for four key regions of eastern Australia: NMDB, SMDB, northern coastal (NC) and southern coastal (SC) regions. The populations in Lake Sorell (Tasmania), coastal rivers in Western Australia and irrigation channels were considered separately. The hydrological scenarios and timeframes modelled were determined by Fisheries Research and Development Corporation and were considered the 'worst' (Flood) and 'best' (Drought) case scenarios for managing Carp population outcomes. Flood: 3 wet years, full wetland inundation, followed by 2 'average' years; and Drought: 3 dry years, followed by 2 'average' years. A 1 in 20-year flood frequency was chosen to represent wet years where floods inundate Carp feeding and breeding floodplain habitats and similarly a 1 in 20-year drought frequency was used with these wetland areas disconnected.

Results

The resultant predicted population biomasses for 2023 can vary considerably from the static 2018 estimate. These estimates vary depending on the hydrological scenario (Drought or Flood) and also for each region and initial distribution and population size of Carp. In general, the Drought scenario produced about the same or slightly reduced biomasses from the static 2018 estimate. The estimates of Carp biomasses in 2023 using an initial population size of the 2018 mean estimate are 167 960 - 172 895 t for the Drought scenario and 428 808 - 444 144 t for the Flood scenario. A maximum additional biomass from Western Australia, Tasmania and irrigation channels was be considered to be 30 464 t.

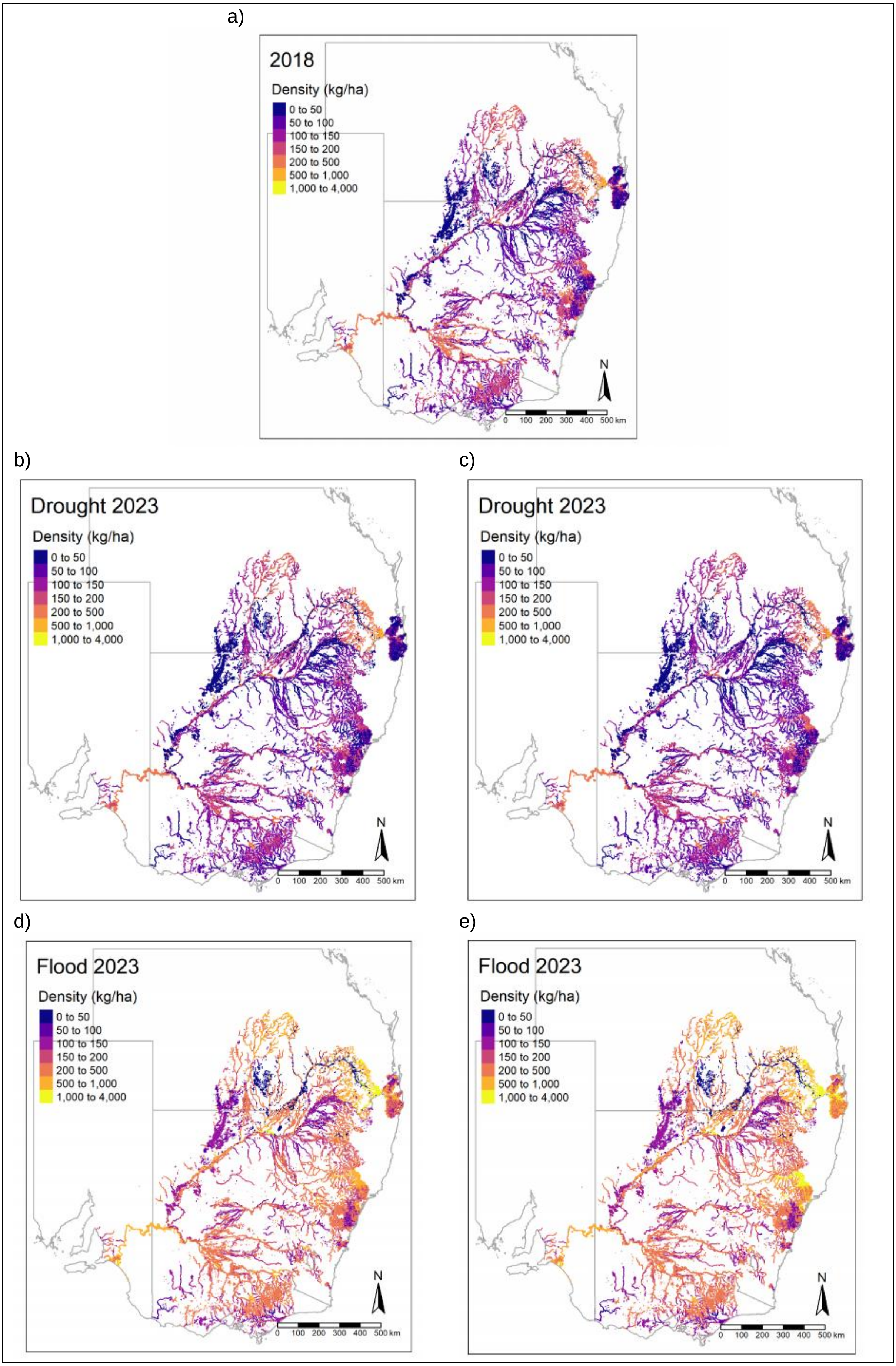


Figure. Carp density heat maps: a) 2018 Stuart et al. (2019) static estimate; b) Drought scenario 2023 Area distribution method; c) Drought scenario 2023 Biom distribution method; d) Flood scenario 2023 Area distribution method; and e) Flood scenario 2023 Biom distribution method.

The distribution of Carp densities, across eastern Australia for 2018 (from Stuart et al. 2019) and for 2023 under both Drought and Flood scenarios, is illustrated in the Figure above. The Carp density heat maps show minor decreases in density in the 2023 Drought scenario compared with the 2018 Stuart et al. (2019) estimate, however, there are large increases in density in the 2023 Flood scenario compared with the 2018 Stuart et al. (2019). Area and Biom denote two differing distribution methods used for the use of available habitat areas by Carp.

The Flood scenario produced much higher biomasses in all cases with estimates using the Biom method predicting the following population increases: NMDB ~x 3; SMDB ~x 2; NC ~x 7; and SC ~x 1.7. Collectively, the overall increase in Carp biomass from 2018 to 2023 with the Flood scenario would be about 250 Kt (~x 2.3). In the Flood scenario, biomass increases immediately and continues to rise even during the subsequent average years as adult biomass continues to increase as juveniles develop in to adults during the subsequent 'average' years. During the Drought scenario, the biomass declines and then recovers with the two following 'average' years. The mean initial biomass estimate does not provide any information on the age structure of the population which can greatly influence future population outcomes, and exploration of populations structure was included to provide variation around these estimates.

Conclusions and management implications

The dynamic Carp population model provides a valuable resource to help evaluate the potential release of the Carp virus under the National Carp Control Program. The resultant predicted population biomasses for 2023 differ considerably from the initial 2018 static estimate. For the NCCP, understanding the potential increase in Carp biomass during flood scenarios within each of these regions is essential to plan for a potential release of the Carp virus. Multiple wet year scenarios support a significantly greater Carp biomass than during average or dry years. A strength of the dynamic model is that it can be used to inform the NCCP at other future time points or under different hydrological scenarios. These estimates vary depending on the hydrological scenario (Drought or Flood) and region. In general, the Drought scenario produced similar or slightly reduced biomasses, for a range of flow scenarios. The differences evident between the regions highlight the usefulness of modelling scenarios at a finer spatial scale, including additional case studies. Modelling could also be used to explore the impacts of climate change scenarios which may produce differing hydrological regimes. Additional modelling can also be undertaken to predict the likely response of Carp populations in relation to hydrological conditions following the release of the virus and a range of knock-down scenarios.

Introduction

Carp (*Cyprinus carpio*) is one of the world's most invasive pest fish and has spread throughout most of south-eastern Australia since their introduction in the late 1960s (Koehn 2004) as well as becoming established in small regions of Western Australia and Tasmania. They can inhabit a diverse array of habitats causing a range of ecological impacts (Koehn et al. 2000). Whilst there are a range of possible management options (Roberts and Tilzey 1997), most of these only operate at local scales (Hillyard et al. 2010; Thwaites et al. 2010; Conallin et al. 2016) and it is likely that an integrated combination of such conventional and more innovative biological control methods is required for management at large scales. To facilitate more effective management, the Australian Government is considering release of a Carp herpesvirus (CyHV-3) ('Carp virus'), as a potential biological control agent (McColl et al. 2014, 2016, 2018). Preparation for this includes the development of a National Carp Control Plan (NCCP) to examine all factors concerning the feasibility of releasing the Carp virus. A key component to understanding the scope of the Carp management problem is quantifying the Carp population, which, from a clean-up and management perspective has been determined as Carp biomass. This led to the establishment of the Carp biomass project (Stuart et al. 2019) with the objective of developing and applying robust methods to estimate the biomass of Carp across Australia. Static estimates were made for the range of major aquatic habitat types (rivers, lakes, billabongs and estuaries) at appropriate geographic scales (local, river reach, river basin and inter-basin) across the recorded Carp distribution. The results of this project were then to be used to inform the NCCP.

The Carp biomass project, however, provided static 'point-in-time' (for May 2011 and May 2018) estimates derived from the available historic catch data collected across a range of environmental conditions over the past 20-years. Importantly, the spatial mapping of aquatic habitat area was static and so the carp biomass estimate was driven by changes in the underlying catch data rather than increases or decreases in aquatic habitat area. So, in a sense that project described a static environment with no specific population processes incorporated to account for future population changes (Stuart et al. 2019).

Carp populations, however, can respond rapidly to hydrological conditions, especially flood events that provide access to preferred spawning habitats and can lead to significant recruitment. The population outcomes depend on subsequent hydrological conditions (Koehn et al. 2016, 2018). Multiple wet years can lead to large population growth and multiple dry years leading to population stagnation or decline. The 2011 and 2018 biomass estimates (Stuart et al. 2019) were based on static spatial mapping and as such, do not explicitly consider antecedent or subsequent hydrological conditions. Hence, the 2011 and 2018 biomass estimates cannot specifically be applied to future scenarios where the Carp virus may be released some years from these investigations, depending on the intervening hydrological conditions. Stuart et al. (2019) recommended the use of a dynamic model that would allow Carp population modelling to provide future estimates of biomass, taking into account likely impending hydrological scenarios (e.g. Koehn et al. 2018). This project undertakes that modelling using a Carp population model developed for the southern Murray-Darling Basin (Koehn et al. 2016).

Project objective

The aim of this project is to modify and apply the existing Carp population model to provide forward temporal estimates of likely Carp biomass and numbers for a range of hydrological scenarios, using the biomass estimate for the 2018 time point provided from the Carp biomass project.

Methods

Background

A Carp population model was developed by the Arthur Rylah Institute for use in the southern Murray-Darling Basin (SMDB) (Koehn et al. 2016). This model has been used to predict the likely outcomes of hydrological scenarios at a range of sites (Koehn et al. 2018). Whilst developed for the SMDB, a project has also been completed to scope the modification and use of this model for the northern Murray-Darling Basin (NMDB) (Koehn et al. 2015). Appraisal of the use of the existing Carp model (designed for the SMDB) (Koehn et al. 2016), together with an evaluation of the recommendations for its modification for the NMDB (Koehn et al. 2015), were used with the methods and results from the static 2018 Carp biomass estimate (Stuart et al. 2019) to develop a model and methodology suitable for modelling estimates of future potential Carp biomasses.

The existing Carp population model is an age-based, stochastic model with 28 age classes and is described in detail in Koehn et al. (2016). It includes estimates of survival, based on age-frequency data, and age-specific fecundity as well as demographic and environmental variation (see for example Todd and Lintermans 2015). The model was constructed from a review of the up-to-date published biological and ecological knowledge of Carp, including conceptual models on key aspects of Carp life history assessed through expert workshops (Koehn et al. 2016). It utilized a modelling approach and methods previously described for several other freshwater fish species (e.g. Todd et al. 2004, 2005; Koehn and Todd 2012; Todd and Lintermans 2015) and undertaken within a stochastic population modelling framework (Todd and Lovelace 2019). The model accounts for the first year of life with the early life history stages of egg, larval and young of the year survival being explicitly related to habitat type. Flow then determines whether adult Carp get access to these habitat types that are more or less productive for these early life history stages. Survival rates of these early stages was estimated through expert elicitation for the appropriate habitat types, from poor to highly conducive to survival.

Habitat analysis is undertaken to determine the habitat types available to Carp under differing flow conditions and this relates to the appropriate habitat type survival rates. For example, if elevated flows provided access for spawning adults to an inundated habitat type for 30 days or longer then the early life history survival rates were applied to offspring in that habitat type. This provided the basis for the modelled Carp response to flows by assigning different survival rates to the early life history stages depending on the habitat types accessed due to those flows. Only early life history survival rates were altered depending on flow type, with fish aged one and older having survival rates drawn from distributions with age-specific means and 10% coefficient of variation, representing environmental (non-flow) variation (as per Todd and Lintermans 2015). The modelled population was constrained through application of a carrying capacity to juveniles in each region. If the population rises above the carrying capacity, the survival rates of juveniles are proportionally reduced by the ratio of total population size to carrying capacity. Assessment of early life history survival for each habitat type allowed the calculation of Carp population growth rates for the various habitat types in each case (Koehn et al. 2018).

There was a need for the modelling undertaken in this project to be congruent with Stuart et al. (2019). This required initial work with the key authors from that project (Ivor Stuart, Ben Fanson and Shane Brooks) who were added to our project team to provide a consistent, compatible approach, especially with the spatial scales and outputs of that work. Two workshops were held to conceptualise the new population model and to ensure alignment with the Carp biomass project outputs. Discussions were directed with reference to the works of Koehn et al. (2015, 2016) and Stuart et al. (2019) and the ability to use (perhaps with modifications) their modelling approaches, data and output layers. It was agreed that there were no major impediments to this study progressing satisfactorily and that the approach would be a conceptual combination of SMDB, NMDB and coastal model components.

The assumptions from the Carp biomass model (Stuart et al. 2019) were considered reasonable and accepted for this project but these need to be recognised (below).

Carp biomass model assumptions

Spatial area: Spatial area was treated as a constant (known with certainty). However, there was uncertainty as river and waterbody surface areas are temporally dynamic and quantifying variable areas requires specialised hydrological models not available for this project. Furthermore, river widths for most rivers were predicted from flow volumes and estimates of waterhole areas in the Paroo River were poor.

Area vs. volume: Carp density by area is the most common method used for reporting densities (e.g. Driver et al. 2005; Gilligan et al. 2010; Bajer and Sorensen 2012; Farrier et al. 2018). This reality is due more to convenience (i.e. it is much simpler to measure surface area than waterbody volume), rather than area providing any inherently superior reflection of Carp population processes. Carp actually inhabit three-dimensional habitats and whilst volume would have been the preferred unit of measure, area rather than volume was used because quantifying volume would have been an unachievable task.

Missing zeros in existing data: Though they were requested, we suspect that some field surveys in which no Carp were caught were not included in the data sets submitted for the database. This would lead to an overestimation of catch per unit effort (CPUE), though most likely in lower density areas, mitigating some of the bias.

Estimates of biomass for waterbodies: Few attributes were available for waterbodies (compared with rivers) to use in predictive models of CPUE and fish mass. Hence, predictions of Carp biomass for waterbodies were based primarily on habitat class (lake, wetland, or storage) and spatial region. Such a simplification likely misses the true heterogeneity in waterbodies. Furthermore, our model assumes a constant Carp density for the whole waterbody (or one for the littoral zone and one for the offshore zone). This was necessary as there was no other information with which to adjust biomass estimates. Therefore, the biomass estimates for waterbodies should be viewed as very coarse (which is reflected in the large Bayesian credible intervals).

Juvenile biomass: Young-of-the-year (YOY) juvenile biomass from the Carp biomass project was a significant unknown, with YOY Carp difficult to catch and to estimate their density. Without any available information on detection rates, the conservative approach of using the conversion factor for fish >150 mm fork length (FL) was taken. Carp <150 mm FL are considered not yet to be one year old fish. The population model is a discrete model with census date being August 1st, as at August 1st there are no Carp less than 150 mm FL, there is only one year old, two year old and adult fish in the model. If the Carp virus is released subsequent to August 1st then there may be additional biomass from new recruitment not accounted for in the population estimate. Therefore, it is possible that YOY juvenile Carp are considerably underestimated and hence this impacts the total biomass.

Irrigation channels: Due to the lack of adequate spatial mapping, it was not possible to include irrigation channels in detail. Whilst originally excluded, a channels layer was produced by Stuart el al. (2019) but the lack of monitoring in channels to provide CPUE data was recognised as a significant source of error. This channel data was included in our estimate as separate process.

Potential bias in the conversion factor: Estimates of conversion factors may underestimate the true conversion factor for standard Sustainable Rivers Audit (SRA) protocols.

Modelling Carp at large spatial scales

There are several key ecological concepts that are different across the larger spatial scales for Carp populations in Australia; especially between the NMDB and SMDB. These were raised by Koehn et al. (2015) and needed to be considered before the existing SMDB Carp population model could be applied to the NMDB. Each conclusion is outlined below with the resultant resolution for this project (in italics) following workshop discussions:

1. The larger spatial scales (distances) that occur across the NMDB need to be taken into account when applying the population model.

    - *The model can be applied to any scale, and the scales used in this project are very broad, so this is not an issue*.
2. The habitat types and areas available to Carp are different to the SMDB.
    - *Habitat types will be renewed with new ones created.*
3. Boom and Bust conditions are provided by the wet and dry seasons; with flood flows, followed by cease-to-flows. Importantly, these cease to flow events create waterhole habitats which warrant their own discussion.
    - *Waterholes will be added as a new habitat type using the existing habitat layer from the static biomass project.*
4. High variability in flows means that while there are large expanses of floodplain in the NMDB; river to wetland connections are often short-lived.
    - *Accommodated by habitat layers*.
5. Recolonisation rates will be key factors of Carp population expansion because of limited refuges and patch habitats due to extended dry spell durations.
    - *The large scales of this modelling will not require immigration and emigration and habitat area dynamics will be accounted for in the habitat layers.*
6. While it is recognised that many of these differences are not binary between the NMDB and SMDB, with some on a north-south gradient; it was agreed that for general simplicity, the use of ecological principles discussed for the Carp population model would be applied to regions geographically north of the Lachlan River and Menindee Lakes.
    - *Agreed this was applicable for this project.*

Incorporating regions and habitat updates to the existing Carp model

A 28-age class stochastic population model was constructed for Carp (details in Koehn et al. 2016). Within the resources available it was most efficient to convert the existing Carp population model to four individual population models that adequately represent four regions of eastern Australia. These were: NMDB, SMDB, northern coastal (NC) and southern coastal (SC) regions (Figure 1). The populations in Lake Sorell (Tasmania), coastal rivers in Western Australia and irrigation channels will be considered separately as they have different population drivers and comprise a very small component of Australia's Carp biomass. Lake Sorell populations will be impacted by removal efforts and lake water levels which are largely dependent on lake management and Western Australia populations are considered to be similar to those of southern coastal (SC). Therefore, it was necessary to reconfigure the 2016 Carp model with the addition of extra habitat components identified for the NMDB model; waterholes, non-perennial rivers and storages (Koehn et al. 2015). There was then also a need to match habitat types from Koehn et al. (2016) (Appendix 1) with Stuart et al (2019) which used the following categories Riverine: perennial, non-perennial; waterholes; estuary; waterbodies: lake, storage; wetlands (>4 ha). Waterholes, storages and estuaries were not included as habitat categories in the original Carp model (Koehn et al. 2016).

The first two habitats, waterholes and storages, were included, but inclusion of estuaries was not necessary as these were usually incorporated into wetland layers or were too saline to support Carp populations. Floodplains were not explicitly included by Stuart et al. (2019) because the biomass estimate was derived for 'average' conditions when only some, low-lying floodplain were inundated. They were included in this project as they provide important spawning and recruitment habitats for population processes under flood conditions. A floodplain map was therefore created using existing inundation modelling data (detailed below). Storages were considered as deep and littoral zones. The existing habitat categories were considered suitable for the coastal river models. Due to the lack of adequate spatial mapping and monitoring in channels to provide CPUE data it was not possible to include irrigation channels in this project. The data layers produced by the static Carp biomass project were also deemed suitable for use in this project albeit that there was the need for further manipulation of the data in the process of aligning habitat types. The final habitat categories for modelling are described in Table 1.

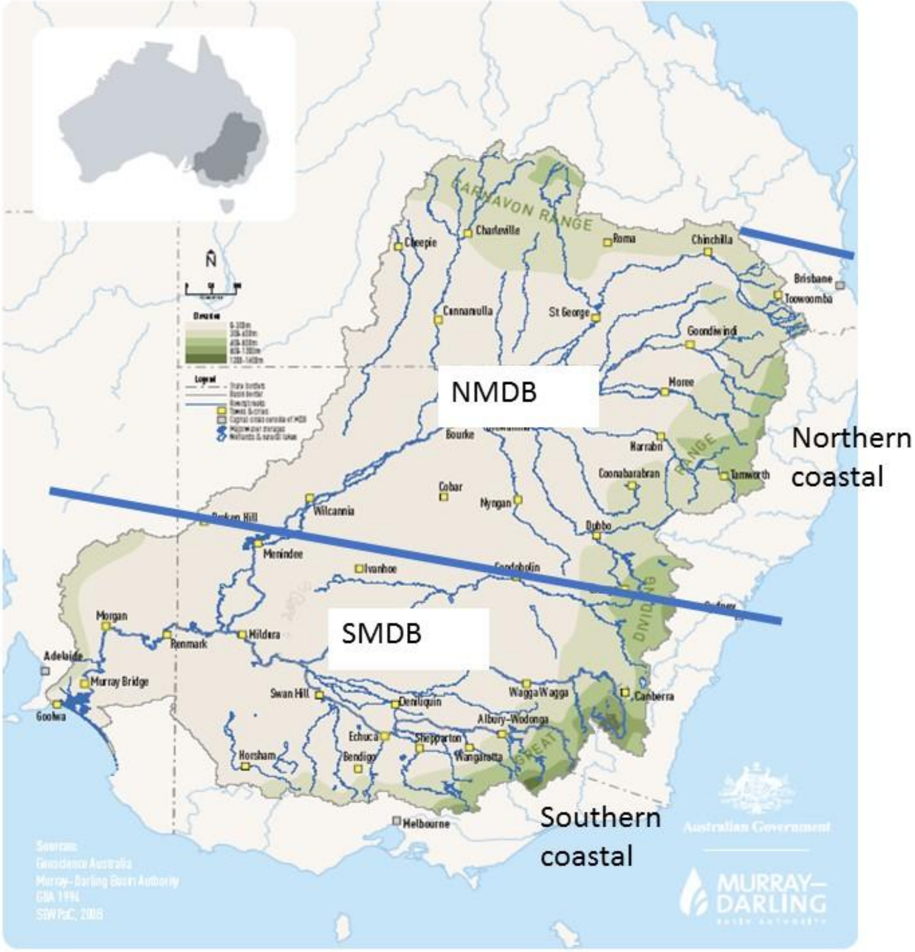


Figure 1. Map depicting the different regions delineated for modelling in this project.

Note that not all of these habitats will be applicable to each region or scenario. Ephemeral lakes were considered equivalent to ephemeral wetlands and only littoral zones were used for all lakes, wetlands and storages as it was considered that no spawning or recruitment would take place in these deeper zones, and irrigation channels were excluded due to lack of CPUE data.

The existing 2016 Carp population model survival parameters were examined to consider how they may apply across these regions for the new habitat types (Table 1), and the associated survival rates for the Carp early life stages were estimated from the original model (Table 2) (see Appendix 1 for habitat types and survival rates used in Koehn et al. 2016). An additional mortality estimate of 10% for adults and juveniles was incorporated for the NMDB under Drought scenarios to accommodate the greater mortality rates (especially in drying water holes) under those conditions.

Table 1. Description of habitat types used for Carp biomass population model and the equivalent survival schedule from Table 2.

No.	Habitat type (Stuart et al. 2019)	Equivalent habitat-flow type from Koehn et al. (2016)
1	Waterholes	H1
2	Non-perennial rivers	H1 Drought, H2 average, H3 Flood
3	Perennial rivers	H1 Drought, H2 average; H3 Flood
4	Natural floodplain inundation	H4 Flood
5	Wetland Permanent	H5

6	Wetland Temporary	H6
7	Lake Permanent	H7
8	Lake Temporary	H7
9	Storages	H8

Table 2. Percentage survival and associated population growth rate for each life stage and habitat type used in the Carp biomass population model (modified from Koehn et al. 2016).

Habitat	Egg survival (%)	Larval survival (%)	Fingerling survival (%)	Young-of-the-year survival (%)	Population growth rate (years)	Population doubling time (years)
H1	0.72	1.82	3.31	6.31	0.77	–
H2	1.36	3.84	5.88	7.25	0.88	–
H3	2.45	5.24	6.89	11.00	1.02	35.00
H4	10.90	8.15	20.31	21.39	2.41	0.79
H5	4.68	7.10	14.84	14.76	1.52	1.66
H6	7.96	5.70	16.83	7.96	1.46	1.83
H7	5.21	5.91	13.09	13.69	1.42	1.98
H8	7.96	5.70	16.83	7.96	1.46	1.83

Western Australia, Tasmania and irrigation channels all pose difficulties for estimating Carp biomasses, have been treated differently by Stuart et al. (2019) and contribute limited biomasses to the national estimate. Following Stuart et al. (2019). These were all treated as additional biomasses that could be added to the national estimate, rather than modelled in this project. As the modelled estimate for Carp in Lake Sorell is now approximately 20 fish in poor condition, this was excluded (John Diggle, Inland Fisheries Service, Tasmania, pers. comm.).

Hydrological scenarios modelled

Determination of the timeframes and scenarios to be considered in this project were made after consultation with Fisheries Research and Development Corporation (FRDC) (Table 3). These were considered the ‘worst’ (Flood) and ‘best’ (Drought) case scenarios for managing Carp population outcomes. The regions suggested by FRDC were NMDB, SMDB and coastal regions, where the coastal region was divided in to NC and SC to give 4 regions resulting in a total of 8 scenarios. Additional scenarios suggested to be modelled following the outcomes of this project are included in Appendix 2.

