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Sustained and delayed noisy miner suppression at an avian hotspot

ROSS CRATES,*[1] LAURA RAYNER,[1] MATTHEW WEBB,[1]
DEJAN STOJANOVIC,[1] COLIN WILKIE[2] AND ROBERT HEINSOHN[1]
[1]*Fenner School of Environment and Society, Australian National University, Linnaeus Way, Acton, Canberra, Australian Capital Territory, 2601 (Email: ross.crates@gmail.com); and* [2]*Australian Vertebrate Pest Management Ltd., Port Macquarie, New South Wales, Australia*

Abstract To mitigate the impact of noisy miners *Manorina melanocephala* on Australia's woodland birds, there is a need to identify locations where noisy miner suppression can be affordable, sustainable and facilitate woodland bird recovery. In 2017, we suppressed noisy miners from the Goulburn River, NSW for at least three months. During this period, six pairs of critically endangered regent honeyeaters nested in the treatment area. In 2018, we continued monitoring the original noisy miner treatment area, which was expanded to include our 2017 control area, and established a new control area downstream. In 2019, the removal effort was again expanded to include the 2018 control area. In the 2017 treatment area, noisy miners remained suppressed up to 27 months post-removal. Their numbers here were lower 1 year after the initial cull than in the week after it. In the 2018 and 2019 treatment areas, noisy miner abundance was significantly lower after respective culls than at all pre-removal periods. In 2018, around 20 vulnerable painted honeyeaters occupied the 2018 treatment area. In 2019, two regent honeyeater pairs nested in and at least 40 painted honeyeaters occupied the treatment area. Songbird abundance increased within seasons and also up to a year following noisy miner removal, and plateaued thereafter. We show how, in strategic locations, a week of noisy miner suppression each spring can sequentially create ever-larger landscapes where noisy miner impacts on threatened woodland birds are minimal.

Key words: Australia, conservation: invasive species, *Manorina melanocephala*.

INTRODUCTION

The negative impacts of Australia's burgeoning noisy miner *Manorina melanocephala* population on woodland birds have been reported widely (Piper & Catterall 2003; Mac Nally *et al.* 2012; Maron *et al.* 2013). To help prevent the imminent extinction of Australia's most threatened bird species, there is a need to devise methods to mitigate the impacts of noisy miners (Maron *et al.* 2013). Whilst large-scale habitat restoration is undoubtedly the long-term solution (Clarke & Oldland 2007), reducing the impacts of noisy miners over coming decades requires their active suppression in areas where they pose a demonstrable threat to highly vulnerable species such as the regent honeyeater *Anthochaera phrygia* (Crates *et al.* 2019).

Recent studies have evaluated the potential to obtain conservation benefits through noisy miner removal, but with mixed success. Two large-scale culls in New South Wales (Davitt *et al.* 2018; Beggs *et al.* 2019) reported rapid noisy miner recolonisation, with minimal increases in other songbird populations. In farming landscapes where woodlands and shrubs have been extensively cleared (Bradshaw 2012), noisy miners are widespread. The cost of successful noisy miner suppression to assist songbird population recovery in such areas appears to be prohibitively expensive (Beggs *et al.* 2019). In contrast, we successfully suppressed noisy miners from a hotspot of avian diversity at the Goulburn River in the northern Blue Mountains, NSW (Crates *et al.* 2018). By removing 350 noisy miners from 430 Ha of riparian box-gum woodland, we significantly reduced the noisy miner population for at least the spring breeding period, allowing six pairs of regent honeyeaters to nest in the treatment area.

For targeted noisy miner suppression to represent an affordable and effective management strategy, however, reductions in noisy miner abundance must be sustained for longer than a single breeding season because recovery of woodland bird populations requires longer time frames (Kavanagh & Stanton 2003). Longer-term suppression of noisy miners would also allow the incremental creation of ever-larger noisy miner-free landscapes, not only releasing more habitat for songbird populations, but also increasing the duration of noisy miner suppression by eliminating nearby source populations (Beggs *et al.* 2019).

*Corresponding author.
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We aimed to assess the potential for targeted noisy miner suppression to represent an affordable, longer-term noisy miner management strategy in areas of high conservation value that are vulnerable to noisy miner invasion. Because the landscape matrix surrounding our study site is heavily forested (and therefore largely unsuitable to noisy miners, Piper & Catterall 2003), we predicted that noisy miner recolonisation of the 2017 treatment area would have been minimal up to 12 months post-removal, allowing an expansion of noisy miner removal into new areas in 2018 and 2019. Given the results of the 2017 study (Crates *et al.* 2018), we also predicted that noisy miner suppression in the new removal areas in 2018 and 2019 would lead to similar reductions in noisy miner abundance and increases in songbird abundance during the following spring.

