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Increasing water-use efficiency in rice fields threatens an endangered waterbird

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ABSTRACT

Many species have adapted successfully to traditionally cultivated agricultural environments but, as production systems are intensified, this adaptation is reaching its limits. Conflicting facets of sustainability compound the problem. Here we describe how reductions in the use of water in rice fields is compromising the persistence of the largest known breeding population of the Australasian Bittern (*Botaurus poiciloptilus*), a globally endangered waterbird. In fields with traditional, early permanent water, bitterns began nesting around 77 days after inundation, with 65% of nests having sufficient time for all chicks to fledge before harvest. Our breeding success model showed that all nests could potentially be successful if permanent water was applied by early November, with a ponding period – the phase when fields are flooded – of at least 149 days. The modelling suggests that successful bittern breeding was unlikely where rice was grown using new water-saving methods – drill-sown and delayed permanent water – because the ponding period is too short. These methods have become the rice industry standard in Australia, rising from 34% of fields in 2014 to 91% in 2020. While this saved 1.5-4.5 megalitres/ha per year, it has undermined the habitat value of these agricultural wetlands. 'Bittern-friendly' rice growing incentives could encourage timely nesting and maximise breeding success. Early and sufficient ponding can be complemented by establishing adjacent wetland habitat refuges, maintaining grassy banks, and creating dedicated patches to fast-track nesting. Increasing water-use efficiency in agro-ecosystems is widely touted as being beneficial to the environment, but our research demonstrates the urgent need to manage trade-offs with biodiversity conservation.

KEYWORDS: Water resource management, Agricultural intensification, Australasian bittern *Botaurus poiciloptilus*, Murray-Darling Basin, Wildlife-friendly farming, Bittern-friendly rice

1. Introduction

Managing agricultural habitats to incorporate biodiversity conservation effectively is essential for sustainability, but complex trade-offs need to be addressed (Altieri, 1999; Macchi et al. 2020; Saunders et al. 2016; Segre et al. 2020; Teuscher et al., 2015; Kremen and Merenlender, 2018; Fastré et al. 2020). Adjusting or maintaining farming practices to meet biodiversity objectives can struggle to balance agronomic development, economic pressures and conflicting sustainability imperatives (McShane et al., 2011; Roos et al. 2019; Samnegård et al. 2019, Wright et al. 2012). Agricultural expansion and intensification affect 62% of the world's threatened or near-threatened species (Maxwell et al., 2016), and collectively are considered the most important threats to birds, being implicated in the decline of 74% of the 1,469 species considered to be globally threatened (Birdlife International, 2018). In farming landscapes, agricultural intensification maximises production through increased fertiliser and pesticide use, mechanisation, loss of field-margin habitats, and resource-use efficiency. This has helped feed a growing human population, generated substantial economic benefits and improved some facets of sustainability, but in many cases it is jeopardizing the habitat values of agriculture (Birdlife International, 2018; Donald et al., 2006; Hayhow et al., 2019; Huntsinger et al. 2017; Gonthier et al., 2014; Maxwell et al., 2016; Stanton et al., 2018; Tscharntke et al., 2012).

Unlike other fields that dominate global agriculture, such as corn, wheat and soy, rice farming involves the creation of agricultural wetlands, and has traditionally supported substantial and important aquatic biodiversity (Czech and Parsons, 2002; Elphick et al. 2010; Hasegawa and Tabuchi, 1995; Herring and Silcocks, 2014; Kasahara et al. 2020; Katoh et al. 2009). Given that around 160 million hectares of rice are planted annually, and that rice is eaten by three billion people every day (FAO, 2020a), the contribution of rice wetlands is significant at a global scale. Natural wetlands are among the most impacted ecosystems on Earth, with global loss estimated at 64-71% since 1900, and a majority of the remainder being degraded (Davidson, 2014), so augmenting the role of agricultural wetlands, like rice fields, in providing surrogate habitat is appealing (Elphick, 2000). However, rice farming across the world is under pressure to reduce water-use, with shorter season varieties, upgraded irrigation infrastructure, and new growing methods like alternate wetting and drying, drill-seeding, delayed permanent water and mid-season drainage (Darbyshire et al., 2019; Dunn and Gaydon, 2011; DPI 2015; 2018; FAO, 2016; Farooq et al., 2011; SRI, 2019; Yamano et al., 2016). These alternatives to early permanent water and traditional, continuous flooding are lauded not just for their water-use efficiency but also for their roles in reducing methane emissions (LaHue et al., 2016; Miniotti et al., 2016; Peyron et al., 2016; Xu et al., 2016; Kunimitsu and Nishimori, 2020). Still, weed infestation under such water-saving schemes can incur large yield losses (Farooq et al., 2011) and higher nitrous oxide emissions (Ahn et al., 2014; Yang et al., 2012), nitrogen losses and agrochemical contamination risks (Pittelkow et al., 2016). Little attention, however, has been paid to the trade-offs with biodiversity and habitat values, even though they could be considerable. For example, in Italy, dry-seeding reduced bat activity in organic rice (Toffoli and Rughetti 2020) and reduced amphibian densities, possibly causing declines in nearby heron and egret breeding colonies (Fasola and Cardarelli 2015), while in Japan, productivity gains from incorporating direct-seeding machinery, modern drainage systems and increased synthetic fertilizer and pesticides have come at the expense of wetland biodiversity (Fujioka and Lane, 1997; Katayama *et al*., 2015; Koji *et al*. 2014; Kidera et al., 2018). In California, reduced water availability and efforts to reduce greenhouse gas emissions by decreasing the amount of time fields are flooded, challenge the practice of winter-flooding of harvested rice fields which provides critically important non-breeding habitat for millions of migratory waterfowl and shorebirds (Golet et al., 2018; Petrie et al., 2014; Sesser et al., 2016, 2018; Strum et al., 2013).