Table 3. Hydrological scenarios applied to all regions modelled in this project.

Scenario	Hydrological scenarios applied to all regions
Scenario 1 (worst case)	3 wet (Flood) years, full wetland inundation, followed by 2 ‘average’ years
Scenario 2 (best case)	3 dry (Drought) years, followed by 2 ‘average’ years

A 1 in 20-year flood frequency was chosen to represent wet years where floods inundate Carp feeding and breeding habitats with sufficient frequency, magnitude and duration to influence Carp population dynamics. The area of floodplain inundated by a 1 in 20-year flood was estimated over the four regions (Figure 1) by calibrating the frequency that water was detected in Landsat satellite imagery (Water Observations from Space (WOfS) dataset; Mueller et al. 2016) to the Murray-Darling Basin Floodplain Inundation Model Version 2.0 (MDB-FIM2) 1 in 20-year Annual Return Interval (ARI) model (Overton et al. 2010, Chen et al. 2012). This provided a cross-check of the experimental MDBFIM2 inundation predictions and a means to extrapolate to the coastal catchments outside the domain of the model. Pixels in the MDBFIM2 1in20 ARI maximum extent raster were considered “flooded” when the model predicted >50% of a pixel would be inundated. A threshold test was then applied to WOfS to eliminate the least frequently watered areas with the result that WOfS was a reasonable match to MDBFIM2’s 1 in 20 ARI when areas inundated in only 1-2% of clear satellite views were removed (Figure 2). Floodplain area was then measured and used in flood year model runs.

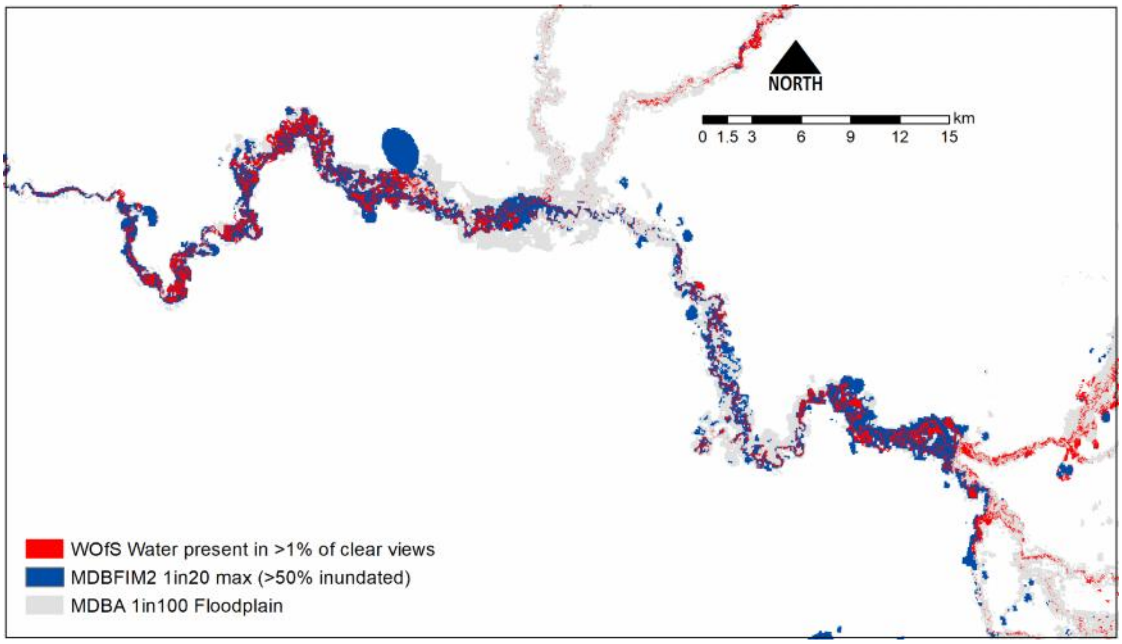


Figure 2. Example of the area of floodplain inundated in a 1 in 20-year flood estimated by aligning Water Observations from Space (WOfS) (red) to the Murray-Darling Basin Inundation Model (MDBFIM2) 1 in 20 ARI inundation (blue) for the SMDB.

For the Drought scenarios, inundated floodplains were excluded, and waterbody areas reduced to levels found in 2007 during eastern Australia’s Millennium Drought. Lakes and storages were at low levels during 2007 due to six consecutive years of below-average rainfall (Bureau of Meteorology annual rainfall anomaly for eastern Australia 1900 to 2018- see Appendix 3). Waterbody areas were measured using the extent of water observed in the 2007 annual WOfS data set (Figure 3). Temporary waterbodies in which water was not detected by WOfS were excluded as “dry”. WOfS cannot reliably detect water in emergent marshes where the vegetation signal dominates reflected wavelengths, however in the context of a drought year we can confidently assume such areas are also likely to be dry. The areas of the habitat types were calculated for each region (Table 4).

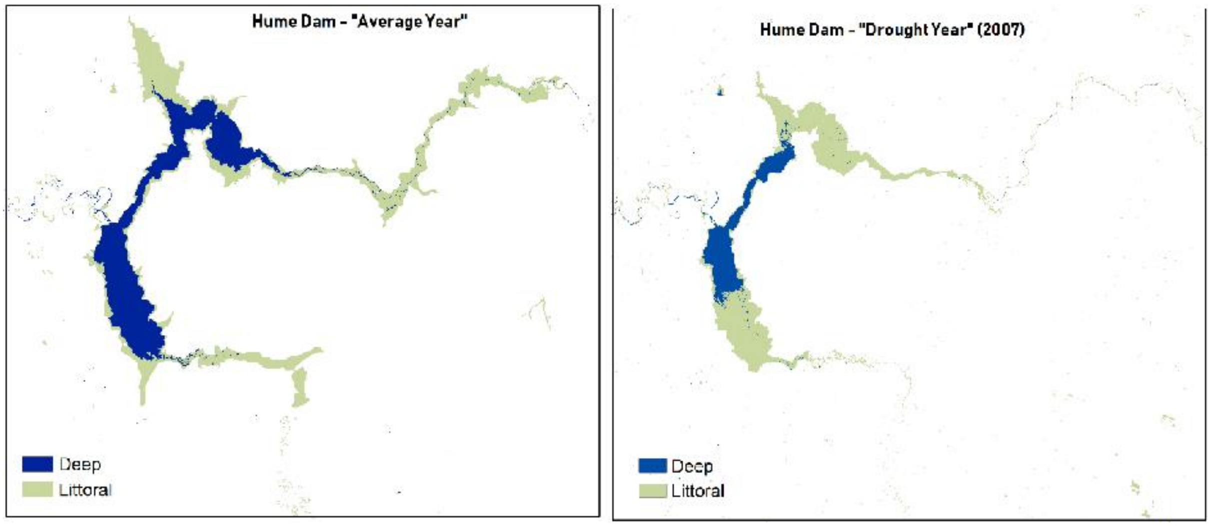


Figure 3. Example of the reduction in habitat area for water storages in the Drought scenario using the 2007 drought year WOfS.

Table 4. Habitat type in hectares (ha) for each habitat type in each region.

Hydrologic condition	**Habitat Type**	**NMDB (ha)**	**SMDB (ha)**	**NC (ha)**	**SC (ha)**
Riverine	Waterhole	23162	0	0	0
	Non-perennial	37483	49240	14873	16802
	Perennial	15506	55161	14362	21112
Flood	Floodplain	1130719	401037	9615	15170
Average	Permanent wetland	50007	32585	0	12487
	Temporary wetland	293889	180124	7586	3907
	Permanent lake	23947	27317	1388	27172
	Temporary lake	150360	146178	62	3145
	Storage	64655	43060	4551	17762
Drought	Permanent wetland	12768	3634	0	6810
	Temporary wetland	77335	2439	339	1043
	Permanent lake	9926	7281	436	18887
	Temporary lake	27912	2764	3	713
	Storage	21935	19219	1948	10225

Carp model summary

In summary, using the 28-age class stochastic population model for Carp, the first year of life was divided in to four stages: eggs; larvae; fingerlings; and young-of-the-year (Koehn et al. 2016). Each of these stages was assigned a survival rate depending on habitat type (Tables 1 and 2; see Koehn et al. 2016). Age specific survival rates and fecundity rates were estimated from data collected throughout eastern Australia (see Koehn et al. 2016 for estimates). Each habitat type corresponded to the habitat types used in Stuart et al. (2019). Four regions were established: 1) Northern Murray-

Darling Basin (NMDB); Southern Murray-Darling Basin (SMDB); Northern Coastal (NC); and Southern Coastal (SC) (Figure 1). The scenarios considered were: 1) a Flood scenario of 3 flood years followed by 2 average years; and 2) a Drought scenario of 3 drought years followed by 2 average years (Table 3). The areas of the habitat types were calculated for each region (Table 4) as well as the biomass of Carp of each habitat type in each region (Table 5).

Two methods were used to assign Carp to the different habitat types in each region based on: 1) the proportional habitat areas (Area distribution method) for a 1 in 20-flood year, an average year and a 1 in 20 drought year; and 2) the proportional biomass (Biom distribution method) of Carp in the habitat types during a flood year (2011), average year (2018) (Stuart et al. 2019) were then linearly extrapolated to a drought year because of an absence of data (Table 6). For method 2, where the extrapolated Carp biomass in a drought year for a habitat type was negative, we set the biomass at 5% of the habitat type in an average year, as a positive non-zero biomass was appropriate. Density dependence was applied to juveniles (1-year-old and 2-year-old Carp) with the associated survival rates proportionally decreased by multiplying the survival rates by the ratio of carrying capacity to total population, when the total population was calculated to be above the carrying capacity. Carrying capacity was approximated conservatively as 1.5 times the average year population estimate (Table 7).

For each scenario we ran 3 simulations with different initial population sizes: an initial population size of the mean; the lower credible interval (CI); and the upper CI (Table 7). Each initial population size used the mean, the lower CI and the upper CI weight per Carp (Table 8) to ensure the initial biomass for the population model aligned with the estimated biomass from Stuart et al. 2019 (Table 9). The weight per age (Table 10) was estimated from age-weight data and used to calculate the age class biomass and then total biomass in 2023.

There is no information on the initial age class distribution, however Stuart et al. (2019) provide estimates of kg/Carp for the different regions that can be used to estimate age class distribution. To solve this, the initial age class distribution was determined by $IPS_{Age} = IPS \times \left(df_r\right)^{Age}$, where IPS is the initial population size and df_r the distribution factor for a region which determines if the initial population structure was dominated by adults or juveniles. The initial age class distribution was normalised, to provide a relative frequency or the age probability mass function $P\left(Age\right) = IPS \times \left(df_r\right)^{Age} \Big/ \sum_{Age=1}^{Age=28} IPS_{Age}$. Age weight data was used to estimate weight given age (Table 10), $weight_{Age}$, if $weight_{Age}$ is treated as a random variable and multiplying this by the age probability mass function then the sum of this product is the expected value of weight for the region, that is $av.\,weight_r = \sum_{Age=1}^{Age=28} weight_{Age} \times IPS \times \left(df_r\right)^{Age} \Big/ \sum_{Age=1}^{Age=28} IPS_{Age}$, where the $av.\,weight_r$ is found in Table 8. Solving the equation for df_r returns the regional distribution factor (Table 8) given $av.\,weight_r$. A low regional distribution factor yields an initial age distribution dominated by juvenile Carp whereas a high regional distribution factor yields an initial age distribution dominated by adult Carp.

Table 5. Biomass (t) for each habitat type in each region under flood, average and drought hydrological conditions.

Habitat Type	Hydrologic condition	NMDB	SMDB	NC	SC
Waterhole	Flood	4770	0	0	0
	Average	5528	0	0	0
	Drought	6285	0	0	0
Non-perennial	Flood	4927	8747	2395	3151

	Average	3890	6183	1447	2225
	Drought	2853	3618	499	1299
Perennial	Flood	2774	20481	2062	5605
	Average	2292	15617	1131	3276
	Drought	1810	10753	200	947
Permanent wetland	Flood	7088	15541	0	4733
	Average	3343	7260	0	2270
	Drought	167	363	0	113
Temporary wetland	Flood	27191	77444	2561	1032
	Average	12308	399723	1207	480
	Drought	615	1998	60	24
Permanent lake	Flood	2554	66222	737	19538
	Average	1069	33010	320	9208
	Drought	53	1650	16	460
Temporary lake	Flood	15767	35233	18	1035
	Average	6668	15745	8	460
	Drought	333	787	0	23
Storage	Flood	7795	22103	1742	5592
	Average	3315	11475	788	2996
	Drought	165	846	39	400

Table 6. Proportional distribution of the Carp population to different available habitat types in each region under flood, average and drought hydrological conditions using the proportional habitat areas (Area) and proportional biomass (Biom) methods.

Habitat type	Distribution type	Hydrologic condition	NMDB	SMDB	NC	SC
Waterhole	Area	Flood	0.0129	0	0	0
	Biom	Flood	0.038	0	0	0
	Area	Average	0.0351	0	0	0
	Biom	Average	0.1439	0	0	0
	Area	Drought	0.1025	0	0	0
	Biom	Drought	0.5117	0	0	0
Non-perennial	Area	Flood	0.0209	0.0527	0.2836	0.1429
	Biom	Flood	0.0393	0.0199	0.1866	0.047
	Area	Average	0.0569	0.0923	0.3473	0.2062
	Biom	Average	0.1013	0.0478	0.2952	0.1064
	Area	Drought	0.1658	0.3524	0.4653	0.2223
	Biom	Drought	0.2323	0.1808	0.6122	0.3976
Perennial	Area	Flood	0.0087	0.059	0.2739	0.1796

	Biom	Flood	0.0221	0.0465	0.1607	0.0836
	Area	Average	0.0235	0.1034	0.3354	0.2062
	Biom	Average	0.0597	0.1208	0.2307	0.1566
	Area	Drought	0.0686	0.3947	0.4493	0.2793
	Biom	Drought	0.1474	0.5372	0.2452	0.2899
Floodplain	Area	Flood	0.6318	0.4291	0.1834	0.129
	Biom	Flood	0.4192	0.4417	0.2585	0.393
	Area	Average	0	0	0	0
	Biom	Average	0	0	0	0
	Area	Drought	0	0	0	0
	Biom	Drought	0	0	0	0
Permanent wetland	Area	Flood	0.0279	0.0349	0	0.1062
	Biom	Flood	0.0565	0.0353	0	0.0706
	Area	Average	0.0759	0.0611	0	0.122
	Biom	Average	0.087	0.0562	0	0.1085
	Area	Drought	0.0565	0.026	0	0.0901
	Biom	Drought	0.0136	0.0181	0	0.0347
Temporary wetland	Area	Flood	0.1642	0.1927	0.1447	0.0332
	Biom	Flood	0.2167	0.1759	0.1995	0.0154
	Area	Average	0.446	0.3375	0.1771	0.0003
	Biom	Average	0.3204	0.3092	0.2463	0.0229
	Area	Drought	0.3421	0.0175	0.0106	0.0138
	Biom	Drought	0.0501	0.0998	0.0741	0.0073
Permanent lake	Area	Flood	0.0134	0.0292	0.0265	0.2311
	Biom	Flood	0.0204	0.1504	0.0575	0.2915
	Area	Average	0.0363	0.0512	0.0324	0.2654
	Biom	Average	0.0279	0.2554	0.0654	0.4402
	Area	Drought	0.0439	0.0521	0.0137	0.2499
	Biom	Drought	0.0044	0.0824	0.0197	0.1409
Temporary lake	Area	Flood	0.084	0.1564	0.0012	0.0268
	Biom	Flood	0.1257	0.08	0.0015	0.0154
	Area	Average	0.2282	0.2739	0.0015	0.0307
	Biom	Average	0.1736	0.1218	0.0017	0.022
	Area	Drought	0.1235	0.0198	0.0001	0.0094
	Biom	Drought	0.0271	0.0393	0.0005	0.0071
Storage	Area	Flood	0.0361	0.0461	0.0868	0.1511
	Biom	Flood	0.0621	0.0502	0.1357	0.0834

	Area	Average	0.0981	0.0807	0.1063	0.1735
	Biom	Average	0.0863	0.0888	0.1607	0.1433
	Area	Drought	0.097	0.1375	0.061	0.1353
	Biom	Drought	0.0135	0.0423	0.0483	0.1225

Table 7. Population estimates (mean and credible intervals) for each region from Stuart et al. (2019) and carrying capacity (numbers).

Region	Mean	Lower CI	Upper CI	Mean CC
NMDB	53767211	27139560	104271589	81000000
SMDB	118987104	61374234	214761574	180000000
NC	3814643	1581539	8292659	6000000
SC	13946719	6274700	33019861	21000000

Table 8. Estimates of the average weight per Carp (kg, mean and credible intervals; Stuart et al. 2019) and the regional distribution factor (*df*) for each region.

Region	Mean	Lower CI	Upper CI	***df*** **mean**	***df*** **Lower CI**	***df*** **Upper CI**
NMDB	0.7224	0.5389	0.9166	0.5188	0.3856	0.6221
SMDB	1.0915	0.8715	1.3353	0.6935	0.6007	0.7696
NC	1.3051	0.8394	1.8484	0.7613	0.5846	0.8767
SC	1.5438	1.0380	2.1337	0.8195	0.6734	0.9204

Table 9. Biomass (t) estimate (mean and credible intervals) for each region.

Region	Mean	Lower CI	Upper CI
NMDB	38417	4903	129264
SMDB	35471	4315	122863
NC	19796	2034	66274
SC	75006	11549	232878

Table 10. Estimates of the weight (kg) (median, mean and credible intervals) per age class.

Age	Mean	Median	Lower CI	Upper CI
1	0.2428	0.2025	0.0480	0.5627
2	0.7272	0.5840	0.1518	1.8771
3	1.2339	1.0400	0.4193	3.3618
4	1.7113	1.2575	0.5230	6.5994
5	1.9440	1.4205	0.7810	7.0425
6	2.0805	1.6500	0.8221	6.8295

7	2.1362	1.7650	0.8520	5.3550
8	2.1654	1.9385	0.9883	4.6308
9	2.4090	2.1630	1.0490	4.8777
10	2.5592	2.3280	1.0733	5.2045
11	2.6440	2.3440	1.1419	5.5755
12	2.8416	2.4390	1.1486	5.5331
13	2.8826	2.4890	1.1045	5.9885
14	2.8168	2.4860	1.0280	5.5680
15	3.0075	2.4300	1.4139	6.1019
16	3.1481	2.8160	1.0548	6.2645
17	2.9399	2.6810	1.1582	5.7853
18	2.9843	2.6130	1.1654	5.9139
19	3.0220	2.9955	1.0156	5.4074
20	2.8916	2.7150	1.1579	4.8986
21	3.3139	2.9120	1.2165	7.5625
22	3.1328	3.1150	1.0412	6.3842
23	3.5321	3.5940	1.1899	6.6661
24	3.6904	3.6300	1.6775	6.8538
25	3.6689	3.9320	1.2580	5.1422
26	3.6203	4.1065	2.2868	4.6484
27	3.7460	3.8960	1.5859	5.1284
28	4.8106	3.8320	2.8899	10.1993

Results

The best estimate of Carp biomass in 2023, with an initial population size of the 2018 mean estimate (Table 7), is 167 960 - 172 895 t for the Drought scenario (Table 11) and 428 808 - 444 144 for the Flood scenario (Table 12). Mean, median and credible intervals for the four regions using Biom and Area distribution methods are also included in Tables 11 and 12 with a summary in Figure 4.

The mean initial biomass estimate does not provide any information on the age structure of the population; and this can greatly influence future population outcomes. Using the regional distribution factor (Table 8), where a lower value of the distribution factor structures the population with more juveniles and a higher value of the distribution factor structures the population with more adults.

As can be readily seen from Figure 4, the resultant predicted population biomasses for 2023 can vary considerably for the static 2018 (Stuart et al. 2019) estimate. These estimates vary depending on the hydrological scenario (Drought or Flood) and also for each region. In general, the Drought scenario produced about the same or slightly reduced biomasses. The Flood scenario produced much higher biomasses in all cases with estimates using the Biom method predicting the following population increases: NMDB ~x 3; SMDB ~x 2; NC ~x 7; and SC ~x 1.7. Collectively, the overall increase in Carp biomass from 2018 to 2023 with the Flood scenario would be about 250 Kt (~x 2.3).

Table 11. Drought scenario biomass (t) estimates (mean, median and credible intervals) for each region for 2023 using the proportional habitat areas (Area) and proportional biomass (Biom) methods.

Carp Distribution	**Mean**	**Median**	**Lower CI**	**Upper CI**
NMDB				
Area	37 601	38 062	24 709	46 720
Biom	31 910	32 580	16 605	45 986
SMDB				
Area	113 665	113 200	84 992	143 768
Biom	113 613	113 001	84 755	143 684
NC				
Area	3 883	3 782	2 069	6 163
Biom	4 919	4 779	2 612	8 067
SC				
Area	17 746	17 696	12 598	23 164
Biom	17 519	17 349	12 491	23 056
Total				
Area	172 895	172 740	124 369	219 815
Biom	167 960	167 710	116 463	220 793

Table 12. Flood scenario biomass (t) estimates (mean, median and credible intervals) for each region for 2023 using the proportional habitat areas (Area) and proportional biomass (Biom) methods.

Carp Distribution	**Mean**	**Median**	**Lower CI**	**Upper CI**
NMDB				
Area	109 520	109 250	79 251	141 641

Biom	115 429	115 639	75 049	151 784
SMDB				
Area	263 183	261 472	196 334	342 165
Biom	261 254	259 731	195 175	338 324
NC				
Area	20 614	19 242	8 188	42 146
Biom	34 400	32 366	12 956	63 706
SC				
Area	35 492	35 427	25 458	45 956
Biom	33 060	32 901	24 304	42 603
Total				
Area	428 808	425 392	309 231	571 908
Biom	444 144	440 637	307 483	596 418