Table 1. Summary of time period definitions relative to the timing of first noisy miner removal in each treatment area at the Goulburn River, New South Wales

2017 treatment	2017 control/ 2018 treatment	2018 control/ 2019 treatment
Pre	Pre	
Post 2 days	Pre	
Post 1 month	Pre	
Post 3 months	Pre	
Post 1 year	Pre	Pre
Post 1 year 2 days	Post 2 days	Pre
Post 1 year 3 months	Post 2 days 3 months	Pre
Post 2 years	Post 1 year	Pre
Post 2 years 2 days	Post 1 year 2 days	Post 2 days
Post 2 years 3 months	Post 1 year 3 months	Post 3 months

METHODS

In August 2017, we established 143 monitoring sites within a treatment area, and 44 monitoring sites within an adjacent control area. Each monitoring site was a fixed GPS location encompassing the surrounding 50m radius. We visited each site in the treatment and control areas twice during a week-long period prior to noisy miner removal. We recorded the maximum count of noisy miners and all other songbirds detected either visually or audibly across repeat site visits, each lasting 5 min, along with habitat covariates (Appendix S3). Noisy miners were then removed from the treatment area during the following week by two licensed marksmen. Commencing two days (treatment only), one month and three months after the noisy miner cull, we re-surveyed all sites within the treatment and control areas.

In the first week of August 2018 (1 year post-cull), we re-surveyed all 188 sites in the treatment and control areas. We added eight monitoring sites to the original control area, which then became part of the treatment area in 2018, and established a new control area the '2018 control', with 36 monitoring sites approximately two km downstream (Fig. 1). In the second week of August 2018, noisy miners were removed from both the original treatment area and the 2017 control/2018 treatment area (Fig. 1), following the protocol described in Crates *et al.* (2018). We then made repeat visits to all monitoring sites in the weeks commencing 2 days and 3 months post-cull. In 2018, we dropped the post-1 month survey round because the results of the 2017 surveys at 1 and 3 months post-cull were very similar (Crates *et al.* 2018). In the first week of August 2019, we again made repeat visits to each site. In the second week of August 2019, noisy miners were then removed from all three treatment areas, with 4 days of culling focussed on the 2017 and 2018 treatment areas, and 3 days focussed solely on the new treatment area for 2019 (i.e. previously the 2018 control area). We then re-surveyed all 233 sites commencing 2 days and 3 months post the 2019 cull.

In summary, our study comprised 233 monitoring sites with three treatment levels (i.e. areas, Fig. 1):

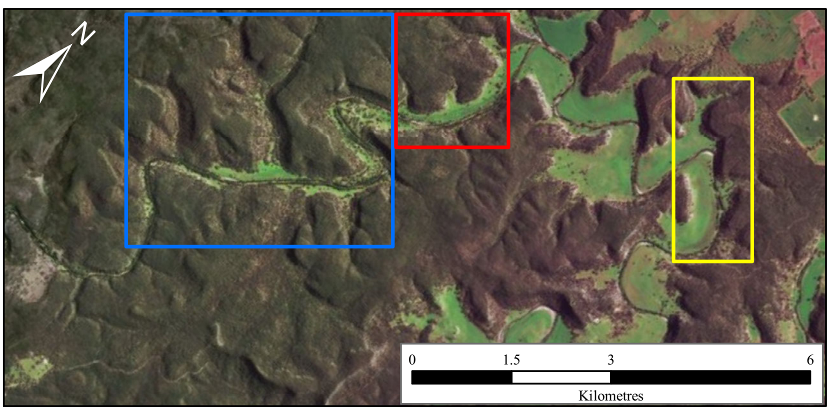

Fig. 1. Spatial location of noisy miner treatment areas within the Goulburn River study site. 2017 treatment area (blue/left); 2017 control/2018 treatment area (red/centre); 2018 control/2019 treatment (yellow/right).

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Table 2. Summary of noisy miners removed by treatment area and year at the Goulburn River study site

Treatment area	2017	2018	2019
2017 treatment	350	56	52
2017 control/2018 treatment	0	318	62
2018 control/2018 treatment	0	0	135 + 103 surrounds
Cumulative total	350	722	1074

- 2017 treatment – 144 sites (430 Ha) surveyed up to 27 months post the initial cull.
- 2017 control/2018 treatment – 44 sites plus 8 added in 2018 (120 Ha), surveyed up to 15 months post the initial cull.
- 2018 control/2019 treatment – 36 sites added in 2018 (100 Ha), surveyed up to 3 months post the initial cull.

