Threatened Species Recovery Hub

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Litoria aurea (Green and Golden Bell Frog) Dynamic Occupancy Analysis Report for the NSW Saving Our Species Program: 2016/2017 - 2018/2019

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Cover Image: *Litoria aurea* (Green and Golden Bell Frog). Photo: M. Clancy

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Executive Summary

This report documents the results of a dynamic occupancy analysis to evaluate the status of the Green and Golden Bell Frog (GGBF) and inform management requirements across seven management zones in New South Wales as part of the Saving Our Species (SoS) program. Survey data was collected during three field seasons, including at six management zones (227 wetland sites) in 2016/2017, four zones (188 wetland sites) in 2017/2018 and five zones (275 sites) in 2018/2019. The analysis examined biophysical variables that may influence the detection, occurrence, persistence and colonisation of GGBF. The choice of biophysical variables was selected in consultation with key stakeholders and guided by their relevance to the management of extant GGBF populations.

There were positive relationships between the initial probability of occupancy in 2018/2019 and wetland electrical conductivity and the percentage cover of wetlands within 1km of a site. There was a strong positive relationship between the probability of persistence and connectivity to permanent wetlands, and a negative relationship with the presence of Gambusia. The probability of site colonisation increased at more ephemeral wetlands.

From 2016/2017 to 2018/2019, there was a decrease in the mean estimated proportion of occupied sites at Crookhaven, Kooragang Island and Sydney Olympic Park. There was not enough data to estimate changes in occupancy for other management zones. Like 2017/2018, rainfall was low during 2018/2019 and may have contributed to the low site occupancy across all management zones. Further monitoring, as the drought breaks, is required to determine if populations can rebound after a prolonged dry period.

Site connectivity to permanent wetlands and the presence of Gambusia are currently predicted to be the most important factors influencing the persistence of GGBF at sites. The importance of other factors (like the role of chytrid infection) cannot yet be determined as additional data is required to verify their influence on GGBF occupancy dynamics.

Management intervention may be required at Kooragang Island, Crookhaven, Sydney Olympic Park and Molonglo to increase site occupancy. This is because declines in occupancy appear to have occurred at Kooragang Island, Crookhaven and potentially Sydney Olympic Park; and the proportion of occupied sites is low at Molonglo relative to other management zones.

Key recommendations:

1. Management actions that create or increase connectivity to permanent wetlands are likely to promote increased GGBF occupancy within management zones.
2. Management actions that eradicate non-native fish species (like Gambusia) are likely to promote increased GGBF occupancy within management zones. The creation of ephemeral wetlands close to permanent wetlands may provide fish-free breeding sites. Additional data on the presence of Gambusia and other non-native fish at sites should be collected for future years of the program.
3. Additional data is required to clarify changes in occupancy across most management zones and to further understand the drivers of GGBF persistence and colonisation at sites. Notably, additional data on wetland hydrology, chemistry and temperature is required.
4. GGBF should be swabbed at key sites throughout the eight management zones to collect chytrid infection data to understand the influence of the pathogen on GGBF site occupancy.
5. Future assessments should seek to verify spatial autocorrelation effects on the study results.

A wetland at Yuraygir, New South Wales. Image: David Newell

Introduction

Saving our species project

Conservation concerns for *Litoria aurea* (Green and Golden Bell Frog; GGBF) are currently being addressed by the New South Wales Government's *Saving our Species* (SoS) program. The GGBF is listed as 'Endangered' under the NSW Biodiversity Conservation Act 2016. Around 40 extant populations of GGBF occur within NSW, vastly less than the number that would have occurred prior to European settlement (White & Pyke 2008). Most NSW GGBF populations are continuing to decline, although recent evidence suggests that some populations may be stable, based on population size estimates (Goldingay et al. 2017). Further monitoring is required to determine the population trajectories of the GGBF to clarify its conservation status and management requirements.

The GGBF SoS project was established in 2016 and aims to ensure a 95% likelihood of the GGBF persisting within NSW for the next 100 years. To achieve this, the SoS program has committed funding for a 5-year period for monitoring and management actions at eight of the 40 populations. Knowledge gained at these eight populations or "management zones" will be used to inform appropriate protection and management of other NSW populations. These management zones have been prioritised by the SoS program because of extensive prior research efforts at these zones or their comparatively large GGBF population sizes. Consequently, the chance of delivering tangible conservation outcomes for GGBF is considered higher at these zones than for other populations. The eight management zones are distributed relatively widely (but independently) along the NSW coast or Southern Ranges. Listed in a north to south order the eight management zones are:

1. Yuraygir
2. Crescent Head
3. Broughton Island
4. Kooragang Island
5. Sydney Olympic Park
6. Crookhaven
7. Meroo
8. Molonglo

Key threatening processes for GGBF populations include: 1) habitat loss and degradation resulting from urban, rural and industrial developments, 2) infection of frogs by amphibian chytrid fungus (*Batrachochytrium dendrobatidis*) causing the disease chytridiomycosis, and 3) predation by the mosquitofish (*Gambusia holbrooki* – hereafter called Gambusia). The relative importance of each threatening process to the long-term persistence of GGBF throughout these management zones remains unclear. Once the importance of these factors has been clarified, evidence-based site-specific management actions can be undertaken to promote long-term population persistence.

Ecology of the Green and Golden Bell Frog

The GGBF is a highly mobile frog species that has a life history characteristic of colonising species: being a habitat generalist and having high fecundity, rapid growth, early sexual maturity, and relatively high dispersal ability (Hamer & Mahony 2007). This life history is atypical of most declining species and suggests that GGBF populations should be able to recover quickly if the processes linked to declines can be ameliorated. The life history of GGBF also suggests that the size of remnant populations could fluctuate widely over time in response to climatic conditions, producing 'boom-bust' cycles linked to rainfall patterns (Alford & Richards 1999).

The GGBF is known to be distributed as patchy populations within larger metapopulations, inhabiting a mosaic of wetlands throughout a single breeding season, and with frequently dispersing individuals resulting in relative high population turnover (Hamer et al. 2008; Hamer & Mahony 2010). Hence, population recovery is likely dependent on spatial processes such as colonisation or re-colonisation (hereafter collectively referred to as colonisation) of sites from nearby refuge habitats. Studies from one management zone (Kooragang Island) showed that occupancy and colonisation rates are highest at wetlands that closely neighbour other occupied sites (Hamer et al. 2002; Hamer & Mahony 2010). Moreover, spatiotemporal patterns exist in occupancy and movement patterns, which are linked to habitat use within breeding seasons. For example, on Kooragang Island, GGBF typically reside in permanent waterbodies where they exhibit high site fidelity, but during periods of high rainfall they disperse for several hundred metres to ephemeral waterbodies when they become inundated (Hamer et al. 2008). Reproductive activity (e.g. calling) typically occurs over several nights at these ephemeral waterbodies. Thereafter, individuals move back to permanent waterbodies, which are regarded as refuge or "core" habitats.

Occupancy as a Population Metric

Occupancy has been designated as the primary population metric for the GGBF SoS program to assess the status and distribution patterns of the GGBF at sites within the management zones. Understanding a species' status and distribution is challenging when their detection at sites is imperfect. Species detection can be influenced by multiple factors, including survey methods (Wassens et al. 2017) or climatic or site-specific conditions (Weir et al. 2005). Occupancy modelling can be used to account for imperfect species detection and also to provide insight into the factors that influence a species' detection and occupancy at sites (MacKenzie et al. 2006). The status of a species at a site and within a management zone can be determined through repeated surveys within a single season. Changes in population status, for example, in response to management interventions, can also be assessed by repeating the occupancy analysis over multiple seasons. Multi-season or dynamic occupancy analyses can also be used to evaluate the extinction risk of metapopulations by taking colonisation and extinction processes into account (MacKenzie et al. 2003).

This report evaluates the occupancy status of GGBF at the management zones in the third year (2018/2019) of the SoS program, as well as factors that influence the probability of detection and occupancy within each of the eight management zones. Factors that influence GGBF persistence and colonisation at surveyed sites in 2017/2018 and 2018/2019 were investigated. One management zone (Yuraygir) was surveyed in 2017/2018 but was excluded from the occupancy analysis as the zone consists of only two main waterbodies and mark-recapture methods are used to estimate population size. Sydney Olympic Park was added to the SoS project in the second year of the project and data from that site, collected in both 2017/2018 and 2018/2019, is incorporated in the current analysis.

Summary of Occupancy Analysis 2016/2017

The results of the single-season occupancy analysis following the first season of the project were included in the 2016/2017 annual monitoring report (West et al. 2017). The analysis predicted that a greater number of sites were occupied in 2016/2017 than the number of sites where frogs were observed during field surveys. The estimated proportion of occupied sites over all six management zones was 0.74 (95% CI: 0.68 – 0.79). Kooragang Island had the highest estimated proportion of occupied sites (0.99), whereas Molonglo had the lowest estimated proportion of occupied sites (0.33). The results of the first season's analysis provided a baseline so that changes in GGBF site occupancy could be evaluated in subsequent seasons.

In 2016/2017 the probability of GGBF occupancy was found to increase with the percentage of surrounding wetlands and connectivity to permanent wetlands, both measured at a 1-km radius around a site. These results highlighted the importance of connectivity of wetlands within GGBF management zones. However, relationships between GGBF occupancy and the other biophysical variables examined were unclear. The probability of detection increased with survey effort and varied with survey date. The analysis concluded that management actions that create new wetlands and increase connectivity between wetlands are likely to increase the proportion of sites occupied by GGBF within management zones.

A key recommendation following the single-season occupancy analysis was to use dynamic occupancy modelling to evaluate the extinction risk and population trajectories of GGBF populations at the management sites in future years.

Summary of Occupancy Analysis 2017/2018

Dynamic occupancy analysis in year two of the program included data collected at six management zones (228 wetland sites) in 2016/2017 and three zones (87 wetland sites) in 2017/2018 (West et al. 2018).

The analysis found that there was a substantial decline in the estimated proportion of occupied sites at Kooragang Island and Crookhaven from 2016/2017 to 2017/2018 (Fig 1). At Kooragang Island (n = 29 sites) the mean proportion of sites occupied declined from 0.99 (range: 0.96-1.00) in 2016/2017 to 0.74 (range: 0.59-0.86) in 2017/2018. At Crookhaven (n = 30 sites) the mean proportion of sites occupied declined from 0.52 (range: 0.47-0.63) in 2016/2017 to 0.26 (range: 0.17-0.40) in 2017/2018. The change in occupancy was unclear at Molonglo as the analysis resulted in wide credible intervals for the number and proportions of sites occupied. At Molonglo (n = 28 sites) the mean proportion of sites occupied in 2016/2017 was 0.37 (range: 0.25-0.71) and in 2017/2018 was 0.42 (range 0.14-0.78). Across all management zones (referred to as the global sites: n = 228) the mean proportion of occupied sites was estimated to be 0.73 (range: 0.67-0.80) in 2016-2017 and 0.58 (range: 0.25-0.78) in 2017/2018.

The probability that a previously unoccupied site became colonised by GGBF was found to increase with increased connectivity to permanent and occupied wetlands. There were no clear relationships between the probability of persistence of GGBF at sites and the eight biophysical variables examined. Rainfall was low during 2017/2018 and may have contributed to declines in occupancy, although the influence of rainfall could not be evaluated during the analysis in that year.

