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Rice fields support the global stronghold for an endangered waterbird

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ABSTRACT

Novel, agricultural habitats are increasingly recognised for the conservation opportunities they present. Rice fields show particular promise for waterbirds and 'wildlife-friendly' farming initiatives, but most work has focussed on conspicuous, well-known species and the value of flooding harvested fields to provide non-breeding habitat. The Australasian bittern (*Botaurus poiciloptilus*) is a cryptic, globally endangered waterbird that breeds in rice crops in the Riverina region of New South Wales, Australia. To assess the size of the population, we surveyed rice fields from 2013-2017 on randomly selected farms in the Murrumbidgee valley. Occupancy modelling yielded population estimates ranging from 368-409 for 'early permanent water' crops. With conservative estimates for the unsurveyed Murray region, and for fields with 'delayed permanent water', we suggest that in most years the Riverina's rice fields attract approximately 500-1000 individuals to breed, representing about 39% of the global population. Water allocations for irrigation drive the area of rice grown, with the total Riverina rice crop ranging from 5,000-113,000 ha during 2010-2019. Previously overlooked, rice fields can play an integral role alongside natural wetlands in the conservation of the Australasian bittern. Contraction of the ponding period to increase water use efficiency and the transition of Riverina irrigators to cotton farming are immediate threats to this population. We recommend trialling 'bittern-friendly' rice growing incentives, development of supportive policy and acknowledgement that some water allocated to agriculture in the Murray-Darling Basin can have explicit environmental benefits. The significance of rice fields to other cryptic wetland species should also be assessed.

Keywords: novel habitat, agricultural wetland, threatened waterbirds, Australasian bittern, Murray-Darling Basin, environmental water.

1. Introduction

Agriculture is a major driver of biodiversity loss, but some of the novel habitats it creates have important biodiversity values (Jóhannesdóttir et al., 2019; Meddenhall et al., 2012; Millennium Ecosystem Assessment, 2005; O'Bryan et al., 2016; Tilman et al., 2001). These values are increasingly recognised for the conservation opportunities they present (Chester and Robson, 2013; Martínez-Abraín and Jiménez, 2016; Scherr and McNeely, 2008; Sirami et al., 2013; Wright et al., 2012). Once largely dismissed as being incompatible with conservation, agricultural areas are being re-imagined for their role in improving species habitat and ecological function concurrent with food production (Bowman et al., 2017; Stoeckli et al., 2017). 'Wildlife-friendly' and 'land sharing' approaches have been championed to integrate biodiversity conservation into agriculture as an alternative to 'land sparing', which is, theoretically, centred on expanding protected areas alongside more intensive production (Balmford et al., 2005; Fischer et al., 2008; Green et al., 2005; Phalan et al., 2011; Pywell et al., 2012; Tscharntke et al., 2012). More recently, the implied, inevitable trade-off between yield and biodiversity of these two approaches has been challenged and their potential synergistic role highlighted (Fischer et al., 2017; Gonthier et al., 2014; Kremen, 2015; Kremen and Merenlender, 2018).

Rice is considered one of the world's key human food crops; grown on over 163 million hectares and eaten by over 3 billion people every day (FAO, 2017). The habitat value of rice fields is widely acknowledged and, while they are no substitute for natural wetlands, their conservation role as agricultural wetlands for wildlife-friendly farming is growing. Waterbirds have been a focal group for much of this research, particularly in North America and Europe (e.g. Czech and Parsons, 2002; Elphick, 2000; Elphick et al., 2010; Fasola and Ruiz, 1996; Longoni et al., 2011; Strum et al., 2013; Tourenq et al., 2001), but also other regions (e.g. India: Sundar and Kittur, 2013; Japan: Usio, 2014). However, much of this work has focused on conspicuous, well-known species and the value of flooding harvested fields to provide non-breeding habitat, and little is known of the use of rice fields by Australian waterbirds, especially for cryptic and threatened species (Elphick, 2015; Herring and Silcocks, 2014; Ibáñez et al., 2010; Taylor and Schultz, 2010).