To model the effect of noisy miner removal on noisy miner abundance, we used generalised additive models (GAMs). The maximum count of noisy miners detected across repeat site visits at each time period was the response metric. With a negative binomial distribution and a log-link function, we fitted a global model including all habitat covariates (Appendix S3) to account for site-level variation in habitat features and a smoothed bivariate spatial term *s*(Lat,Long) to account for any remaining spatial autocorrelation in the dataset. The noisy miner models also included a treatment*period interaction term. We first included treatment as a 2-level factor (i.e. only 2017 treatment and 2017 control/2018 treatment). Period was a multi-level factor, described for each treatment area in Table 1.

We used *mgcv* v1.8-23 (Wood 2018) to implement the GAMs, and *MuMIn* v1.40.4 (Bartoń 2018) to identify the most parsimonious models based on lowest AICc and highest Akaike weight W_i. We assessed their goodness of fit using function *gam.check* in *mgcv* and by evaluating R^2, % deviance explained, normality of residuals and the degree of residual spatial autocorrelation. We then repeated the GAMs using only data from the 2018 control/2019 treatment area.

To assess the effect of noisy miner suppression on songbird abundance, we used the same GAMs but with noisy miner abundance included as an additional covariate. The songbird models included the maximum count of each species recorded across repeat site visits at each time period. To account for potential variation in songbird response to noisy miner culling by body size or residency status (Mac Nally *et al.* 2012), we then repeated the analysis with only small (body mass <60 g), migrant or resident songbird abundance as the response metric (Appendix S4). All data and a fully annotated R script are available in Appendix S9.

RESULTS

The total number of noisy miners removed from each area in each year is shown in Table 2. The cost of removing 1074 noisy miners from c650 hectares of high conservation value woodland over a three week period was AU$33 000, or $11 000 per year.

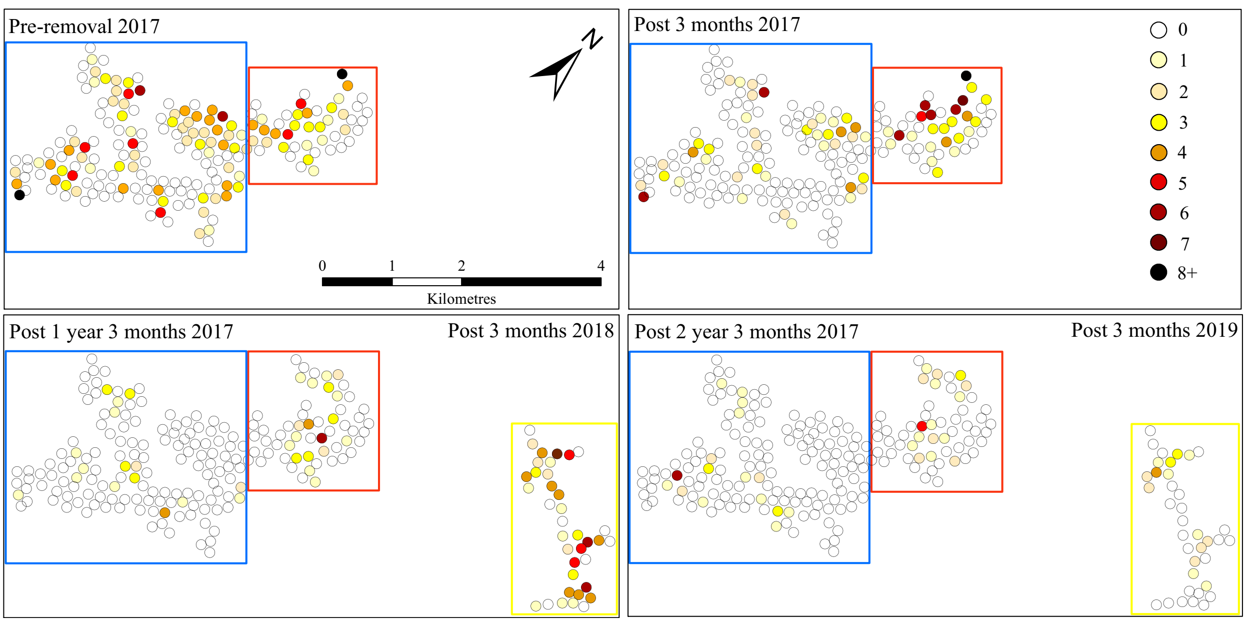

Fig. 2. Abundance of noisy miners detected at each monitoring site at the Goulburn River at periods pre- and post-noisy miner removal in August 2017 (pre-first cull) and November 2017, 2018 and 2019 (3 months post each annual cull). Polygons denote 2017 treatment area (blue/left), 2017 control/2018 treatment area (red/centre) and 2018 control/2019 treatment area (yellow/right).