In Australia, water availability is the central issue affecting rice farming (Ashton et al., 2016). From 2010-2020, the total rice field ranged from 4000-113,000 ha, driven by water allocations to permanent entitlements, together with the price of water on the temporary market (Ashton et al., 2016; RMB, 2020). Low allocations and high water costs undermine the economic viability of rice farming (Aither, 2020). The Australian rice industry is concentrated in the Riverina region of southern New South Wales, where recent severe droughts have increased adoption of water-use efficiency measures, with predictions that dry conditions will become more frequent and intense (Dunn and Gaydon, 2011; Humphries et al., 2006; MDBA, 2020). Concurrently, there is both increasing competition for alternative water uses, notably cotton and almonds (Aither, 2020; Booth Associates, 2014) and water reforms in the broader catchment – the Murray-Darling Basin – that aim to restore degraded ecosystems and conserve biodiversity through environmental water recovery from irrigated agriculture (MDBA, 2010). These reforms assume a dichotomy between agriculture and nature conservation, and compound reduced water availability for irrigation, reinforcing pressure on growers to maximise rice yield per megalitre of water used (Aither, 2020; Gross and Dumaresq, 2014; Mushtaq et al. 2013). However, to date, the measures used to increase water-use efficiency have largely ignored the biodiversity that exists in rice fields despite the habitat value, including for threatened species.

The Riverina's rice fields were recently found to support the stronghold for the globally endangered Australasian bittern (*Botaurus poiciloptilus*), a cryptic waterbird with 1000-2500 mature individuals remaining (Birdlife International 2021; Herring et al., 2019). Australasian bitterns rely on dense wetland vegetation for nesting and, before our present study, no detailed, field-based research on their breeding ecology had been undertaken (Kushlan and Hancock, 2005; O'Donnell, 2011). Bitterns from the Riverina region spend the non-breeding season at coastal wetlands, as well as more local sites, and usually arrive in rice fields in December, approximately two months after sowing, when there is both sufficient cover and abundant prey. First, males establish their territories then females start nesting (Herring et al., 2019). The aim of this study was to assess the impacts of water-use efficiency measures on bitterns breeding in rice fields, with a view to determining how rice growers could incorporate bittern conservation into their management by growing 'bittern-friendly' rice, a concept supported by the rice growers themselves (Bitterns in Rice Project, 2021). Given the trend towards a contraction of the ponding period – the number of days the fields are flooded – and the limited opportunity for bitterns to breed successfully before harvest, we aimed to determine the water and habitat management guidelines most appropriate for bittern conservation in rice fields. Our key hypothesis was that a contraction of the ponding period would reduce opportunities for bitterns to fledge before the end of the rice season.

2. Methods

2.1 Study area: Riverina rice farming

Rice farming in the Riverina region of southern New South Wales, Australia, commenced in the early 1900s and expanded rapidly during the 1970s and 1980s, peaking in the 2000-2001 season at around 1.75 million paddy tonnes on about 184, 000 ha before the decade-long ‘millennium drought’ (SunRice, 2002). Rice is grown in the Riverina from October to May with irrigation water primarily drawn from channels supplied by upstream dams in the Murray and Murrumbidgee River valleys. There are two main sowing and water management methods used for growing rice in the Riverina: 1): ‘early permanent water’ with continuous flooding from the time of aerial (water-seeded) or dry broadcast sowing, usually in October or early November; and 2) direct drill-sowing, with similar sowing times but no permanent water until mid-late November through to December, and often with ‘delayed permanent water’ that involves periodic flooding pulses, then continuous ponding after germination. In both agronomic systems the depth of permanent water is initially around 5 cm and gradually increased to around 25 cm and maintained, then the water supply is terminated and draining occurs in preparation for harvest, which peaks in April (Ashton et al. 2016; DPI, 2015, 2018; Troldahl et al. 2020). A Riverina rice field usually includes 3-10 interconnected bays, each surrounded by banks, and managed collectively.