The Australasian bittern (*Botaurus poiciloptilus*) is both cryptic and threatened, and there has been an urgent need to identify its most important breeding areas (Hafner et al., 2000; Kushlan and Hancock, 2005). Like the closely related Eurasian Bittern (*B. stellaris*; Longoni et al., 2007; 2011), the Australasian bittern has been known to occur in rice crops for several decades (Disher, 2000). However, the significance of the population using rice fields has not been documented. Before a severe drought from 2000-2009, Australia was thought to support approximately 2500 mature Australasian bitterns (Garnett and Crowley, 2000), but in 2011 a revised national population estimate of 247-796 individuals (Garnett et al., 2011) resulted in the species being listed as Endangered in Australia under the *Environment Protection and Biodiversity Conservation Act 1999* (Threatened Species Scientific Committee, 2011). The Australian population was divided among Tasmania, which was thought to support 12-100 individuals, the presumably isolated population in south-western Australia with 38-124, and 197-574 individuals occurring in south-eastern Australia, between south-east South Australia and south-east Queensland (Garnett et al., 2011). This last population is probably panmictic as satellite-tracked bitterns from the Riverina region in the centre of this area have been recorded flying 400-600 km to coastal wetlands in Victoria, South Australia and New South Wales (M. Herring, I. Veltheim, A. Silcocks, unpublished data). Before the current study, the largest known breeding concentrations occurred in the Barmah-Millewa wetland complex along the Murray River in New South Wales and Victoria, where up to 73 booming males occur after major flooding events (Belcher et al., 2017), and in the ephemeral swamps of the Bool Lagoon wetland complex in South Australia, with up to 20 booming males (B. Green and A. Silcocks, pers. comm.). Globally, the species also occurs in New Caledonia and New Zealand. The last records in the former were two calls heard in 1998 (Ekstrom et al., 2002) and, if it persists, there are probably fewer than 50 individuals (Martínez-Vilalta, 2019). In the latter, a national population estimate of 580-725 birds from nearly 20 years ago (Heather and Robertson 2000) could now be considered too high given the rate of habitat degradation and decline in the number of booming males at key wetlands, including Whangamarino, the nation's most important bittern site (O'Donnell and Robertson, 2016; Ogle and Cheyne, 1981). The global population is currently estimated at 1000-2499 mature individuals, with the species considered *Endangered* (Birdlife International, 2019).

It is important to understand the conservation significance of the bittern population using rice fields because major water reforms in the Riverina and broader catchment – the Murray-Darling Basin – aim to restore degraded ecosystems and conserve biodiversity by addressing the over-allocation of water for irrigated agriculture. The *Murray-Darling Basin Plan*, enacted by the Australian Government is 2012, is recovering 'environmental water' through buybacks and infrastructure upgrades (MDBA, 2016; Pittock and Connell, 2010; Ross and Connell, 2016). This contentious, highly politicized reform has polarized water resource management, pitting environmentalists and irrigators against each other (Gross and Dumaresq, 2014), with nature conservation and farming posited as mutually exclusive. The presence of bitterns in rice suggests that the reality is more complex. This was recognised in 2012 by the creation of the *Bitterns in Rice Project* as a collaboration between the Ricegrowers' Association of Australia and Birdlife Australia. The project aims to be an inclusive, grassroots initiative that raises awareness of the bittern, increases understanding of its use of rice fields and identifies what rice growers can do to support bittern conservation alongside profitable food production (Bitterns in Rice Project, 2019). Pivotal to this project, and pertinent to the broader debate about environmental water recovery and use, is quantification of the Australasian bittern population breeding in the Riverina rice fields.

2. Methods

2.1 Study area

The Riverina region of New South Wales, Australia, comprises two major river valleys; the Murrumbidgee and Murray. While it is dominated by highly modified agricultural landscapes, it still contains remnant wetlands of high conservation value that are known to support substantial numbers of waterbirds (Bino et al., 2015; Kingsford et al., 2013). Our study focused on the Murrumbidgee Valley, which comprises two main irrigation areas: Murrumbidgee and Coleambally. Rice is grown from October to May in irrigated bays with water that has been stored in upstream reservoirs (or diverted directly from rivers), then distributed through networks of channels. The rice crop area varies greatly between years and is primarily dependent on the amount of water available for irrigation, which is determined through regional allocations that are driven by dam levels from floods and droughts (Ashton et al. 2016). The 2000-2001 season was the largest on record with 184 400 ha, while the 2007-2008 season was the lowest since 1929 with 2160 ha (SunRice, 2002; 2008).

Rice seed is almost exclusively supplied to growers by SunRice®, a Riverina-based company that has the sole rice export license for New South Wales. Rice is grown in two main ways in the Riverina: 1) aerially-sown from light aircraft or ground-based machinery into bays that are flooded, typically in October, with water ponded throughout the growing season ('early permanent water'); or 2) direct drill-sown into bays that are periodically flushed with water and not ponded until after germination, typically in December ('delayed permanent water'). Outside Australia, the former is often referred to as 'water seeded', and the latter as 'alternate wetting and drying' (LaHue et al., 2016; Sander et al., 2017). In both crop types, water levels are initially around 5 cm once 'permanent water' is applied, then gradually increased to 25-30 cm and maintained until about February/March when water levels recede in preparation for harvest, with any excess water drained. The agronomic practice of 'lasering' (the combination of geographic information systems with earth-moving machinery to create the desired microtopography) results in near-uniform water levels in each rice bay except in the surrounding ditches, which are deeper. Crops are usually rotated every 1-3 years to avoid a build-up of weeds (Ashton et al., 2016; Department of Primary Industries, 2015).