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The most parsimonious model explaining variation in noisy miner abundance was as follows:

$$\text{Noisy miner} \sim \text{grass} + \text{mid storey} + s(\text{lat, long}) + \text{shrub} + \text{stand age} + \text{tree} + \text{treatment}^{\star}\text{period}$$

ΔAICc from the next best model = 1.38, W_i = 0.43, R^2 = 0.41, deviance explained = 49%. In the 2017 control area, noisy miner abundance was significantly lower at all post-cull periods than before the 2017 cull and was lower one year after the cull than all other intervening post-cull periods (Figs 2,3, Table 3). In the 2017 control/2018 treatment area, noisy miner abundance was significantly lower in the periods after the 2018 cull than at all periods before (Figs 2,3, Table 3). Noisy miner abundance in the 2018 control area did not change during the spring, but decreased significantly following their removal from this area in 2019 (Fig. 2 and Appendix S1, Table 3).

The most parsimonious model explaining variation in songbird abundance was as follows:

$$\text{Songbird abundance} \sim \text{grass} + \text{mistletoe} + \text{nectar} + \text{noisy miner} + s(\text{lat, long}) + \text{stand age} + \text{vegetation composition} + \text{period}^{\star}\text{treatment}$$

ΔAICc from the next best model = 0.28, W_i = 0.26, R^2 = 0.34, deviance explained = 38.4%. The response of the songbird community to noisy miner suppression was mixed. Within each breeding season following the culls, there were consistent increases in total songbird abundance within the 2017 and 2018 treatment areas, but not the 2019 treatment area (Fig. 4 and Appendix S1, Table 3 and Appendix S5). Much of this increase could be attributed to the arrival of summer migrants later in the spring (Appendices S1,S5). However, effect sizes