2.2 Bittern breeding

Bitterns were located primarily during population surveys from 2013-2017 at 189 sites on 95 randomly selected rice farms (Herring et al. 2019), complemented by opportunistic surveys at 25 additional rice fields where related research was being undertaken. All of these sites were rice fields with early permanent water because a pilot study indicated these were favored by bitterns (Herring et al., 2019). Nest searches were undertaken at a subset of these sites (n=32) that were selected because of the presence of a territorial male, which makes a distinctive, readily detectable, ‘booming’ call, and detection of at least two individuals. Although Gilbert et al. (2007) found that only around half of wetland sites with booming male Eurasian bitterns (*Botaurus stellaris*) supported nesting females, booming is a simple and widely used indicator of bittern breeding (Kushlan and Hancock, 2005) because the nests themselves are very difficult to locate and inevitably many went undetected. Searches primarily involved walking through fields – with landholder permission – in areas where nesting was suspected based on the location of booming males and observations of bitterns made by scanning fields with binoculars for birds, including those that could be females delivering food to nestlings or returning to incubate after feeding (see Gilbert *et al*. 2007). Searches ranged from 1-12 hours per site, covered 1-10 ha and were concentrated on the parts of bays furthest from the banks. Repeat visits were avoided in order to minimize disturbance at located nests, except when an additional visit was required to improve estimates of nesting commencement date.

Information on Australasian bittern breeding phenology was augmented with data from its better-studied closest relative, the Eurasian bittern. Thus we assumed that: a full clutch was four or five eggs with eggs laid every second day; the incubation period was 25 days for each egg, beginning at the time of laying, with asynchronous hatching; chicks had left the nest by 15 days and fledged at 55 days (Puglisi and Bretagnolle 2005; Demongin et al. 2007; Kushlan and Hancock, 2005; O’Donnell 2011; Polak 2016). This meant a clutch of five eggs required 88 days from the time of nesting commencement until all chicks had fledged. For full clutches, the estimated date for nesting commencement – the first egg laid – was determined by hatching date of the oldest nestling (n=7), or assuming the mid-way point of incubation for eggs when found (n=4). For nests where there was evidence of breeding (i.e. old, unhatched egg, dead chick, substantial trampled vegetation around nest), and the chicks had presumably already begun roaming and were not locatable, 15 days since hatching was assumed (n=5), representing minimum ages, while one nest was found at the second egg stage.

2.3 Water management

In November 2018, all Riverina rice growers who grew rice during the 2017-18 season (n=625) were sent a link by SunRice to complete a 25-minute anonymous, online questionnaire, and encouraged to do so through rice industry networks, social media and the *Bitterns in Rice Project*. The survey included questions about the timing and duration of permanent water, irrespective of their water management and its potential suitability for bitterns. Ethics approval for this survey was obtained through the Charles Darwin University Human Ethics Committee (H17123). The survey was refined through two focus groups and tested with seven rice growers before implementation.

From this survey, water management data were collected for 191 fields from 58 growers (response rate of 9%). Water management data were also collected for the 14 fields where 17 nests were found. The hydroperiod, referred to hereafter as 'ponding period' – where the field is flooded during the growing season – was calculated using date ranges supplied for permanent water commencement and for 'lock-up' or drainage. It does not include the drawdown period when some water is still present in the field, especially in pools along field edges. For the 14 fields where nests were found, ponding period was calculated using permanent water commencement dates and by deducting 21 days from supplied harvest commencement dates, unless known. By harvest time, rice fields and adjacent channels have usually dried out, with little or no aquatic prey like frogs and fish remaining for bitterns.

To assess the relationships between ponding commencement, ponding period and days to nesting commencement, the Spearman correlation coefficient was used as it is superior when the relationship is not necessarily linear (Zar 2010). To test for significant differences in ponding commencement and ponding period between the breeding fields and the grower survey fields, we used a Satterthwaite's approximate t test because it compensates for the possibility of unequal variances when using small sample sizes (Zar 2010).

2.4 Breeding success model

Australasian bittern chicks begin roaming from the nest within two weeks of hatching (Kushlan and Hancock, 2005), and could evade harvesting machinery prior to fledging, but the loss of wetland habitat once the rice season ends is likely to increase mortality from predation and starvation, especially in the absence of adjoining habitats, and hence overall fecundity. We developed a simple predictive model incorporating data on agronomic water management and bittern breeding phenology to detect successful breeding opportunities. By applying a laying-since-ponding commencement parameter with the 88-day period for nesting commencement to fledging of all five chicks, and a 21-day period to harvest, we assessed how many of the 191 fields from the grower survey could have supported successful breeding before harvest. We applied 95% CLM (confidence limits of the mean) for upper and lower ranges.

3. Results

3.1 Bittern Breeding

A total of 17 nests were located, including 13 from ten of the 189 primary study sites, and four from the opportunistic sites, resulting in 14 individual fields with confirmed breeding. These were widely distributed across the study area (Figure 1). The two fields with multiple nests included one with three concurrently active nests, but with only one booming male, suggestive of polygyny, while another site appeared to be re-nesting following failure, as only one male and one female was present.

The mean date for estimated nesting commencement was 4 January (+-14 days; range: 15 December-27 January), with 1 April (+-14 days; range: 12 March – 24 April) the mean for fledging of the youngest chick. The mean number of days until harvest for fledging of the youngest chick was 6.6 (+- 14.8; range -19-31.), with all chicks able to fledge before harvest in 65% (11/17) of nests (Figure 2). There was a moderate negative relationship between nesting commencement and potentially successful breeding before harvest ($R^2 = 0.52$, Figure 2).