2.2 Pilot study 2012-13

Community engagement was initially undertaken in November and December 2012 to elicit bittern sightings from rice growers throughout the Riverina. Members of the newly formed *Bitterns in Rice Project* committee encouraged the reporting of bittern sightings through their respective networks, while local radio, newspaper, websites and field days complemented these efforts. From the reported sightings, a verification process was undertaken to identify Australasian bittern sites during the 2012-13 rice season. The elimination of Nankeen night-herons (*Nycticorax caledonicus*), which are commonly misidentified as Australasian Bitterns, was usually achieved during phone conversations, with most of these erroneous sightings recognised because of the large number of birds reported or the presence of birds roosting in trees. A naïve occupancy estimate of 0.38 (17/63 sites) from a single 1-hour survey suggested a large, significant bittern population was using rice fields, particularly in the Coleambally and Murrumbidgee Irrigation Areas, but the extent of bias in sites sampled was unknown. We then sampled 30 randomly selected rice farms in the Coleambally Irrigation Area. This 1057 ha sample represented 5.7% of Coleambally's rice area during the 2012-13 season. It produced a lower naïve occupancy of 0.17 (5/30 sites) but still suggested that the population was substantial. The variability in site area (7.3-93.5 ha), the small sample size and zero-inflated data made modelling problematic. All five of the randomly selected farms with bitterns had aerially-sown crops with 'early permanent water'. These types of crops became the focus of random sampling in subsequent seasons and site area was standardised.

2.3 Random farm selection 2013-17

Bitterns were surveyed at randomly selected rice farms during four rice seasons (2013/14-2016/17) in the Murrumbidgee and Coleambally Irrigation Areas, with the exception of the 2013-14 season, when only the Coleambally Irrigation Area was sampled (Table 1). Farms growing rice in the Murrumbidgee Irrigation Area were identified from a list provided by SunRice® Grower Services of all rice farms that had placed a seed order; water orders were used to identify farms in the Coleambally Irrigation Area. The proportion of sites in each region reflected historic total rice crop areas: one third in Coleambally and two thirds in Murrumbidgee. Properties were selected randomly and landholders were contacted to verify a current rice crop and its area, and to determine the sowing method. If the crops were aerially sown, then access was sought to conduct a bittern survey. We surveyed 26 to 80 sites per season, with all sites sampled twice, except during the 2015-16 season when sites were only sampled once. Permission to conduct a bittern survey was not granted at three farms across the entire study, a number we considered negligible given the sample size.

2.4 Standardized surveys and study sites

Standardized survey methods specific to rice fields were developed to target the species. The discrete, relatively small and homogeneous habitat patches, with low vegetation and on-farm access tracks, offer methodological consistency not available other Australasian bittern habitats (e.g. Williams et al., 2018). The surveys were undertaken at each site during the mid-part of the rice season (December-March), primarily from mid-December to early February. This period coincides with the bittern breeding season, when there is sufficient rice cover to support bitterns, and encompasses the time when males make a distinctive territorial booming call. The intention of the surveys was to record both sexes but only mature individuals. While there is no data on age at first breeding of the Australasian bittern, the Eurasian bittern can breed after one year (Kushlan and Hancock, 2005). The timing meant it was implausible that any of the recorded birds were locally fledged young from the season, but there is a possibility that a small number of juveniles from nests early in the season could have dispersed to rice fields after fledging in the few suitable natural wetlands in the region. Each survey commenced before three hours after sunrise or within three hours before sunset to maximize detection, as the species is crepuscular and the booming call of males is given mostly around dawn and dusk (Kushlan and Hancock, 2005; Williams et al., 2018). Surveys were not undertaken when wind speed exceeded 30 kmph. Each survey lasted one hour, consisting of approximately 30 minutes of driving on vehicular tracks around rice fields and between bays, where tracks were available, at approximately 8 kmph; and 30 minutes of walking and standing, scanning crops with binoculars and listening for booming males.

For inclusion of a bittern during a survey it had to have either been observed on-site, or triangulation of the booming call revealed with certainty that the bird was on-site. Triangulation was not always possible because calls were either too faint or distant, or because access was constrained by a shortage of tracks. During surveys, bitterns were regularly confirmed off-site at distant rice crops. The risk of double-counting was addressed in several ways (see also *Occupancy modeling* below). After booming, males raise their heads above the crop, allowing them to be located through triangulation and observed. Since males are concealed while booming, any seen are additional but were only included when the previously recorded birds were concurrently accounted for.

Individual sites (N=189; Table 1, Figure 1) across the four seasons ranged from 23-30 ha. This corresponded to the smallest rice crops on an individual farm but was sufficient to encompass a booming male's home range, as suggested by the pilot study and studies of the Eurasian bittern (e.g. Gilbert et al., 2005). Sites on each farm were delineated to be as similar in area as possible and to encompass an entire rice field. However, rice fields of 31-45, 61-68 and 91 ha (i.e. where site combinations of 23-30 ha did not encapsulate the entire field) occurred on 15 of the 95 farms sampled from 2013-2017. The residual area on these farms was not sampled.