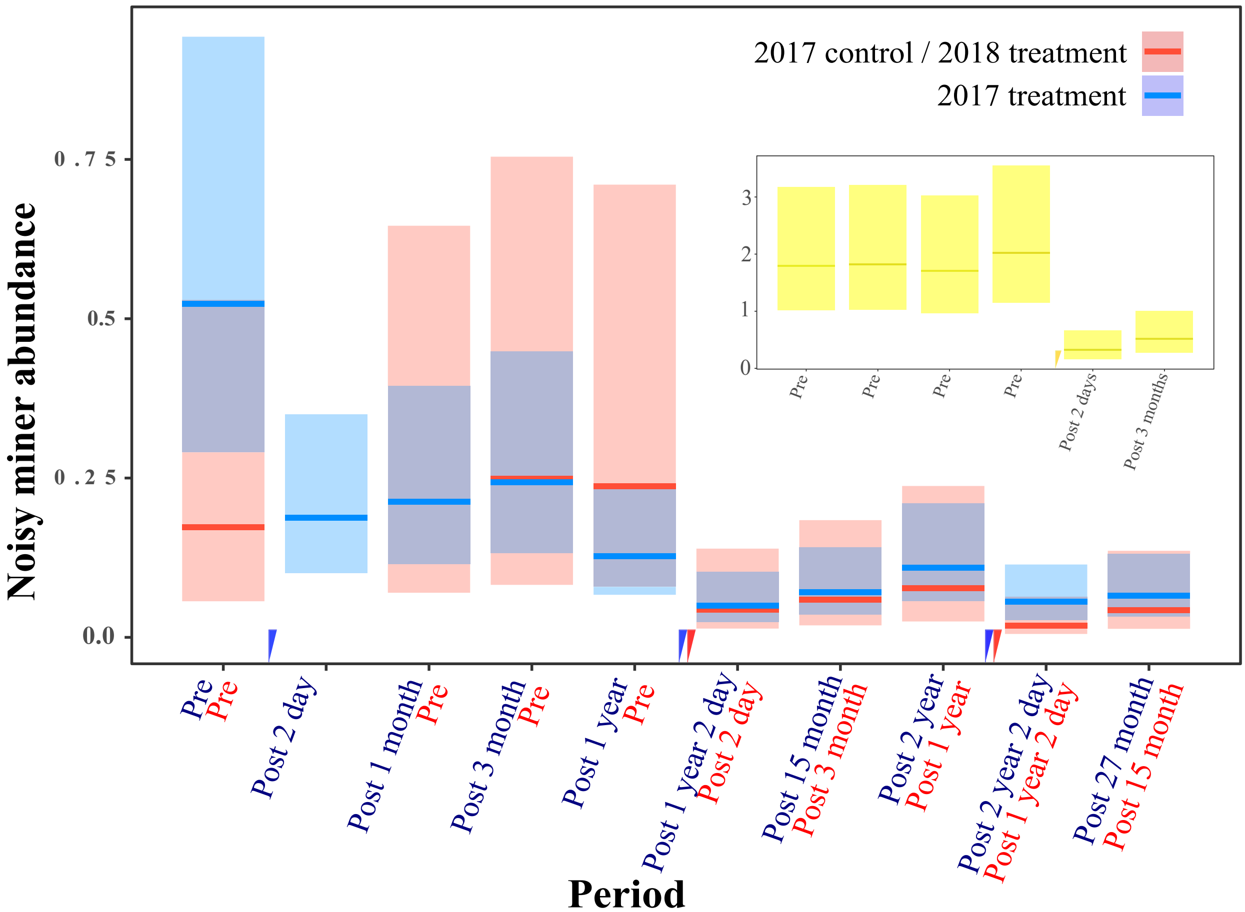

Fig. 3. Changes in median noisy miner abundance (±95% CIs) at 2017 treatment and 2017 control/2018 treatment areas at the Goulburn River. Period labels denote time since first noisy miner removal for the 2017 treatment area (blue/first) and the 2017 control/2018 treatment area (red/second). Inset: corresponding data from the 2018 control/2019 treatment area (yellow). Coloured markers on *x*-axes denote timing of noisy miner removal from each area.

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of the treatment*period term were greater for the treatment areas in the years in which noisy miner control was implemented in each area (Fig. 4 and Appendix S1, Table 3 and Appendix S5). There were also slight increases in overall songbird abundance across years, particularly within the 2017 and 2018 treatment areas (Fig. 4 and Appendix S1). Increases in songbird abundance in the 2017 and 2018 treatment areas had generally plateaued 1–2 years after the initial noisy miner cull. Migrant songbirds showed the greatest temporal variability, being lower at some periods in 2018 than at corresponding periods in 2017 (Appendix S1). No regent honeyeaters were detected in 2018, but approximately 20 painted honeyeaters *Grantiella picta* occupied the 2018 treatment area during the spring. In 2019, two pairs of regent honeyeaters nested in the original treatment area and approximately 40 painted honeyeaters were detected across the study area.

DISCUSSION

Identifying methods to limit the impact of noisy miners on woodland bird populations is an urgent conservation priority (Maron *et al.* 2013). Following 3 years of intensive monitoring, we provide experimental evidence that, in strategic areas of high conservation value, noisy miner culling can affordably and sustainably suppress noisy miners at a landscape scale to facilitate woodland bird conservation.

Against our predictions, noisy miner abundance in the 2017 treatment area was lower one year after the cull than at all previous post-cull periods. This delayed response to suppression suggests the noisy miners' capacity to recolonise the study area was limited, emphasising the need for longer-term monitoring to fully evaluate the success of noisy miner culling efforts. Delayed declines following suppression also suggest complex social factors drive colony establishment in noisy miners (Dow 1979). Despite

Table 3. Beta coefficients of period*treatment interaction terms in top-ranked GAMs of noisy miner and songbird abundance at the Goulburn River