3.2 Water Management

Of the 58 growers who completed the online questionnaire, 45% said they used early permanent water; 36% used direct-drill and delayed permanent water; and 14% used a combination, while 3% had early permanent water with mid-season drainage. Of their 191 fields, 43% commenced ponding in October, and 33% had a ponding period of at least 141 days. There was a strong negative relationship between ponding commencement and ponding period (Spearman Correlation Coefficient; $R_s = -0.81$, $p<0.0001$). Ponding commencement date was significantly earlier, by an average of 25 days, at the 14 breeding fields compared to the 191 fields from the grower survey

(Satterthwaites approximate t test; T = 10.3, df = 42.2, p <0.001; Figure 3). The breeding fields had a mean ponding period of 151 days, significantly higher than the 126 day mean for the grower survey fields (Satterthwaites approximate t test; T = -6.6, df = 18.4, p <0.001; Figure 3).

Bitterns began nesting an average of 77 days after flooding and sowing (range: 53-106; 69-85, 95% CLM; Table 1). There was no significant relationship between ponding period and days to nesting commencement (Spearman Correlation Coefficient; R_s= 0.25, p<0.3969), or ponding commencement and days to nesting commencement (Spearman Correlation Coefficient; R_s= -0.39, p<0.1664) but the latter showed a tendency for later ponding to have fewer days until nesting commencement.

3.3 Breeding success model

For the 191 fields described in the grower survey, 20.4% (39/191; +-12% 95% CLM) were predicted to provide a successful breeding opportunity before harvest (Table 1), including 40% (34/83) of fields with ponding commencement in October and 4.6% (5/108) after October (Table 2). All 39 of the predicted successful breeding fields had a ponding period of 149 days or more, while none of the fields where breeding was predicted to be unsuccessful before harvest had a ponding period of more than 141 days (Figure 4; Table 2).

4. Discussion

4.1 Saving water at the expense of successful bittern breeding

Alternatives to early, continuous flooding in order to save water and reduce greenhouse gas emissions are promoted around the world as increasing the sustainability of rice farming (FAO, 2020b; Sustainable Rice Platform, 2020). However, improving sustainability in one facet of a system is often only achieved by trading off benefits gained from others, with biodiversity commonly being disadvantaged (Fastré et al. 2020; Huntsinger et al. 2017; Marcilio-Silva et al. 2018; McInerney and Helton, 2016; Sesser et al. 2016; Thomson et al. 2019). We show here that the benefits of traditional rice farming practices to a globally endangered waterbird are inadvertently being traded off to increase water-use efficiency and maximise profit. Australasian bitterns will be unlikely to breed successfully in rice fields under the new agronomic protocols, undermining the ecological value of these important agricultural wetlands.

Potentially all nests could have been successful before harvest in rice fields with traditional, early permanent water that had a ponding period of at least 149 days, with 170 days between ponding commencement and harvest, but no nests in direct-drill and delayed permanent water fields with ponding less than 138 days ponding were likely to have succeeded. Unfortunately, the 77-day gap between ponding to nesting commencement recorded for aerial and broadcast sown early permanent water fields is unlikely to be markedly shorter in direct-drill and delayed permanent water fields because they attain heights that provide cover for bitterns later (B. Dunn, pers. comm.; L. Vial, pers. comm.), and the period between booming territory establishment and nesting in the Eurasian bittern is 1-2 months (Gilbert et al. 2007). Indeed, no bittern nests have ever been recorded in direct-drill and delayed permanent water fields. The early flooding appears to be more important for breeding success than prolonged ponding, given the moderate negative correlation between nesting commencement date and successful fledging before harvest. Early booming and nesting of

Eurasian bitterns in reedbeds is associated with increased breeding success, larger clutches and the capacity to re-nest or double brood, with the onset of booming linked to higher water levels and fish density (Mallord et al. 2000; Puglisi and Bretagnolle 2005; Gilbert et al. 2003; 2005; 2007).

4.2 Water-use efficiency trends in the Australian rice industry

If rice growing is to be bittern-friendly, then early ponding and extended water retention will be essential for successful breeding, but the industry trend is in the opposite direction. During our study, delayed permanent water and drill-sowing, which involve a contraction of the ponding period, became the rice industry standard in Australia’s Riverina, rising from 7% of fields in 2000, to 34% in 2014, and 91% in 2020, though in 2021 it was 56% due to higher rainfall and favorable water allocations (Derbyshire et al. 2019; Ford, 2006; Herring et al. 2019; M. Groat, pers. comm). Water savings ranged from around 1.5-4.5 megalitres/ha per year, with approximately 11.9-14.9ML/ha needed for aerial sown rice with early permanent water compared to 10.4-12.9ML/ha in direct-drill sown rice with delayed permanent water, which offer substantial improvements in profit margin, especially in drought years (Dunn and Gaydon, 2011; Garnett et al., 2017; Dunn, 2018). The trend is reinforced by the increasing volatility of water markets and marginal water allocations, which delay sowing decisions and favour growing of short season varieties (Troldahl et al. 2020).