Table 1: Sample size and proportion of total area for Early Permanent Water (EPW) crops in four rice seasons for the Murrumbidgee and Coleambally Irrigation Areas. Proportions of EPW based on 2014-15 data. *Coleambally Irrigation Area only

Rice season	No. farms	No. sites	Sample total (ha)	Per cent of total EPW crops
2013-14*	26	44	1149	17.61*
2014-15	41	80	2155	9.86
2015-16	12	26	703	6.14
2016-17	16	39	1017	3.77

2.5 Occupancy modeling

Occupancy modelling can be useful for population studies of rare and elusive species because of the relatively low numbers of individuals and imperfect detection during surveys, with multiple surveys used to account for detectability (MacKenzie et al., 2004). Although Mackenzie and Royle (2005) suggest that with rare species it is most efficient to survey more sampling units less intensively, they still recommend sampling units be surveyed a minimum of three times, even when detection probability is high (> 0.5 survey^{-1}). We could not sample units more than twice so prioritised sample size over repeat sampling. We used the pilot study data and followed Stauffer et al. (2002) to determine the probability of detecting the species when present and thus estimate appropriate sample sizes. We used a single season rather than multiple season occupancy model (Hines et al., 2010; MacKenzie et al., 2002) because new random farms had to be selected each season because of crop rotation.

We fitted a base model using constant detection (p: the probability of detection of the species within a site when it is present) and occupancy (ψ: the proportion of rice field sites occupied) throughout each of the four seasons and two surveys per season as the starting point. We then compared this model to models that included survey specific detection probabilities, annual differences in occupancy and detection, and the relationship of detection probability with several covariates. We used Akaike's information criteria (AIC) to assess which, if any, of the models were considered more parsimonious than the base model.

All occupancy models were fitted using Presence ® software (Hines, 2006) and model fit was assessed using the observed and expected frequencies of detection histories (MacKenzie and Bailey, 2004). In general, although the data we collected were sparse and fitting models with multiple parameter estimates was problematic, we were able to extract estimates by using constrained models with fixed parameter estimates. Potential violations of the site 'closure' assumption (Mackenzie et al., 2004) were addressed by restricting sampling to the breeding season, and discounting potentially erroneous records. Twice on farms with contiguous sites where bitterns had been recorded during the first survey, additional 'occupied' sites recorded during the second survey were discounted and excluded from analyses. Also, twice in 2013-14, and once in each 2015-16 and 2016-17, we discounted single individuals seen flying from the direction of another site surveyed earlier on the same day.

2.6 Covariates used in occupancy modelling

We measured the following explanatory, survey-specific variables that may influence bittern detectability:

1: Minutes elapsed since sunrise or until sunset; calculated from the mid-way point of a survey.
2-3: Wind speed, and ambient temperature**.**
4-6: Rice height, rice aerial cover per cent and water depth; each calculated as the mean of two measurements in separate rice bays.
7-8: Vegetation cover on banks and weed cover in rice bays; each calculated on a scale of 1-5.
9: Area of *Typha* spp. around edges of bays; estimated to the nearest square metre.

2.7 Population size estimates

For each rice season, the Australasian bittern population size was approximated using the adjusted occupancy estimate and the total ‘early permanent water’ rice crop area, with a standardised site area of 26.5 ha, and mean abundance when present applied. Rice crop area data were obtained from RMB (2018) and it was assumed that 66% of the areas had ‘early permanent water’, based on sowing and water management data provided by SunRice® for the 2014-15 season. For the 2013-14 season, data for the Coleambally Irrigation Area was extrapolated to incorporate the Murrumbidgee Irrigation Area into the estimate.