			Noisy miner abundance				Songbird abundance			
Treatment	Period	Relative to	β	SE	*z*	*P*	β	SE	*z*	*P*
2017 treatment	Post 2 days	Pre-cull 2017	−1.02	0.18	−5.50	**<0.001**	0.16	0.07	2.22	**<0.05**
	Post 1 month		−0.90	0.18	−4.95	**<0.001**	0.48	0.07	6.65	**<0.001**
	Post 3 months		−0.76	0.18	−4.30	**<0.001**	0.60	0.07	8.12	**<0.001**
	Post 1 year		−1.41	0.20	−6.97	**<0.001**	0.20	0.07	2.72	**<0.01**
	Post 1 year 2 days		−2.35	0.27	−8.81	**<0.001**	0.36	0.07	5.03	**<0.001**
	Post 15 months		−2.00	0.24	−8.38	**<.001**	0.43	0.07	6.00	**<0.001**
	Post 2 years		−1.56	0.21	−7.41	**<0.001**	0.54	0.07	7.42	**<0.001**
	Post 2 years 2 days		−2.24	0.26	−8.70	**<0.001**	0.49	0.07	6.62	**<0.001**
	Post 27 months		−2.08	0.24	−8.51	**<0.001**	0.53	0.08	6.89	**<0.001**
2017 control/2018 treatment	Post 1 month (pre)	Pre-cull 2017	0.19	0.27	0.68	0.50	0.22	0.16	1.38	0.17
	Post 3 months (pre)		0.35	0.27	1.28	0.20	0.55	0.15	3.56	**<0.001**
	Post 1 year (pre)		0.30	0.26	1.17	0.24	0.72	0.15	4.87	**<0.001**
	Post 1 year 2 days (post 2 day)		−1.39	0.32	−4.39	**<0.001**	1.13	1.14	8.02	**<0.001**
	Post 15 months (post 3 months)		−1.10	0.30	−3.64	**<0.001**	1.07	0.14	7.55	**<0.001**
	Post 2 years (post 1 year)		−0.82	0.29	−2.83	**<0.01**	1.09	0.14	7.63	**<0.001**
	Post 2 years 2 days (post 1 year 2 days)		−2.25	0.39	−5.79	**<0.001**	0.97	0.14	6.70	**<0.001**
	Post 27 months (post 1 year 3 months)		−1.42	0.32	−4.44	**<0.001**	0.94	0.14	6.54	**<0.001**
2018 control/2019 treatment	Post 2 days (pre)	Pre-cull 2018	0.01	0.16	0.07	0.94	0.05	0.12	0.41	0.68
	Post 3 months (pre)		−0.05	0.16	−0.31	0.76	−0.15	0.14	-1.09	0.28
	Post 1 year (pre)		0.12	0.16	0.75	0.46	0.22	0.14	1.62	0.11
	Post 1 year 2 days (post 2 days)		−1.72	0.28	−6.21	**<0.001**	−0.02	0.14	−0.13	0.89
	Post 15 months (post 3 months)		−1.24	0.23	−5.40	**<0.001**	0.11	0.16	0.67	0.50

Periods in parentheses denote periods after the 2018 noisy miner cull in the 2017 control/2018 treatment area and after the 2019 noisy miner control in the 2018 control/2019 treatment area, C/F Table 1. Beta coefficients for songbird sub-groups are shown in Appendix S5.

Bold *P*-values denote significant effects at the p <0.05 level.

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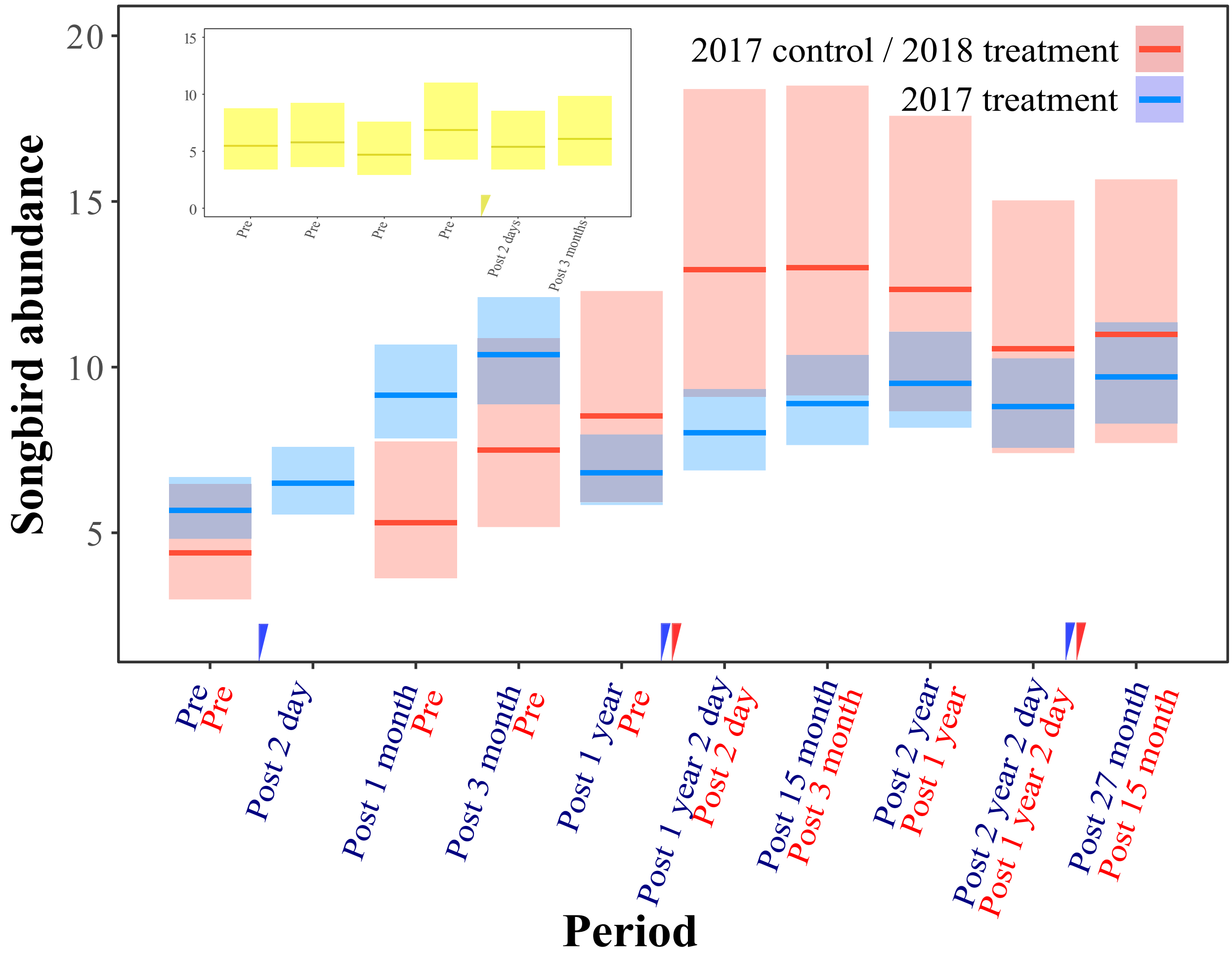