4.3 The importance of bittern prey

Important relationships are likely to exist between breeding success, water management and bittern prey. Results from a pilot study suggest the bitterns’ preference for nesting in fields with earlier ponding might be related to tadpole abundance, which was 12.3 times higher in December, as nesting commences, than those with the water-saving methods (Herring, M., unpublished data). Fish are also key prey for *Botaurus* bitterns (Kushlan and Hancock, 2005; Gilbert et al. 2007; Polak 2007,

2016) and can be more abundant as a result of early ponding: in Japan, the abundance of Cobitidae loaches, one species of which uses Riverina rice fields (*Misgurnus anguillicaudatus*; M. Herring, pers. obs.), was negatively correlated with ponding commencement date, probably because earlier inundation allowed more individuals to enter the rice fields and spawn (Katayama et al., 2011, 2019). In the Eurasian bittern, starvation was the main cause of chick mortality, significantly higher than predation (Puglisi and Bretagnolle 2005; Gilbert et al. 2007), emphasizing the importance of prey abundance. In Riverina rice fields, the non-native, invasive common carp (*Cyprinus carpio*) was found to be the most abundant fish species, providing key prey for waterbirds (Taylor and Schultz, 2008), although their value may decline with the new agronomy and if a proposed large-scale, government-funded biological control program goes ahead (McColl, 2016; Kopf et al. 2019). There is also growing recognition of the latent value of integrating modern irrigation systems and inland fisheries to achieve multiple objectives for sustainability (Lynch et al. 2019; McCartney et al. 2019) and incorporating native fish conservation and fish farming in Riverina rice fields, while simultaneously producing rice, is appealing on multiple fronts beyond provision of waterbird prey. For example, the supply of zooplankton from rice fields to an adjoining river was associated with increased juvenile abundance of an endangered Japanese fish, Itasenpara bitterling (*Acheilognathus longipinnis*; Nishio et al., 2017), while Californian rice fields are being used to rear juvenile Chinook Salmon (*Oncorhynchus tshawytscha*) as part of their upland-oceanic migration (Katz et al. 2017), and rice-fish farming systems can reduce synthetic inputs (Berg et al. 2017; Nayak et al. 2018) and improve food security (Ahmed and Garnett 2011).

4.4 Managing trade-offs to reduce biodiversity loss

Novel habitats can sometimes have higher conservation values than their natural counterparts (Maclagan et al. 2018; Sousa et al. 2019), but problems may arise when the habitat on which a species has come to depend becomes less economically desirable and land-use changes (Luck et al.

2013, 2014; Singer and Parmesan, 2018; Stock et al. 2013). The biodiversity value of at least some rice fields could be maintained by using incentives that enable farmers to persist with early, continuous inundation, as well as triggering others to resume the traditional method. The bittern breeding habitat provisioning services of Riverina rice fields could be optimised for these fields, with the remainder continuing to focus on water-use efficiency and maximising yield per megalitre. As noted by Jessop *et al.* (2015), in optimizing restored wetlands for nutrient storage and removal, it is unrealistic to expect all ecosystem services to be maximised at every site. Incentives to alter agronomic practise have been used successfully elsewhere in the world, particularly in Europe and North America. For example, adjusting harvest and mowing regimes can increase the breeding success of bird species of conservation concern (e.g. Arbeiter et al., 2018; Bretagnolle et al., 2011; Holyoak et al. 2014; Santangeli et al., 2014; Weintraub et al. 2016). In Australia, such work could have benefits beyond bitterns, with a recent study showing this bird has the highest potential as a cost-effective, threat-based umbrella species among all current focal threatened taxa in Australia (Ward et al. 2020). Indeed, increasing the hydroperiod, while still maintaining a seasonal flooding-drying regime, has been identified as a key conservation action for successful reproduction in the threatened southern bell frog (*Litoria raniformis*), which uses Riverina rice fields and is key bittern prey (Hamer et al. 2016; Menkhorst, 2012; Wassens et al. 2010).

4.5 Adjacent refuges, grassy banks and nesting patches

In addition to an early and sufficient ponding period, we have identified three management priorities for bittern conservation on rice farms. Firstly, bittern-friendly rice growing could incorporate dedicated refuges adjacent to rice fields, perhaps augmenting existing supply and drainage channels, and storage dams. In this way, irrigation infrastructure could complement rice field habitat during the growing season and enable use of rice farms after harvest, offering young birds additional time before dispersal, as well as earlier in the season prior to fields reaching adequate heights that provide cover for bitterns. Water retention structures (excavated ditches) surrounding rice fields have been incentivised in Italy and Japan to reduce the negative effects of drying periods on aquatic organisms, offering a refuge from where recolonization of the rice field can occur, with larger, deeper structures being most successful (Giuliano and Bogliani, 2019; Miyu et al. 2020). Secondly, maintaining vegetated banks will provide cover from predators, along with assisting in integrated pest management (e.g. see Horgan *et al.* 2017), and supporting other cover-dependent wetland bird species. Many rice field banks are sprayed with herbicide to reduce weed prevalence but, in Italy, not only was rice field use by Eurasian bitterns higher in areas with vegetated banks (Longoni *et al*. 2011) but so too was butterfly and orthopteran diversity and abundance (Giuliano et al., 2018). Thirdly, to incentivise earlier bittern nesting within the field, rice growers could be compensated to create small nesting patches (e.g. 10-25 m^2), where taller and thicker rice growth is encouraged, or other vegetation such as reeds is propagated in slightly deeper areas which would then retain both water and cover after field drainage and harvesting.