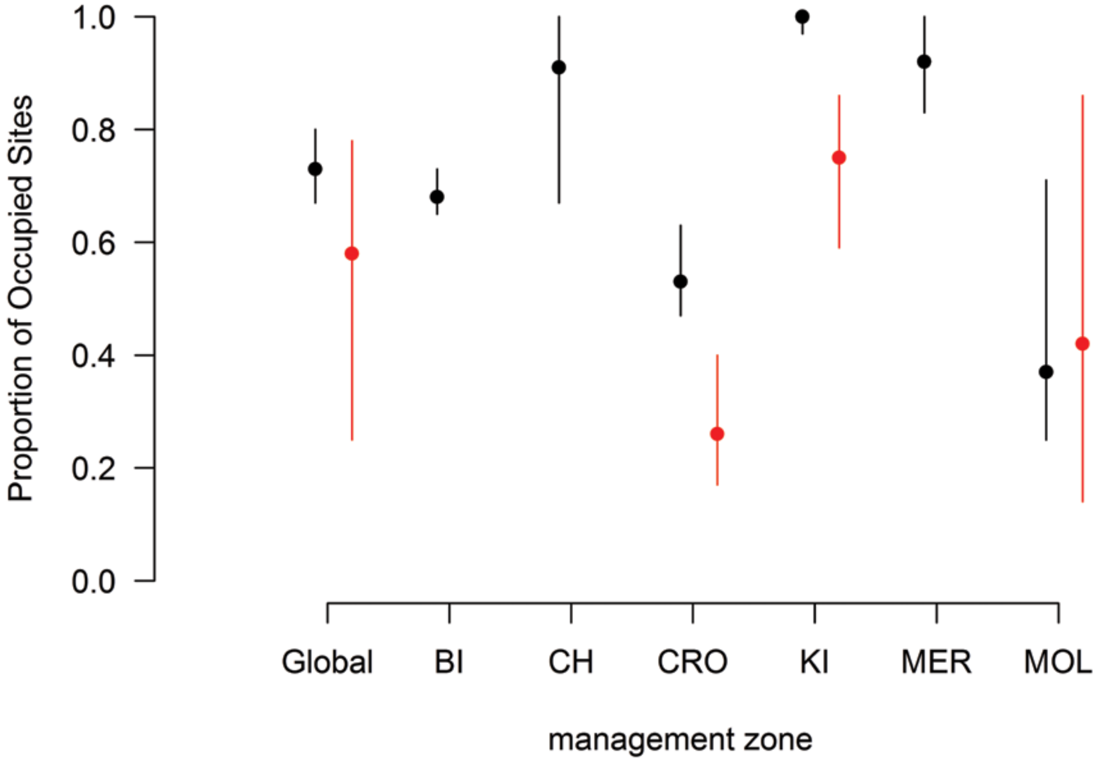


Figure 1. Dynamic occupancy analysis results in year two. Estimated proportion of sites occupied by GGBF at each management zone and overall (global). Points indicate the mean estimated proportions of occupied sites and vertical lines represent 95% credible intervals. Black points and lines are shown for estimates of site occupancy in 2016/2017 (year 1) and red points and lines show estimates of site occupancy in 2017/2018 (year 2). Results of 2017/2018 site occupancy are only shown for the zones at which data was collected. The six management zones are: BI = Broughton Island; CH = Crescent Head; CRO = Crookhaven; KI = Kooragang Island; MER = Meroo; MOL = Molonglo.

Methods

Management Zones and Sites for Dynamic Occupancy Analysis

Six management zones were initially selected for the SoS GGBF occupancy assessment program. Within each management zone, wetland sites were selected to include a range of a priori occupied and unoccupied sites that varied in waterbody size, type (e.g. permanent, semi-permanent, or ephemeral), habitat structure (percentage cover of aquatic vegetation), and degree of isolation (i.e. distance among waterbodies). The selection of these sites is discussed further in the 2016/2017 annual monitoring report (West et al. 2017).

In total, 342 individual "sites" were identified and included in the occupancy study across seven management zones:

1. Crescent Head: 36 sites
2. Broughton Island: 75 sites (sites were aggregated to form 20 sites in 2018/2019)
3. Kooragang Island: 28 sites (27 sites in 2017/18 and 2018/2019)
4. Crookhaven: 31 sites
5. Meroo: 30 sites
6. Molonglo: 28 sites
7. Sydney Olympic Park: 114 sites

Occupancy surveys were conducted at six management zones in 2016/2017, four management zones in 2017/2018 and five management zones in 2018/2019. The number of sites surveyed in each season varied and is summarized in Table 1.

Surveys were not conducted at Crescent Head and Meroo in 2017/2018 and 2018/2019 because the SoS Monitoring Plan outlines that these management zones are only to be surveyed every three to four years. No surveys were conducted at Broughton Island in 2017/2018. GGBF surveys were conducted at Yuraygir but were excluded from the analyses for reasons previously outlined. In 2018/2019 the sites at Broughton Island were surveyed using two approaches; the first approach was to survey all 75 sites and the second approach was to cluster the 75 sites into 20 grouped sites. This was because many of the original 75 sites were very small pools or puddles in the same water catchment and were often very close to one another, and therefore were not independent sites. Further details of how sites were grouped and the relationship between variables at sites can be found in Table 1.

*Table 1. Sites at each management zone that were surveyed and included in the 3-season dynamic occupancy analysis. In 2018/2019 the 75 sites at Broughton Island were surveyed individually and were also grouped to form 20 sites and surveyed as such. The 2016/2017 data from the 75 sites at Broughton Island was aggregated to form the new 20 sites. Occupancy analysis was performed with and without the aggregated Broughton Island survey approach. The number of sites in the aggregated analysis is shown with an asterisk * and in parenthesis.*

Management Zone	2016/2017	2017/2018	2018/2019	Max Sites in Zone
Broughton Island	75 (20*)	-	75 (20*)	75 (20*)
Crescent Head	36	-	-	36
Crookhaven	30	31	31	31
Kooragang Island	28	27	27	28
Meroo	30	-	-	30
Molonglo	28	28	28	28
Sydney Olympic Park	-	102	114	114
All Zones (Global)	**227 (172*)**	**188**	**275 (220*)**	**342 (287*)**

Survey Methods

In 2016–2017, each site was surveyed during 2 – 11 occasions between October 2016 and March 2017. Up to 11 surveys were conducted at Broughton Island sites, but at other management zones a maximum of four (mean 3.9) surveys were conducted. The time interval between survey occasions at each site varied widely, from one to three months. Sites were surveyed during 1–4 occasions at the four management zones examined during 2017–2018 and at the five management zones sampled during 2018–2019.

Survey sites were often grouped into clusters to maximise survey efficiency. The chronology of clusters was randomised on each survey period to remove any potential biases in detecting the species, e.g., at dusk versus a few hours after dusk. Diurnal surveys only were conducted at the Molonglo management zone, between 1030 – 1630 hrs, and in 2016–2017, surveys were conducted during the day at Broughton Island as well as during the night. Nocturnal surveys were conducted at all other zones and sites. GGBF were surveyed with the aid of LED head torches via timed visual encounter survey (VES) and call playback at some sites and commenced at dusk. The amount of time spent surveying at each site was proportional to the size and habitat complexity of each location, but survey times were capped at one hour at wetland sites that were large or supported complex habitats. Mark-recapture methods were also employed on Broughton Island in 2016–2017, but as a separate exercise following the occupancy surveys. Additional analyses are also planned for the Kooragang Island data.

In all seasons, habitat surveys were undertaken at each survey site during the day to record information on water body type, substrate, dominant plant species composition and cover, and water chemistry. The number of habitat surveys at a site varied from one in November (Kooragang Island and Crookhaven), or during each survey for a total of four measurements (Meroo, Molonglo, and Broughton Island). One habitat survey was conducted at Crescent Head in October/November with some additional water depth assessments in January.

A different research group undertook surveys at each of the management zones, and the number and make-up of the field teams varied between each survey.

Data Collection During Frog Surveys

A standard *proforma* for data collection was set up for all surveys.

General data: The time, date, and survey effort (duration of survey and number of field members) was recorded by each team during each site visit.

GGBF observations: All life stages of GGBF that were observed or heard during surveys were identified and recorded (adults, juveniles, metamorphs, and tadpoles). GGBF and other frogs recorded more than 20m from the edge of water were not recorded as occurring within survey sites. Rather, these were recorded as opportunistic observations, as were other GGBF recorded outside survey sites or outside the allocated survey time. Surveys for tadpoles were not systematic at all sites and so were excluded from the occupancy analysis. Similarly, any other frog species observed at a site were excluded from the occupancy analysis on this occasion.

Gambusia presence: The presence of fish species, particularly Gambusia, was generally assessed by visual inspection of the water during the day when habitat surveys were conducted, or at night with a spotlight during frog surveys. Dip-net surveys were conducted during the day at Molonglo and Broughton Island. Given that these surveys were not systematic at all sites, but Gambusia may be an important influence on GGBF occupancy, the Gambusia data was reduced to a binary "detected" = 1 or "not detected" = 0 variable for each site.

Local weather conditions: Weather conditions were generally recorded at the time of survey, including air (dry and wet bulb) and water temperatures at the start and finish times, and the water level as a percentage of the full water-holding capacity of the site. Water depth (in cm) was recorded at Crookhaven and Broughton Island. Given that weather data was not always consistently recorded at sites or at a consistent time of day, weather records used in the analysis were downloaded from the Australian Government Bureau of Meteorology Australian Water Availability Project (AWAP). Rainfall and maximum daily air temperature may be a potentially important factor influencing GGBF detection. AWAP rainfall data was collated for the seven days prior to each survey at each site. AWAP maximum air temperature data was summarized for each site and each day that a survey was conducted.

Data Collection During Habitat Surveys

Water chemistry: Water chemistry was only recorded when waterbodies contained free-standing water. Water temperature, electrical conductivity (EC; μS/cm), salinity (ppt), Total Dissolved Solids (TDS), and pH were measured at the water surface, 0.5–1.0m from the shoreline using a range of handheld digital meters. The number of water quality samples taken at each site varied in respect to the size of the waterbody (one to six samples per site) and the results were averaged.

Wetland Hydrology and Size: The percentage of the full water-holding capacity of each wetland site was recorded during field surveys. Water depths were recorded at Crookhaven and Broughton Island.

Aquatic Vegetation: The percentage of the wetland surface area covered by aquatic vegetation (Aqveg) was estimated during the habitat surveys. Aquatic vegetation strata comprised emergent, submerged, and floating vegetation, and the proportion cover of each were estimated by eye. Emergent and submerged vegetation were defined as aquatic vegetation that extended above or below the water surface, respectively. Floating vegetation included surface algae and rooted macrophytes. Aquatic vegetation cover was expressed as the mean of the three individual estimates of each plant strata cover. The percentage of open water at a site was recorded. The percentage of wetland perimeter covered by fringing vegetation (within 1m of the shoreline) and percentage canopy cover over the wetland was also recorded. Dominant plant species in each vegetation strata were noted. The mean value for emergent, submerged and floating aquatic vegetation was used in the analysis. Aqveg can be regarded as a measure of aquatic vegetation diversity as well as total proportional cover.

Data for Landscape Variables

GIS layers were used to calculate three landscape-level variables (Wetlands, Native Vegetation and Impervious Surfaces), and each were calculated at multiple spatial scales.