Fig. 4. Temporal changes in median songbird abundance following noisy miner suppression in the 2017 treatment area and the 2017 control/2018 treatment area at the Goulburn River, New South Wales. Period labels denote time since first noisy miner removal for the 2017 treatment area (blue/first) and the 2017 control/2018 treatment area (red/second). Inset: corresponding data from the 2018 control/2019 treatment area (yellow). Coloured markers on *x*-axes denote timing of noisy miner removal from each area. See Appendices S4 and S5 for further information.

delayed declines in the 2017 treatment area, we found that noisy miner numbers did increase within seasons, particularly within the 2017 control/2018 treatment area. We suggest that partial recolonisation of the 2017 control/2018 treatment area is probably because this area is in closer proximity than the 2017 treatment area to noisy miner source populations in the north and east of the study site (R. Crates, pers. obs., 2017). Thus, patterns of noisy miner recolonisation can vary, even over relatively small spatial scales. Although numbers of recolonising individuals were generally low, noisy miner management should involve ongoing removal efforts to successfully suppress noisy miner numbers and facilitate woodland bird recovery in the longer term (Tobin *et al.* 2011). At the Goulburn River, the initial cost to remove noisy miners from the 2017 treatment area was $11 000. In the second and third years, we were able to maintain low noisy miner numbers in the 2017 treatment area and therefore expand the size of the treatment area without increasing costs. Thus, ongoing removal efforts will also help minimise management costs over time. Identifying areas where noisy miner management can be a viable long-term investment is an important consideration when deciding where to implement noisy miner management in future.

Whilst culling clearly reduced noisy miner abundance at the Goulburn River, evidence that the songbird community responded positively was less clear. Increases in songbird abundance in the 2017 treatment and the 2017 control/2018 treatment areas had generally plateaued after one to two years, whilst songbird abundance in the 2018 control/2019 treatment area did not increase in the three months after noisy miners were removed from this area. Severe

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drought and a drop in nectar availability in 2018 and 2019 likely suppressed nectarivore abundance (including regent honeyeaters) and resident breeding activity relative to 2017 (Mac Nally *et al.* 2009). Although noisy miners were having an impact upon songbird populations at the Goulburn River (Crates *et al.* 2018), their density here was much lower than in other landscapes (Davitt *et al.* 2018; Beggs *et al.* 2019). Songbird population recovery may have been limited because the negative impacts of noisy miners on songbirds may not have fully manifested prior to removal. Identifying locations where noisy miners can be managed in a precautionary manner may be key to preserving vulnerable songbird populations (Leung *et al.* 2002).