4.6 Targeted restoration and wetland management

Another way to reduce the impact of increased water-use efficiency on bitterns is through restoration or augmentation of wetland habitats beyond rice farms. Fortunately, concerted bittern conservation efforts are underway, such as the targeted delivery of environmental water at key sites (DPIE, 2020), the design and modification of wetlands to encourage bittern breeding (Paloczi, 2020), and strategic burning to maintain early successional stages in reed-beds (GHCMA, 2019). Natural wetlands can support higher bittern breeding densities than occur in rice fields (Belcher et al. 2017), and bitterns appear to have no preference for breeding in rice, so despite the possibility of lower breeding success, it is unlikely rice fields will operate as ecological traps (see Battin, 2004). However, there is potential, as a result of increasing water-use efficiency, for a population sink to develop, with reproductive output falling below replacement levels. The risk of this would be reduced through bittern-friendly rice growing and restoration of natural wetlands, the relative costs and multiple benefits of which need to be considered (e.g. see Gardali et al. 2021.).

5. Conclusion

While improved water-use efficiency in farming is widely touted as being beneficial to the environment and is a common feature of sustainable intensification, the effects on biodiversity have been neglected. We show here that the value of rice fields to the endangered Australasian bittern is being undermined by efforts to save water and it is likely other species are also impacted. We recommend development of bittern-friendly incentives for rice growers to maximise bittern breeding success while still producing an economically viable crop. Incentives should be targeted at providing a ponding period from October or early November and sustained for at least 149 days. This could be supplemented by: 1) providing or augmenting adjacent habitat refuges such as vegetated channels and storage dams, 2) maintaining grassy banks, and 3) trialling nesting patches. Future research should help understand the potential role of incentives, novel water policy and the feasibility of bittern-friendly rice products, where the consumer pays a premium to cover additional costs to growers. The capacity for farmland to complement biodiversity conservation in protected areas is greatly reduced with a simplistic, binary framing that water resources are either used to produce food and fibre, or used for the environment. The use of rice fields by bitterns provides an opportunity to develop and test integrated water management scenarios, managing trade-offs and maximising the multifunctional benefits per megalitre used.

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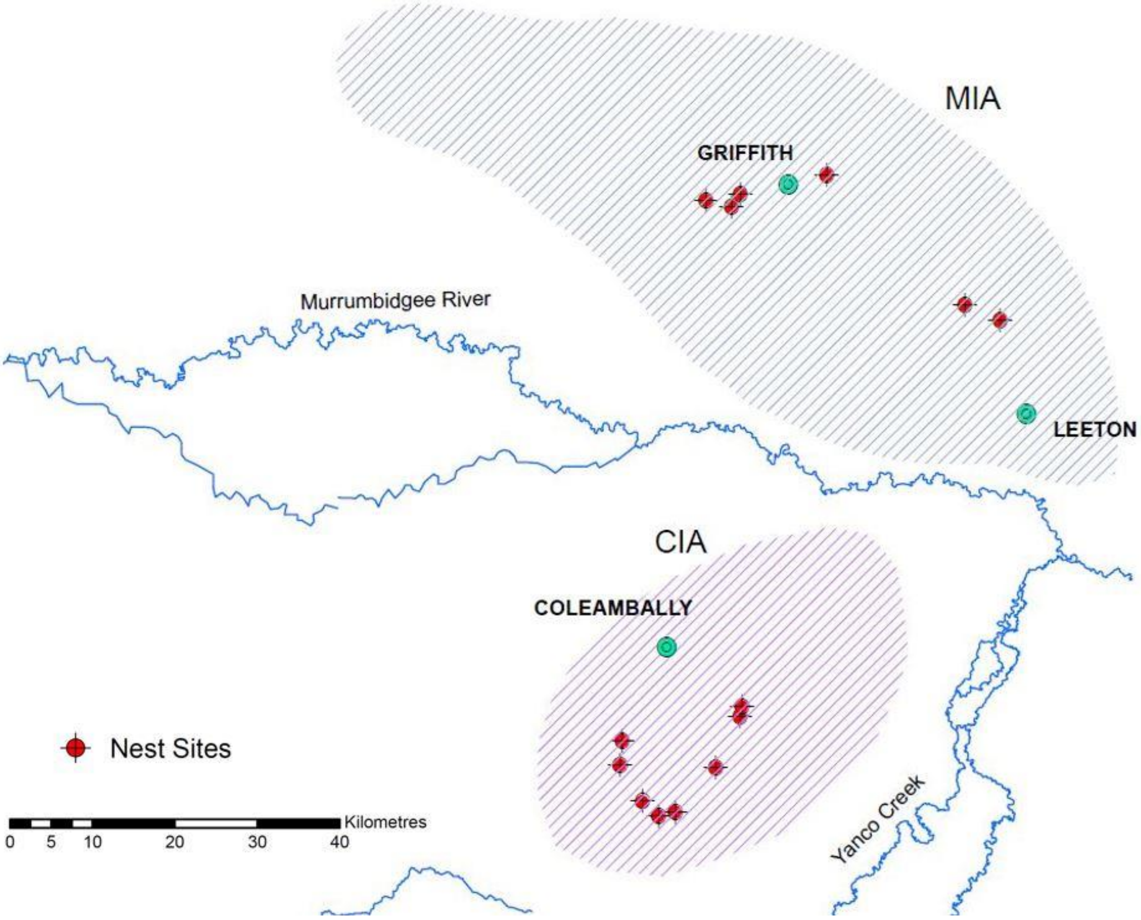

Figure 1: Location of 14 rice fields where 17 Australasian bittern nests were located from 2013-2018 across the Murrumbidgee Irrigation Area (MIA) and Coleambally Irrigation Area (CIA) in the Riverina region, New South Wales.