The first time the landscape level variables were calculated, mangrove and saltmarsh vegetation classes were included in both the Native Vegetation and Wetland landscape-level variables. This was realised after the first report on the single season occupancy analysis was completed. For this reason, the single season occupancy analysis was run again to check if the inclusion of the mangrove/saltmarsh areas in either Wetland or Native Vegetation variables altered the analysis results. We found that there was not a clear difference and decided to use the original method for calculating each of the landscape variables (including the overlap) for the dynamic occupancy analysis.

Wetlands %: Surveys at each management zone did not assess all possible wetlands within the zone, and these other wetlands may also influence GGBF occupancy rates at the surveyed sites. To account for this, the percentage of area that is wetlands surrounding each site was calculated at 100m, 1km, and 2km radii from the perimeter (edge) of each site. The surface area of wetlands was calculated either using digitised maps, or small wetlands were measured directly in the field (e.g. Broughton Island). The measurements of wetland area also included each wetland site included in this SoS study, which had been digitised. The final models included areas of mangrove/saltmarsh as Wetlands.

Impervious Surfaces %: The percentage of area of impermeable surface ('Impermeable': roads and paved surfaces, houses and buildings; urban infrastructure) surrounding each site was calculated at 100m, 1km, and 2km radii from the perimeter (edge) of each site. The impermeable surfaces variable was included as a potential factor inhibiting dispersal between wetlands.

Native Vegetation %: The area of native vegetation ('Vegetation') surrounding each site was calculated at 100m, 1km, 2km, and 5km radii from the perimeter (edge) of each site. The final models included areas of mangrove/saltmarsh as Native Vegetation. The native vegetation variable was included as a potential factor facilitating dispersal between wetlands.

Spatial Connectivity

Edge-to-edge distances were measured between each focal wetland site and its surrounding neighbouring sites that were also SoS wetlands, within a 1000m radius. These distances were then weighted by the relationship between the probability of dispersal and the neighbouring distances. The probability of dispersal was calculated using distances moved by GGBF during a mark-recapture study of 122 GGBF on Kooragang Island (see Hamer et al. 2008). The weighting function was a negative exponential relationship between the probability of dispersal from wetland *i* to *j* and their edge-to-edge distances ($d_{i,j}$, at 10-m increments)

$$w_{i,j} = e^{-0.005181 d_{i,j}}$$

Connectivity was measured as the distance-weighted sum of surrounding permanent wetlands within a 1km radius, weighted by this relationship. Only permanent wetlands within 1km were used as they are likely to provide refuge habitat during dry periods when ephemeral wetlands are dry. This approach aligns with that of Valdez et al. (2015), that the number of permanent waterbodies within 1km of sites was the best predictor of GGBF occupancy on Kooragang Island. Permanent wetlands had a permanent hydroperiod (hydroperiod score = 3).

Spatial connectivity of each site ($Conn_i$) to other surveyed sites was calculated as:

$$Conn_i = \log_e\left(\sum\left(w_{i,j} \times perm_j\right) - \left(w_{i,i} \times perm_i\right)\right)$$

where $w_{i,j}$ is a distance-weighting function, and $perm_j$ is a binary variable defining each neighbouring site's (*j*) hydroperiod as either permanent and equal to 1, or zero otherwise.

Variable Correlations

A matrix of correlation coefficients was constructed to determine relationships between habitat and landscape variables considered in the occupancy model (Appendix A, Fig A.1). Strong correlations were regarded as those with an absolute co-efficient of > 0.6. There were strong correlations among the landscape variables measured at radii of 100m, 1000m and 2000m (see 2016/2017 annual monitoring report (West et al. 2017). Appendix A, Fig A.2). Accordingly, the landscape variable with the most biologically plausible influence on GGBF occupancy was retained for the occupancy modelling: 'Wetlands % 1km'. There was a moderately-positive correlation between connectivity and Wetlands % 1km (r = 0.54), which was not unexpected given that wetland permanency and wetland configuration were both elements of each variable. There was also a moderate correlation between connectivity and the mean percentage cover of aquatic vegetation (r = 0.59). A correlation between connectivity and effective wetland area (r = 0.57) likely results from wetland permanence being a component of both variables. Nonetheless, these correlation coefficients were all <0.6.

Dynamic Occupancy Modelling

A dynamic (three-season) site-occupancy model was constructed to estimate the probabilities of GGBF occupancy (ψ), detection (ρ), persistence (ϕ), and colonisation (col) (MacKenzie et al. 2003). This model was fitted to the observation data for GGBF (frogs seen and heard only, excluding tadpoles and any opportunistic observations) at the 227(172*) sites surveyed during the 2016/2017 season, and to data collected at the 188 sites surveyed in 2017/2018 and at the 275(220*) sites surveyed in 2018/2019. Variables that were suspected to influence the detection or occurrence of GGBF were selected for inclusion as covariates in the model.

The following variables were included to examine their influence on the **probability of GGBF detection** (ρ) at each site during each survey:

1. **Effort** = survey effort; i.e. the survey duration in minutes × number of surveyors;
2. **Date** = survey date converted to a Julian date format, since July 1st, and transformed to a scale between 0-2ϖ and modelled as a trigonometric function (sine and cosine);
3. **MaxT** = maximum daily air temperature on day of the survey;
4. **Rain** = standardised rain in previous 14 days to a survey;
5. **Wet** = whether a site was wet (contained water) or was dry during a survey; and
6. **zoneRE** = a random effect term for detection specific to each management zone. The random effect accounted for additional unmeasured factors that may have influenced detection of GGBF; for instance, regional variation in breeding phenology.

The following variables were included to examine their influence on the **initial probability of GGBF occupancy** (ψ) at sites:

1. **EC** = Mean electrical conductivity (in 2016/2017) measured in µS/cm and log transformed;
2. **Aqveg** = Mean percentage cover of aquatic vegetation calculated using estimates of the percentage cover of three major groups of aquatic vegetation strata at each site: submerged, emergent, and floating vegetation (in 2016/2017);
3. **Gambusia** = Presence/absence of Gambusia (in 2016/2017);
4. **Aqveg × Gambusia** = an interaction between percentage of Aquatic vegetation and presence of Gambusia at a site;
5. **Wetlands%1km** = Percentage cover of wetlands within a 1km radius;
6. **ImpSurf%1km** = Percentage of impervious surface cover within a 1km radius;
7. **NatVeg%1km** = Percentage of native vegetation cover within a 1km radius;

The following variables were included to examine their influence on the **probability of persistence** (ϕ) of GGBF occupancy at sites within Kooragang, Crookhaven, and Molonglo management zones in 2017/2018 and 2018/2019:

1. **EC** = Mean electrical conductivity (in 2016/2017) measured in µS/cm and log transformed;
2. **Aqveg** = Mean percentage cover of aquatic vegetation calculated using estimates of the percentage cover of three major groups of aquatic vegetation strata at each site: submerged, emergent, and floating vegetation (in 2016/2017);
3. **Gambusia** = Presence/absence of Gambusia (in 2016/2017);
4. **Aqveg × Gambusia** = an interaction between percentage of aquatic vegetation and presence of Gambusia at a site;
5. **Wetlands%1km** = Percentage cover of wetlands within a 1km radius;
6. **Perm_Conn** = Distance-weighted connectivity to permanent wetlands within a 1km radius (log transformed), see Spatial Connectivity section above;

The Conn.Occ parameter (distance-weighted connectivity to occupied wetlands) was examined as a potential influence of the **probability of GGBF colonisation (col)** at sites surveyed after the first year (Eqn. 6). Conn.Occ was estimated by summing the number of distance-weighted sites that were estimated to be occupied in the first year (2016/2017) within a 1km radius (and log transformed). This approach allowed meta-population dynamics to be considered as colonisation could occur from neighbouring occupied wetlands. The Perm parameter was a score of water permanence (1 = semi-permanent or permanent hydrology, 0 = ephemeral or sporadic hydrology) assessed to determine if GGBF colonised sites based on their observed hydroperiod.

Probabilities of detection (Eqn. 3), initial occupancy (Eqn. 4) and persistence (Eqn. 5) were each modelled as an additive logistic function of the above variables. Each variable was included as a linear term except the interaction term for Aqveg and Gambusia, and trigonometric function for date. All variables except Perm and Gambusia (which were binary variables: 1 or 0) were standardised by subtracting the mean from each value and dividing by 2 standard deviations. Missing values for survey effort were replaced by the mean over all samples in that management zone.

The model structure was as follows:

$$GGBFobservations = Bernoulli\ (\mathrm{Occ}_t \times \rho) \qquad Eqn. 1$$

$$Occ_{t=1} = Bernoulli\ (\psi) \qquad Eqn. 2$$

$$\begin{aligned} logit(\rho) = {} & \alpha_p + \beta_{\rho 1} \times Effort + \beta_{\rho 2} \times sine\left(\frac{date \times 2 \times \pi}{365}\right) \\ & + \beta_{\rho 3} \times cosine\left(\frac{date \times 2 \times \pi}{365}\right) + \beta_{\rho 4} \times MaxT \\ & + \beta_{\rho 5} \times Rain + \beta_{\rho 6} \times Wet + ZoneRE.p_{zone_i} \end{aligned} \qquad Eqn. 3$$

$$\begin{aligned} logit(\psi) = {} & \alpha_\psi + \beta_{\psi 1} \times EC + \beta_{\psi 2} \times AqVeg + \beta_{\psi 3} \times Gambusia \\ & + \beta_{\psi 4} \times AqVeg \times Gambusia + \beta_{\psi 5} \times Wetlands\%1km \\ & + \beta_{\psi 6} \times \mathrm{ImpSurf\%1}km + \beta_{\psi 7} \times \mathrm{NatVeg\%1km} \end{aligned} \qquad Eqn. 4$$

$$\begin{aligned} logit(\phi) = {} & \alpha_\phi + \beta_{\phi 1} \times EC + \beta_{\phi 2} \times AqVeg + \beta_{\phi 3} \times Gambusia \\ & + \beta_{\phi 4} \times AqVeg \times Gambusia \\ & + \beta_{\phi 5} \times Wetlands\%1km + \beta_{\phi 6} \times Perm\ Conn \end{aligned} \qquad Eqn. 5$$

$$\begin{aligned} logit(\mathrm{col}) = {} & \alpha_{\mathrm{col}} + \beta_{\mathrm{col1}} \times Conn.Occ_{t-1} \\ & + \beta_{\mathrm{col2}} \times Perm_{t-1} \end{aligned} \qquad Eqn. 6$$

$$Occ_{t+1} = Occ_{t=1} \times \phi + (1 - Occ_{t=1}) \times col \qquad Eqn. 7$$

where α is the intercept and β is the coefficient for each variable examined for the probabilities of detection (ρ) and occupancy (ψ) in the model.

A Bayesian occupancy model was fitted to the data using Markov chain Monte Carlo (MCMC) sampling in JAGS version 4.2.0 (Plummer 2016) and called from program R using the JagsUI package (Kellner 2017). Uninformative vague priors were used for each alpha (α; intercept) and beta coefficient (β) parameter (~dnorm(0, 0.01)). Parameter estimates and their 95% credible intervals (95% CIs) were drawn from 400,000 MCMC samples after a burn-in of 200,000 samples and thinning every tenth Markov chain. Model convergence was assessed over the three Markov chains using the Gelman-Rubin statistic with an R-hat <1.01 considered an acceptable threshold of convergence. The relative importance of estimated parameters in the model was assessed using the magnitude of the parameter estimates (i.e. absolute values) and the 95% CIs. Parameters with 95% CIs that did not overlap zero were considered to indicate a stronger and clearer relationship than parameters with 95% CIs overlapping zero.