The mixed response in the abundance of songbirds to noisy miner suppression suggests that songbird population recovery is also dependent upon the underlying quality of woodland habitats (Ford *et al.* 2009). The 2018 control/2019 treatment area was selected because it was deemed to be the 'next most suitable' breeding habitat for regent and painted honeyeaters within the study site. Despite detecting painted honeyeaters there for the first time in 2019, this area was smaller than the other treatment areas and had a smaller proportion of high-quality riparian box-gum woodland, which supported the highest songbird densities in the other two treatment areas (Crates *et al.* 2018). Maximising the conservation return on investments in noisy miner management may also require implementing management in areas with a high proportion of high-quality and well-connected riparian box-gum woodland (Ford *et al.* 2009; Nimmo *et al.* 2016).

Although we show that noisy miner management can yield short-term conservation benefits if it is targeted in space and time, broad-scale revegetation of lowland woodland and understorey is clearly the long-term solution to mitigate noisy miner impacts on Australia's woodland birds (Debus 2008; Mac Nally *et al.* 2009; Clarke & Grey 2010). However, reductions in noisy miner abundance in response to revegetation occurs over >10 years (Law *et al.* 2014). Revegetation cannot therefore address the immediate threat posed by noisy miners to the most vulnerable species, such as the regent and painted honeyeater. Limited available evidence suggests that, by minimising local noisy miner abundance and increasing resistance to dispersal, high forest cover extent in the surrounding landscape may be a key predictor of successful noisy suppression (Piper & Catterall 2003). Given the relatively low cost (which decreased per unit area over time) of suppressing noisy miners for >27 months at the Goulburn River, we suggest there is no shortage of other areas of riparian woodland, particularly within the greater Blue Mountains, where noisy miner suppression is a potential management option (Appendix S2).

Repeating our study over longer periods at locations with varying extents of forest cover and noisy miner density could help limit the impact of noisy miners and help draw more robust inferences on the determinants of successful noisy miner suppression. This information could help identify other locations where strategic noisy miner management, implemented as an affordable, annual management regime, could complement revegetation efforts to maximise conservation gains and minimise future biodiversity losses for the least ethical and financial cost.

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AUTHOR CONTRIBUTIONS

Ross Crates: Conceptualization (lead); data curation (lead); formal analysis (lead); funding acquisition (lead); investigation (lead); methodology (lead); project administration (lead); visualization (lead); writing-original draft (lead); writing-review & editing (lead). **Laura Rayner:** Formal analysis (supporting); writing-original draft (supporting). **Matthew H Webb:** Writing-review & editing (supporting). **Dejan Stojanovic:** Writing-review & editing (supporting). **Colin Wilkie:** Data curation (supporting); funding acquisition (supporting); investigation (supporting); methodology (supporting); project administration (supporting); resources (supporting). **Robert Heinsohn:** Funding acquisition (supporting); project administration (supporting); resources (supporting); supervision (supporting); writing-original draft (supporting); writing-review & editing (supporting).

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SUPPORTING INFORMATION

Additional supporting information may/can be found online in the supporting information tab for this article.

Appendix S1. Temporal change in the abundance of small-bodied (<60 g), resident and migrant songbirds at the Goulburn river over a 27 month period following experimental noisy miner removal. Dashes denote timings of noisy miner culls within the 2017 treatment area (blue) and the 2017 control / 2018 treatment area (red).

Appendix S2. Study location within the greater Blue Mountains (red) and the locations of other potential areas for targeted noisy miner management (blue). North-south: Goulburn River (downstream); Baerami Valley; Widden Valley; Capertee National Park; Capertee Valley (Glen Alice); Capertee Valley (Glen Davis); Wolgan Valley.

Appendix S3. Description of site-level covariates tested in models of noisy miner abundance and the abundance and diversity of other songbirds before and after experimental noisy miner removal. See Crates et al. (2018) for justifying citations.

Appendix S4. Species groups classifications for models assessing the effect of noisy miner removal on the abundance of songbirds at the Goulburn River, New South Wales, Australia. Body size defined as relative to body size of noisy miners. Species with state or national level population threat status of 'vulnerable' or greater highlighted in bold.

Appendix S5. Beta coefficients of period*treatment interaction terms in top-ranked GAMs of the abundance of songbird sub-groups at the Goulburn River. Periods in parentheses denote periods after the 2018 noisy miner cull in the 2017 control / 2018 treatment area and after the 2019 noisy miner control in the 2018 control / 2019 treatment area, C/F Table 1.

Appendix S6. GNoisy miner dataset for the 2017 treatment and 2017 control/2018 treatment areas (csv).

Appendix S7. Noisy miner dataset for the 2018 control/2019 treatment area (csv).

Appendix S8. R script for data analysis.

Appendix S9. R script for data analysis.

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