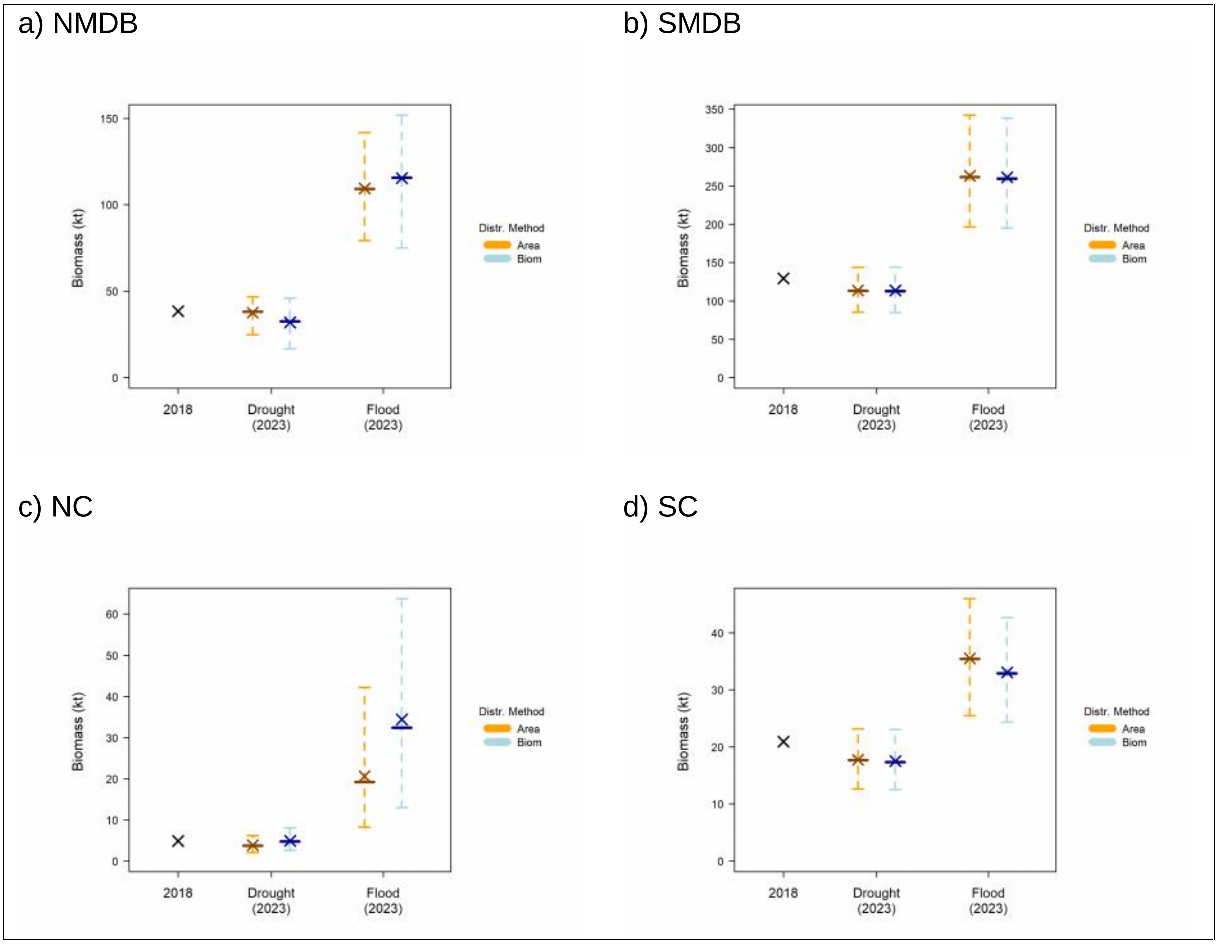
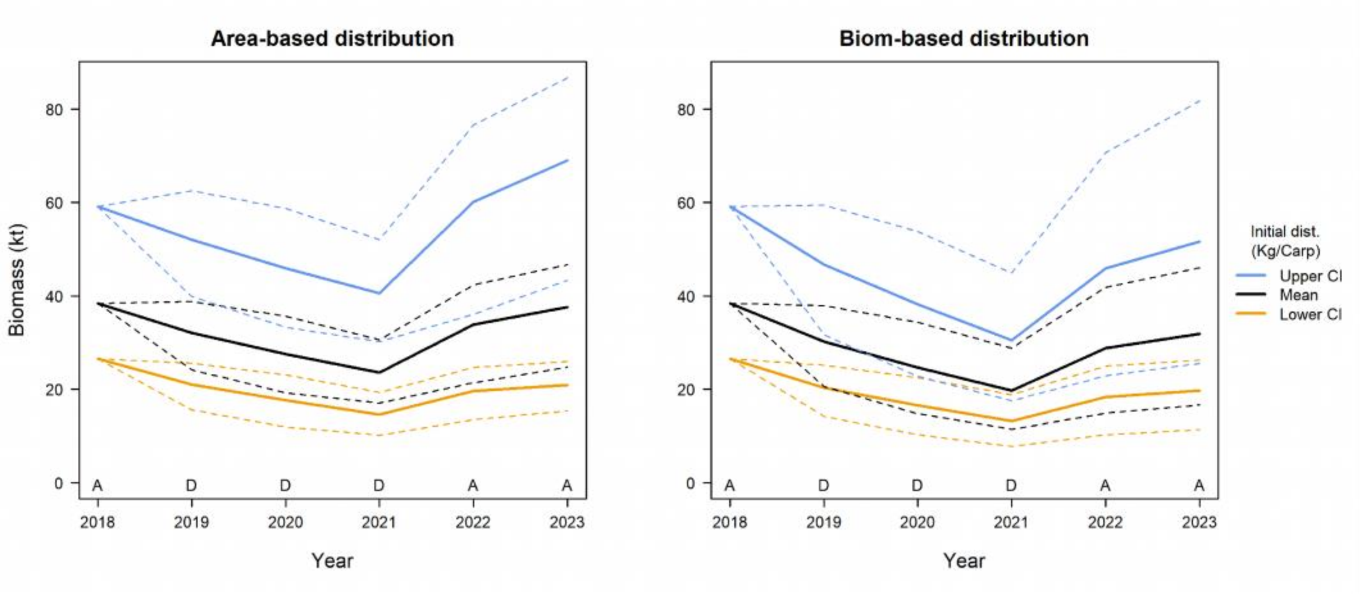
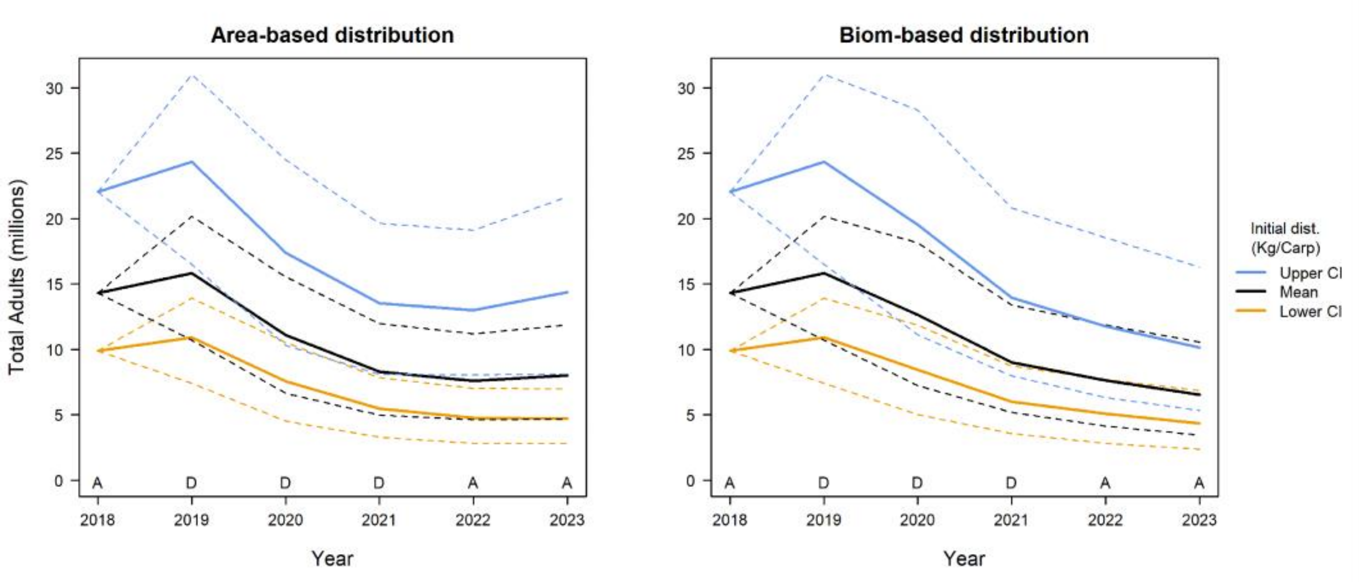


Figure 4. Summary of 2023 biomass estimates using the Biom and Area distribution methods for each region compared with the 2018 initial biomass estimate (Stuart et al. 2019) under Drought and Flood scenarios. Note the different scales for each region.

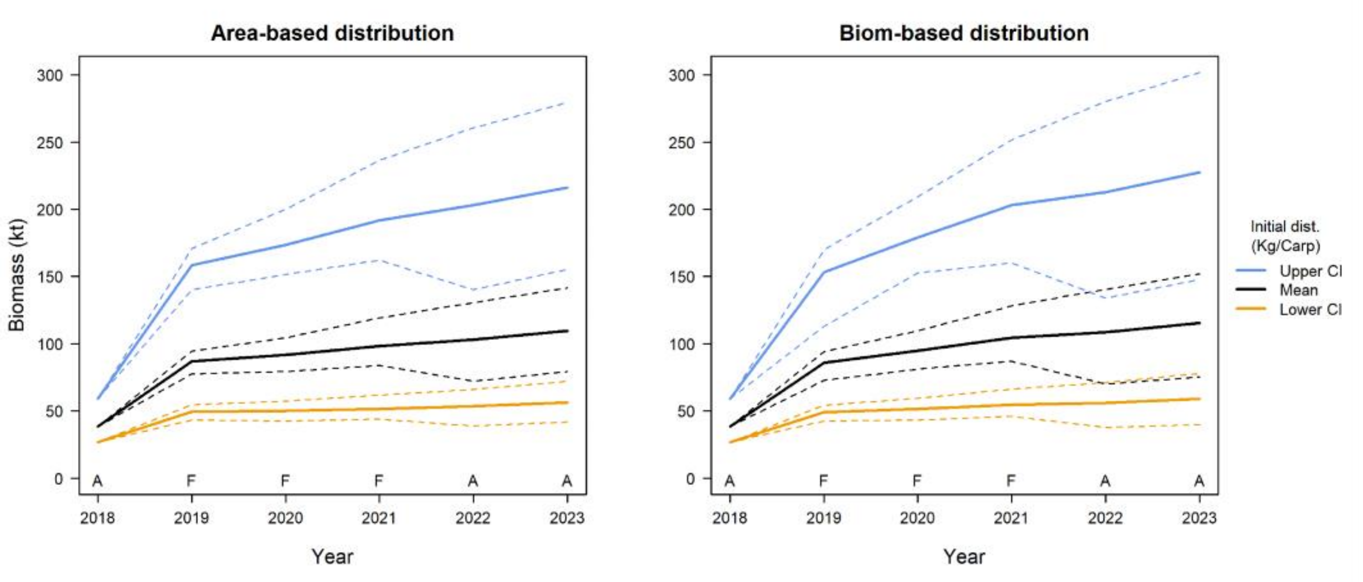
a) NMDB Drought Biomass



b) NMDB Drought Adults



c) NMDB Flood Biomass



d) NMDB Flood Adults

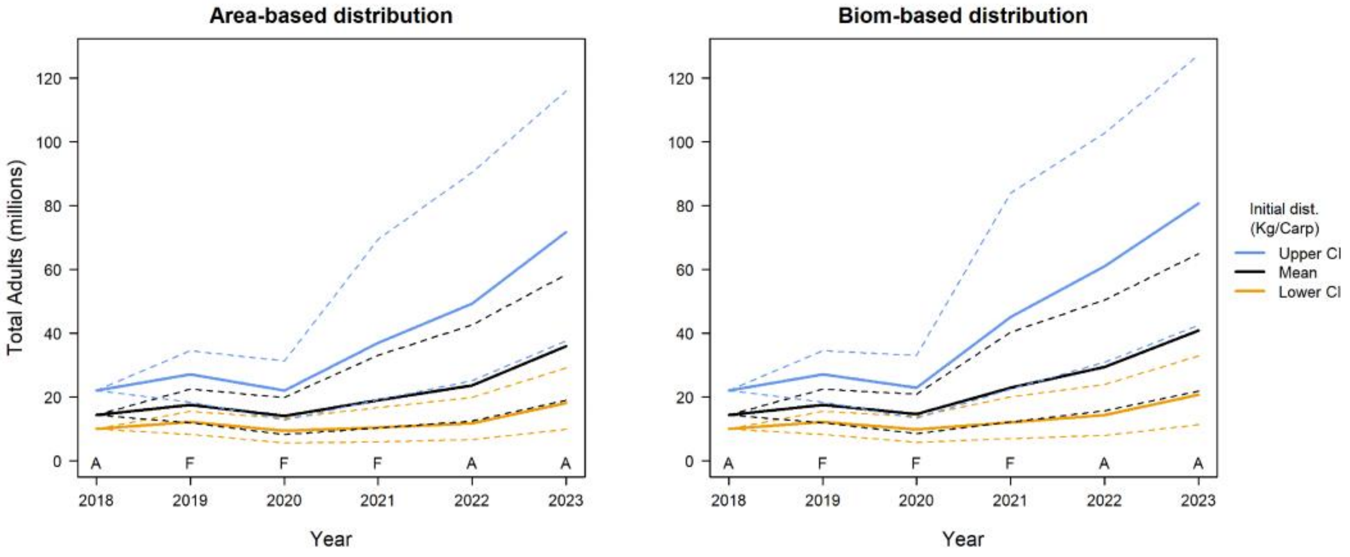
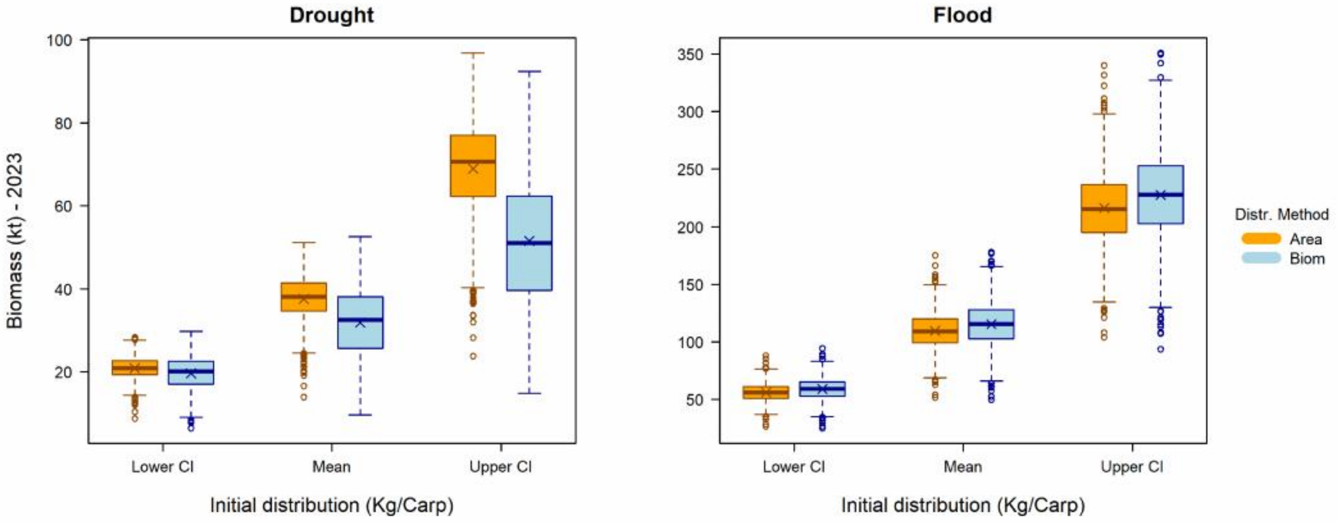


Figure 5. An example of the different dynamics of Carp Biomass and Adult numbers for Drought and Flood scenarios in the NMDB with different initial population structures. Note the different scales for biomass on the y axes. See Appendix 4 for additional examples.

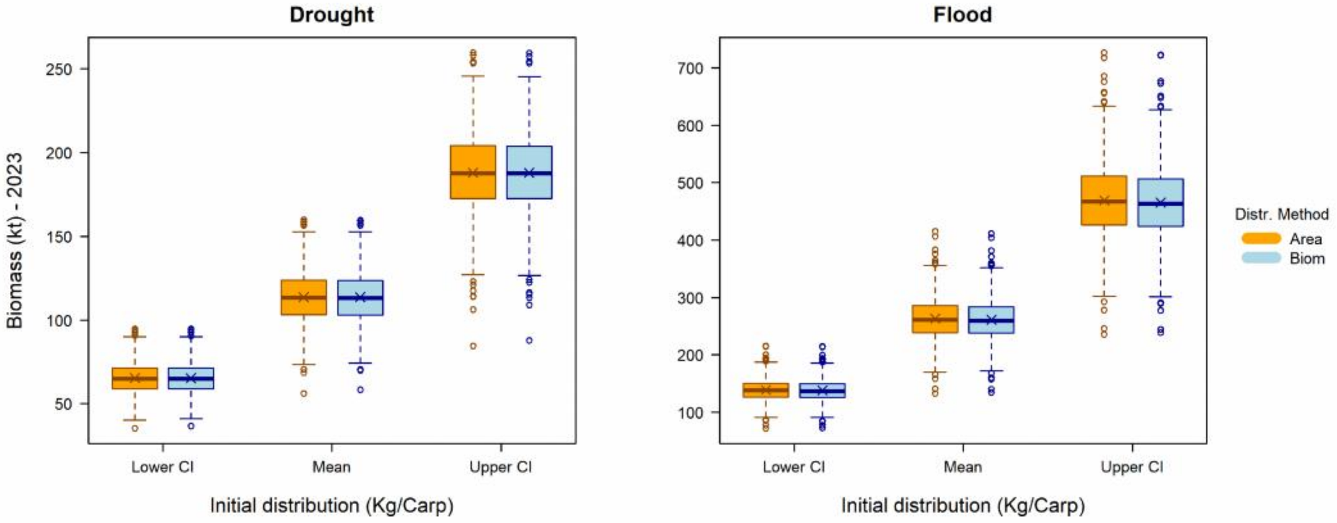
The Drought scenario is dynamically different to a flood sequence. During the Drought scenario the biomass declines and then recovers with the two following average years, compare this with the adult numbers which continue to decline, as new recruits from the average years have yet to become adults (Figure 5 a and b). In the Flood scenario the biomass increases immediately and continues to rise even during the subsequent average years as adult biomass continues to increase as juveniles develop in to adults during the average years (Figure 5 c and d). Biomass estimates, total Carp, adults and juveniles through time with differing population structures for all hydrological and region scenarios modelled are included in Appendix 4.

The results presented in Table 11 and 12 are generated from using the mean regional distribution factor. If the initial population distribution is set at the lower CI or the upper CI the population outcomes strongly vary (Figure 6), with, generally speaking, a regional distribution factor using the upper CI produces a larger biomass. The summary statistics for Carp biomasses for all scenarios modelled are included in Appendix 5.

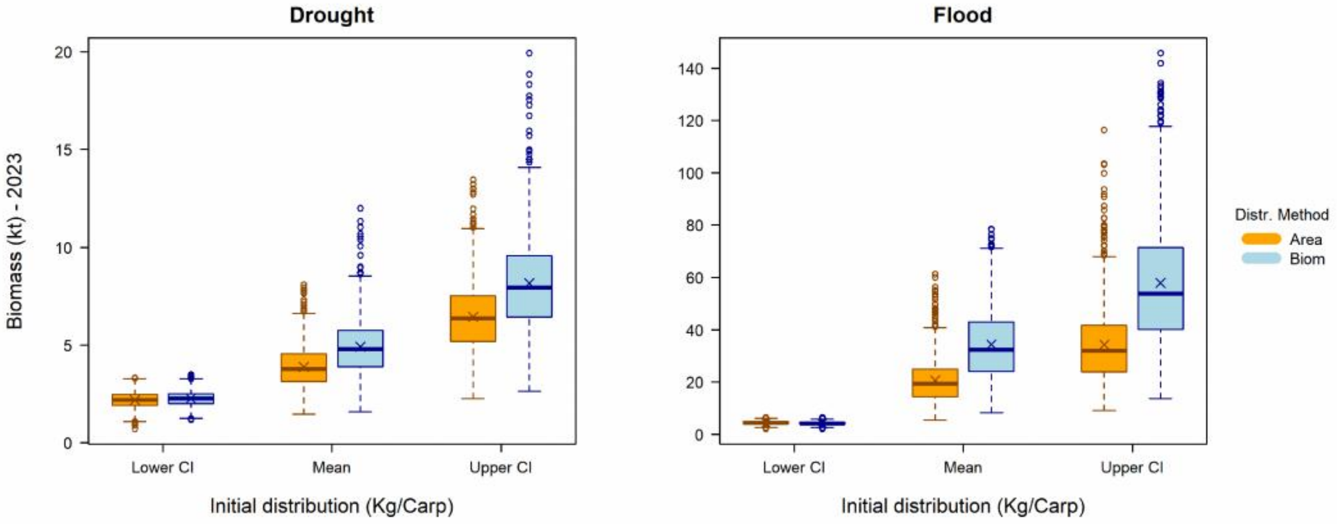
a) NMDB



b) SMDB



c) NC



d) SC

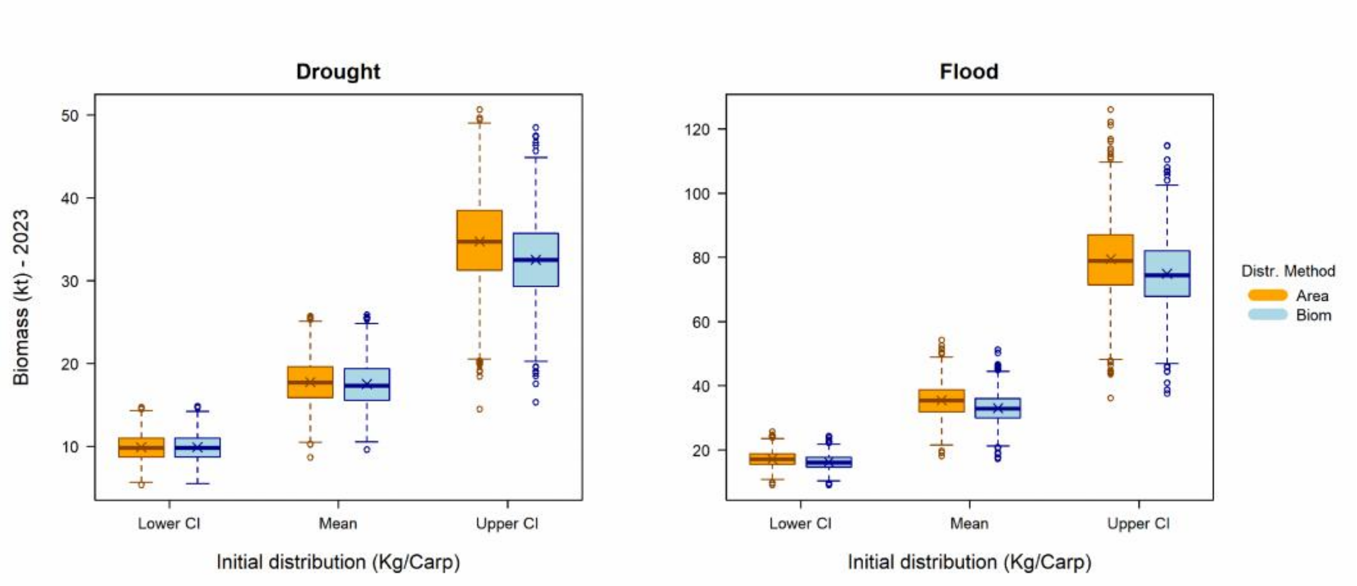
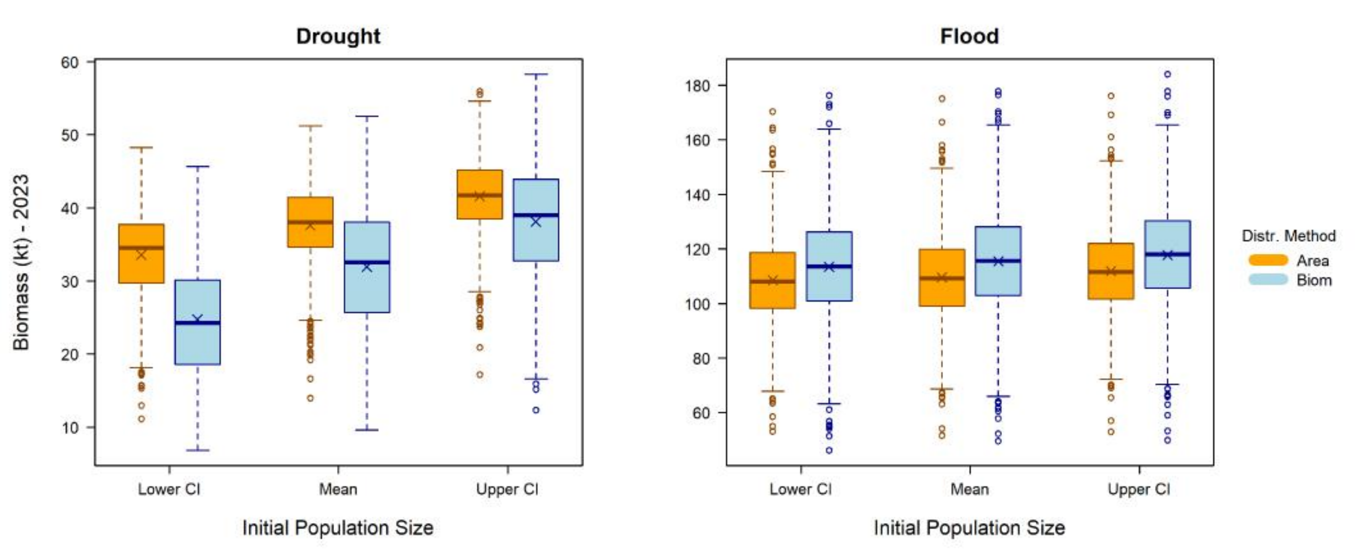


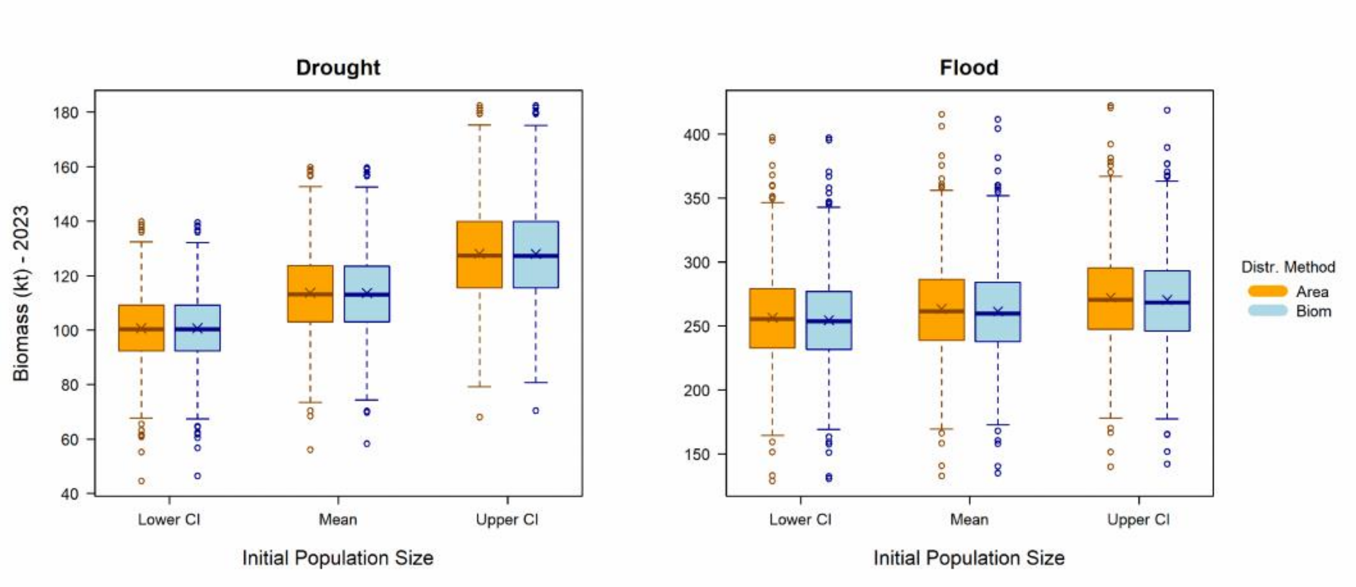
Figure 6. Regional differences in biomass estimates with differing initial population structure under Drought and Flood scenarios. The mean, lower CI and upper CI are for the regional distribution factor in Table 8. Note the different scales for biomass on the y axes.