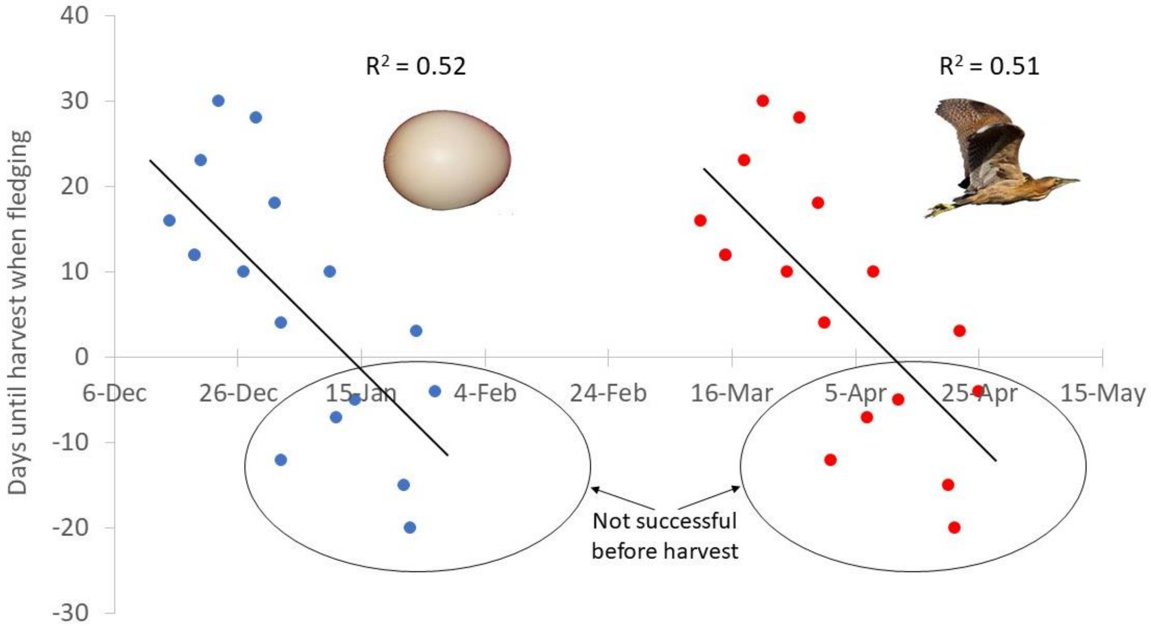

Figure 2: Estimated nesting commencement (blue points) and final chick fledging date (red points), with number of days until rice harvest when the final chick fledged, for 17 Australasian bittern nests from 2013-2018 in the Riverina region, New South Wales, with separate coefficients of determination.