Results

Parameter Estimates and General Model Performance

The three-season dynamic occupancy model for the GGBF across the seven management zones produced several clear relationships. These relationships are described for the two models where the Broughton Island sites were aggregated or unaggregated:

Aggregated Model

Factors Influencing GGBF Detection:

There was a strong positive relationship between the probability of detection and survey effort (Table 2, Fig 2), indicating that detection increased with the number of surveyors and/or duration of the survey. The probability of detection also increased if the site was wet (i.e. contained water; Table 2, Fig 2). The date or time of year of the survey did not appear to influence the probability of detection as the 95% CI overlapped zero (Table 2, Fig 2). There were also no clear relationships between the maximum daily temperature on the day of the survey or rainfall in the previous 14 days and the probability of detecting GGBF.

The random error term on the probability of detection was clearly positive for the Meroo management zone, with a 95% CI that did not overlap zero, while the error term for the Crookhaven management zone was clearly negative (Table 2, Fig 2). These results indicate that the probability of detection in these two populations was different from the other five management zones, with detection being higher and lower in the Meroo and Crookhaven populations, respectively.

Factors Influencing Initial GGBF Occupancy Probability:

There was a strong positive relationship between the probability of occupancy and wetland electrical conductivity (Table 2, Fig 3). There was a strong positive relationship also with the percentage cover of wetlands within 1km of a site (Table 2, Fig 3). The relationship of initial occupancy with the four remaining variables was unclear, as the 95% CIs of the regression coefficients overlapped zero. However, previous analyses (e.g. year 2) suggest some of these variables may also influence GGBF site occupancy, although further data is required to clarify these relationships. For example, the regression coefficient for aquatic vegetation was positive and the 95% CI overlapped zero only slightly (Table 2). Also, the interaction between aquatic vegetation and the presence of Gambusia tended towards a negative relationship (Table 2), which suggests that Gambusia may influence GGBF occupancy when the percentage of aquatic vegetation cover is low.

Factors Influencing GGBF Persistence Probability:

There was a strong positive relationship between the probability of persistence and connectivity to permanent wetlands (Table 3, Fig 4). There was a negative relationship between the probability of persistence and the presence of Gambusia at a site, although the 95% CI overlapped zero slightly (Table 3, Fig 4). There were no clear relationships between persistence and the remaining three variables examined (Table 3, Fig 4). Despite the uncertainty, the estimated beta coefficients tended to suggest a negative influence of wetland electrical conductivity, and a positive influence of aquatic vegetation.

Factors Influencing GGBF Colonisation Probability:

There was a negative relationship between the probability of GGBF colonisation and the hydrology of the site if it was a permanent or semi-permanent wetland, although the 95% CI overlapped zero slightly (Table 3, Fig 5); i.e. GGBF were more likely to colonise ephemeral wetlands. There was also a positive relationship between colonisation and the connectivity to occupied neighbours for the model that included the aggregated data at Broughton Island. This result suggests that colonisation tended to be more likely when sites contained water and were situated near other occupied sites.

Unaggregated Model

Results for the unaggregated model were generally like those obtained for the aggregated model. Differences and similarities between the models are highlighted below.

Factors Influencing GGBF Detection:

As in the aggregated model, there was a strong positive relationship between the probability of detection and survey effort (Table 2, Fig 2). However, the probability of detection also increased with survey date (cosine) indicating that detection was higher later in the season, although the relationship was relatively weak (Table 2, Fig 2). There was a strong positive relationship between detection and site wetness (Table 2, Fig 2). Results for the random error terms on the probability of detection were similar to those obtained in the aggregated model.

Factors Influencing Initial GGBF Occupancy Probability:

Unlike the aggregated model, there were no clear relationships between the probability of occupancy and either wetland electrical conductivity or the percentage cover of wetlands within 1km (Table 2, Fig 3).The relationship of initial occupancy with the four remaining variables was also unclear, as the 95% CIs of the regression coefficients overlapped zero.

Factors Influencing GGBF Persistence Probability:

Like the aggregated model, there was a strong positive relationship between the probability of persistence and connectivity to permanent wetlands (Table 3, Fig 4). There was a negative relationship between persistence and the presence of Gambusia at a site, although the 95% CI overlapped zero slightly (Table 3, Fig 4). There were no clear relationships between persistence and the other three variables examined (Fig 4).

Factors Influencing GGBF Colonisation Probability:

Like the aggregated model, there was a negative relationship between GGBF colonisation and hydrology of the site if it was a permanent or semi-permanent wetland (Table 3, Fig 5). However, unlike the aggregated model, the relationship between colonisation and the connectivity to occupied neighbours was uncertain for the unaggregated model.

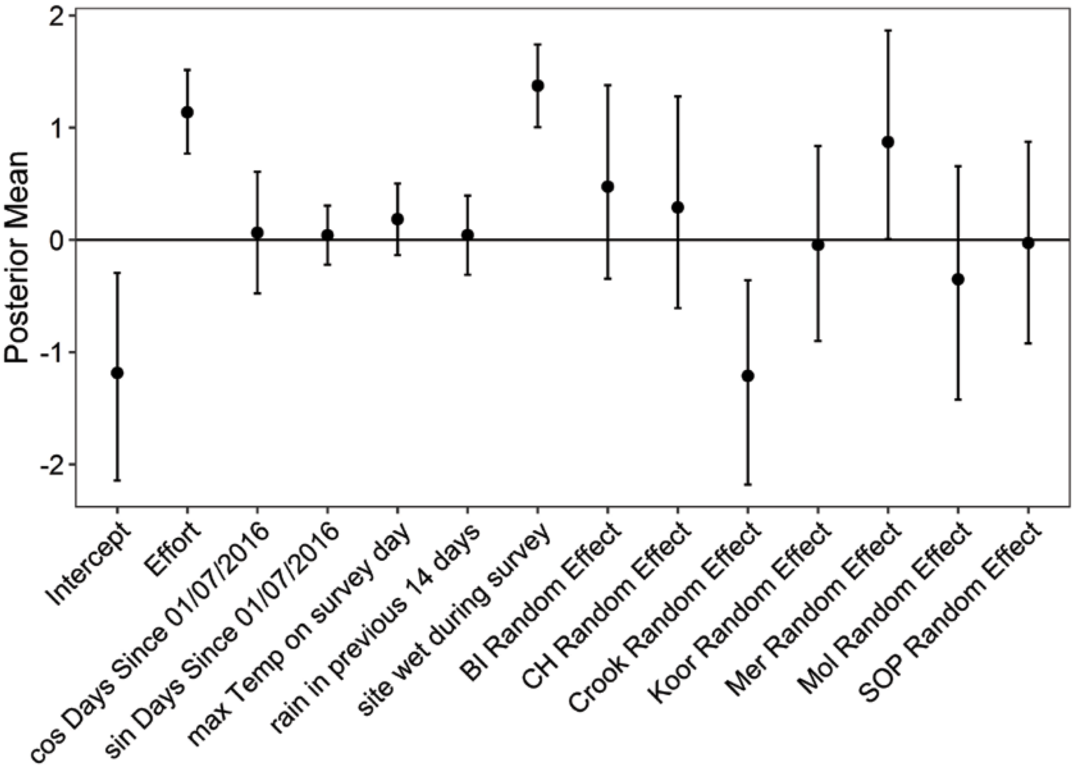
Table 2. Intercept and beta coefficient parameter estimates derived for detection and occupancy probabilities from a dynamic occupancy model for the GGBF, based on observation records collected at six management zones in NSW. Model results were taken from the two models where the Broughton Island sites were aggregated or unaggregated. Model results are presented as the mean of the posterior distributions, and the 2.5th and 97.5th percentiles (95% credible intervals). Results in **bold** *highlight important relationships (95% CIs do not overlap zero). Random error terms for the probability of detection correspond to the six management zones: BI = Broughton Island; CH = Crescent Head; CRO = Crookhaven; KI = Kooragang Island; MER = Meroo; MOL = Molonglo; SOP = Sydney Olympic Park; SD = standard deviation.*

Variable	Aggregated Model	Non-aggregated Model
Prob. of Detection		
Intercept	**-1.2 (-2.1 - -0.3)**	**-1.2 (-2.1 - -0.21)**
Survey effort	**1.1 (0.8 - 1.5)**	**1.0 (0.7 - 1.4)**
Survey date (*sine)	0.1 (-0.5 - 0.6)	0.4 (-0.1 - 0.8)
Survey date (*cosine)	0.0 (-0.2 - 0.3)	0.2 (0.0 - 0.5)
Max. air temp	0.2 (-0.1 - 0.5)	0.3 (0.0 - 0.6)
Rainfall	0.0 (-0.3 - 0.4)	0.1 (-0.2 - 0.4)
Wet	**1.4 (1.0 - 1.7)**	**1.2 (0.9 - 1.5)**
Random error: BI	0.5 (-0.3 - 1.4)	-0.3 (-1.2 - 0.6)
Random error: CH	0.3 (-0.6 - 1.3)	0.3 (-0.7 - 1.3)
Random error: CRO	**-1.2 (-2.2 - -0.4)**	**-1.1 (-2.2 - -0.27)**
Random error: KI	0.0 (-0.9 - 0.8)	0.1 (-0.8 - 1.0)
Random error: MER	**0.9 (0 - 1.9)**	**1.1 (0.2 - 2.1)**
Random error: MOL	-0.4 (-1.4 - 0.7)	-0.4 (-1.6 - 0.6)
Random error: SOP	0.0 (-0.9 - 0.9)	0.2 (-0.7 - 1.1)
SD (random error)	**0.9 (0.4 - 2.0)**	**1.0 (0.5 - 2.2)**
Prob. of Initial Occupancy		
Intercept	**1.7 (0.7 - 3.7)**	**1.5 (0.5 - 4.2)**
EC	**2.1 (0.3 - 4.2)**	0.9 (-0.8 - 2.3)
Aqveg	0.4 (-0.8 - 1.8)	1.1(-0.4 - 3.7)
Gambusia	0.4 (-1.3 - 4.5)	1.0 (--1.9 - 9.9)
Aqvegx Gambusia	-1.0 (-4.8 – 2.0)	1.1 (-6.0 - 10.5)
Wetland 1km	**2.1 (0.3 - 4.5)**	-1.0 (-1.3 - 5.7)
Impervious Surfaces 1km	-0.2 (-1.5 - 1.9)	-0.4 (-2.1 - 0.9)
Native Veg 1km	0.8 (-0.6 - 2.5)	0.1 (-2.2 - 1.8)

Table 3. Intercept and beta coefficient parameter estimates derived for variables influencing persistence and colonisation probabilities from the two dynamic occupancy models for the GGBF (aggregated and unaggregated Broughton Island sites), based on observation records collected at seven management zones in NSW. Model results are presented as the mean of the posterior distributions, and the 2.5th and 97.5th percentiles (95% credible intervals). Results in **bold** *highlight important relationships (95% CIs do not overlap zero). The estimated model deviance is also shown.*