In addition to the initial population structure influencing biomass outcomes for 2023, the initial population size also has an influence on the biomass outcomes. The results presented in Table 11 and 12 and Figure 4 are generated from using the mean estimate of the 2018 biomass (Table 9). If the lower CI and upper CI are used to generate the initial population size, then the biomass outcomes for 2023 vary depending on region and hydrological scenario (Figure 7). For example, the Drought scenario in the NMDB generates a mean 2023 biomass of: 33 556 (Area) and 24 726 (Biom) (initial population size from the 2018 lower CI biomass); 37 601 (Area) and 31 910 (Biom) (initial population size from the 2018 mean biomass); and 41 570 (Area) and 38 106 (Biom) (initial population size from the 2018 upper CI biomass)

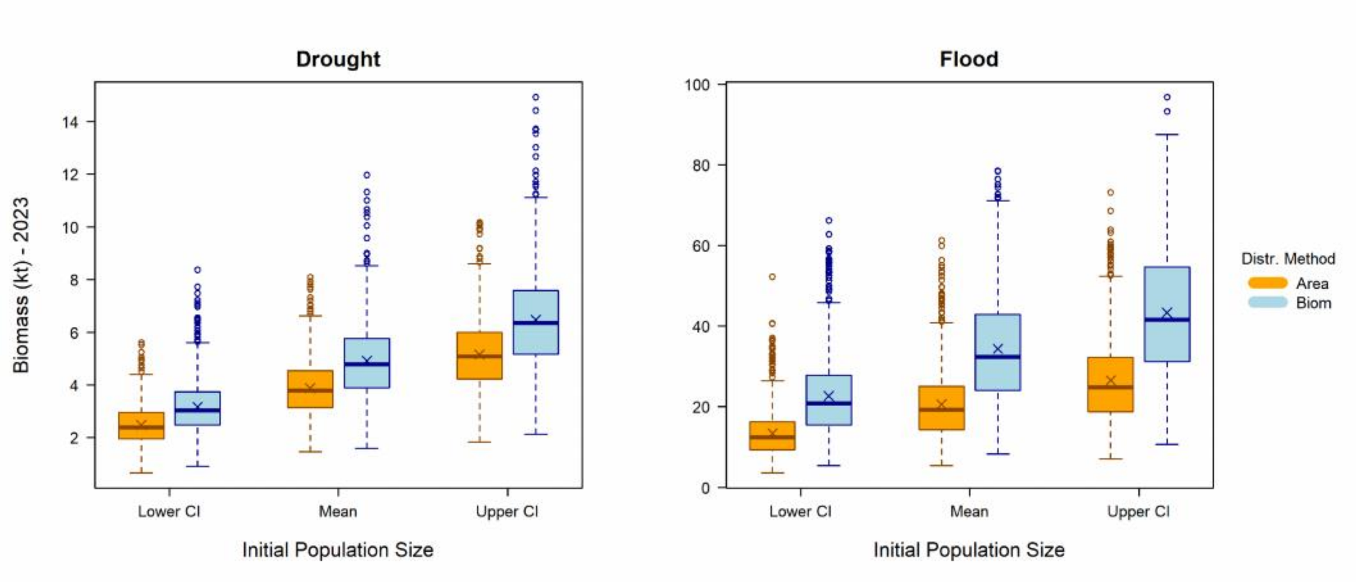
a) NMDB



b) SMDB



c) NC



d) SC

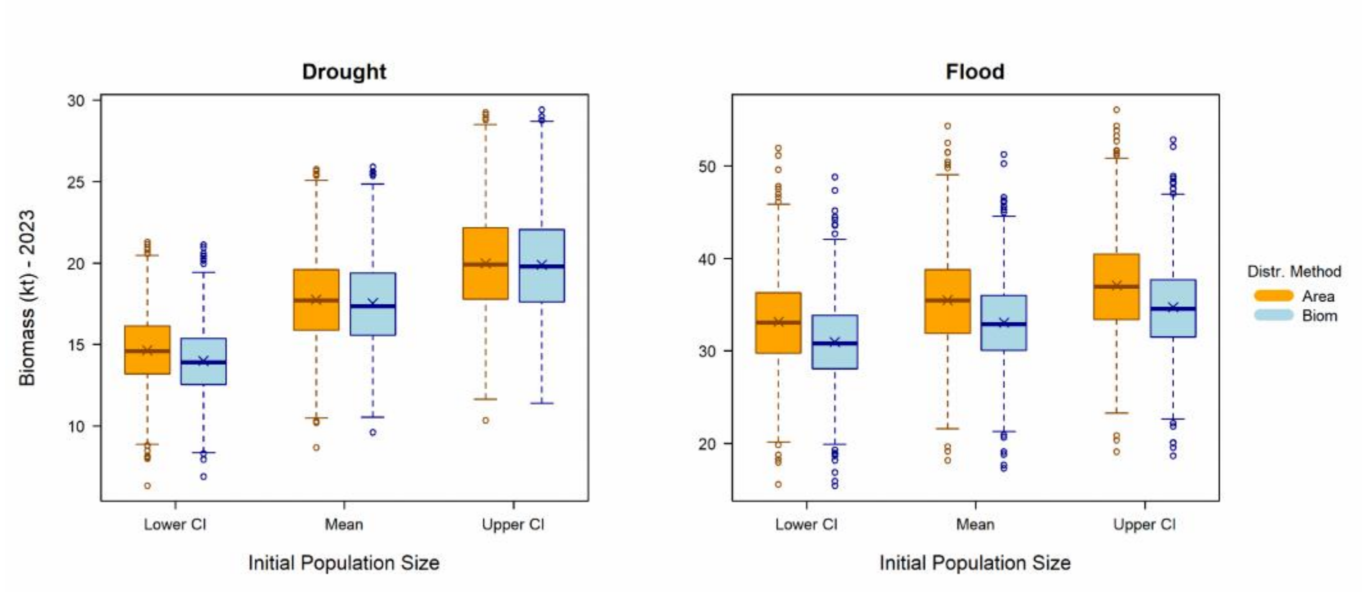


Figure 7. Regional differences in biomass estimates with differing initial population size under Drought and Flood scenarios. Note the different scales for biomass on the y axes.

The distribution of Carp densities, across eastern Australia for 2018 (from Stuart et al. 2019) and for 2023 under both Drought and Flood scenarios, is illustrated in Figure 8. The Carp density heat maps show minor decreases in density in the 2023 Drought scenario compared with the 2018 Stuart et al. (2019) static estimate, however, there are large increases in density in the 2023 Flood scenario compared with the 2018 estimate.

The highest Western Australia and irrigation channel estimates from Stuart et al. (2019) are included as separate biomass contributions and not added to the total in Tables 11 and 12. As Western Australian catchments were considered closest to those of the north coast in eastern Australia (NC) the highest biomass estimate (15 855 t) was multiplied by a factor of 1.7 (see below) for a Flood scenario to give a maximum estimate of 26 954 t. As flow in irrigation channels is determined by irrigation demand (which is partially independent of climate) and does not alter any other habitat values, the highest estimate of 3 510 t was used as a constant figure. Hence, maximum additional biomass from both Western Australia and irrigation channel could be considered to be 30 464 t.

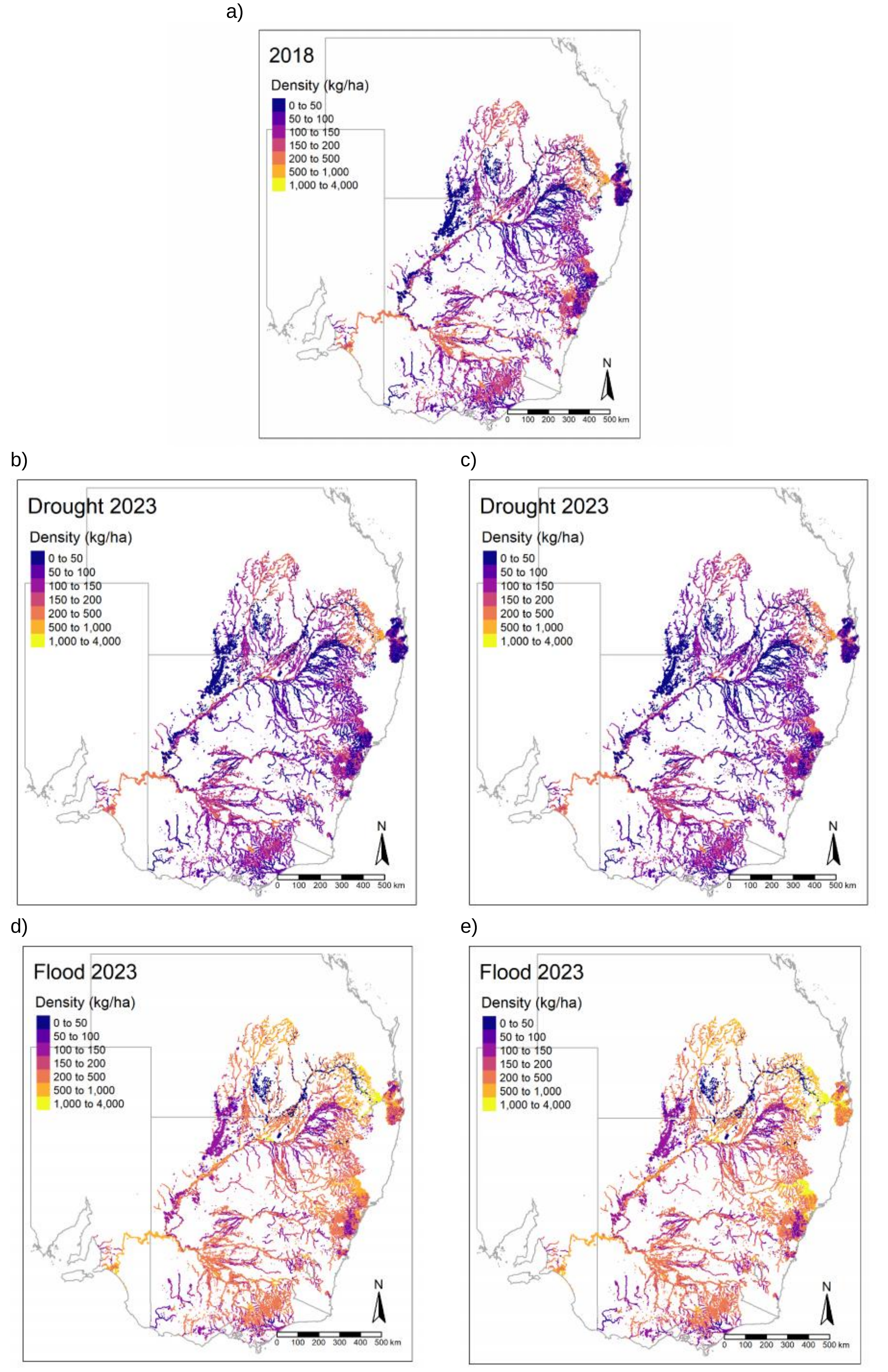


Figure 8. Carp density heat maps: a) 2018 Stuart et al. (2019) estimate; b) Drought scenario 2023 Area distribution method; c) Drought scenario 2023 Biom distribution method; d) Flood scenario 2023 Area distribution method; and e) Flood scenario 2023 Biom distribution method.

Discussion

This project has used a stochastic population model for Carp to provide projections of the variation in biomass estimates over time in relation to differing hydrological circumstances (Drought or Flood scenarios). Stuart et al. (2019) estimated the biomass of Carp in eastern Australia in May 2018 to be 205 774 tonnes (CI: 117 532, 356 482). Results from projecting this biomass estimate to the year 2023 demonstrate some substantial differences depending on the initial population biomass (Table 13). An additional biomass from Western Australia and irrigation channels could be considered to be a maximum of 30 464 t.

Table 13. Summary 2023 biomass (t) estimates (mean, and credible intervals) in eastern Australia for Drought and Flood scenarios (Area and Biom distribution methods) with different initial population biomass estimates (2018).

	Drought				**Flood**		
	Mean	**Lower CI**	**Upper CI**		**Mean**	**Lower CI**	**Upper CI**
2018 mean for both initial population and mean kg/carp biomass							
Area	172 895	124 369	219 815	Area	428 808	309 231	571 908
Biom	167 960	116 463	220 793	Biom	444 144	307 483	596 418
2018 lower CI for both initial population and mean kg/carp biomass							
Area	84 626	60 812	107 639	Area	208 450	153 759	269 947
Biom	82 153	57 310	107 704	Biom	209 117	150 121	271 304
2018 upper CI for both initial population and mean kg/carp biomass							
Area	331 336	237 249	420 442	Area	825 937	591 196	1 106 923
Biom	319 327	221 278	419 627	Biom	858 218	589 616	1 158 001

Carp populations vary widely, being strongly linked to hydrological conditions and increase substantially in response to flooding and access to favoured breeding habitats (floodplain and wetlands) (Koehn et al. 2016). It is not surprising therefore that the biomass predictions vary widely under the differing hydrological conditions, with much greater biomasses occurring following sequential flood years. Under the dry/average hydrological scenarios using the 2018 mean estimate as an initial population biomass, the Carp dynamic population model biomass estimate (Area: 172 895 tonnes, CI: 124 369, 219 815; Biom: 167 960 tonnes, CI: 116 463, 220 793) is broadly similar to the static point-in-time estimate for 2018 (205 774 tonnes; CI: 117 532, 356 482) (Stuart et al. 2019). By contrast, the dynamic Carp biomass estimate is much greater for the three consecutive flood year scenario (Area: 428 808 tonnes, CI: 309 231, 571 908; Biom: 444 144 tonnes, CI: 307 483, 596 418) which is higher than the single flood year of 2011 (368,357 tonnes; CI: 184,234, 705,630; Stuart et al. 2019). The underlying reasons for this divergence are twofold. Firstly, the two models use a different spatial structure, where the GIS layer for the dynamic model includes the floodplain for the flood scenario but not for the dry scenario. By contrast, the static model simply includes a single spatial layer for an abstract ‘average’ point-in-time. Secondly, the modelled consecutive flood scenarios represent a worst-case scenario where carp populations sequentially grow. In reality, three consecutive major floods across eastern Australia is an unlikely hydrological scenario and has seldom occurred within the gauged record (i.e. the 1970s floods). Hence, while the models provide a simulation of complex ecological/hydrological processes, it is actually the magnitude of biomass change that should be used to inform decisions rather than the specific modelled Carp tonnage.

The dynamic Carp population model provides a valuable resource from which to help evaluate the potential release of the Carp virus under the National Carp Control Program. We present a quantitative understanding of the location and magnitude of Carp biomasses across four broad spatial regions, for a range of flow scenarios. The resultant predicted population biomasses for 2023 differ considerably from the initial 2018 static estimate (Stuart et al. 2019). These estimates vary depending on the hydrological scenario (Drought or Flood), especially under flood conditions, and also for each region. In general, the Drought scenario produced about the same or slightly reduced biomasses. The Flood scenarios produced much higher biomasses in all regions with estimates using the Biom distribution method predicting the following population increases: NMDB ~x 2.8; SMDB ~x 2; NC ~x 8; and SC ~x 1.6. Collectively, the overall increase in Carp biomass from 2018 to 2023 with the Flood scenario would be about 240 Kt (~x 2.2). Taking into account the extremes of variation in initial population size (lower and upper CI), and variation in modelling outcomes (lower and upper CI), 2023 population biomasses could potentially vary from 82 153 (absolute best-case scenario) to 1 158 001 tonnes (absolute worst-case scenario) depending on hydrological conditions. Biomasses also change with populations over time (Figure 5), hence dynamic modelling can provide a more flexible approach for management, that can take into account intervening climatic or flow conditions. It is also important to note that with the Flood scenarios that adult numbers continue to increase immediately following a flood as the juveniles produced during the flood years develop in to adults.

For the NCCP, understanding the potential increase in Carp biomass during flood scenarios within each of these regions is essential to plan for a potential release of the Carp virus. Multiple wet year scenarios support a significantly greater Carp biomass than during average or dry years. A strength of the dynamic model is that it can be used to inform the NCCP at other future time points or under different hydrological scenarios. This dynamic type of modelling is an important step forward in Carp management as it provides managers with an up-to-date estimate of populations and the management task at hand. In the case of this project, and consideration for release of the Carp virus (McColl et al. 2014, 2016, 2018), it can highlight areas of highest biomasses and indicate the relative needs to management actions such as the clean up or impacts of large numbers of dead fish. Such estimates are also useful to inform other methods of Carp control (see Robert and Tilzey 1997; Koehn et al. 2000) and could be used to assess the range of other priority management actions that may be needed for this alien fish species (Koehn and MacKenzie 2004). While the predictions in this study are only over five years, such population fluctuations also occur over longer time frames (Koehn et al. 2016). Knowledge of such variations are important to inform management decisions as they provide evidence of the magnitude of the immediate issue at hand, but also provide indications of how populations may respond in the years following management actions.

For the NCCP it is important to note that population models invariably incorporate a range of assumptions. For instance, in the case of the dynamic Carp population model the spatial inputs are critical. We used a 1-in-20 year flood boundary whose area was treated as a uniform certainty but this is not the case in reality. Floods would be much more spatially and temporally variable than possible for us to accurately quantify in this project. In addition, we did not include other aquatic habitats (i.e. farm dams and irrigation channels) for which fish survey data are inadequate. We would have preferred to present biomass as a function of water volume, rather than area, but volume data do not presently exist. The static biomass estimate of Stuart et al. (2019) likely underestimated the juveniles less than one year old, because these fish are not efficiently collected in the field using standard survey methods (e.g. boat electrofishing), and this may have impacted on our results.

In order to address a complex life history that can function over large scales, and without constructing a complex model that would not be possible to parameterise, we made assumptions about the distribution of Carp and how they would utilise preferred spawning habitats. The proportional habitat areas method for distributing Carp (Area method: see Model summary) allows Carp to access different habitat types with Carp distributed to the habitat types simply based on area. This approach may not be entirely reasonable given it uses no information about known habitat preferences. The biomass method for distributing Carp (Biom distribution method: see Model summary) uses biomass distribution data from Stuart et al. (2019), estimated by habitat type for 2018, as a predictor of habitat utilisation for modelling Carp to the year 2023. In some instances, the Area distribution method generates higher estimates of Carp biomass in 2023 and in other instances the Biom distribution method generates higher estimates. To err on the side of caution, it may be prudent to use the largest estimate from either method (Tables 11 and 12).

Antecedent flow conditions are also known to be important for the future production of fishes and their recruitment into populations (Balcombe et al. 2006, 2010). The modelling undertaken also indicates that there are numerous sensitivities that will influence the outcomes. The outcomes are very sensitive to the initial population structure, where generally speaking a population structure dominated by adults (using *df* upper CI: Table 8) will generate higher biomass estimates in all regions and hydrological scenarios (Figure 5; Upper CI). This corresponds with having a larger adult population and therefore a large spawning stock (Figure A4.5 and A4.6). Conversely a population dominated by juveniles (using *df* lower CI: Table 8) will generate comparatively lower biomass estimates in all regions and hydrological scenarios (Figure 5; Lower CI). The outcomes are also sensitive to the initial population biomass. When using either the lower CI or the upper CI biomass estimate (Table 9) to initialise the population model, the outcomes vary. The combination of initial population size and initial population structure produces the greatest variation in outcomes (see Tables A5.1-A5.4). If the 2018 or 2011 static biomass estimates (Stuart et al. 2019) are considered underestimates, then it may be more prudent to use the generated biomass for 2023 based on the upper CI initial population size. However, if these static biomass estimates (Stuart et al. 2019) are considered overestimates then it may be more prudent to use the generated biomass for 2023 based on the lower CI initial population size.

As population models are based on life stages and age classes together with the number of individuals in each, data on these life stages are important for improved accuracy of population predictions. Hence the collection of data in these categories (age, length, weight, abundance) is important in future sampling regimes to ameliorate some of the parameter assumptions that were necessary in both this project and that of Stuart et al. (2019). The examination of existing population structure also highlights the reality that population processes function through individual numbers of fish, and numerical abundances rather than biomass should be the monitoring measure, with biomasses calculated as a conversion as a second step.

This project has provided a range of estimates for the biomass of Carp for 2023 for four regions of eastern Australia by utilising the 2018 point-in-time estimate (Stuart et al. 2019). It highlights the variability of populations with differing hydrological and ecological conditions and provides updated estimates to assist with risk and management planning, including clean-up. There may be a need for further estimates beyond 2023 and this is possible through supplementary use of the population model. The differences evident between the regions highlight the usefulness of modelling scenarios at a finer spatial scale, including the case studies suggested in Appendix 1. Modelling could also be used to explore the impacts of climate change scenarios (Balcombe et al. 2011), which may produce differing hydrological regimes. Additional modelling can also be undertaken to predict the likely response of populations in relation to hydrological conditions following the release of the virus and knock-down of populations.

References

Bajer P.G., and Sorensen P.W. (2012). Using boat electrofishing to estimate the abundance of invasive common Carp in small Midwestern lakes. *North American Journal of Fisheries Management* **32,** 817-822.

Balcombe, S.R., Arthington, A.H., and Sternberg, D. (2014) Fish body condition and recruitment responses to antecedent flows in dryland rivers are species and river specific. *River Research and Applications* **30,** 1257-1268.

Balcombe, S.R., Arthington, A.H., Foster, N.D., Thoms, M.C., Wilson, G.A., and Bunn, S.E. (2006) Fish assemblages of an Australian dryland river: abundance, assemblage structure and recruitment patterns in the Warrego River, Murray-Darling Basin. *Marine and Freshwater Research* **57,** 619-633.

Balcombe, S.R., Sheldon F., Capon S.J., Bond N.R., Hadwen W.L., Marsh N., and Bernays S.J. (2011) Climate-change threats to native fish in degraded rivers and floodplains of the Murray-Darling Basin, Australia. *Marine and Freshwater Research* **62,** 1099-114.

Chen, Y., Cuddy, S.M., Merrin, L.E., Huang, C., Pollock, D., Sims, N., Wang, B., and Bai, Q. (2012). Murray-Darling Basin Floodplain Inundation Model Version 2.0 (MDB-FIM2). Technical Report. CSIRO Water for a Healthy Country Flagship, Australia

Conallin, A.J., Smith, B.B., Thwaites, L.A., Walker, K.F. and Gillanders, B.M. (2016). Exploiting the innate behaviour of common Carp, *Cyprinus Carpio*, to limit invasion and spawning in wetlands of the River Murray, Australia. *Fisheries Management and Ecology* **23**, 431-449.

Driver, P.D., Harris, J.H., Closs, G.P., and Koen, T.B., (2005). Effects of flow regulation on Carp (*Cyprinus Carpio* L.) recruitment in the Murray–Darling Basin, Australia. *River Research and Applications* **21,** 327-335.

Farrier, S. M., Brashers, Z., and Koupal, K.D. (2018). Assessment of common Carp biomass in Rat and Beaver lake. *Great Plains Research* **28,** 65-72.

Gilligan, D., Jess, L., McLean, G., Asmus, M., Wooden, I., Hartwell, D., McGregor, C., Stuart, I., Vey, A., Jefferies, M., and Lewis, B. (2010). Identifying and implementing targeted Carp control options for the Lower Lachlan Catchment. Fisheries Final Report Series 118.

Hillyard, K.A., Smith, B.B., Conallin, A.J., and Gillanders, B.M. (2010). Optimising exclusion screens to control exotic Carp in an Australian lowland river. *Marine and Freshwater Research* **61,** 418-429.

Koehn, J.D. (2004). Carp (*Cyprinus Carpio*) as a powerful invader in Australian waterways. *Freshwater Biology* **49**, 882-894.

Koehn, J.D., Brumley, A.R. and Gehrke, P. (2000). *Managing the Impacts of Carp.* Bureau of Rural Resources, Canberra, Australia.

Koehn, J.D., and MacKenzie, R.F. (2004) Priority management actions for alien freshwater fish species in Australia. *New Zealand Journal of Marine and Freshwater Research* **38,** 457-472.

Koehn, J. D., and Todd, C.R. (2012). Balancing conservation and recreational fishery objectives for a threatened species, the Murray cod, *Maccullochella peelii*. *Fisheries Management and Ecology* **19,** 410-425.

Koehn, J.D., Todd, C.R., Zampatti, B.P., Stuart, I.G., Conallin, A., Thwaites, L. and Ye, Q. (2018). Using a population model to inform the management of river flows and invasive Carp (*Cyprinus Carpio*). *Environmental Management* **61,** 432–442.

Koehn, J., Todd, C., Thwaites, L., Stuart, I., Zampatti, B., Ye, Q., Conallin, A., Dodd, L., and Stamation, K. (2016). Managing Flows and Carp. Arthur Rylah Institute for Environmental Research Technical Report Series No. 255. Department of Environment, Land, Water and Planning, Heidelberg, Victoria.

Koehn, J.D., Todd, C.R., Balcombe S.R., and Raymond S. (2015). Applicability of an Existing Carp Population Model to the Northern Murray-Darling Basin. Arthur Rylah Institute for Environmental Research. Unpublished Client Report for the Murray-Darling Basin Authority. Department of Environment, Land, Water and Planning. Department of Environment, Land, Water and Planning, Heidelberg, Victoria.

McColl, K.A., Cooke, B.D., and Sunarto, A. (2014). Viral biocontrol of invasive vertebrates: lessons from the past applied to cyprinid herpesvirus3 and Carp (*Cyprinus Carpio*) control in Australia. *Biological Control* **72**,109–117.

McColl, K.A., Sunarto, A., and Holmes, E.C. (2016). Cyprinid herpesvirus 3 and its evolutionary future as a biological control agent for Carp in Australia. *Virology journal* **13(1)**, 206.

McColl, K.A., Sunarto, A., and Neave, M.J. (2018). Biocontrol of Carp: more than just a herpesvirus. *Frontiers in Microbiology* **9**, 2288.

MDBA. (2018). Murray-Darling Basin mapped floodplain extent (1 in 100), BWS Layers.

Mueller, N., Lewis, A., Roberts, D., Ring, S., Melrose, R., Sixsmith, J., Lymburner, L., McIntyre, A., Tan, P., Curnow, S., and Ip, A. (2016). Water observations from space: Mapping surface water from 25 years of Landsat imagery across Australia. Remote Sensing of Environment 174, 341–352.

Overton, I.C., McEwan, K., Gabrovsek, C., and Sherrah, J.R. (2006). The River Murray Floodplain Inundation Model (RiM-FIM): Hume Dam to Wellington.

Roberts, J. and Tilzey, R. (Eds) (1997). *Controlling Carp in Australia. Proceedings of a Workshop*, *22-24 October 1996.* CSIRO, DPIE, MDBC, Canberra.

Stuart, I., Fanson, B., Lyon, J., Stocks, J., Brooks, S., Norris, A., Thwaites, L., Beitzel, M., Hutchison, M., Ye, Q., Koehn, J., Marshall J., and Bennett A. (2019). A national Carp biomass estimate for Australia. Unpublished Client Report for the Fisheries Research and Development Corporation. Arthur Rylah Institute for Environmental Research, Department of Environment, Land, Water and Planning, Heidelberg, Victoria.