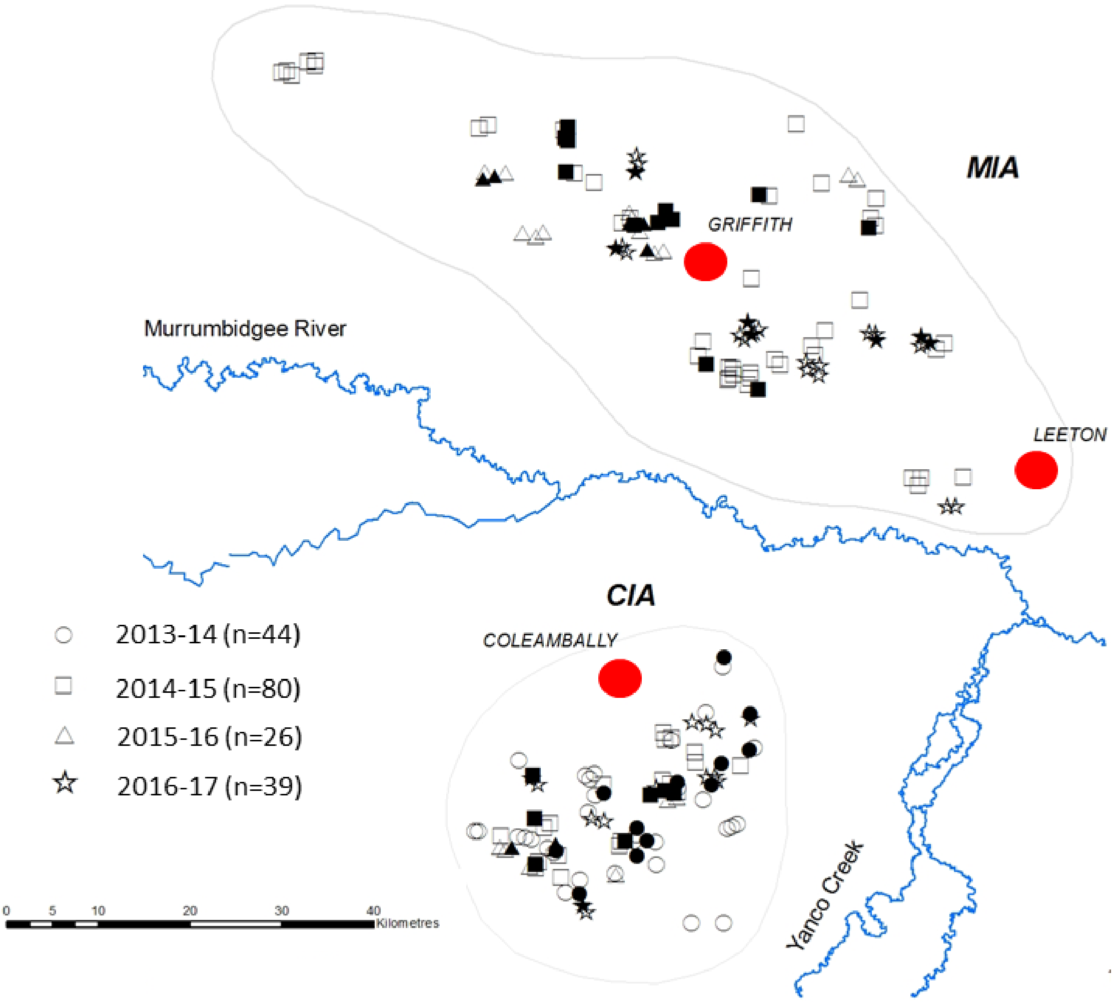

Figure 1. Study site locations (n=189) across the Murrumbidgee Irrigation Area (MIA) and Coleambally Irrigation Area (CIA) from 2013-2017. Solid shapes represent detected bitterns.

3. Results

Bitterns were recorded at 21-31 per cent of sites across the four rice seasons, with mean abundance when present of 1.33-1.75 bitterns/site (Figure 1; Table 3). A total of 72 bitterns were recorded, of which at least 24 were booming males, on 37-58 per cent of randomly selected farms with 'early permanent water' rice crops. For the occupancy modeling, data from the 2015-16 season were excluded because there were no repeat visits, even though occupancy was higher than in other seasons. The results are based on the other three seasons, all of which had two surveys per site per season, and showed a much better fit overall (χ^2 = 2.42, p > 0.34, 1000 permutations, $\hat{c}$ = 1.1) than when all four seasons were included (χ^2 = XXXX, p > XXX, 1000 permutations, $\hat{c}$ = XXX). Because only two of the surveys detected bitterns in the same site in both samples in one season, the models suggested that true occupancy was 0.96-1.0 and limited the ability to fit more than a single detectability covariate at a time. We then estimated the relationships between covariates and detection probabilities of bitterns by manually fixing the occupancy parameter. This approach allows the maximum likelihood algorithm to estimate fewer parameters because it ignores the error and achieves better detection and covariate estimates (D Mackenzie pers. comm.). For this analysis, fixed occupancy values of 0.4 to 0.8 were determined after assessing the AIC scores for models fitted using potential occupancy values of 0.1 to 0.9 (Table 2). The weights for each of the models fitted for each combination of covariates were then used to calculate the weighted average relationship between bittern detectability and the covariate and detection probabilities between surveys 1 and 2 in each season (Figure 2).

The models fitted using fixed occupancy estimates (Table 2) found that detectability was always higher in the first survey regardless of the relationship with the covariates, but decreased with minutes from sunrise/sunset and water depth but increased with rice cover and rice height (Figure 2). No other covariates showed a relationship with bittern detectability. The annual occupancy of bitterns in the study area in each of the three years was estimated by fitting models using fixed detection rates per survey of 0.15 and 0.10 for the first and second surveys respectively, approximated from the covariate analyses (Figure 2). The estimated occupancy was 0.35 in 2014, 0.32 in 2015 and 0.23 in 2017 but with no significant differences between years (Figure 3).

For the three seasons with two samples, total population estimates for 'early permanent water' crops in the Murrumbidgee and Coleambally Irrigation Areas ranged between 368 (243-520, 95% CI) and 409 (198-743, 95% CI), while a single-survey estimate using naïve occupancy for 2015-16 was 304 (Table 3).

Table 2. Models assessing the relationship between covariates and bittern detectability. In all except the last model, the occupancy was set at a fixed value of 0.4, 0.6 or 0.8 to allow the maximum likelihood procedure to have fewer parameters to estimate. Models are ranked from most to least informative relative to the base model that includes a fixed occupancy and survey specific detection probabilities. Model weights are used to generate detection curves in Figure 2.