Variable	Aggregated Model	Non-aggregated Model
Prob. of Persistence		
Intercept	**1.8 (0.7 - 4.4)**	**4.2 (1.3 - 13.7)**
EC	-0.1 (-1.8 - 1.6)	0.7 (-1.2 - 2.5)
Aqveg	0.5 (-1.2 - 2.8)	0.3 (-5.2 – 6.9)
Gambusia	-1.0 (-3.3 - 0.1)	-2.9 (-12.4 - 0.1)
Aqveg × Gambusia	-1.6 (-4.2 - 0.6)	0.8 (-5.7 - 6.5)
Wetlands%1km	-0.2 (-1.2 - 1.0)	-0.6 (-1.9 - 1.0)
Perm Conn	**5.1 (0.1 - 16.3)**	**9.3 (0.3 - 25.2)**
Prob. of Colonisation		
Intercept	1.5 (-1.5 - 14)	0.1 (--3.0 - 3.7)
Conn.Occ	0.8 (-0.2 - 5.7)	0.7 (-0.2 - 4.1)
Perm	-6.0 (-21.6 - 0.4)	**-8.7 (-24.0 - -1.3)**
Model Deviance	1372.7 (1307.7 - 1447)	1880.9 (1802.1 - 1963.5)

A wetland at Kooragang Island, New South Wales during a survey for the green and golden bell frog. Image. Chad Beranek



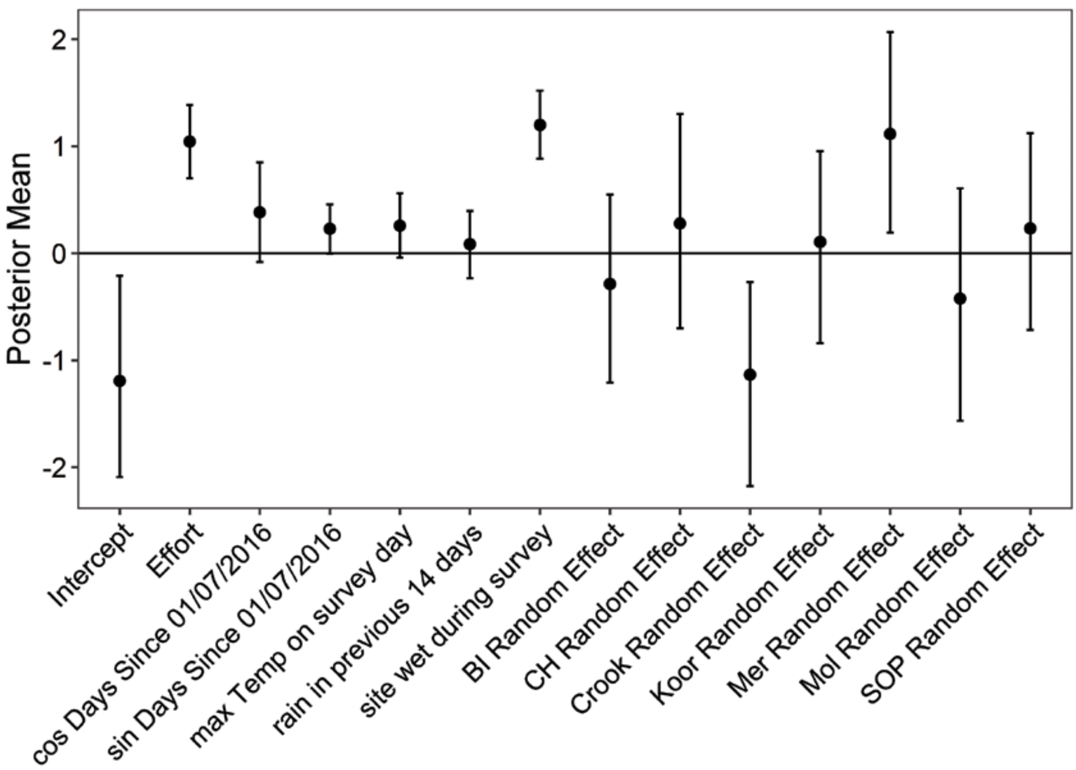


Figure 2. Estimated intercept and coefficient parameters and random zone effects for the logistic regression of the ***probability of GGBF detection*** *at sites. Top panel: Model results following aggregation of Broughton Island sites (aggregated model). Bottom panel: Model results including all 75 Broughton Island sites (unaggregated model). Random zone effects are coded as the zone name prefix followed by "Random Effect".*

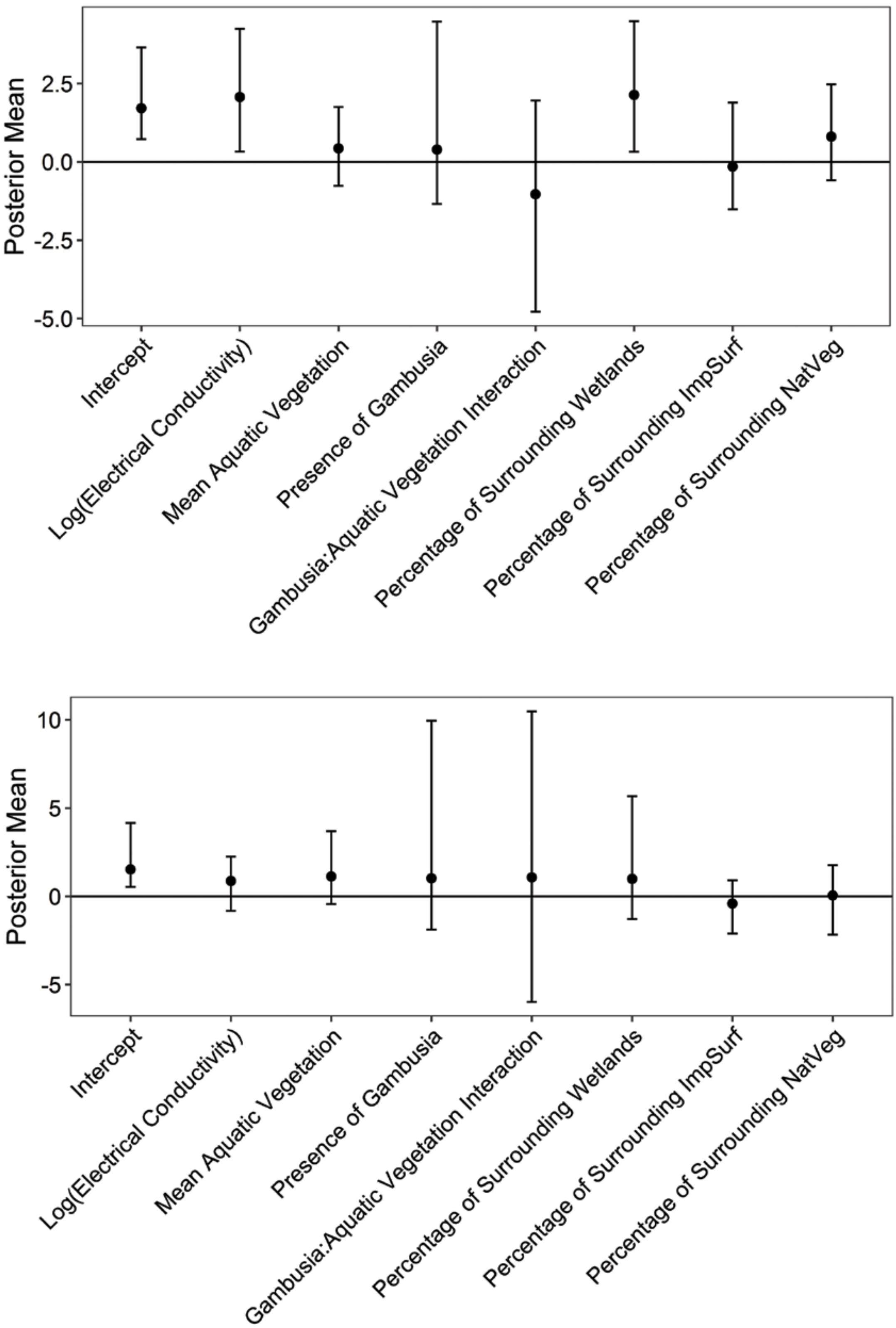


Figure 3. Estimated intercept and coefficient parameters for the logistic regression of the ***probability of initial GGBF occupancy*** *at sites (first year that zone was surveyed).* *Top panel:* *Model results following aggregation of Broughton Island sites (aggregated model).* *Bottom panel:* *Model results including all 75 Broughton Island sites (unaggregated model). The presence of Gambusia was modelled as 1 = detected, 0 = not detected; all other variables were standardized (centred) prior to inclusion in the analysis.*

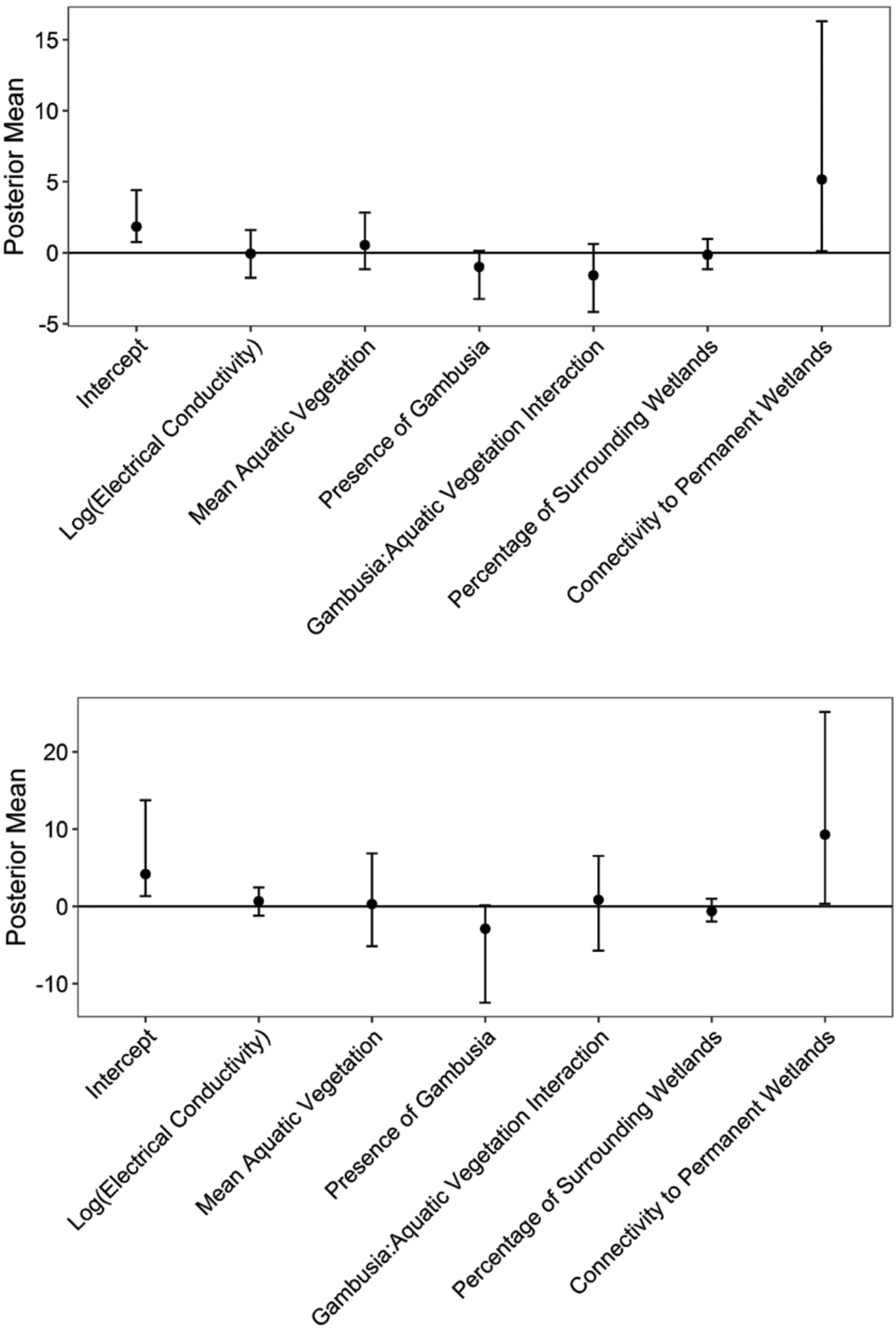


Figure 4. Estimated intercept and coefficient parameters for the logistic regression of the ***probability of GGBF persistence*** *at sites.* Top panel: *Model results following aggregation of Broughton Island sites (aggregated model).* Bottom panel: *Model results including all 75 Broughton Island sites (unaggregated model). Hydroperiod was modelled as 1 = semi-permanent or permanent hydrology; 0 = ephemeral or sporadic hydrology; all other variables were standardized (centred) prior to inclusion in the analysis.*