Thwaites, L., Smith, B., Decelis, M., Fleer, D., and Conallin, A. (2010). A novel push trap element to manage Carp (*Cyprinus Carpio* L.): a laboratory trial. *Marine and Freshwater Research* **61**, 42–48.

Todd, C.R., and Lintermans, M. (2015). Who do you move? A stochastic population model to guide translocation strategies for an endangered freshwater fish in south-eastern Australia. Ecological Modelling, **311,** 63–72.

Todd, C.R., and Lovelace, P.R. 2017. Essential version 2.20. Retrieved from https://www.ari.vic.gov.au/__data/assets/file/0021/57522/Essential-Install-2017.zip

Appendices

Appendix 1. Habitat types and life stage survival rates used for Carp scenario modelling for the SMDB (Koehn et al. 2016).

Appendix 1.1. Description of habitat types used for Carp scenario modelling for the SMDB (Koehn et al 2016).

No.	Habitat type	Description
H1	Main Channel (Mid Upper Murray)—base flow	Low level not topped up by irrigation flows <50% bankfull. Only occurs during severe drought
H2	Main Channel (Mid Upper Murray)—cover benches	50–70% bankfull irrigation flow
H3	Main Channel (Mid Upper Murray)—bankfull	70% to bankfull irrigation flow
H4	Main Channel (Lower Murray)—base flow	Weir pools at operating height, low flows
H5	Main Channel (Lower Murray)—cover benches	Increase weir pool extent/influence (entitlement + irrigation flows + weir pools)
H6	River Wetland, e.g. Barmah–Millewa	Adjacent low-lying wetlands (without broader floodplain inundation)
H7	Wetland Perennial, e.g. Kow Swamp	E.g. Barren Box Swamp. Off-stream wetlands with permanent water
H8	Wetland Ephemeral, e.g. Hattah Lakes	Off-stream wetlands, high elevation wetlands dry out if not reconnected
H9	Wetland permanently connected, e.g. adjacent weir pool	Wetlands now inundated permanently because of the weir pools follow weir pool dynamics, e.g. all unregulated weir pool wetlands in Lower Murray
H10	Natural floodplain inundation	Broad floodplain inundation (as per high-level natural flood)
H11	Artificial floodplain inundation, e.g. Chowilla	Inundated by regulators
H12	Lakes (off-stream), e.g. Lake Victoria	Lakes Victoria, Cargelligo; permanent water bodies
H13	Lakes (terminal), e.g. Alexandrina	Permanent water bodies at the end of the system
H14	Irrigation channels	High flow in irrigation season, then mostly dry/residual pools

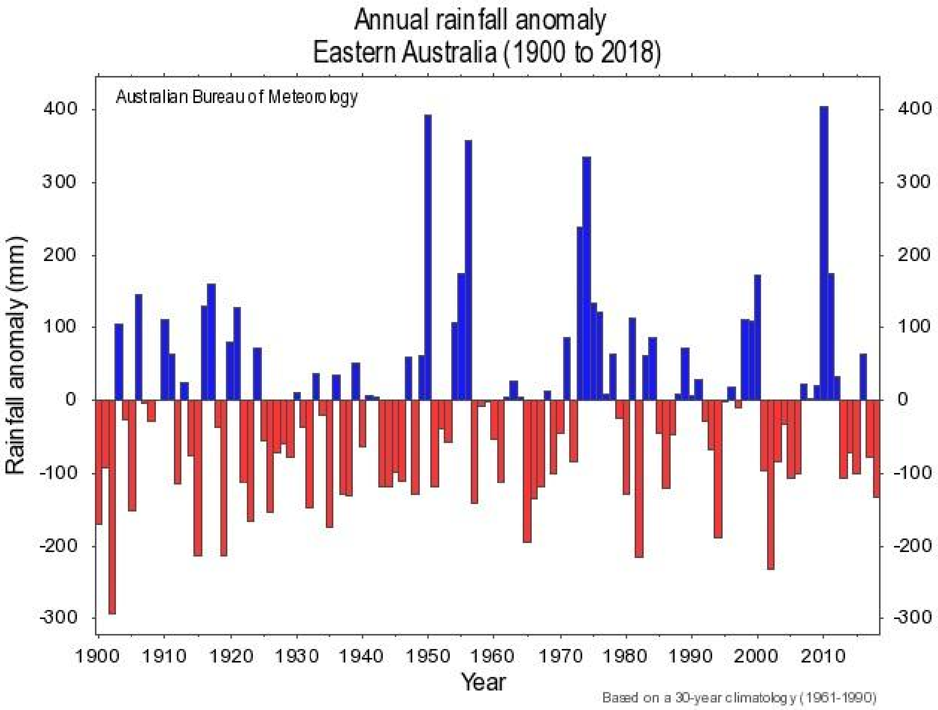
Appendix 1.2. Percentage survival elicited for each life stage and habitat type and the associated population growth rate (Koehn 2016).

Habitat	Egg survival (%)	Larval survival (%)	Fingerling survival (%)	Young-of-the-year survival (%)	Population growth rate	Population doubling time
H1	0.72	1.82	3.31	6.31	0.77	–
H2	1.36	3.84	5.88	7.25	0.88	–
H3	2.45	5.24	6.89	11.00	1.02	35.00
H4	1.50	2.83	5.25	8.15	0.86	–
H5	2.69	5.24	7.36	12.01	1.06	11.90
H6	12.07	10.00	21.41	15.50	2.43	0.78
H7	4.68	7.10	14.84	14.76	1.52	1.66
H8	7.96	5.70	16.83	7.96	1.46	1.83
H9	6.45	6.54	14.84	21.12	1.78	1.20
H10	10.90	8.15	20.31	21.39	2.41	0.79
H11	12.19	11.65	13.51	26.31	2.60	0.73
H12	5.21	5.91	13.09	13.69	1.42	1.98
H13	6.37	7.52	15.03	17.05	1.74	1.25
H14	0.71	2.20	6.70	5.65	0.80	–

Appendix 2. Hydrological scenarios suggested to be modelled as case studies following this project.

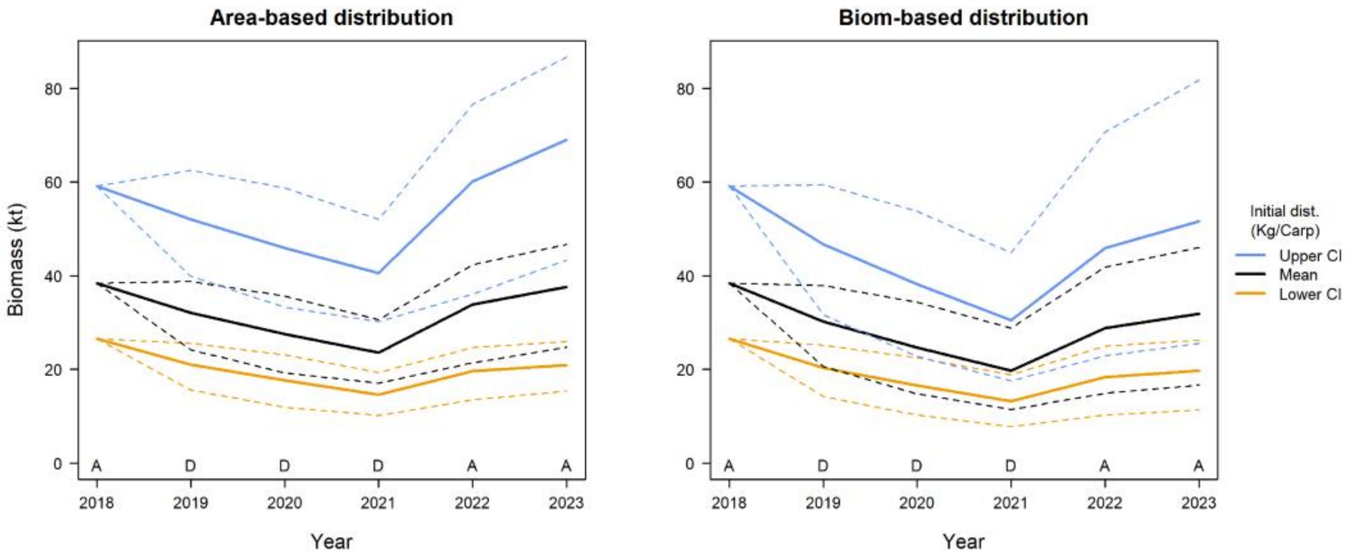
Scenario	Lachlan river	Riverlands (Lock 1 to Lock 3)	Gippsland Lakes
Scenario 1 (worst case)	3 wet (flood) years, full wetland inundation, followed by 2 ‘average’ years	3 wet (flood) years, full wetland inundation, followed by 2 ‘average’ years	3 wet (flood) years, full wetland inundation, followed by 2 ‘average’ years
Scenario 2 (best case)	3 dry (drought) years, followed by 2 ‘average’ years	3 dry (drought) years, followed by 2 ‘average’ years	3 dry (drought) years, followed by 2 ‘average’ years

Appendix 3. Bureau of Meteorology annual rainfall anomaly for eastern Australia 1900 to 2018 indicating dry and wet periods.

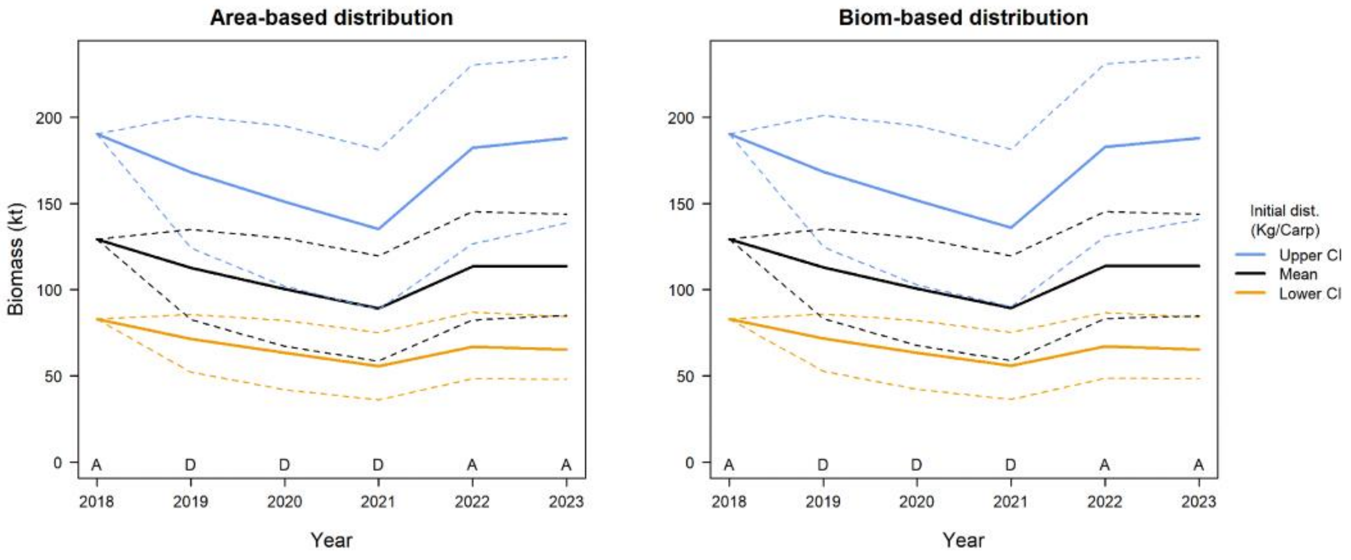


Appendix 4. Estimates of biomass and total carp numbers through time with differing initial population structure under Drought and Flood hydrological scenarios for each region.

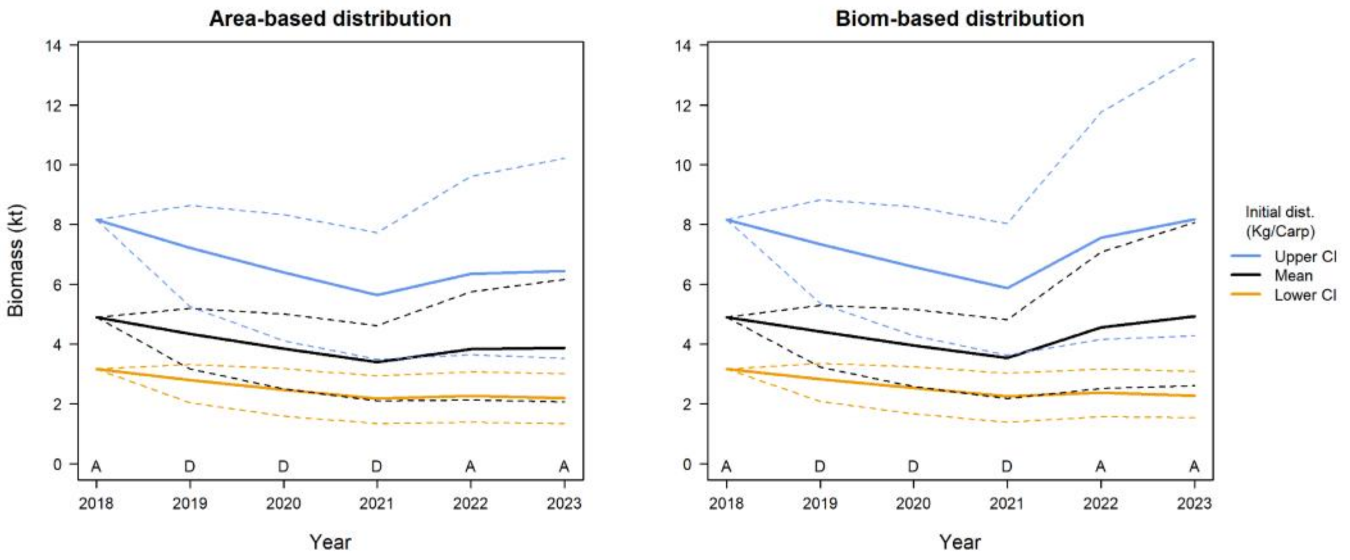
a) NMDB



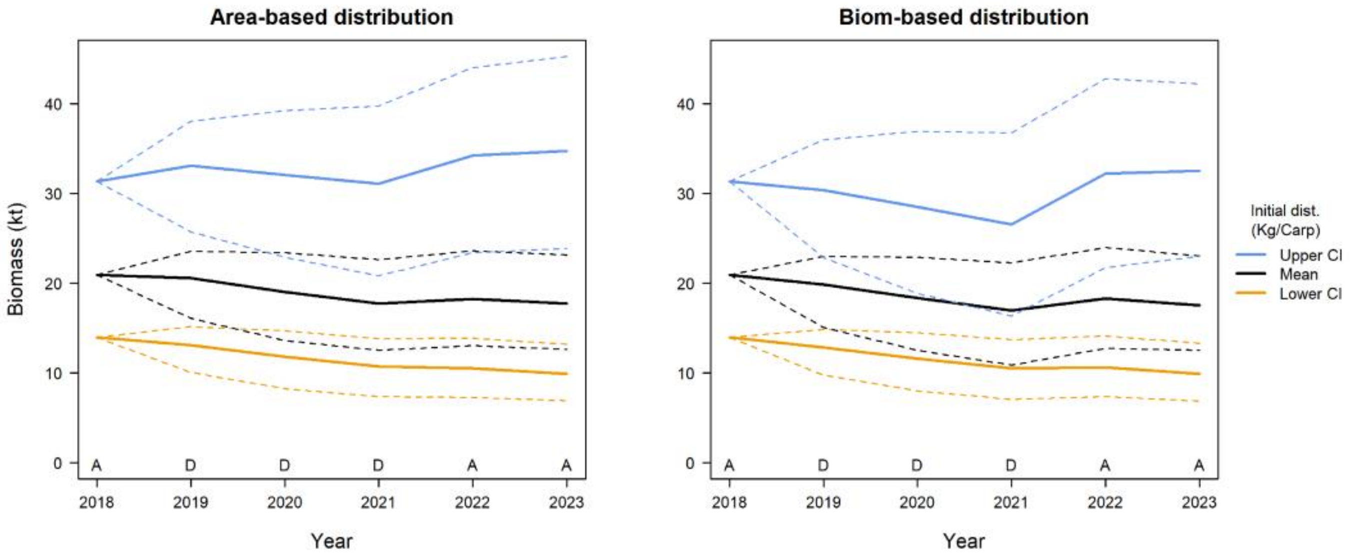
b) SMDB



c) NC

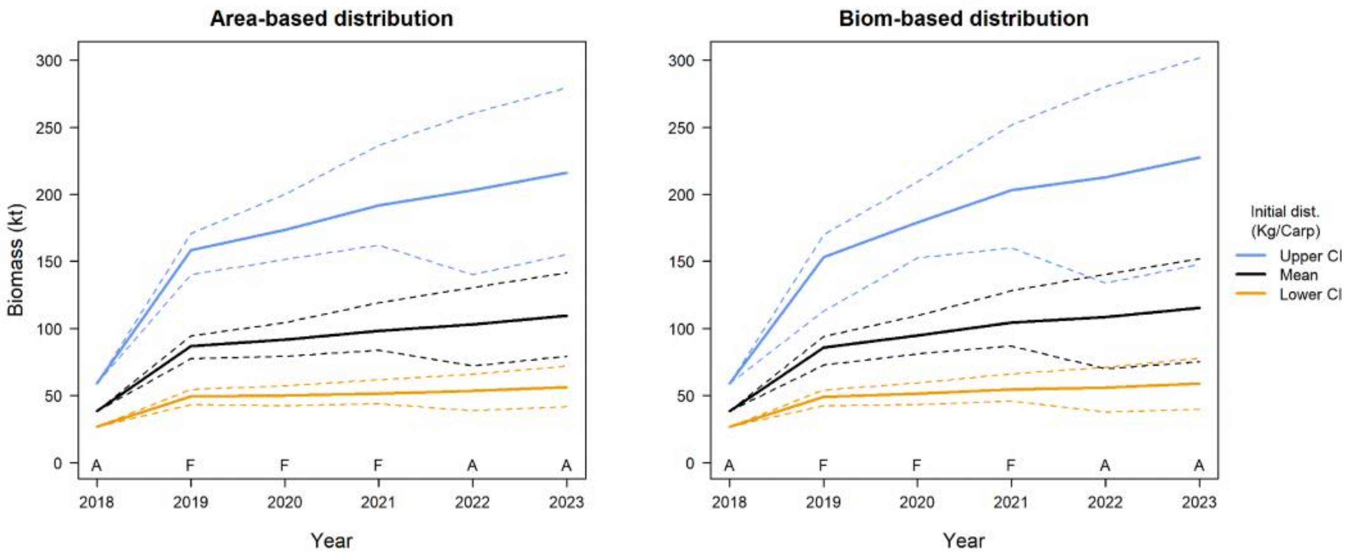


d) SC

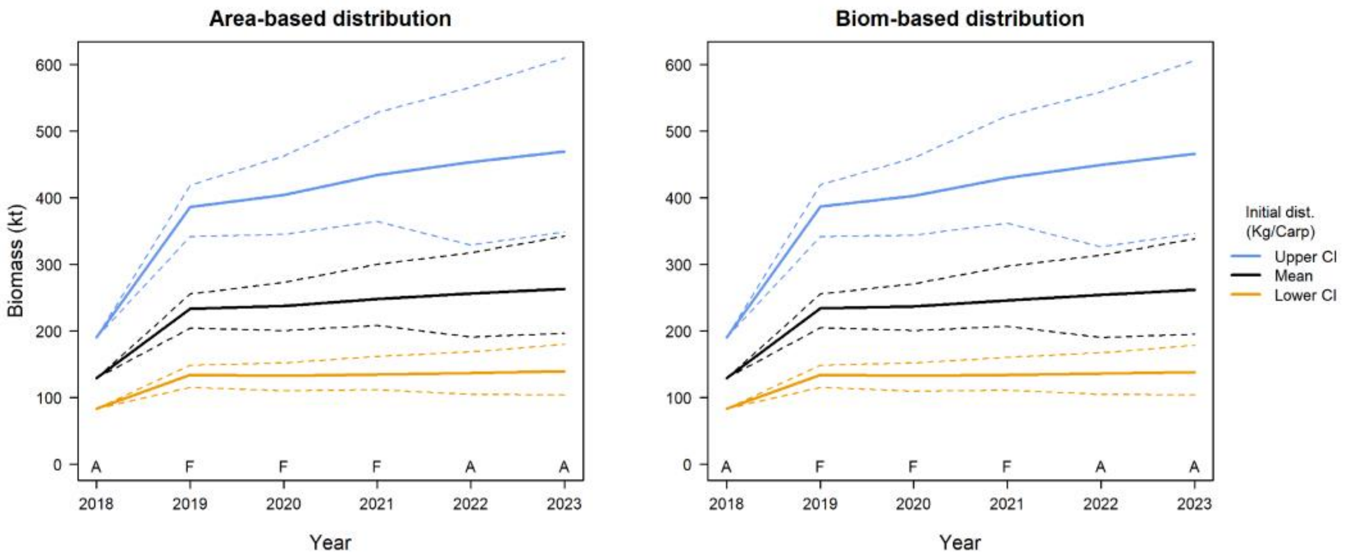


Appendix 4.1. Regional differences in biomass estimates through time with differing initial population structure under the Drought scenario. Note the different scales for biomass on the y axes.