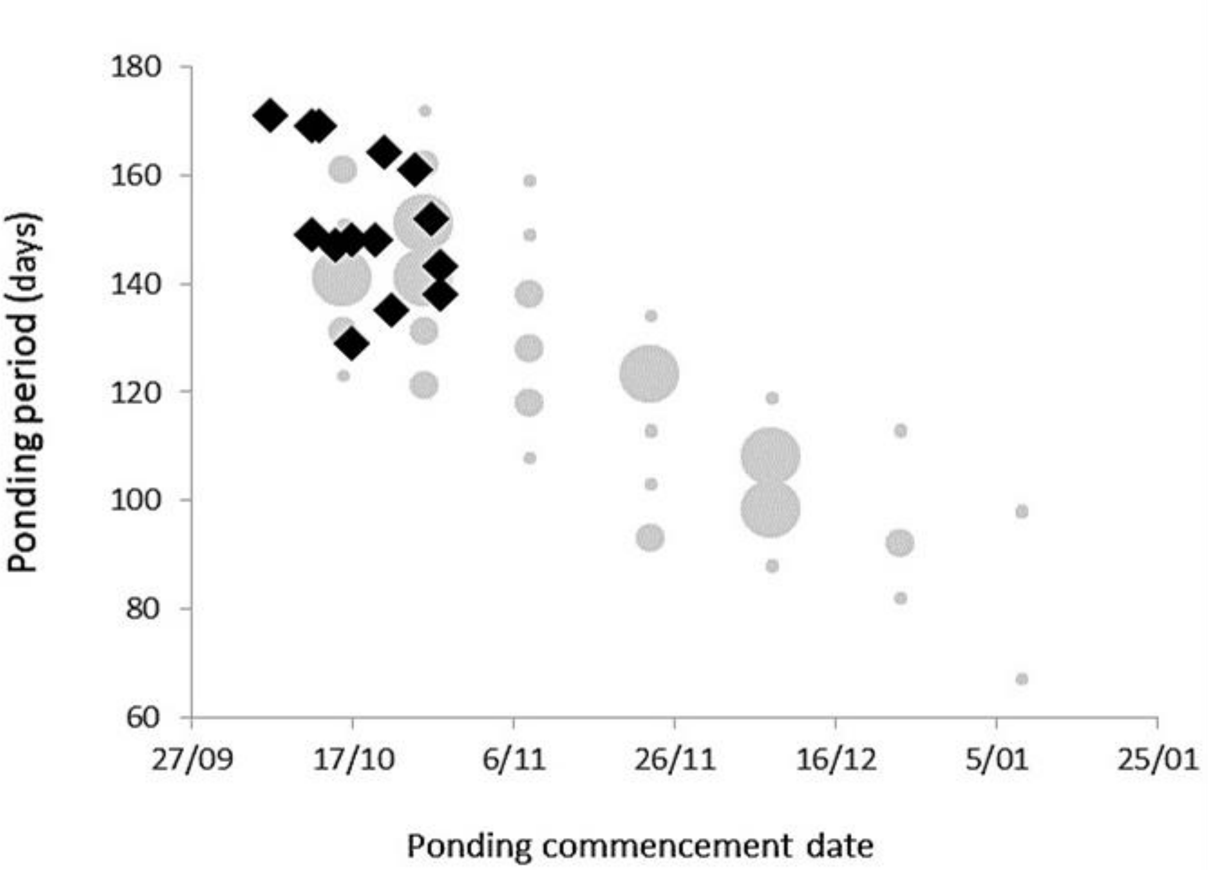

Figure 3: Ponding period and commencement date for 205 rice fields in the Riverina region, New South Wales, including 191 from a grower survey, and 14 where 17 Australasian bittern nests were found (black diamonds). Grey circles represent number of fields (small = 1-4, medium = 5-10, large = 11-18).

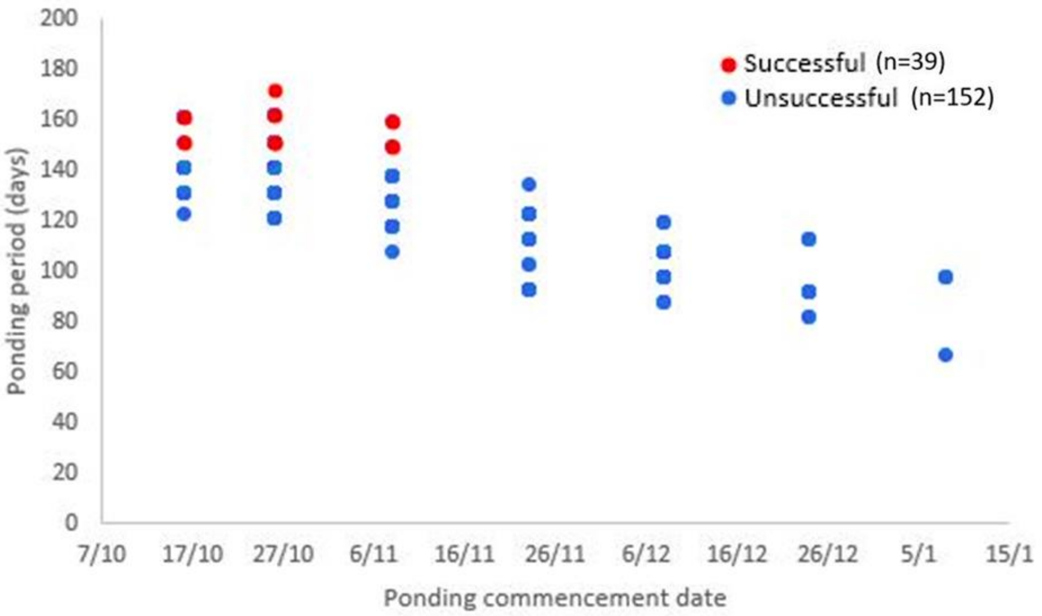

Figure 4: Ponding commencement and period for 191 rice fields in the Riverina region, New South Wales, with predictions for successful Australasian bittern breeding opportunities before harvest indicated in red.

Table 1: Proportion of 191 rice fields in the Riverina region, New South Wales, predicted to have potential successful bittern breeding before harvest for three different ponding to nesting commencement periods: mean, upper and lower 95% CLM.

	69 Ponding Days to Laying (Lower 95% CLM)	**77 Ponding Days to Laying (Mean)**	**85 Ponding Days to Laying (Upper 95% CLM)**
Successful	37% (70)	20% (39)	8% (16)
Unsuccessful	63% (121)	80% (152)	92% (175)

Table 2: Ponding commencement and period for 191 rice fields in the Riverina region, New South Wales, with predictions for successful Australasian Bittern breeding opportunities before harvest (shaded in grey). Numbers are successful fields, with totals in parentheses.

Ponding commencement date	**Ponding period (days)**							
	≥162	**161**	**159**	**151**	**149**	**141**	**<138**	**Successful (%)**
16-Oct		7 (7)		2 (2)		0 (12)	0 (9)	30
26-Oct	7 (7)			18 (18)		0 (12)	0 (16)	47
8-Nov			2 (2)		3 (3)		0 (21)	19
≥ 23-Nov							0 (82)	0
Successful (%)	100	100	100	100	100	0	0	