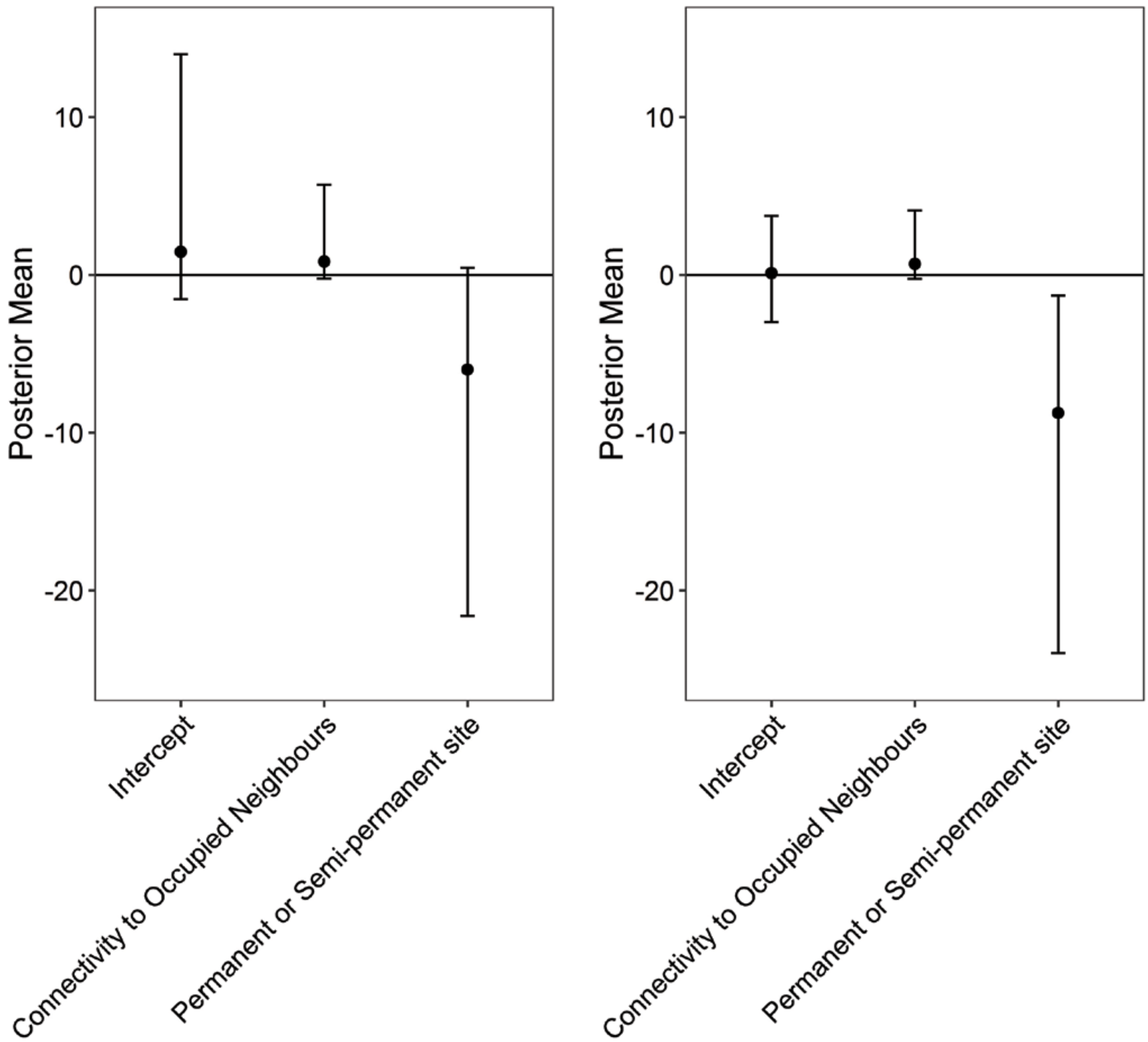


Figure 5. Estimated intercept and coefficient parameters for the logistic regression of the probability of ***GGBF colonisation*** *at sites from year 1 to year 2, and year 2 to year 3.* Left panel: *Model results following aggregation of Broughton Island sites (aggregated model).* Right panel: *Model results including all 75 Broughton Island sites (unaggregated model).*

In terms of model performance, the R-hat values for all parameters were less than 1.01 indicating that the model reached convergence. Node trace plots were also inspected to confirm multi-chain convergence. This suggests the model can be used to make reliable inferences about site occupancy and relationships with the variables that were assessed. The Deviance Information Criterion (DIC) of the unaggregated model (with 75 Broughton Island sites) was 1880.9 and with the aggregated model (20 Broughton Island sites) was 1372.7.

Site Occupancy Estimates

Dynamic occupancy analysis using the aggregated model results suggest that a mean of 175.9 (95% CI: 154.0 – 199.0) of the 287 sites across the seven management zones were occupied in 2018/2019 (Table 4). The estimated overall proportion of occupied sites for the seven management zones in 2018/2019 was 0.61 (95% CI: 0.54 – 0.69; Table 4). This is substantially lower than the proportion of occupied sites estimated in 2016/2017 (0.74; 95% CI: 0.63 – 0.85) and suggests there has been a decline in the number of sites occupied by the GGBF over the three-year period. The unaggregated model suggested a mean of 229.3 (95% CI: 201.0 – 259.0) of the 342 sites across the seven management zones were occupied in 2018/2019 (Table 4). The estimated overall proportion of occupied sites for the seven management zones in 2018/2019 was 0.67 (95% CI: 0.59– 0.76; Table 4), which is slightly higher than the estimated proportion of the aggregated model (but still well within the 95% CI).

In 2018/2019, Broughton Island had the highest estimated proportion of occupied sites in both the aggregated model (0.86, 95% CI: 0.80 – 0.95) and unaggregated model (0.82, 95% CI: 0.72 – 0.89) (Table 4). The estimated proportion of occupied sites for Broughton Island in 2018/2019 clearly exceeded the estimates for Crookhaven, Kooragang Island, Molonglo and Sydney Olympic Park, as the 95% CI for Broughton Island did not overlap with the intervals for the other four management zones (Table 4, Fig 6).The estimated proportion for Broughton Island in the aggregated model was substantially higher than the estimated global proportion of occupied sites, as the 95% CIs do not overlap.

In the aggregated model, Crookhaven had the lowest estimated proportion of occupied sites (0.39, 95% CI: 0.32 – 0.48) in 2018/2019 (Table 4, Fig 6). This estimate was also substantially less than the estimated global proportion of occupied sites, as the 95% CIs do not overlap. However, in the unaggregated model, there were no distinct differences in the estimated proportion of occupied sites across the five management zones, as the wider 95% CIs overlapped one another (Table 4, Fig 6).

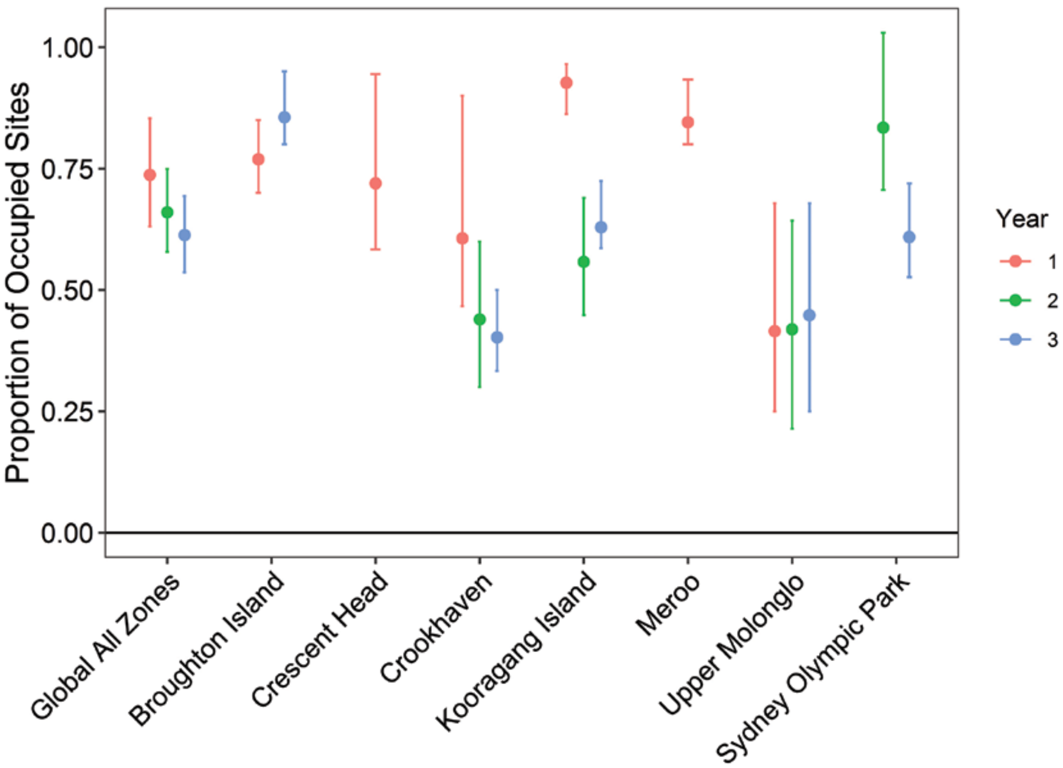
According to the aggregated model, there has also been a clear decline in the proportion of sites occupied at Crookhaven and at Kooragang Island from 2016/2017 – 2018/2019(Table 4, Fig 6). The estimated mean proportion of occupied sites at Sydney Olympic Park declined substantially from 2017/2018 – 2018/2019, however because the 95% CIs are wide and overlap the actual change in occupancy is uncertain (Table 4, Fig 6). The estimated proportion of occupied sites at Molonglo is relatively low and mean occupancy has remained steady at around 0.43 since 2016/2017, with the 95% CIs overlapping for the three years of surveys. However, the wide credible intervals of the Molonglo estimates mean that changes in occupancy are uncertain which is caused by a low number of repeat surveys at sites during the 2nd and 3rd year of the program.