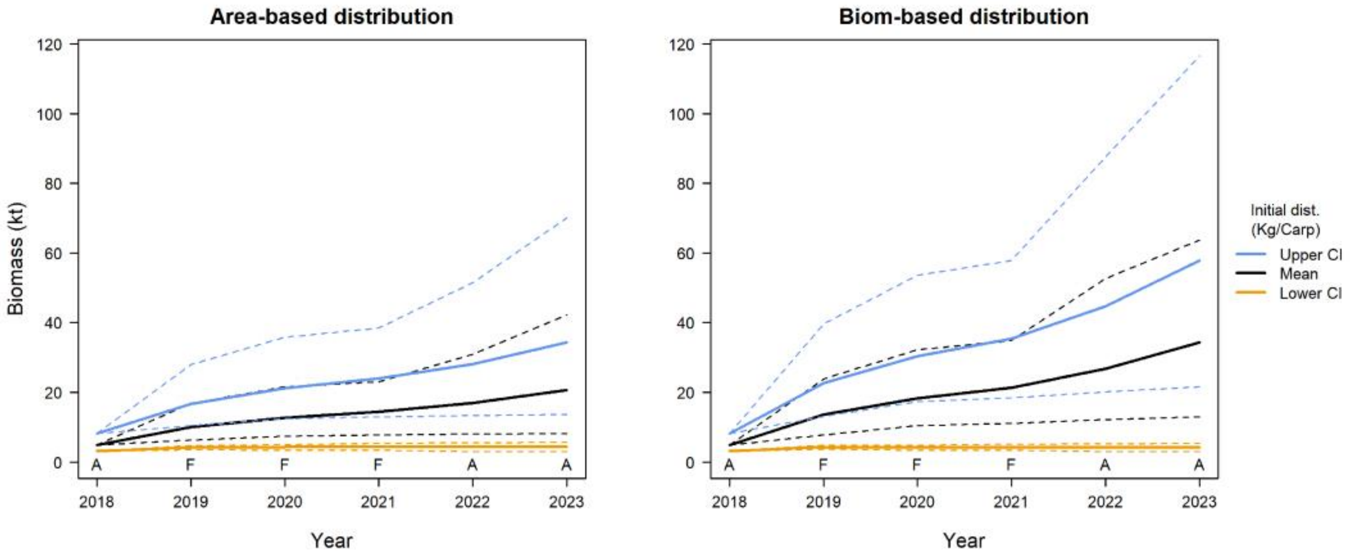
a) NMDB



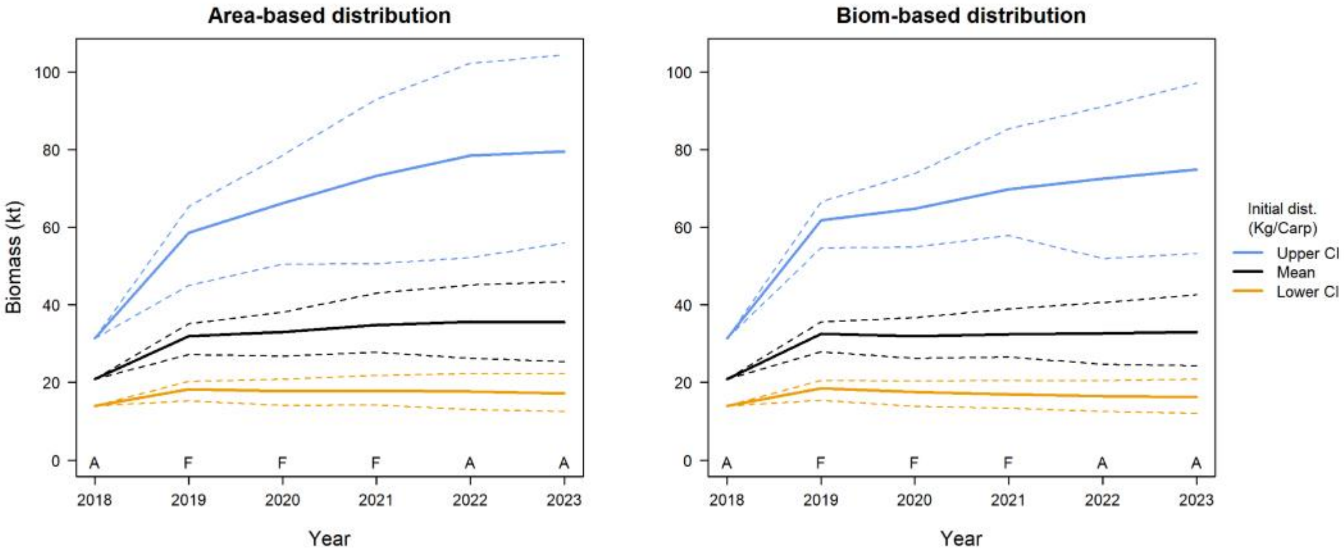
b) SMDB



c) NC

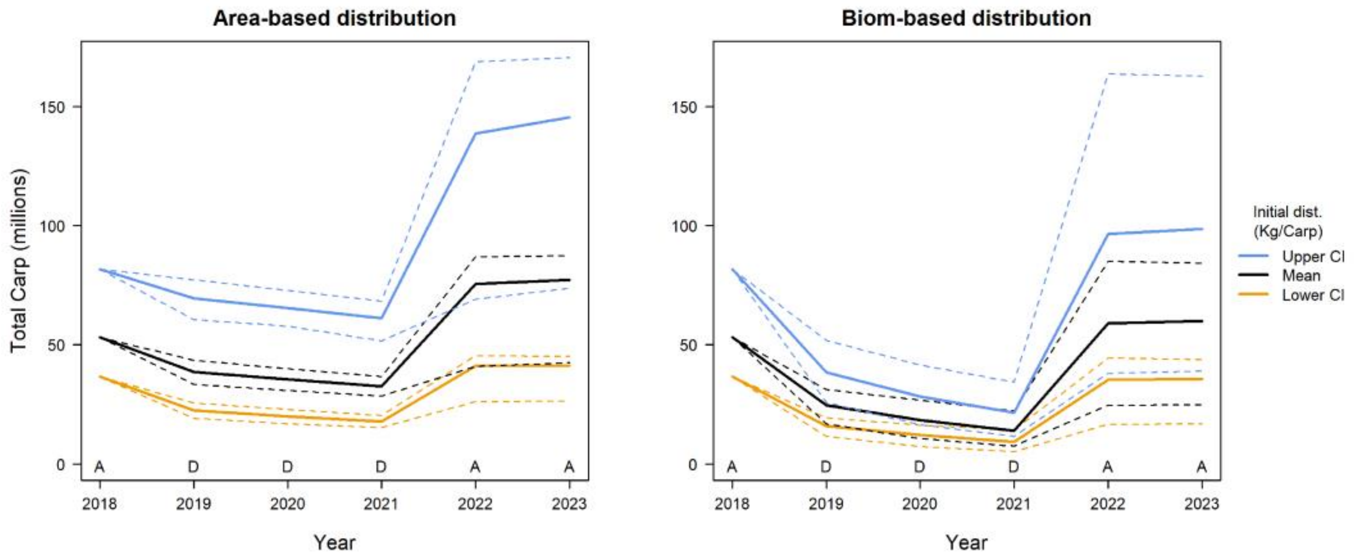


d) SC

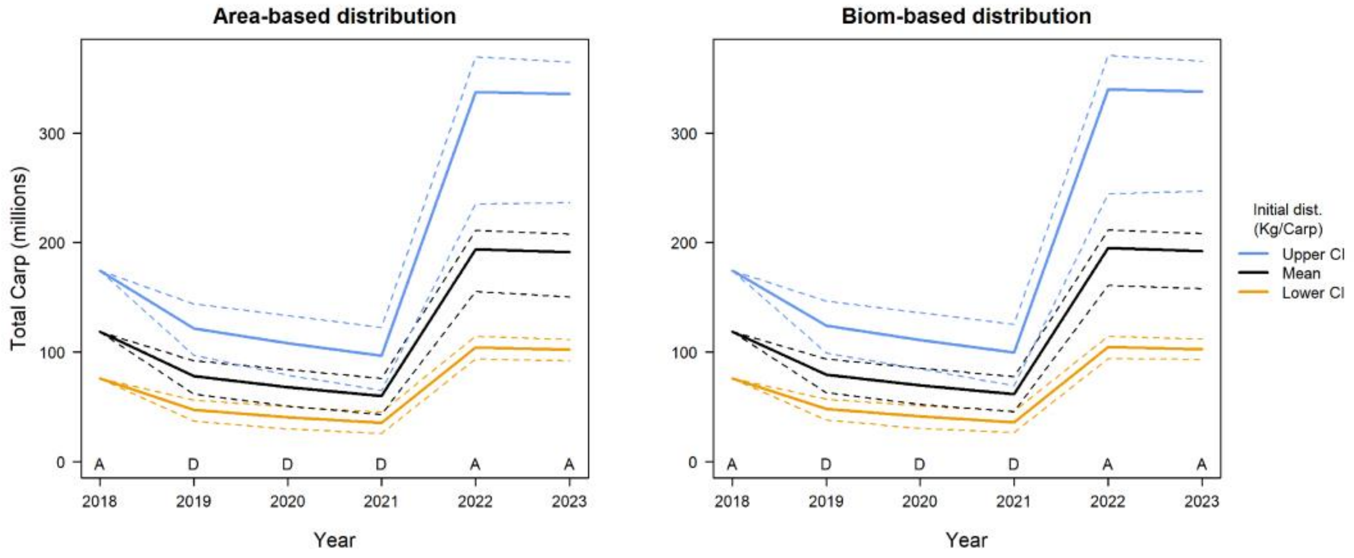


Appendix 4.2. Regional differences in biomass estimates through time with differing initial population structure under the Flood scenario. Note the different scales for biomass on the y axes.

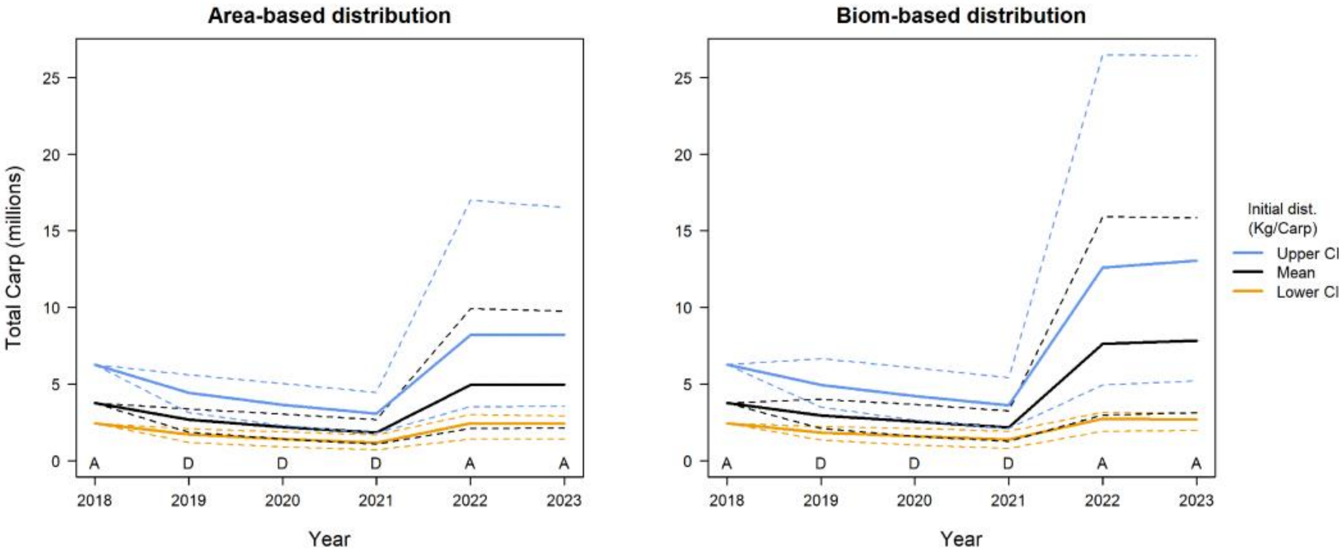
a) NMDB


Area-based distribution
Biom-based distribution
Total Carp (millions)
0
50
100
150
A
D
D
D
A
A
2018
2019
2020
2021
2022
2023
Year
Initial dist.
(Kg/Carp)
Upper CI
Mean
Lower CI

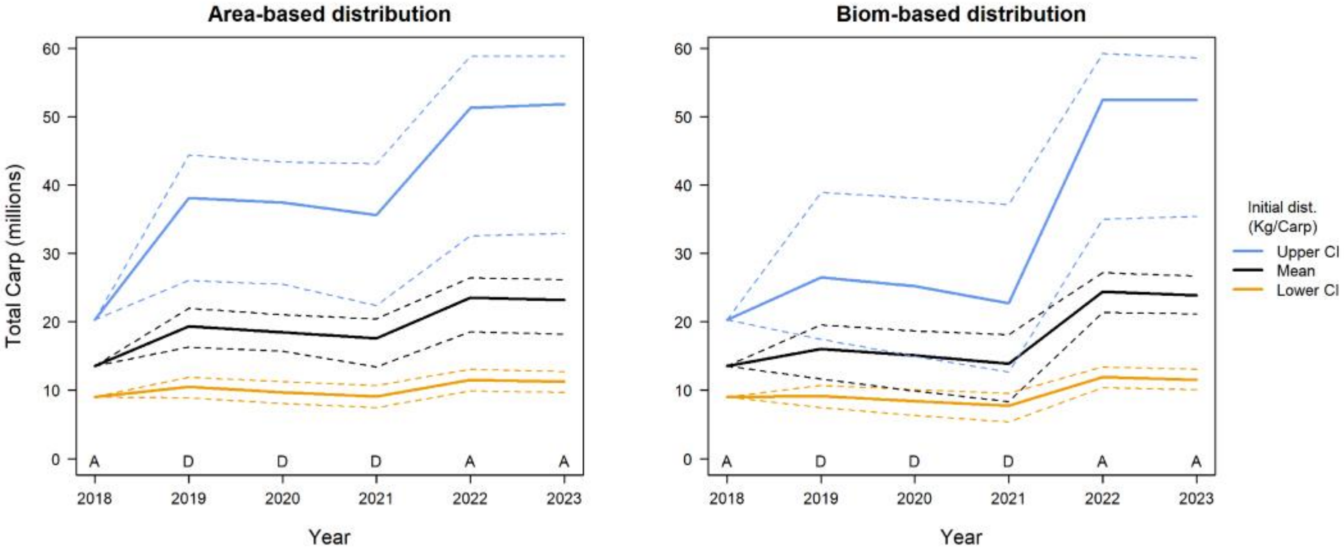
b) SMDB


Area-based distribution
Biom-based distribution
Total Carp (millions)
0
100
200
300
A
D
D
D
A
A
2018
2019
2020
2021
2022
2023
Year
Initial dist.
(Kg/Carp)
Upper CI
Mean
Lower CI

c) NC

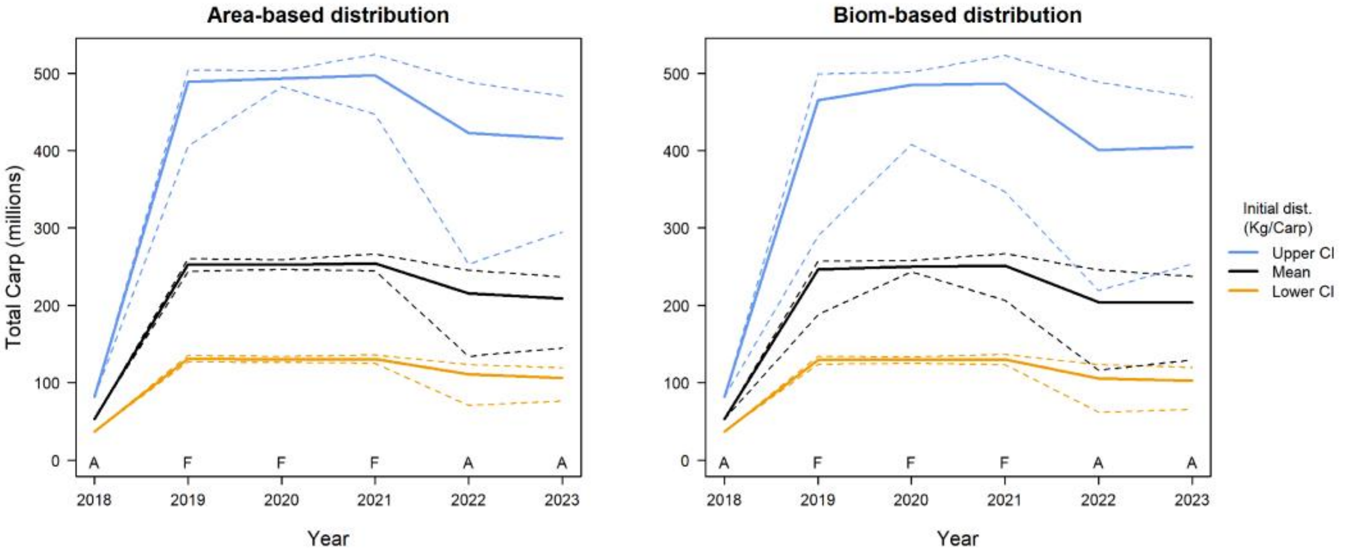


d) SC

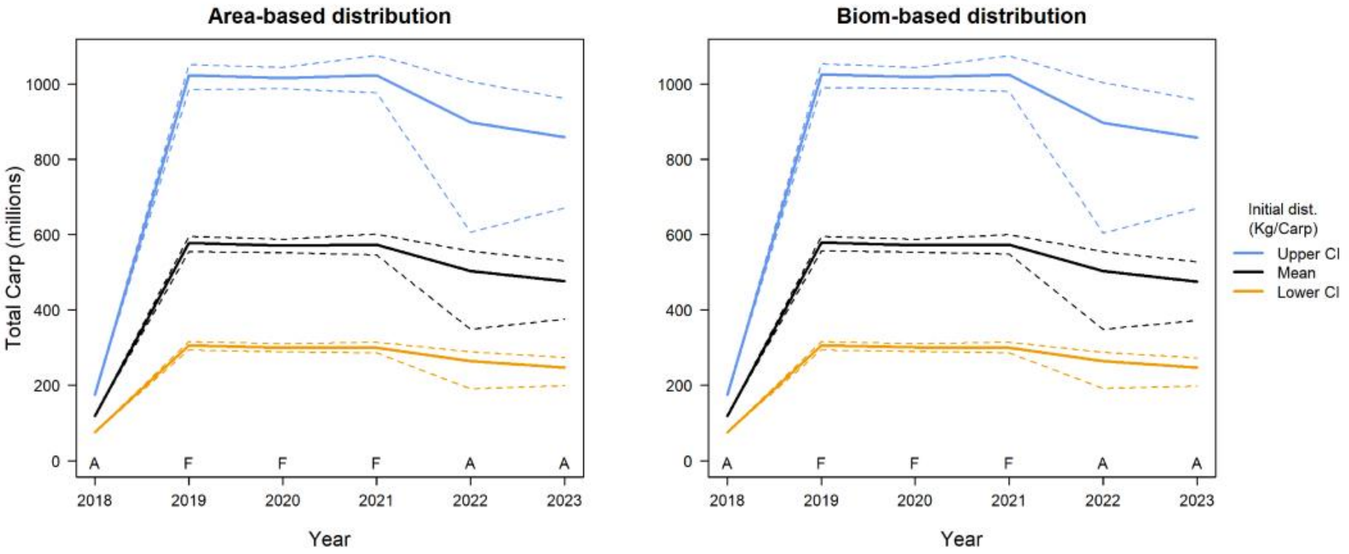


Appendix 4.3. Regional differences in total Carp numbers through time with differing initial population structure under the Drought scenario. Note the different scales for total Carp on the y axes.

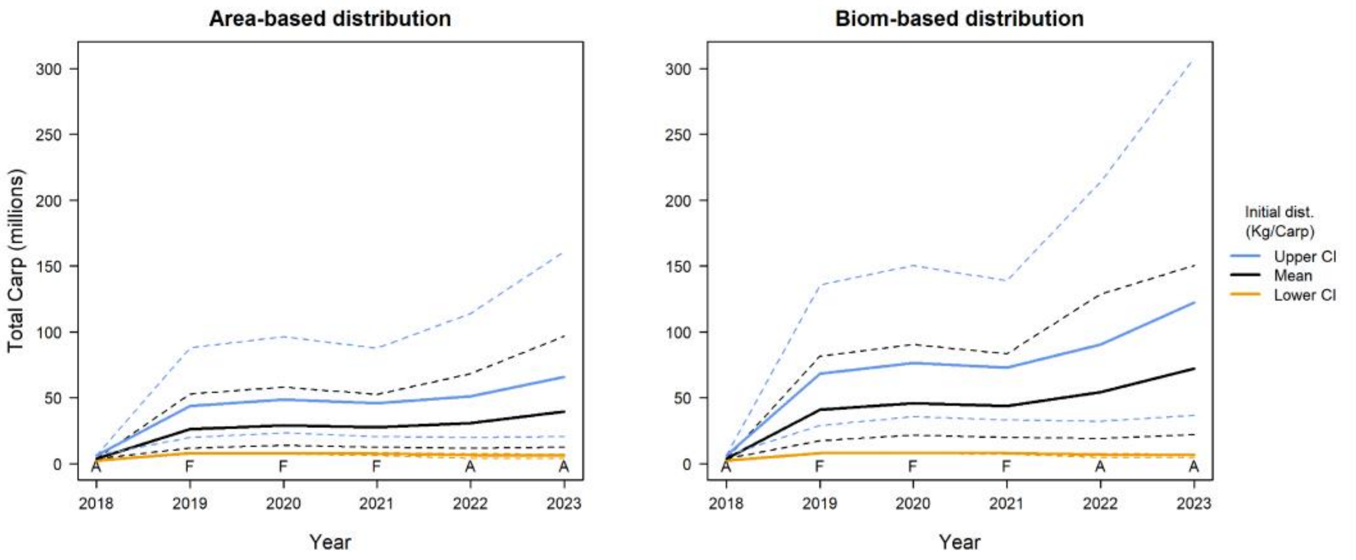
a) NMDB


Area-based distribution
Biom-based distribution
Total Carp (millions)
0
100
200
300
400
500
A
F
F
F
A
A
2018
2019
2020
2021
2022
2023
Year
Initial dist.
(Kg/Carp)
Upper CI
Mean
Lower CI

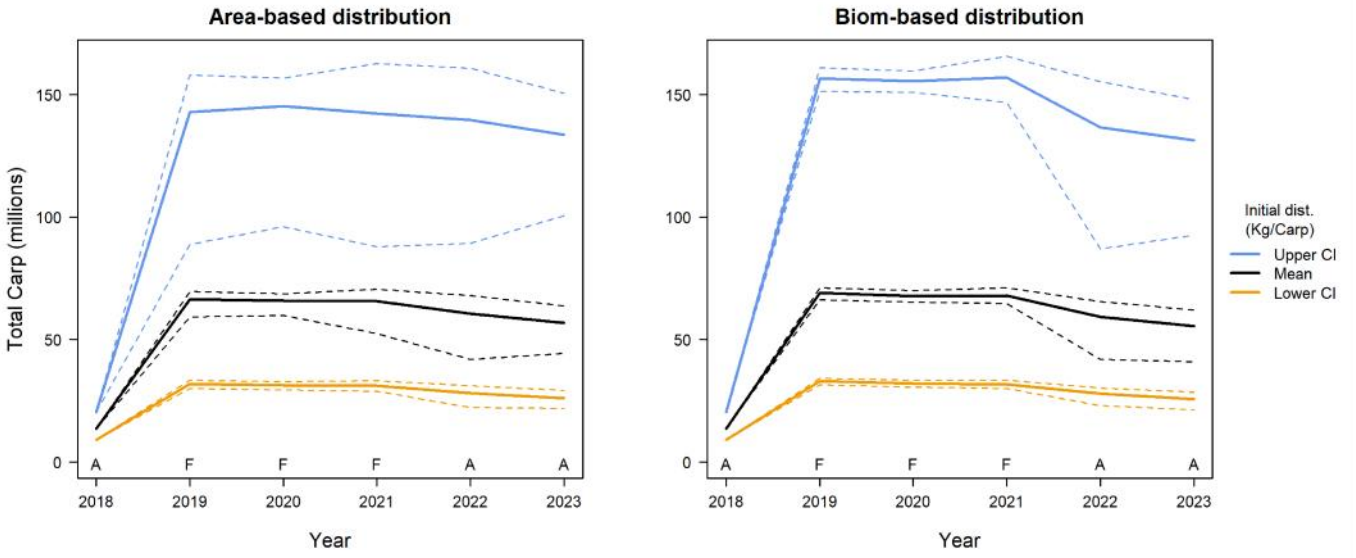
b) SMDB


Area-based distribution
Biom-based distribution
Total Carp (millions)
0
200
400
600
800
1000
A
F
F
F
A
A
2018
2019
2020
2021
2022
2023
Year
Initial dist.
(Kg/Carp)
Upper CI
Mean
Lower CI

c) NC

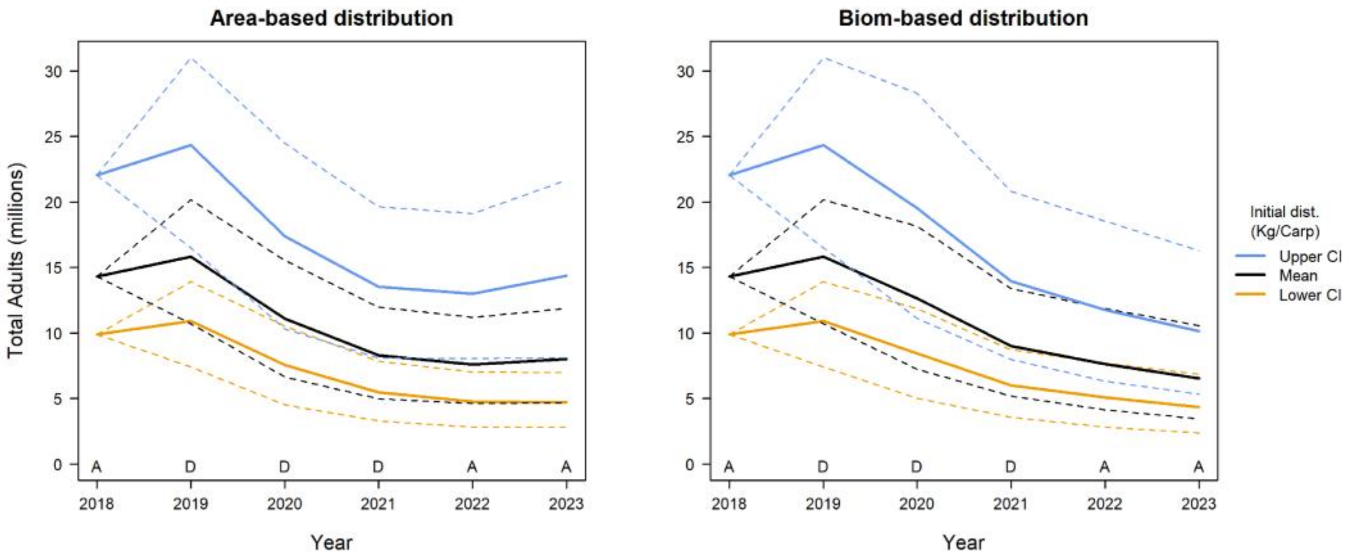


d) SC

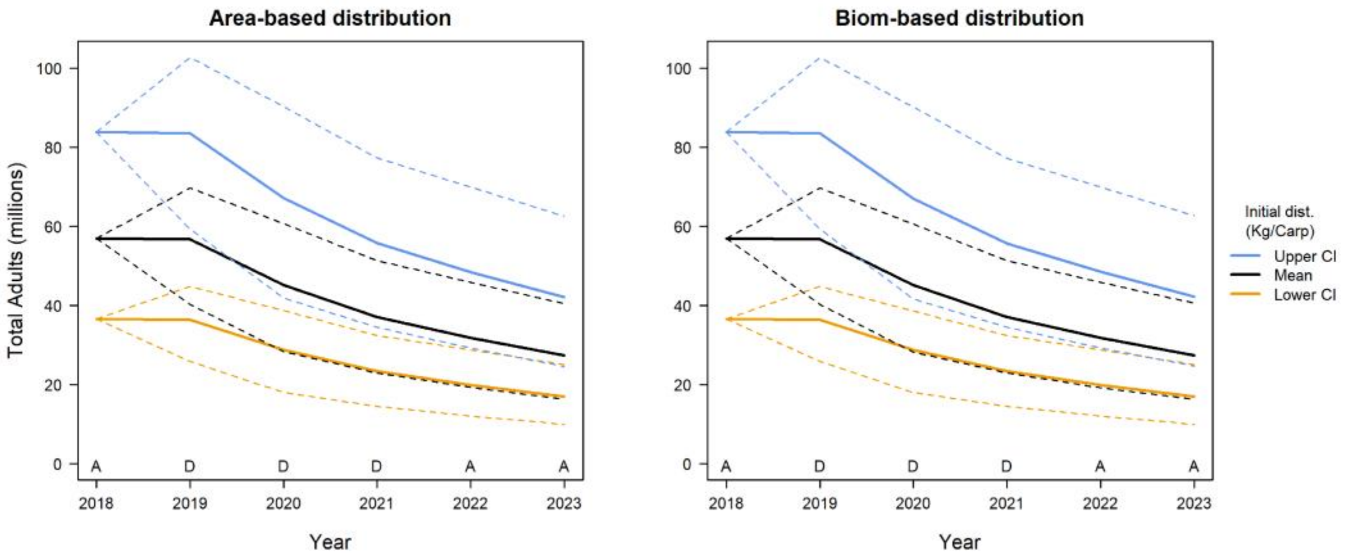


Appendix 4.4. Regional differences in total Carp numbers through time with differing initial population structure under the Flood scenario. Note the different scales for total Carp on the y axes.