Model	Fixed Occupancy (ψ)	Model rank	Model weight
ψ, $\hat{p}_1$×survey, $\hat{p}_2$×sunrise, $\hat{p}_3$× sunrise × survey	0.8	1	0.155
	0.6	2	0.126
	0.4	3	0.095
ψ, $\hat{p}_1$×survey, $\hat{p}_2$× rice cover $\hat{p}_3$× rice cover × survey	0.8	4	0.075
	0.6	5	0.066
	0.4	6	0.055
ψ, $\hat{p}_1$×survey, $\hat{p}_2$× rice height $\hat{p}_3$× rice height × survey	0.8	7	0.036
	0.6	9	0.031
	0.4	12	0.025
ψ, $\hat{p}_1$×survey, $\hat{p}_2$× water depth, $\hat{p}_3$× water depth × survey	0.8	8	0.034
	0.6	10	0.03
	0.4	13	0.024
ψ, $\hat{p}_1$×survey,	0.8	11	0.025
	0.7	14	0.023
	0.6	15	0.021
	0.5	16	0.019
	0.4	17	0.017
$\hat{\psi}$, $\hat{p}_1$×survey,	Occupancy estimated by model	18	0.015

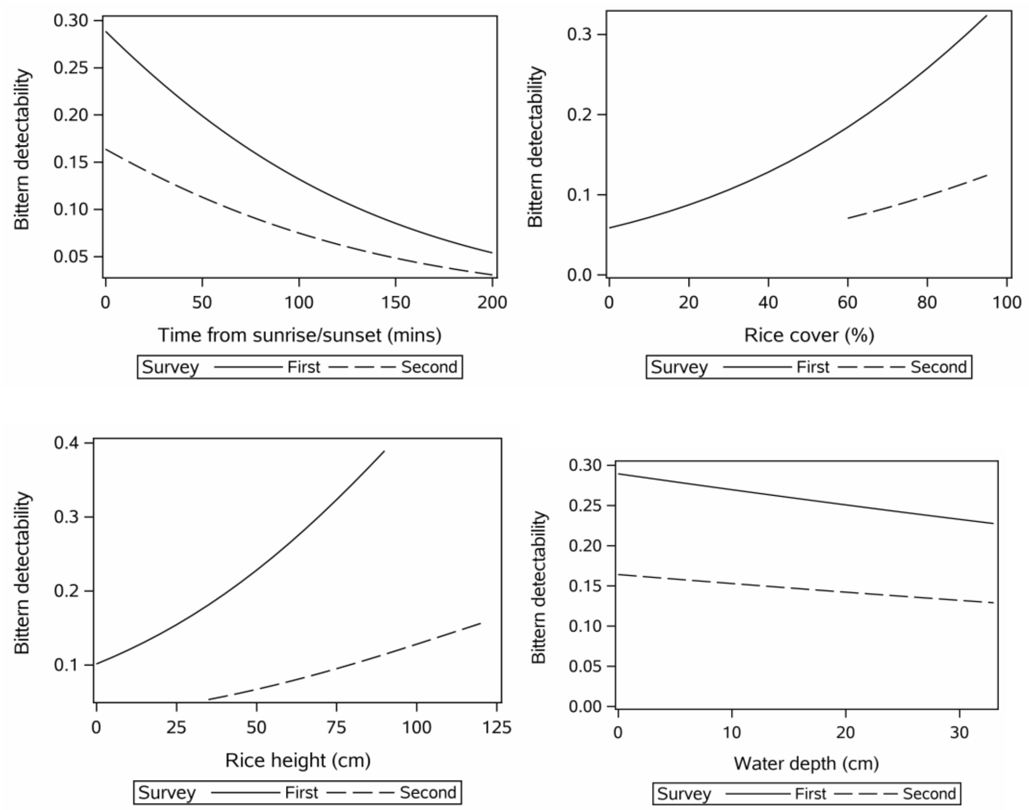

Figure 2. Relationship between bittern detectability (probability of detection) and survey covariates for the first and second surveys of the season.

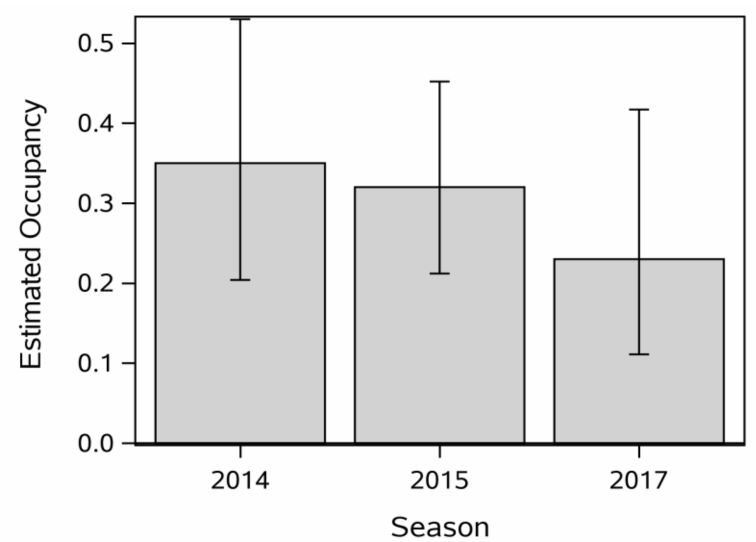

Figure 3. Estimated occupancy (+/-95% confidence interval) of the Australasian bittern at 'early permanent water' rice fields in the Murrumbidgee and Coleambally Irrigation Areas, 2014-2017.