A wetland at Molonglo New South Wales. Image: Ben Scheele

*Table 4 (see opposite). The observed and estimated number of occupied sites (occ.) and proportion (prop.) of occupied sites at the seven GGBF populations. The overall number and proportion of occupied sites for all management zones is shown as occ.global and prop.global, respectively. See Table 1 for an explanation of the zone codes. The number of sites assessed in each zone is shown in parentheses. Note global observations and modelled estimates could only be derived using management zones at which data was collected as indicated by *. Light grey values of estimated site occupancy are for sites where no sampling events occurred, and therefore have relatively wide credible intervals.*

	Apparent Observed Occupancy			Estimated Site Occupancy								
Variable	**2016/2017**	**2017/2018**	**2018/2019**	**2016/2017**			**2017/2018**			**2018/2019**		
				Mean	2.5%	97.5%	Mean	2.5%	97.5%	Mean	2.5%	97.5%
Aggregated Model												
occ.BI (n=20)	14	-	12	**15.4**	14.0	17.0	15.5	10.0	19.0	**17.1**	16.0	19.0
occ.CH (n=36)	21	-	-	**25.9**	21.0	34.0	26.5	19.0	33.0	26.3	18.0	33.0
occ.CRO (n=31)	10	4	10	**18.2**	14.0	27.0	**13.2**	9.0	18.0	**12.1**	10.0	15.0
occ.KI (n=28)	25	11	16	**26.9**	25.0	28.0	**16.2**	13.0	20.0	**18.2**	17.0	21.0
occ.MER (n=30)	24	-	-	**25.4**	24.0	28.0	21.2	15.0	26.0	20.3	14.0	26.0
occ.MOL (n=28)	7	1	1	**11.6**	7.0	19.0	**11.7**	6.0	18.0	**12.5**	7.0	19.0
occ.SOP (n=114)	-	27	55	88.2	63.0	108.0	**85.1**	72.0	105.0	**69.4**	60.0	82.0
*occ.global (n=287)	101	43	94	**211.5**	181	245	**189.4**	166.0	215.0	**175.9**	154.0	199.0
prop.BI	0.70	-	0.53	**0.77**	0.70	0.85	**-**	-	-	**0.86**	0.80	0.95
prop.CH	0.58	-	-	**0.72**	0.58	0.94	**-**	-	-	**-**	-	-
prop.CRO	0.33	0.13	0.32	**0.59**	0.45	0.87	**0.43**	0.29	0.58	**0.39**	0.32	0.48
prop.KI	0.87	0.38	0.53	**0.96**	0.89	1.00	**0.58**	0.46	0.71	**0.65**	0.61	0.75
prop.MER	0.80	-	-	**0.85**	0.80	0.93	**-**	-	-	**-**	-	-
prop.MOL	0.25	0.03	0.04	**0.41**	0.25	0.68	**0.42**	0.21	0.64	**0.45**	0.25	0.68
prop.SOP	-	0.27	0.48	**-**	-	-	**0.75**	0.63	0.92	**0.61**	0.53	0.72
*prop.global	0.35	0.15	0.33	**0.74**	0.63	0.85	**0.66**	0.58	0.75	**0.61**	0.54	0.69

	Apparent Observed Occupancy			Estimated Site Occupancy								
Variable	**2016/2017**	**2017/2018**	**2018/2019**	**2016/2017**			**2017/2018**			**2018/2019**		
				Mean	2.5%	97.5%	Mean	2.5%	97.5%	Mean	2.5%	97.5%
Unaggregated Model												
occ.BI (n=75)	49	-	40	**53.3**	50.0	58.0	59.9	53.0	66.0	**61.6**	54.0	67.0
occ.CH (n=36)	21	-	-	**28.7**	22.0	36.0	27.4	18.0	35.0	28.7	19.0	36.0
occ.CRO (n=31)	10	4	10	**20.3**	15.0	30.0	**14.9**	10.0	21.0	**13.4**	10.0	18.0
occ.KI (n=28)	25	11	16	**26.3**	24.0	28.0	**17.8**	14.0	21.0	**18.5**	17.0	21.0
occ.MER (n=30)	24	-	-	**25.1**	24.0	28.0	22.9	17.0	27.0	21.9	14.0	27.0
occ.MOL (n=28)	7	1	1	**13.9**	8.0	23.0	**13.2**	7.0	21.0	**13.9**	7.0	21.0
occ.SOP (n=114)	-	27	55	86.3	63.0	111.0	**81.3**	67.0	94.0	**71.4**	62.0	84.0
*occ.global (n=342)	136	43	122	**254.0**	222.0	292.0	**237.3**	212.0	262.0	**229.3**	201	259
prop.BI	0.65	-	0.53	**0.71**	0.67	0.77	**-**	-	-	**0.82**	0.72	0.89
prop.CH	0.58	-	-	**0.80**	0.61	1.0	**-**	-	-	**-**	-	-
prop.CRO	0.33	0.13	0.32	**0.65**	0.48	0.97	**0.48**	0.32	0.67	**0.43**	0.32	0.58
prop.KI	0.86	0.38	0.57	**0.94**	0.86	1.0	**0.64**	0.50	0.75	**0.66**	0.64	0.75
prop.MER	0.80	-	-	**0.84**	0.80	0.93	**-**	-	-	**-**	-	-
prop.MOL	0.25	0.03	0.04	**0.50**	0.29	0.82	**0.47**	0.25	0.75	**0.50**	0.25	0.75
prop.SOP	-	0.27	0.48	**-**	-	-	**0.71**	0.59	0.82	**0.63**	0.54	0.74
*prop.global	0.40	0.13	0.36	**0.74**	0.65	0.85	**0.69**	0.62	0.77	**0.67**	0.59	0.76



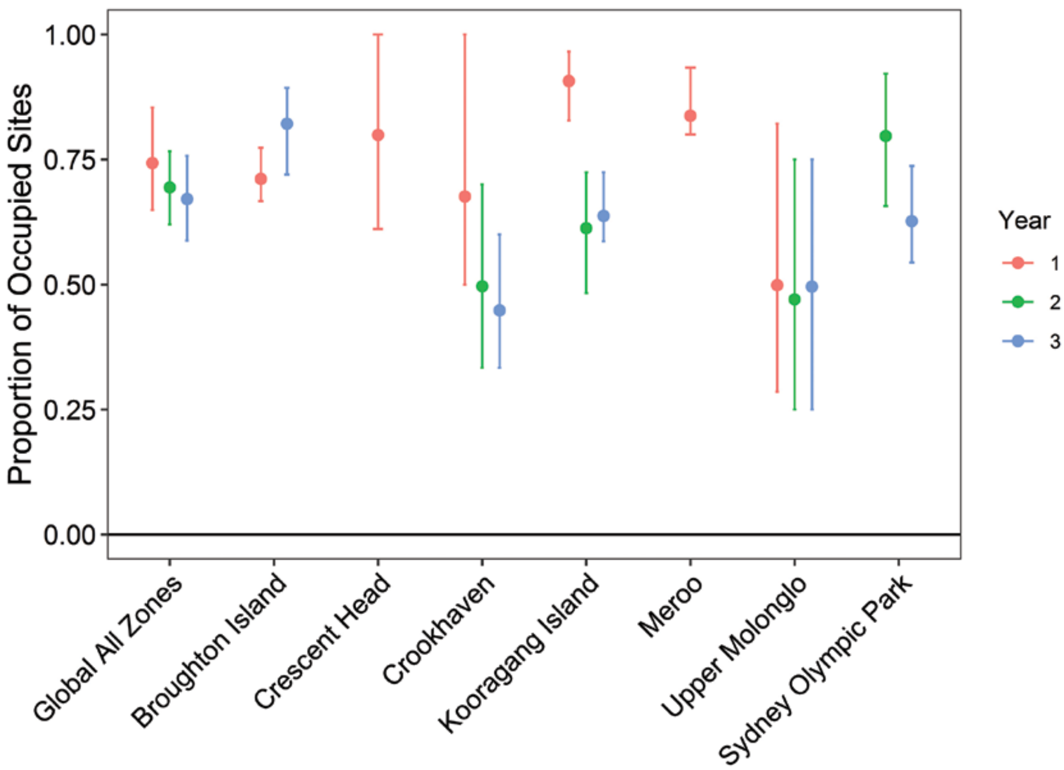


Figure 6. Estimated proportion of sites occupied by GGBF at each management zone and overall (Global). Points indicate the mean estimated proportions of occupied sites and vertical lines represent 95% credible intervals. ***Top panel:*** *Model results following aggregation of Broughton Island sites (aggregated model).* ***Bottom panel:*** *Model results including all 75 Broughton Island sites (unaggregated model). Red points and lines are shown for estimates of site occupancy in 2016/2017 and green points and lines show estimates of site occupancy in 2017/2018 and blue points and lines show estimates of site occupancy in 2018/2019. Results of site occupancy are only shown for the zones at which data was collected. Global Zones Surveyed provides an estimate of the proportion of occupied sites for the sites and zones that were surveyed in each year.*

Discussion

Dynamic Occupancy Model Findings

Dynamic occupancy modelling suggests that the mean proportion of occupied sites has declined across the seven management zones during the three years of the SoS program. Declines appear to have occurred at Crookhaven, Kooragang Island and Sydney Olympic Park, whereas occupancy at the other management zones appears to be relatively stable from 2016/2017 – 2018/2019. Clear changes in occupancy were apparent at Kooragang Island in the aggregated and unaggregated models, and at Crookhaven in the aggregated model. At other zones there were wide and overlapping estimates of the proportion of occupied sites indicating no clear trends in occupancy.

Factors Influencing Initial GGBF Site Occupancy, Persistence and Colonisation

The results of the new analysis modelling factors associated with GGBF occupancy in 2018/2019 were slightly different to results obtained in 2016/2017 and 2017/2018. This is in part due to the provision of new and updated data from field researchers, particularly the new data from Sydney Olympic Park. Like the 2016/2017 and 2017/2018 results, there was a strong positive relationship between the initial probability of occupancy and the proportion of wetlands within 1km (aggregated model only). There was also a strong positive relationship between the probability of persistence and connectivity to permanent/semi-permanent wetlands (both aggregated and unaggregated models). These results highlight the importance of landscape-scale connectivity, especially to permanent wetlands. However, there was a negative relationship between the probability of colonisation and wetland hydrology, indicating that GGBF are more likely to colonise ephemeral wetlands. These results imply that a mosaic of interconnected permanent/semi-permanent and ephemeral wetlands is required to increase the probability of GGBF populations remaining extant. Finally, in 2018/2019 there was a strong positive relationship between the initial probability of occupancy and wetland electrical conductivity (aggregated model only). A detailed discussion of how these variables may be influencing occupancy, and potential reasons why other variables had no apparent relationship with occupancy, is included in the 2016/2017 report.