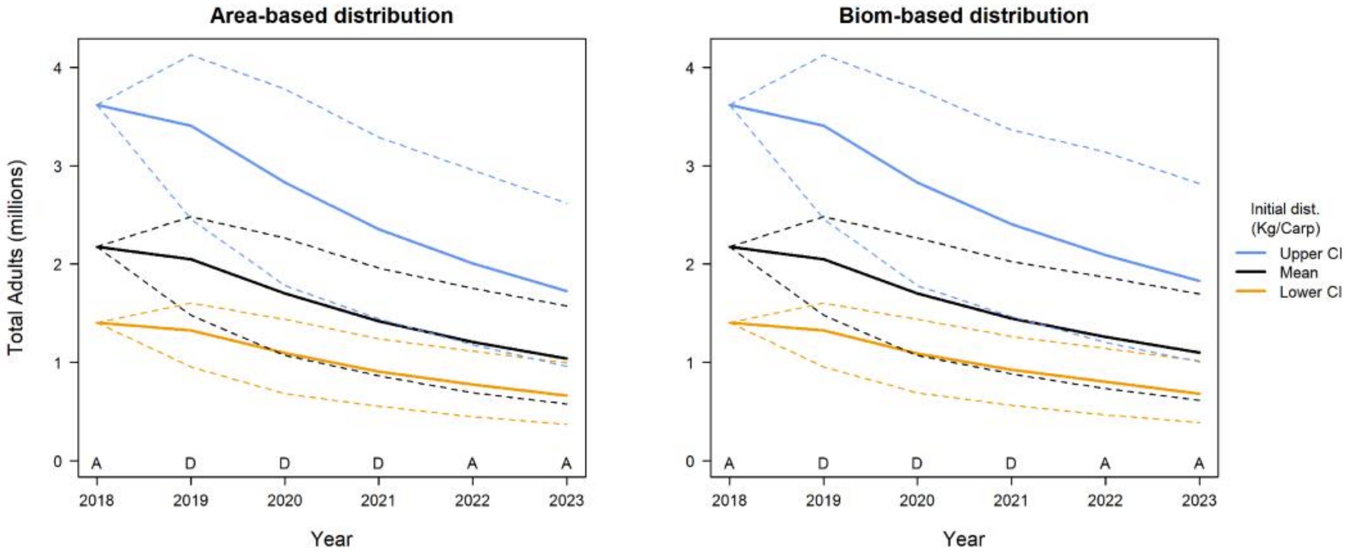
a) NMDB


Area-based distribution
Biom-based distribution
Total Adults (millions)
0
5
10
15
20
25
30
A
D
D
D
A
A
2018
2019
2020
2021
2022
2023
Year
Initial dist.
(Kg/Carp)
Upper CI
Mean
Lower CI

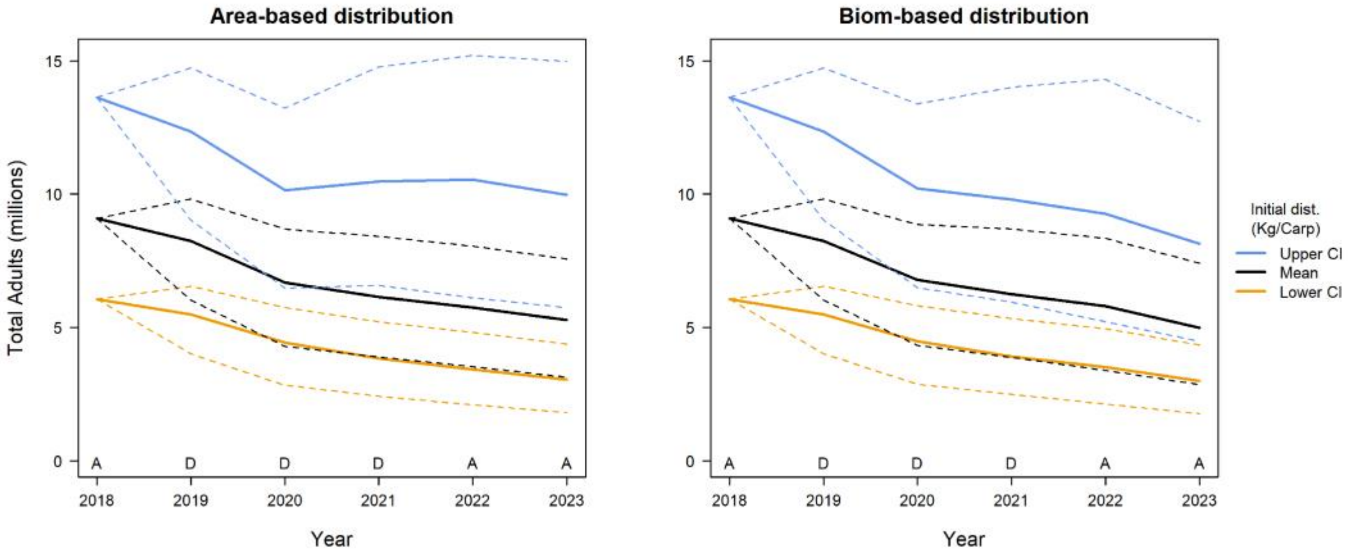
b) SMDB


Area-based distribution
Biom-based distribution
Total Adults (millions)
0
20
40
60
80
100
A
D
D
D
A
A
2018
2019
2020
2021
2022
2023
Year
Initial dist.
(Kg/Carp)
Upper CI
Mean
Lower CI

c) NC

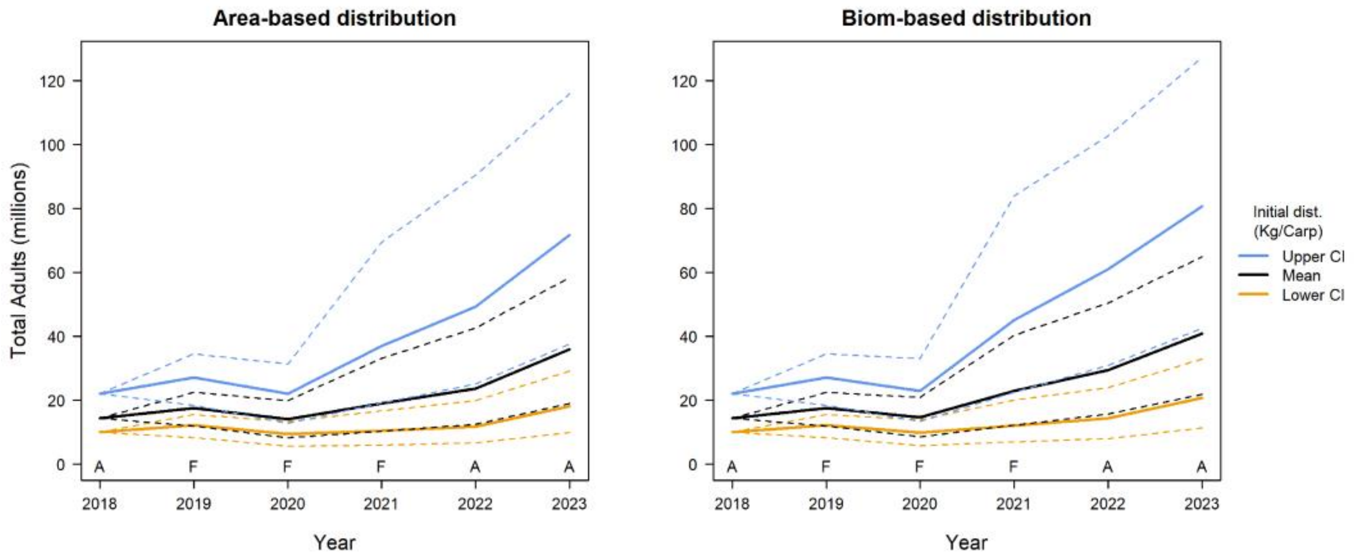


d) SC

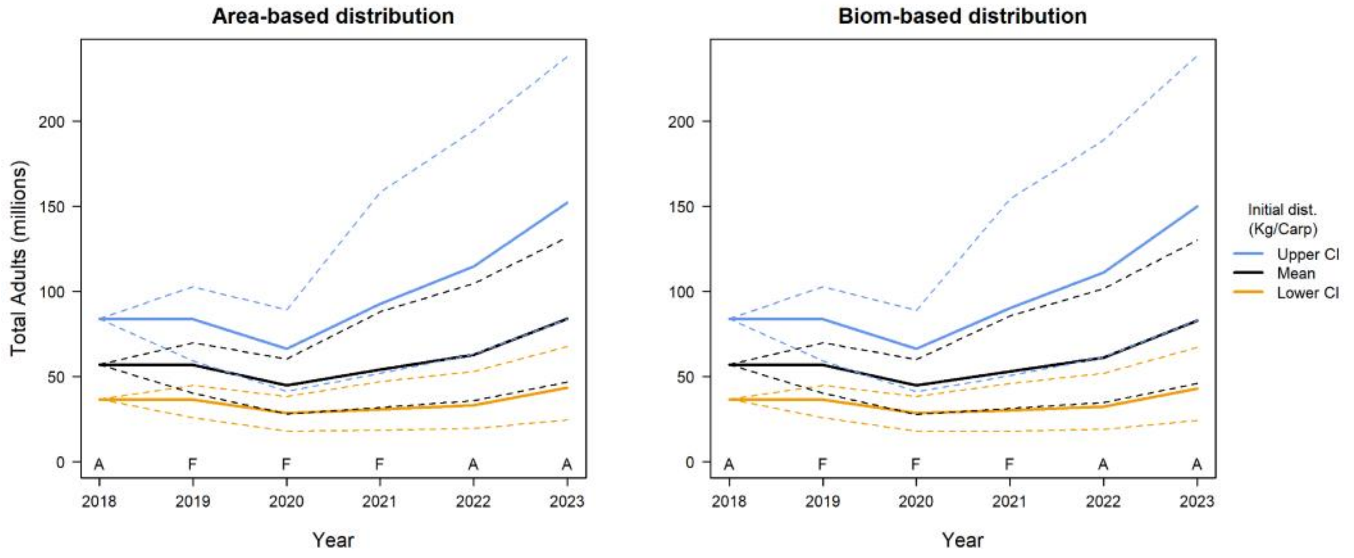


Appendix 4.5. Regional differences in adult Carp numbers through time with differing initial population structure under the Drought scenario. Note the different scales for adult Carp on the y axes.

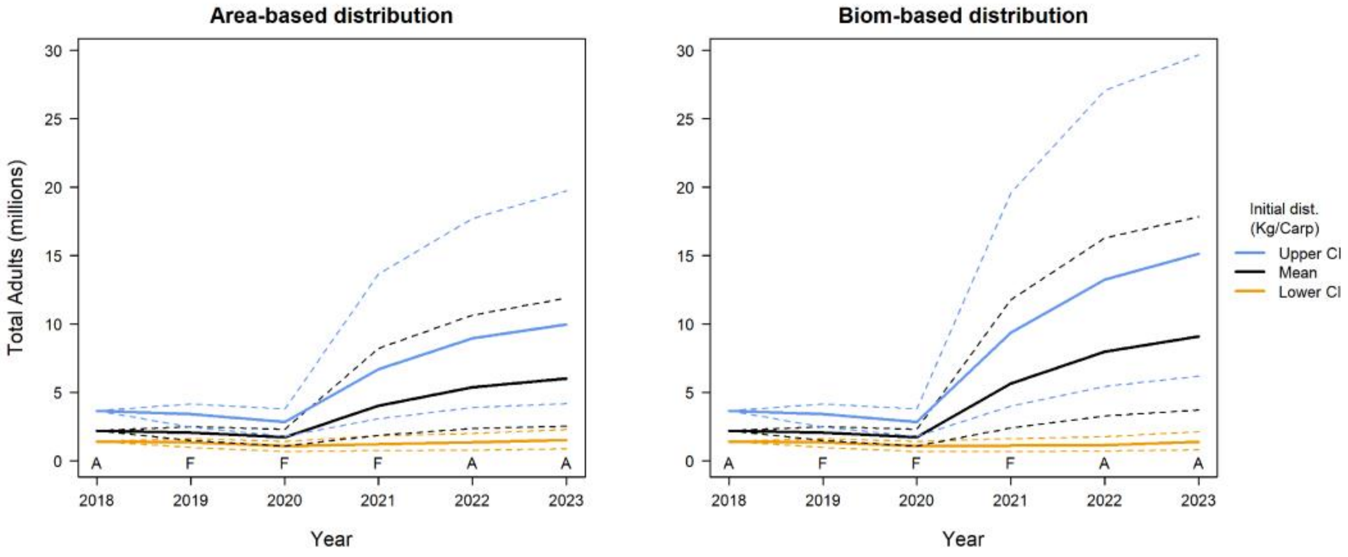
a) NMDB


Area-based distribution
Biom-based distribution
Total Adults (millions)
0
20
40
60
80
100
120
A
F
F
F
A
A
2018
2019
2020
2021
2022
2023
Year
Initial dist.
(Kg/Carp)
Upper CI
Mean
Lower CI

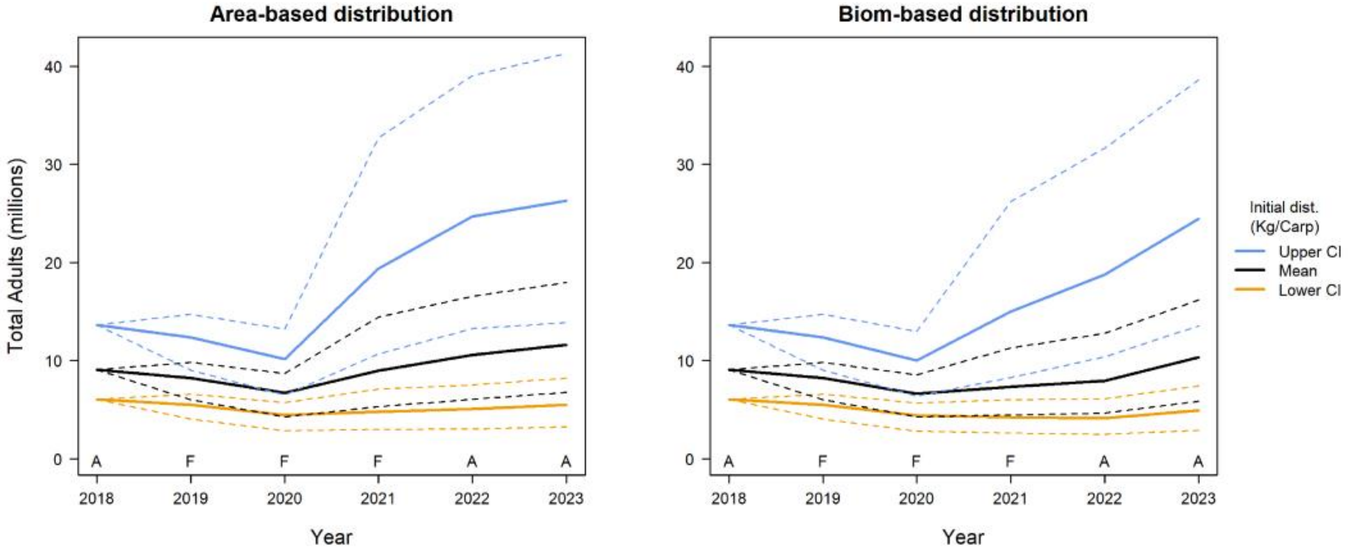
b) SMDB


Area-based distribution
Biom-based distribution
Total Adults (millions)
0
50
100
150
200
A
F
F
F
A
A
2018
2019
2020
2021
2022
2023
Year
Initial dist.
(Kg/Carp)
Upper CI
Mean
Lower CI

c) NC

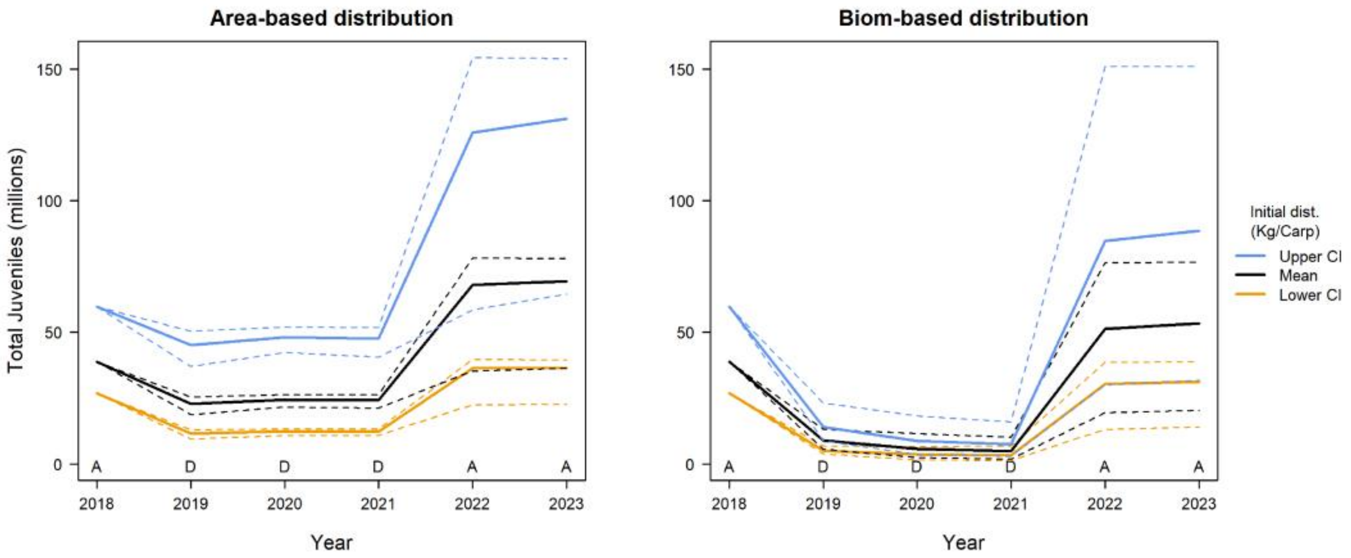


d) SC

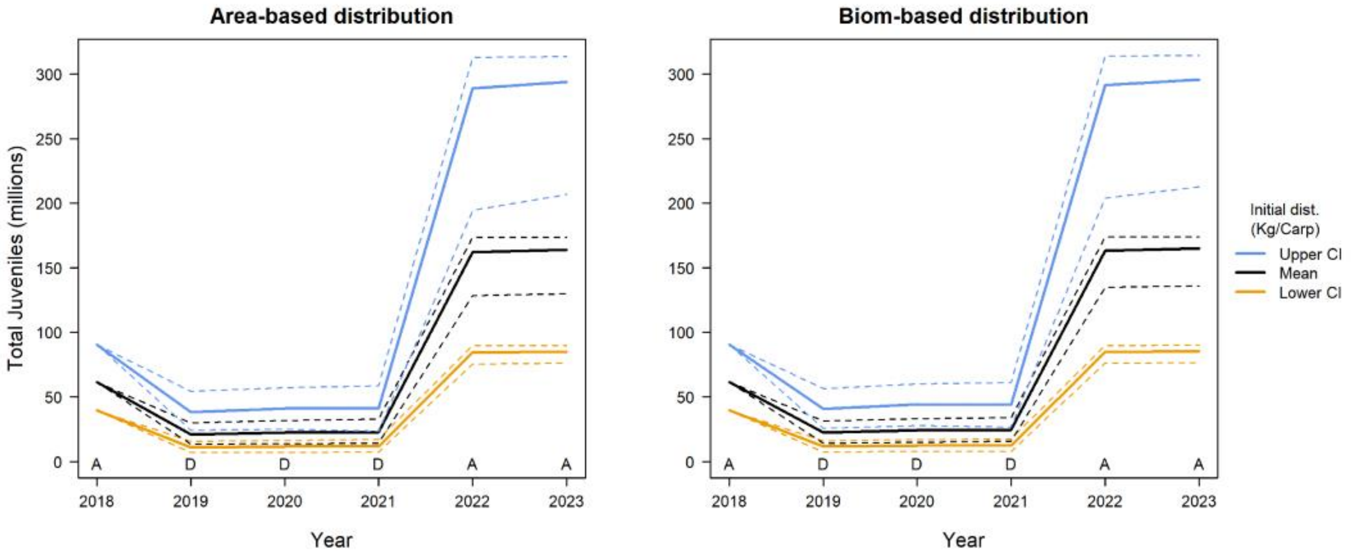


Appendix 4.6. Regional differences in adult Carp numbers through time with differing initial population structure under the Flood scenario. Note the different scales for adult Carp on the y axes.

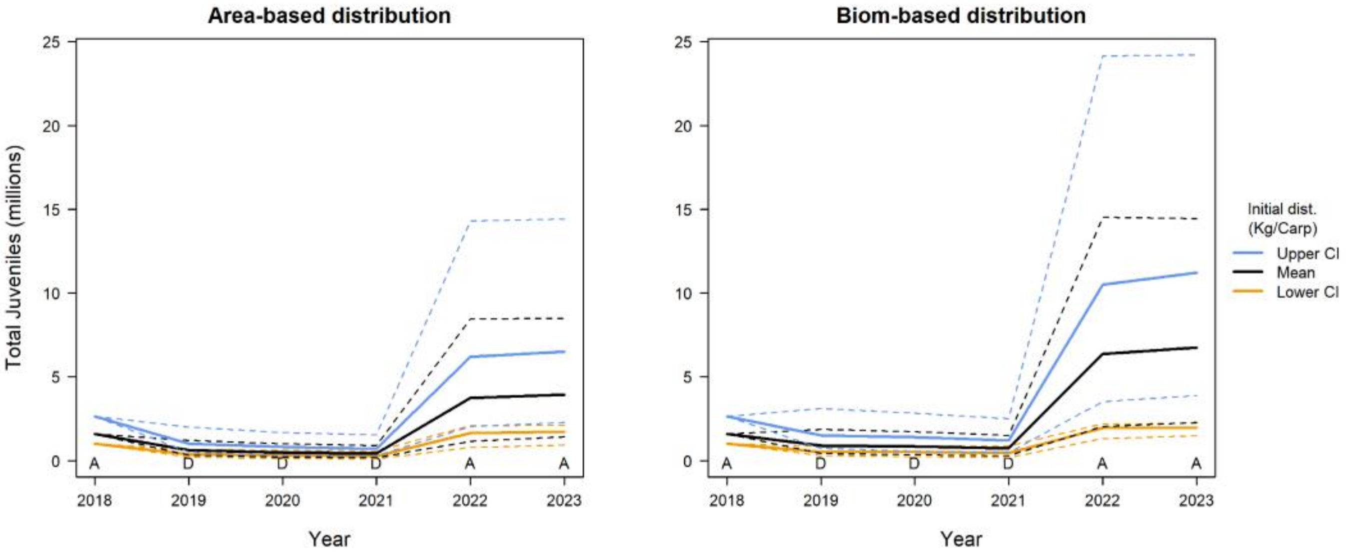
a) NMDB


Area-based distribution
Biom-based distribution
Total Juveniles (millions)
0
50
100
150
A
D
D
D
A
A
2018
2019
2020
2021
2022
2023
Year
Initial dist.
(Kg/Carp)
Upper CI
Mean
Lower CI