Table 3: Australasian bittern population estimates for Early Permanent Water (EPW) rice crops in the Murrumbidgee and Coleambally Irrigation Areas. *2013-14: Using data from Coleambally Irrigation Area only.

Rice season	Occupancy (naïve)	Occupancy (adjusted) (SE)	Rice crop area (EPW, ha)	Estimated sites occupied (95% CI)	Mean abundance	Estimated population size (95% CI)
2013-14*	0.27	0.35 (0.086)	21286	281 (163-425)	1.33	**373** (216-565)
2014-15	0.26	0.32 (0.062)	21855	263 (174-372)	1.40	**368** (243-520)
2015-16	0.31	-	11445	134	1.50	**201**
2016-17	0.21	0.23 (0.079)	26980	234 (113-425)	1.75	**409** (198-743)

4. Discussion

This research demonstrates that rice fields of the Riverina in Australia support the largest known population of the endangered Australasian bittern. It establishes the importance and potential conservation role of agricultural wetlands to this cryptic and cover-dependent species. The population estimates of 368-409 individuals for the combined Murrumbidgee and Coleambally Irrigation Areas (MIA/CIA) are larger than for any other local population, individual wetland, wetland complex or area of comparable size to the Riverina rice-growing region known to support Australasian bitterns. Moreover, they are likely to be significant underestimates. They only incorporate recorded mean site abundance data (1.33-1.75) with strict conditions of inclusion in the occupancy data – avoiding violations of site closure through double-counting and the discounting of faint, unlocatable booms. An unknown number of bitterns also occurred in the unsurveyed 'delayed permanent water' crops, which accounted for 34 per cent of the total MIA/CIA rice crop area used in our analyses. Furthermore, from 2013-2017, the unsurveyed Murray region accounted for an average of 47 per cent of the total Riverina rice crop area (RMB 2018). Bittern surveys in the western Murray region during the 2017-18 season, using the same methods, produced a naïve occupancy of 0.30 (6/20) and mean abundance of 1.33/ha in 'early permanent water' rice crops (M. Herring, unpublished data), comparable to our results for the MIA/CIA. We therefore conservatively and broadly estimate that, in most years, the Riverina's rice fields attract approximately 500-1000 bitterns during the breeding season.

At the time of the most recent estimate of the Australian population, bitterns were not thought to breed in rice and the population was not accounted for (Garnett et al., 2011). Combining mid-range figures for our estimate (500-1000, 750) and the Australian population estimate (247-796, 522; Garnett et al., 2011), with New Zealand (580-725, 626; Heather and Robertson, 2000) and New Caledonia (0-50, 25; Martínez-Vilalta, 2019), the Riverina rice field population accounts for around 39 per cent of the global breeding population and 59 per cent of the Australian population. Regular post-breeding movements of at least adult males and immatures from the rice fields to coastal wetlands suggest duplicated counts are likely. The population in Tasmania may also be supplemented by birds from the mainland, including from the Riverina. Although no crossing of Bass Strait has been documented, the species has been recorded on both Flinders and King Islands in Bass Strait (Green, 1969; Green and McGarvie, 1971; McGarvie and Templeton, 1974), and the Eurasian Bittern is a regular long-distance migrant across marine barriers (Cramp and Simmons, 1977). Local counts in natural wetlands may also be part of the rice field population. For example, at least 34 bitterns were recorded at Fivebough Swamp in the Riverina in November 2015 just before the surrounding rice fields became suitable for bitterns, and all but about four had dispersed by December (M. Herring, K. Hutton, M. O'Sullivan, D. Webb, unpublished data). These connections, although challenging for population estimates, emphasise that rice fields and natural wetlands now complement each other in sustaining the Australasian bittern in south-eastern Australia, with neither habitat able to support the current population year-round.