Wetland (site) connectivity to other permanent wetlands was clearly positively associated with the persistence of GGBF at sites. However, declines at management zones in 2018/2019 are likely to be linked to reductions in rainfall, with many wetlands being dry at the time of the second and third season surveys, despite holding water in 2016/2017. Nonetheless, other biophysical factors may also drive declines in site occupancy that could be identified in subsequent years of the program if additional data is collected. Habitat loss and modification for GGBF are a concern for the long-term viability of populations. For instance, occupancy rates by GGBF at sites in Crookhaven over a three-year period (2013/2014 – 2015/2016) averaged around 0.65, compared to subsequent estimates of 0.59 (2016/2017) and 0.43 (2017/2018), thereby indicating a steady decline in occupancy at this site between 2013 and 2018 (Hamer 2018). The current results suggest that declines at Crookhaven are continuing and may require urgent action to prevent widespread local extinctions and possible extirpation in this management zone.

There was a negative relationship between the probability of persistence of the GGBF at a site and the presence of Gambusia, although there was some uncertainty with the estimates given the slight overlap of the 95% CIs with zero. There were no relationships between persistence and aquatic vegetation. Nonetheless, relationships between the probability of local extinction (the reverse of persistence) of the GGBF at sites have been evidenced with several variables; including at Crookhaven with aquatic vegetation (Hamer 2018), and at Kooragang Island with distance to nearest permanent waterbody (Valdez et al. 2015), the number of permanent waterbodies within 1km of a site (Valdez et al. 2015), and waterbody area and local population size (Hamer & Mahony 2010).

Probability of Detection

As reported in 2016/2017 and 2017/2018, the probability of detection increased with survey effort, indicating that greater numbers of surveyors and more time spent surveying a site is beneficial for detecting GGBF. The results in year 1 and year 2 also showed an increased probability of detection with survey date, but this relationship was only apparent in 2018/2019 in the unaggregated model, suggesting more data is required to clarify this relationship. The probability of detection in year 3 increased if sites contained water, which fits with the results obtained for the relationship between date and detection: the probability was highest early in the season, which was likely due to wetlands containing water in spring when the surveys commenced, because many wetlands had dried out towards the middle of the summer season in January.

Limitations of Dynamic Occupancy Modelling

Surveys were only conducted at four management zones in 2017/2018 and therefore site occupancy could not be estimated at the three unsurveyed zones, which also likely reduced the accuracy of the estimated "global" proportion of sites occupied across all seven management zones.

Collected and reported survey data differed between each of the management zones. Therefore, several potentially important variables (e.g. water depth) could not be thoroughly examined in this analysis.

Saving our Species Program Management Actions

These findings have clear implications for the management of remnant GGBF populations in NSW. Importantly these results highlight that a network of interconnected wetlands is likely to be crucial for GGBF persistence at sites, as connectivity increases the likelihood that GGBF will occupy sites and colonise previously unoccupied sites. Wetland loss and fragmentation, including disconnection from surrounding non-breeding terrestrial habitat, will ultimately lead to reduced occupancy rates and potentially result in local extinction of populations. The results also suggest that GGBF may require some access to permanent wetlands, but that ephemeral wetlands are also likely to be colonised during the breeding season. The findings of this and previous studies (Hamer et al. 2008; Valdez et al. 2015) suggest it would be prudent to recommend that a mosaic of permanent ('deep') and ephemeral ('shallow') wetlands are created. Establishment of a protected network or mosaic of wetlands was proposed as a management action in the SoS program for the Kooragang Island population, while conserving movement corridors was recommended for the Crookhaven population. Whilst the occupancy analysis indicates wetland creation could help to increase GGBF occupancy rates at the management zones surveyed, additional data is required to justify other management activities (see Recommendations).

The proportion of occupied sites has clearly declined at Kooragang Island and occupancy appears to be declining at Crookhaven and Sydney Olympic Park. Management interventions may be required at these management zones to halt further declines in subsequent seasons. The 2017/2018 and 2018/2019 summers in NSW were particularly dry because of the continuing drought. At Kooragang Island, for example, some wetlands dried out that had previously contained water over a 15-year period. A similar situation occurred at Crookhaven and suggests that the best management action may be to create deep wetlands to increase water permanence at sites, as discussed above. Habitat loss for the GGBF continues to occur at Crookhaven and a strategic approach is recommended to ensure that core areas of habitat and habitat corridors are protected. Active management of the GGBF at Sydney Olympic Park should include additional habitat creation and enhancement/augmentation of existing wetlands to increase habitat quality and connectivity within the four habitat precincts. Importantly, evaluating how the populations at each management zone respond to future rainfall and water availability is crucial for guiding management decisions. However, the influence of disease such as chytrid and the role of non-native fish in causing continued declines in population occupancy needs to be explored in each of the management zones.

Recommendations

The results of the dynamic occupancy analysis suggest that further improvements could be made to the current design of the SoS program for the GGBF:

1. GGBF use wet (inundated) sites and our results indicate that connectivity to permanent wetlands is positively associated with GGBF persistence. Therefore, **we recommend management actions that increase the availability of and connectivity to permanent wetlands to enhance GGBF persistence within management zones.** This could be achieved by creating deep wetlands located within the average dispersal distance of currently occupied sites (i.e. within 200m; see Hamer et al. 2008).
2. The analysis suggests a negative relationship between the persistence of GGBF and the occurrence of Gambusia at sites. Therefore, **we recommend management actions that reduce or eradicate Gambusia from sites to enhance GGBF persistence**. The creation of ephemeral wetlands close to permanent wetlands may provide fish-free breeding sites. We also recommend that both tadpole and non-native fish presence and/or abundance should be assessed using consistent techniques during future years of the GGBF SoS program to further verify the nature of the relationship between Gambusia and GGBF.
3. Additional data is required to further clarify the drivers of GGBF occupancy and persistence at sites. Understanding the role of hydrology, water chemistry, and thermal properties of wetland sites upon GGBF occupancy (particularly persistence and colonisation probabilities) are likely to be crucial for informing management actions. This study was not able to clarify the influence of these factors as some zones were not surveyed, and at the surveyed zones there was missing data and inconsistencies in the units of measurement in the supplied data. This may be resolved over time through the collection of additional data (e.g. water availability and water temperature), although more data and consistently collected data from all management zones would further strengthen the inferences that can be drawn from this research. **We therefore recommend that greater attention be given to the collection of consistent data between, and at each of the management zones in the GGBF SoS program**.
4. As highlighted in each year's report, understanding the influence of chytrid fungus on GGBF may be crucial to ensure the species' long-term persistence at some management zones. Chytrid is clearly an important factor for many amphibian populations both within Australia and globally. Research for the closely-related Growling Grass Frog indicates that the species' persistence is dependent on access to some warm and relatively saline wetlands as these wetlands reduce chytrid prevalence and infection intensity (Heard et al. 2014). **We recommend that frogs should be swabbed at key sites throughout the SoS management zones so that the prevalence of chytrid infection can be assessed and related to wetland characteristics and environmental conditions**. Importantly, all swab samples must be able to be related to specific wetland sites within the management zones. We recommend that swabs should be collected from at least 22-25 frogs per season at each site, and preferably from at least five representative sites in each management zone, although alternative sampling protocols could be considered given the low number of frogs detected at some sites. Sampling should be spread across the season and include some sampling during cool and wet periods. Sites should be selected based on their variation in parameters that could influence chytrid prevalence such as their size, depth, vegetation cover, electrical conductivity, salinity, and water pH.
5. **We recommend that additional analyses should be performed to verify the effect of spatial autocorrelation on the results presented in this study**. This could be achieved by clustering sites within each management zone that are near one another and adding a categorical 'cluster term' as a random effect in each model. Stakeholders should be consulted to discuss how best to cluster sites. This will be particularly important for sites like Broughton Island and Sydney Olympic Park where many sites occur near one another. To offset this effect, the data analysis in 2018/2019 was run using models where the sites at Broughton Island were aggregated or unaggregated.

References

Alford RA, Richards SJ. 1999. Global amphibian declines: A problem in applied ecology. *Annual Review of Ecology and Systematics* 30:133-165.

Goldingay RL, Parkyn J, Newell DA. 2017. No evidence of protracted population decline across 17 years in an unmanaged population of the green and golden bell frog in north-eastern New South Wales. *Australian Journal of Zoology* 65:87-96.

Hamer AJ. 2018. Accessible habitat and wetland structure drive occupancy dynamics of a threatened amphibian across a peri-urban landscape. *Landscape and Urban Planning* 178:228-237.

Hamer AJ, Lane SJ, Mahony MJ. 2002. Management of freshwater wetlands for the endangered green and golden bell frog (*Litoria aurea*): roles of habitat determinants and space. *Biological Conservation* 106:413-424.

Hamer AJ, Lane SJ, Mahony MJ. 2008. Movement patterns of adult green and golden bell frogs *Litoria aurea* and the implications for conservation management. *Journal of Herpetology* 42:397–407.

Hamer AJ, Mahony MJ. 2007. Life history of an endangered amphibian challenges the declining species paradigm. *Australian Journal of Zoology* 55:79-88.

Hamer AJ, Mahony MJ. 2010. Rapid turnover in site occupancy of a pond-breeding frog demonstrates the need for landscape-level management. *Wetlands* 30:287-299.

Heard GW, Scroggie MP, Clemann N, Ramsey DSL. 2014. Wetland characteristics influence disease risk for a threatened amphibian. *Ecological Applications* 24:650-662.

Kellner K. 2017. jagsUI: A Wrapper Around 'rjags' to Streamline 'JAGS' Analyses. R package Version 1.4.8, https://CRAN.R-project.org/package=R2jags.

MacKenzie DI, Nichols JD, Hines JE, Knutson MG, Franklin AB. 2003. Estimating site occupancy, colonization, and local extinction when a species is detected imperfectly. *Ecology* 84:2200-2207.

MacKenzie DI, Nichols JD, Royle JA, Pollock KH, Bailey LL, Hines JE 2006. Occupancy estimation and modeling: inferring patterns and dynamics of species occurrence. Academic Press, San Diego.

Plummer M. 2016. JAGS: Just Another Gibbs Sampler, https://sourceforge.net/projects/mcmc-jags/.

Valdez JW, Stockwell MP, Klop-Toker K, Clulow S, Clulow J, Mahony MJ. 2015. Factors driving the distribution of an endangered amphibian toward an industrial landscape in Australia. *Biological Conservation* 191:520-528.

Wassens S, Hall A, Spencer J. 2017. The effect of survey method on the detection probabilities of frogs and tadpoles in large wetland complexes. *Marine and Freshwater Research* 68:686-696.

Weir LA, Royle JA, Nanjappa P, Jung RE. 2005. Modeling anuran detection and site occupancy on North American Amphibian Monitoring Program (NAAMP) routes in Maryland. *Journal of Herpetology* 39:627-639.

West M, Hamer A, McCarthy M. 2017. *Litoria aurea* (Green and Golden Bell Frog) *Occupancy Analysis Report 2016/2017*. The University of Melbourne, Parkville, Victoria.

West M, Hughes N, Hamer AJ. 2018. *Litoria aurea* (Green and Golden Bell Frog) *Dynamic Occupancy Analysis Report for the NSW Saving Our Species Program: 2017/2018*. Unpublished Report for NSW Office of Environment and Heritage.

White AW, Pyke GH. 2008. Green and golden bell frogs in New South Wales: current status and future prospects. *Australian Zoologist* 34:319-333.

Further information:

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