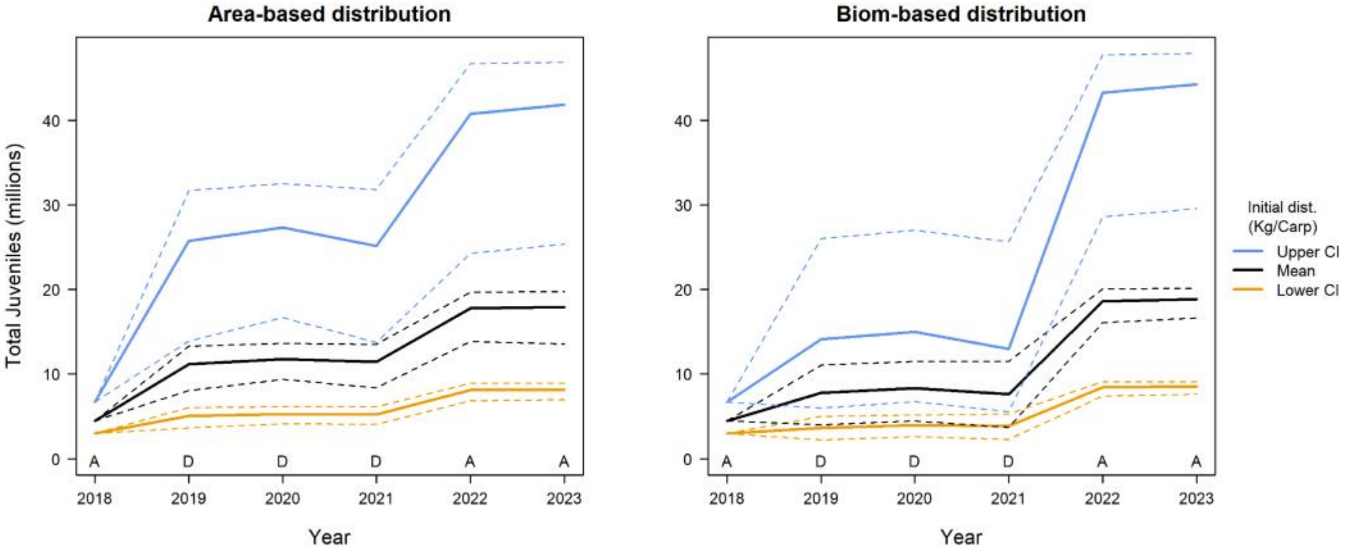
b) SMDB


Area-based distribution
Biom-based distribution
Total Juveniles (millions)
0
50
100
150
200
250
300
A
D
D
D
A
A
2018
2019
2020
2021
2022
2023
Year
Initial dist.
(Kg/Carp)
Upper CI
Mean
Lower CI

c) NC

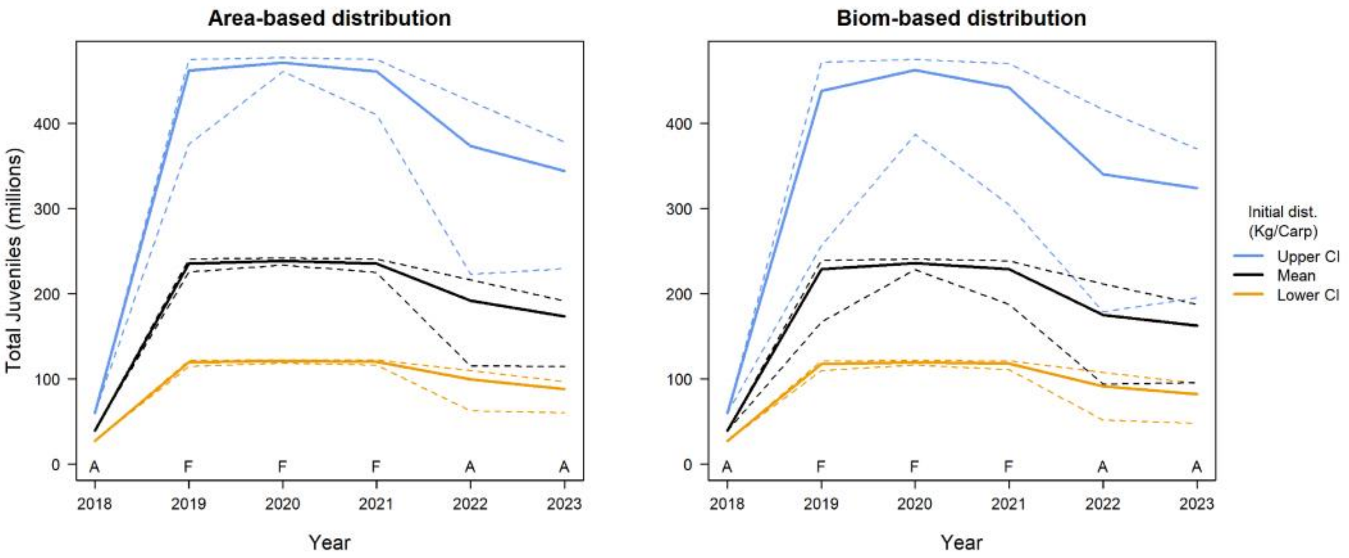


d) SC

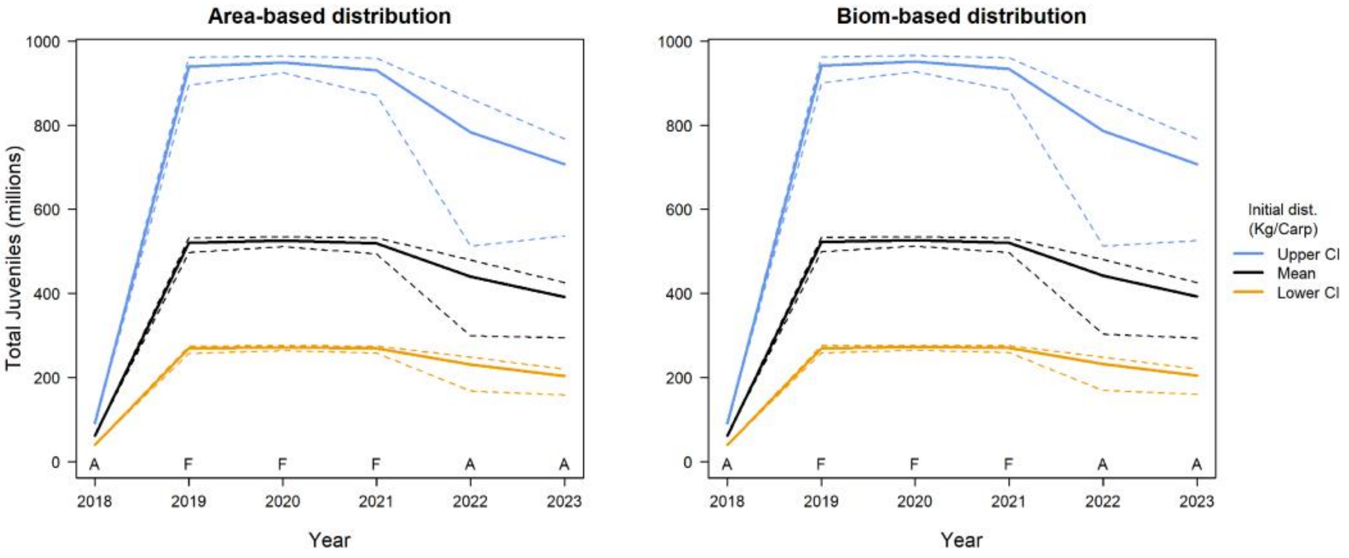


Appendix 4.7. Regional differences in juvenile Carp numbers through time with differing initial population structure under the Drought scenario. Note the different scales for juvenile Carp on the y axes.

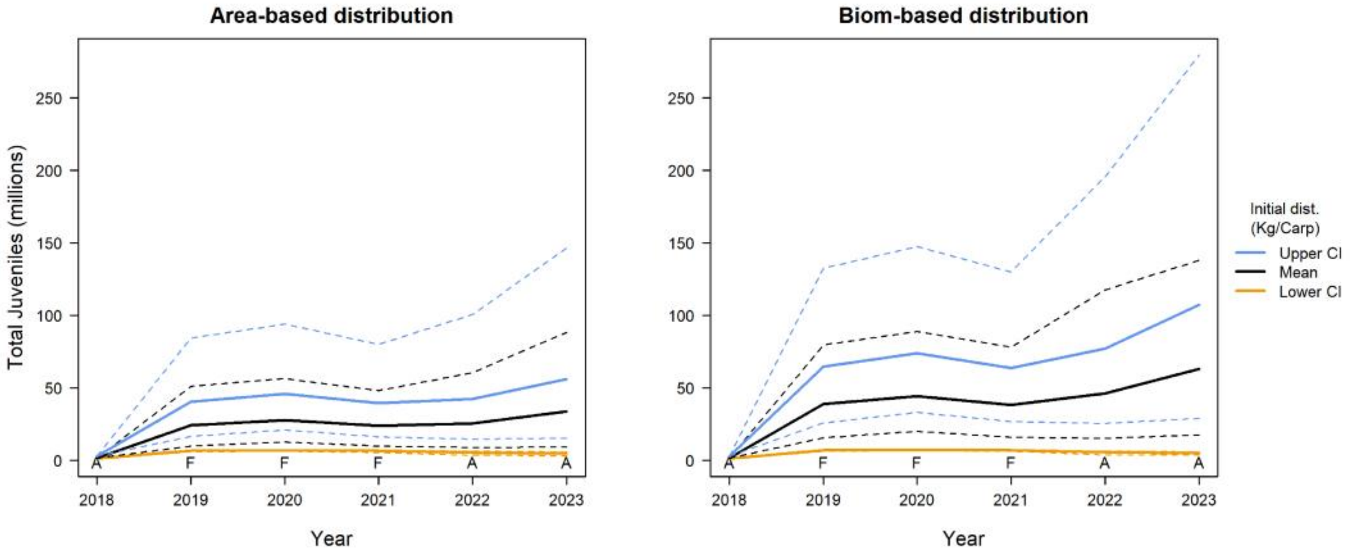
a) NMDB


Area-based distribution
Biom-based distribution
Total Juveniles (millions)
0
100
200
300
400
A
F
F
F
A
A
2018
2019
2020
2021
2022
2023
Year
Initial dist.
(Kg/Carp)
Upper CI
Mean
Lower CI

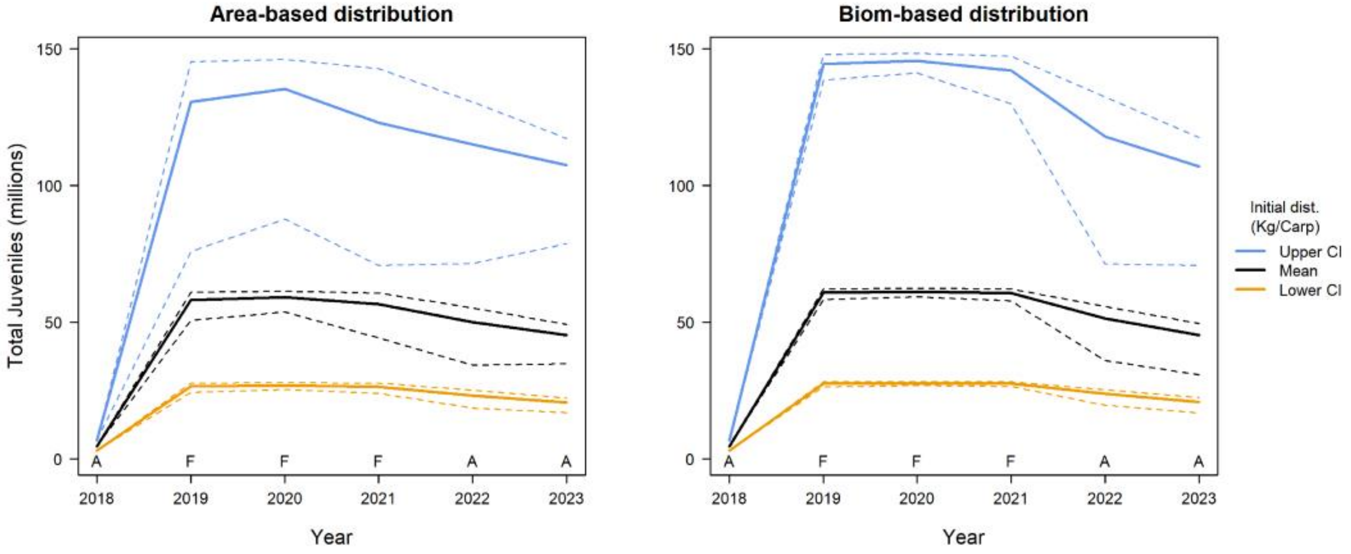
b) SMDB


Area-based distribution
Biom-based distribution
Total Juveniles (millions)
0
200
400
600
800
1000
A
F
F
F
A
A
2018
2019
2020
2021
2022
2023
Year
Initial dist.
(Kg/Carp)
Upper CI
Mean
Lower CI

c) NC



d) SC



Appendix 4.8. Regional differences in juvenile Carp numbers through time with differing initial population structure under the Flood scenario. Note the different scales for juvenile Carp on the y axes.

Appendix 5. Summary statistics of the distribution of Carp Biomass (t) for all scenarios modelled.

Appendix 5.1. Summary statistics of the distribution of Carp Biomass (t) for the Northern Murray-Darling Basin for 2023 of all scenarios modelled.

Scenario no.	Initial Population Biomass	Distribution Method	Kg/Carp	Flow Scenario	Mean	Median	Lower CI	Upper CI
1	Mean	Pr Area	Lower CI	Drought	20944.49	20979.09	15373.1	25954.39
2	Mean	Pr Area	Lower CI	Flood	56112.21	55929.42	41692.52	72026.85
3	Mean	Pr Area	Mean	Drought	37601.07	38061.77	24708.89	46719.66
4	Mean	Pr Area	Mean	Flood	109519.56	109250.35	79250.74	141640.83
5	Mean	Pr Area	Upper CI	Drought	68966.89	70650.93	43337.05	86649.68
6	Mean	Pr Area	Upper CI	Flood	216180.52	215175.65	155400.02	279519.9
7	Mean	Pr Biom	Lower CI	Drought	19686.86	20185.77	11339.01	26204.65
8	Mean	Pr Biom	Lower CI	Flood	59066.9	59216.01	39819.95	77977.86
9	Mean	Pr Biom	Mean	Drought	31909.56	32580.41	16605.32	45986.05
10	Mean	Pr Biom	Mean	Flood	115429.24	115638.9	75048.74	151784.25
11	Mean	Pr Biom	Upper CI	Drought	51567.06	51025.59	25548.22	81764.3
12	Mean	Pr Biom	Upper CI	Flood	227536.58	227734.99	147630.17	301685.96
13	Lower CI	Pr Area	Lower CI	Drought	18488.47	18774.47	11962.55	23135.95
14	Lower CI	Pr Area	Lower CI	Flood	54895.03	54794.52	39829.47	70755.18
15	Lower CI	Pr Area	Mean	Drought	33555.75	34507.1	20650.91	42650.81
16	Lower CI	Pr Area	Mean	Flood	108541.64	108048.71	76935.56	140438.57
17	Lower CI	Pr Area	Upper CI	Drought	62142.51	64267.01	36267.29	81264.33
18	Lower CI	Pr Area	Upper CI	Flood	215167.13	214621.79	153483.07	279987.87
19	Lower CI	Pr Biom	Lower CI	Drought	15952.71	16260.02	7986.81	23135.32
20	Lower CI	Pr Biom	Lower CI	Flood	57766.56	58033.33	37727.04	75992.18
21	Lower CI	Pr Biom	Mean	Drought	24726.47	24204.8	11562.91	40131.38
22	Lower CI	Pr Biom	Mean	Flood	113444.27	113614.59	72963.63	150122.35
23	Lower CI	Pr Biom	Upper CI	Drought	38860.9	37416.92	17793.17	68798.45
24	Lower CI	Pr Biom	Upper CI	Flood	221067.33	221325.44	135214.09	294873.5
25	Upper CI	Pr Area	Lower CI	Drought	23456.49	23344.38	17824.35	29476.5
26	Upper CI	Pr Area	Lower CI	Flood	58185.69	57922.72	43829.24	74725.8
27	Upper CI	Pr Area	Mean	Drought	41570.32	41692.9	30354.11	51381.46
28	Upper CI	Pr Area	Mean	Flood	111813.49	111499.36	82880.9	143941.39
29	Upper CI	Pr Area	Upper CI	Drought	75824.38	76617.86	50738.1	93684.16

30	Upper CI	Pr Area	Upper CI	Flood	218553.8	217827.7	158626.1	282841.21
31	Upper CI	Pr Biom	Lower CI	Drought	23032.28	23307.27	14564.03	29863.56
32	Upper CI	Pr Biom	Lower CI	Flood	61254.85	61278.49	42384.77	79167.73
33	Upper CI	Pr Biom	Mean	Drought	38105.75	38997.55	21674.88	51400.36
34	Upper CI	Pr Biom	Mean	Flood	117762.53	117977.55	78597.8	154948.46
35	Upper CI	Pr Biom	Upper CI	Drought	63299.45	64381.36	33633.51	91189.71
36	Upper CI	Pr Biom	Upper CI	Flood	230551.92	230462.89	150586.03	303560.36

Appendix 5.2. Summary statistics of the distribution of Carp Biomass (t) for the Southern Murray-Darling Basin for 2023 of all scenarios modelled.

Scenario no.	Initial Population Biomass	Distribution Method	Kg/Carp	Flow Scenario	Mean	Median	Lower CI	Upper CI
1	Mean	Pr Area	Lower CI	Drought	65347.81	64938.75	48068.25	84206.18
2	Mean	Pr Area	Lower CI	Flood	139016.09	138066.1	104252.88	179569.37
3	Mean	Pr Area	Mean	Drought	113665.14	113199.79	84991.97	143768.48
4	Mean	Pr Area	Mean	Flood	263182.53	261472.11	196334.26	342164.98
5	Mean	Pr Area	Upper CI	Drought	187843.96	187466.24	138540.93	235005.18
6	Mean	Pr Area	Upper CI	Flood	469229.59	467190.73	348611.22	609377.51
7	Mean	Pr Biom	Lower CI	Drought	65299.74	64824.81	48412.73	84098
8	Mean	Pr Biom	Lower CI	Flood	138076.26	136935.8	103707.04	178144.16
9	Mean	Pr Biom	Mean	Drought	113612.8	113001.42	84754.96	143683.69
10	Mean	Pr Biom	Mean	Flood	261253.84	259730.54	195175.21	338323.59
11	Mean	Pr Biom	Upper CI	Drought	187888.99	187535.28	140832.35	234784.77
12	Mean	Pr Biom	Upper CI	Flood	465587.48	463563.45	346503.39	605625.5
13	Lower CI	Pr Area	Lower CI	Drought	56889.82	56598.43	42521.09	72149.32
14	Lower CI	Pr Area	Lower CI	Flood	133988.6	133196.81	100024.41	173749.65
15	Lower CI	Pr Area	Mean	Drought	100663.21	100399.97	73825.72	125784.91
16	Lower CI	Pr Area	Mean	Flood	256475.57	255191.42	190915.67	333032.26
17	Lower CI	Pr Area	Upper CI	Drought	168126.87	169135.78	115007.67	208890.32
18	Lower CI	Pr Area	Upper CI	Flood	460842.51	458507.35	335437.49	598449.57
19	Lower CI	Pr Biom	Lower CI	Drought	56852.93	56530.29	42790.15	72135.15
20	Lower CI	Pr Biom	Lower CI	Flood	133002.39	132134.19	98994.18	171686.6
21	Lower CI	Pr Biom	Mean	Drought	100690.49	100321.73	75559.51	125811.16
22	Lower CI	Pr Biom	Mean	Flood	254484.92	253439.54	189097.37	330380.64
23	Lower CI	Pr Biom	Upper CI	Drought	168592.95	169094.55	118716.18	208254.31

24	Lower CI	Pr Biom	Upper CI	Flood	457274.03	454647.06	335645.53	592175.03
25	Upper CI	Pr Area	Lower CI	Drought	74767.5	74316.63	53747.08	97805.61
26	Upper CI	Pr Area	Lower CI	Flood	145395.37	144530.81	109080.85	186338.29
27	Upper CI	Pr Area	Mean	Drought	128019.11	127326.25	94440.83	164427.35
28	Upper CI	Pr Area	Mean	Flood	272069.42	270491.96	203885.39	351211.64
29	Upper CI	Pr Area	Upper CI	Drought	208746.3	207988.1	154700.01	263854.97
30	Upper CI	Pr Area	Upper CI	Flood	480687.92	478018.56	357206.22	625225.92
31	Upper CI	Pr Biom	Lower CI	Drought	74726.85	74266.75	53737.5	97826.19
32	Upper CI	Pr Biom	Lower CI	Flood	144482.04	143505.09	108530.41	185239.39
33	Upper CI	Pr Biom	Mean	Drought	127945.03	127255.92	94643.39	164221.27
34	Upper CI	Pr Biom	Mean	Flood	270218.6	268358.34	202230.56	349257.01
35	Upper CI	Pr Biom	Upper CI	Drought	208689.95	207753.84	155793.05	263396.82
36	Upper CI	Pr Biom	Upper CI	Flood	477163.03	474229.11	355770.86	620150.36

Appendix 5.3. Summary statistics of the distribution of Carp Biomass (t) for the Northern Coastal region for 2023 of all scenarios modelled.

Scenario no.	Initial Population Biomass	Distribution Method	Kg/Carp	Flow Scenario	Mean	Median	Lower CI	Upper CI
1	Mean	Pr Area	Lower CI	Drought	2190.84	2206.41	1333.98	3012.64
2	Mean	Pr Area	Lower CI	Flood	4350.97	4367.29	2986.3	5701.8
3	Mean	Pr Area	Mean	Drought	3882.74	3782.17	2069.43	6163.25
4	Mean	Pr Area	Mean	Flood	20613.72	19241.94	8188.18	42146.26
5	Mean	Pr Area	Upper CI	Drought	6446.33	6370.97	3527.16	10208.04
6	Mean	Pr Area	Upper CI	Flood	34328.62	32003.87	13620.48	70100.13
7	Mean	Pr Biom	Lower CI	Drought	2267.48	2264.31	1536.66	3088.93
8	Mean	Pr Biom	Lower CI	Flood	4172.3	4157.11	3003.46	5391.01
9	Mean	Pr Biom	Mean	Drought	4919.23	4779.27	2611.68	8067.14
10	Mean	Pr Biom	Mean	Flood	34400.44	32365.76	12955.79	63706.35
11	Mean	Pr Biom	Upper CI	Drought	8167.99	7949.05	4271.97	13566.69
12	Mean	Pr Biom	Upper CI	Flood	57859.03	53830.76	21548.22	116547.26
13	Lower CI	Pr Area	Lower CI	Drought	1503.3	1493.16	834.23	2197.3
14	Lower CI	Pr Area	Lower CI	Flood	3903.91	3915.46	2651.05	5190.81
15	Lower CI	Pr Area	Mean	Drought	2483.39	2384.52	1272.15	4062.54
16	Lower CI	Pr Area	Mean	Flood	13396.57	12418.07	5314.51	27373.96
17	Lower CI	Pr Area	Upper CI	Drought	4091.38	3965.85	2133	6874.58
18	Lower CI	Pr Area	Upper CI	Flood	22294.25	20656.11	8836.88	45529.25
19	Lower CI	Pr Biom	Lower CI	Drought	1645.74	1666.18	1007.46	2250.11

20	Lower CI	Pr Biom	Lower CI	Flood	3768.49	3763.36	2660.2	4881.71
21	Lower CI	Pr Biom	Mean	Drought	3171.31	3033.85	1566.49	5517.43
22	Lower CI	Pr Biom	Mean	Flood	22665.84	20821.64	8263.43	48568.04
23	Lower CI	Pr Biom	Upper CI	Drought	5246.1	5044.3	2625.79	9010.13
24	Lower CI	Pr Biom	Upper CI	Flood	37875.15	34637.75	13747.75	80789.91
25	Upper CI	Pr Area	Lower CI	Drought	2761.05	2761.16	1738.11	3804.12
26	Upper CI	Pr Area	Lower CI	Flood	4784.11	4780.75	3348.68	6231.63
27	Upper CI	Pr Area	Mean	Drought	5154.08	5075.59	2809.14	7987.36
28	Upper CI	Pr Area	Mean	Flood	26530.46	24812.62	10609.92	54306.87
29	Upper CI	Pr Area	Upper CI	Drought	8546.61	8435.16	4660.7	13287.55
30	Upper CI	Pr Area	Upper CI	Flood	44271.53	41265.4	17643.64	91447.65
31	Upper CI	Pr Biom	Lower CI	Drought	2818.79	2809.85	1882.73	3856.79
32	Upper CI	Pr Biom	Lower CI	Flood	4596.69	4568.73	3328.03	5954.78
33	Upper CI	Pr Biom	Mean	Drought	6472.24	6356.25	3467.5	10456.24
34	Upper CI	Pr Biom	Mean	Flood	43337.99	41650.17	16904.94	74457.76
35	Upper CI	Pr Biom	Upper CI	Drought	10750.05	10536.27	5687.5	17392.92
36	Upper CI	Pr Biom	Upper CI	Flood	73694.3	69440.92	28111.92	134803.9

Appendix 5.4. Summary statistics of the distribution of Carp Biomass (t) for the Southern Coastal region for 2023 of all scenarios modelled.

Scenario no.	Initial Population Biomass	Distribution Method	Kg/Carp	Flow Scenario	Mean	Median	Lower CI	Upper CI
1	Mean	Pr Area	Lower CI	Drought	9875.35	9829.32	6883.05	13169.18
2	Mean	Pr Area	Lower CI	Flood	17234.83	17184.15	12574.59	22281.03
3	Mean	Pr Area	Mean	Drought	17745.63	17696.43	12598.41	23163.55
4	Mean	Pr Area	Mean	Flood	35492.23	35427.23	25457.81	45955.97
5	Mean	Pr Area	Upper CI	Drought	34745.99	34709.1	23868.85	45262.75
6	Mean	Pr Area	Upper CI	Flood	79469.55	78905.46	55925.94	104342.3
7	Mean	Pr Biom	Lower CI	Drought	9892.27	9845.75	6843.56	13267.27
8	Mean	Pr Biom	Lower CI	Flood	16238.12	16113.06	12072.79	20883.31
9	Mean	Pr Biom	Mean	Drought	17518.88	17349.24	12491.24	23055.76
10	Mean	Pr Biom	Mean	Flood	33060	32901.33	24303.73	42603.39
11	Mean	Pr Biom	Upper CI	Drought	32532.27	32489.1	22980.11	42236.73
12	Mean	Pr Biom	Upper CI	Flood	74889.34	74519.81	53282.38	97132.18
13	Lower CI	Pr Area	Lower CI	Drought	7744.05	7722.73	5493.66	10156.51
14	Lower CI	Pr Area	Lower CI	Flood	15662.22	15627.94	11253.85	20251.11
15	Lower CI	Pr Area	Mean	Drought	14635.47	14597.05	10291.18	19050.94

16	Lower CI	Pr Area	Mean	Flood	33162.47	33057.51	23446.56	43236.27
17	Lower CI	Pr Area	Upper CI	Drought	29049.84	29343.38	17669.55	38311.44
18	Lower CI	Pr Area	Upper CI	Flood	73015.02	72450.64	45466.07	98639
19	Lower CI	Pr Biom	Lower CI	Drought	7701.76	7620.31	5525.47	10183.2
20	Lower CI	Pr Biom	Lower CI	Flood	14579.96	14516.45	10739.55	18743.89
21	Lower CI	Pr Biom	Mean	Drought	13996.86	13906.35	10010.46	18349.91
22	Lower CI	Pr Biom	Mean	Flood	30950.09	30802.53	22162.87	40209.15
23	Lower CI	Pr Biom	Upper CI	Drought	26354.14	26628.12	16459.74	34201.36
24	Lower CI	Pr Biom	Upper CI	Flood	72476.17	72184.23	50537.54	94809.18
25	Upper CI	Pr Area	Lower CI	Drought	11437.67	11397.76	7733.35	15401.76
26	Upper CI	Pr Area	Lower CI	Flood	18446	18364.52	13388.53	23794.45
27	Upper CI	Pr Area	Mean	Drought	19974.56	19910.87	13950.86	26283.46
28	Upper CI	Pr Area	Mean	Flood	37092.18	36925.34	26959.84	47860.74
29	Upper CI	Pr Area	Upper CI	Drought	38218.3	38182.84	27150.31	49615.4
30	Upper CI	Pr Area	Upper CI	Flood	82423.56	82300.65	57719.57	107408.65
31	Upper CI	Pr Biom	Lower CI	Drought	11462.98	11440.54	7686.59	15495.75
32	Upper CI	Pr Biom	Lower CI	Flood	17519.09	17371.07	12968.5	22498.96
33	Upper CI	Pr Biom	Mean	Drought	19887.83	19785.48	13916.22	26266.26
34	Upper CI	Pr Biom	Mean	Flood	34726.98	34530.14	25638.72	44840.59
35	Upper CI	Pr Biom	Upper CI	Drought	36587.87	36316.59	26164.2	47647.28
36	Upper CI	Pr Biom	Upper CI	Flood	76809.1	76340.91	55147.5	99486.5

www.delwp.vic.gov.au

www.ari.vic.gov.au

NATIONAL CARP CONTROL PLAN

The National Carp Control Plan is managed by the
Fisheries Research and Development Corporation

Tel: 02 6285 0400
Post: Locked Bag 222, Deakin West ACT 2600

www.carp.gov.au