The loss of natural wetland habitat due to the development of irrigated agriculture has been considered a key threat to the Australasian bittern and is widely implicated in its decline (Garnett et al., 2011; Threatened Species Scientific Committee, 2011). The extent to which the rice farming component of irrigated agriculture may have offset a larger decline is difficult to assess. However, it is clear now that any unmitigated loss of bittern habitat from a reduced rice crop area is itself a threat to the species and could further the decline. Three factors are likely to affect rice crops as a breeding habitat for bitterns. First, water availability through allocations to irrigators' permanent entitlements, and the cost of temporary market water, have a strong influence on the area sown to rice each season. Climate change research predicts more variable and drier conditions in the Riverina (Murray-Darling Basin Authority, 2019). During dry periods, water allocations can be sufficiently low, and temporary market water prices sufficiently high, to make rice growing marginally profitable or uneconomic and the area of rice is greatly reduced. The total Riverina rice crop ranged from 5,000-113,000 ha during 2010-2019 (RMB, 2018; Tom Howard, pers. comm.), while the 2000-2001 season was the largest on record with 184 400 ha, and the 2007-2008 season was the lowest since 1929 with 2160 ha (SunRice, 2002; 2008). During low allocation seasons, the area of natural wetland is also likely to be at its nadir, with only key wetlands maintained with environmental water. Second, alternative crops and plantings can also reduce the area of rice. Cotton has emerged as an important irrigated crop in southern New South Wales, with the area under cultivation increasing steadily from around 12 000 ha in 2003-04 to an estimated 89 320 ha in 2017-18, exceeding rice for the first time (Cotton Australia, 2017; Field, 2017). Over the past 10-15 years, an increasing number of rice growers have transitioned and now choose to use part or all of their water allocations to grow cotton (Booth Associates, 2014). Cotton is irrigated with pulses of water; the fields are not permanently inundated, an aquatic ecosystem does not develop, and they are not known to support bitterns. Third, there are strong incentives to increase water use efficiency in rice farming. Delayed permanent water, shorter season varieties and mid-season drainage are emerging trends that result in a contraction of the ponding period (Department of Primary Industries 2015; 2018). These trends in rice agronomy are likely to make crops less suitable and reduce opportunities for bitterns to breed successfully before harvest (Herring et al., unpublished data). As a form of agricultural intensification, the potential role of water use efficiency in undermining the values of novel wetland habitats is mounting (Giuliano and Bogliani, 2019; Huntsinger et al., 2017; Kidera et al., 2018).

Historically, Australasian Bitterns were probably widespread across south-eastern Australia in freshwater wetlands with emergent macrophyte vegetation. A high proportion of these wetlands have, however, been destroyed or severely modified through draining, river regulation, diversions reducing natural flow, excessive inundation, stock grazing, or have been rendered saline (Kingsford, 2000; Kingsford and Thomas, 2004; Goodman, 2012; Gell and Reid, 2014). The result has been a major reduction in the bittern population, a reduction mirrored in south-western Australia, Tasmania and New Zealand. Across the whole of Australia, the number of 10-minute grid squares in which bitterns were recorded fell from 260 in 1977-1981 to 142 in 1998-2003, and 61 in 2003-2008 (Garnett et al., 2011). In south-eastern Australia, fewer than 30 natural wetlands are now thought to support breeding in most years, or support more than one booming male, with the Barmah-Millewa and Bool Lagoon systems considered the most important (M. Herring, A. Silcocks, unpublished data; Birdlife International, 2019; Belcher et al., 2017). An even lower number act as drought refuges. Adaptation to rice fields is thus of substantial conservation significance. However, the over-allocation of water to irrigated agriculture has long been acknowledged in the Murray-Darling Basin and efforts to recover environmental water have a history extending over much of the last half-century (South Australia Murray-Darling Basin Royal Commission Report, 2019). The presence of the bitterns in rice therefore raises questions around water and conservation policy to which there are no easy answers. The following sets of questions are raised here but can only be resolved by further research.

1. Given that irrigation relies on the availability of adequate water, and bitterns are not accommodated in crops unless scarce and expensive water is used specifically for rice farming, does the stronghold of an endangered bird in rice fields justify the integration of public environmental water with private agricultural water? Is there scope for a separate allocation based on dual outcomes? What trade-offs would such arrangements incur?

2. Driven by water use efficiency, growing rice using 'early permanent water' is becoming less cost-effective, while rice growing generally is being displaced by cotton, primarily due to global commodity prices. Is it appropriate that irrigators be supported by government to grow rice in a way that is ostensibly inefficient economically for the sake of the bitterns? Can the rice market play a key role in bittern conservation? The *Bitterns in Rice Project* is promoting 'bittern-friendly rice' as a potential product that would be sold at a premium (Bitterns in Rice Project, 2019), but what are the extra costs to growers and would government support and consumers' willingness to pay be a sufficient incentive to persuade farmers to grow rice in a bittern-friendly manner? Would such measures receive sufficient 'social license' (Garnett et al., 2018) to engender political support and policy change?

Previously overlooked, rice fields can play an integral role alongside natural wetlands in the conservation of the Australasian bittern. In the Riverina and elsewhere, populations of other cryptic species in rice fields may also be significant and benefit from targeted management by engaged rice growers. This paper suggests that bitterns, having suffered greatly from widespread habitat loss, have recently been benefiting from a propitious phase in the development of the rice industry in the Australian Riverina. However, the newly-apparent benefits of current rice agriculture are tenuous and will only be sustained with assistance from farmers, incentives and supportive policy.

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