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RESEARCH NOTE

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# Evaluating the evidence of culling a native species for conservation benefits

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**Abstract**

Controlling problem species for conservation can be fraught, particularly when native species are subject to lethal control. The noisy miner (*Manorina melanocephala*), has been the target of numerous lethal control efforts. Outcomes of these noisy miner removals have varied substantially, so identifying the circumstances under which they are effective is essential for ethical and effective management. We compiled data for all identified noisy miner removals ($n = 45$), including both permit-based and unofficial removals. We investigated whether methodological and ecological factors explained the effectiveness of removals in reducing noisy miner density or increasing woodland bird richness and abundance. The only predictor of any measure of success was time between first and final culls which was positively related to reduction in noisy miner density. Surprisingly, despite removals mainly failing to reduce noisy miner density to below a threshold above which noisy miners impact smaller birds, woodland birds usually still increased. Disrupted social structure as noisy miners recolonized may have led to less effective aggressive exclusion of small birds. Further removals may not need to reduce noisy miner density to below this threshold to benefit woodland birds, but consistent monitoring and reporting would support better evaluation of effectiveness and correlates of success.

**KEYWORDS**

key threatening process, *Manorina melanocephala*, noisy miner, overabundant native species, population control, woodland

## 1 | INTRODUCTION

Conservation practitioners, including protected area rangers, stewards of private reserves, and agricultural land managers, are often required to make difficult decisions to protect declining species. Sometimes, they have to choose one species over another in attempts to achieve a conservation goal (Grarock, Tidemann, Wood, & Lindenmayer, 2014). For example, species that exert extreme, adverse pressure on populations of other species (hereinafter called "problem species"), may do so by depredating, parasitizing, harassing, and/or outcompeting species of conservation concern. Problem species are often non-native to the area and have been introduced through human activity, but they can also be native species that have become overabundant within or expanded the bounds of their natural distribution following habitat modification and disturbance (Carey, Sanderson, Barnas, & Olden, 2012). Globally, the most prevalent threats to 2,298 of the threatened or near-threatened species listed on the IUCN Red List of Threatened Species are problem invasive and problem native species (Maxwell, Fuller, Brooks, & Watson, 2016), although major global agreements such as under the Convention on Biological Diversity often exclude native species from discussion of this threat (United Nations Environment Program's Strategic Plan for 2011–2020).

Controlling such problem species is critical to the survival of many species at risk of extinction, however, effective control is ecologically complex (Tingley et al., 2017). Common control measures include inhibiting the dispersal of problem species through exclusion fencing (Dickman, 2012), and lethal control of the problem species through baiting (Kinnear, 2010), trapping (El-Sayed, Suckling, Wearing, & Byers, 2006), or shooting (Doherty et al., 2017). Removal of problem species can lead to the successful recovery of the species of conservation concern (Bolam et al., 2021); however, it is important to note that many of these successful removals are achieved on islands (Jones et al., 2016) and island and mainland problem species scenarios often require different management approaches (Baker & Bode, 2016). Furthermore, successful or unsuccessful control of problem species can sometimes have unintended ecological consequences (Marlow et al., 2015), be costly, and ethically contentious (Whisson & Ashman, 2020).

Despite substantial investment in research into control of problem species, there is not always clear evidence that the control was or will be effective in reducing the target population, or in recovering the impacted species (Pople & McLeod, 2010; Walsh, Wilson, Benshemesh, & Possingham, 2012). In addition, evaluating the effectiveness of management actions can be challenging due to insufficient resources for adequately monitoring response to the control (Pullin, Sutherland, Gardner, Kapos, & Fa, 2013). Some research has found that managing the environment (e.g., revegetation) to mitigate threats posed by problem species can be more effective in conserving the species of concern than managing the problem species (Goodrich & Buskirk, 1995). Nevertheless, given the expense, and large time lags involved in habitat restoration (Vesk, Nolan, Thomson, Dorrough, & Nally, 2008), actions such as lethal control of the problem species for conservation can potentially provide more immediate benefits (Crates et al., 2018; Crates et al., 2020), until longer-term solutions are established.

Control of problem species by lethal means can be highly controversial, especially when the target species is iconic (Nimmo & Miller, 2007; Wallach, Bekoff, Nelson, & Ramp, 2015; Whisson & Ashman, 2020), a resource to a particular group of people (Crowley, 2014), or when the problematic species is native to that location (Mehmet & Simmons, 2018; Whisson & Ashman, 2020). Controversy over lethal control is evident even in places where invasive species are the predominant threat, such as Australia (Kearney et al., 2019); and where there is clear evidence of their impact (Doherty et al., 2017; Driscoll et al., 2019; Walsh et al., 2012). For example, the compassionate conservation movement evolved seeking to prioritize management actions which advocate for the intrinsic value and welfare of individuals (Ramp & Bekoff, 2015; Wallach, Bekoff, Batavia, Nelson, & Ramp, 2018). Although this view has been criticized as a threat to effective conservation (Driscoll & Watson, 2019; Hayward et al., 2019), it seems likely that most would agree that lethal control in the name of biodiversity conservation needs to be supported by strong ecological evidence to be both justifiable and also socially acceptable (Grarock et al., 2014).

A prominent example of lethal control of a problem native species for conservation is that of the noisy miner (*Manorina melanocephala*). This abundant, group-living honeyeater occurs in dry sclerophyll woodland and forests throughout eastern Australia (Dow, 1979). Habitat clearing, fragmentation and land-use change (e.g., livestock grazing) has reduced the complexity of vegetation structure, and increased the extent of edge habitat. These changes have, in turn, benefited noisy miners by providing more open habitats in which the noisy miners more easily harass and exclude other birds (Maron et al., 2016; Mortelliti et al., 2016; Thomson et al., 2015). Noisy miners particularly impact small woodland bird species, which are an important subset of broader woodland bird communities, and which also collectively form an assemblage that likely meet the criteria for listing as a Threatened Ecological Community under Australian law (Fraser et al., 2017). The loss of smaller-bodied species diminishes the ecological functions of woodland areas, which become more taxonomically and ecologically homogenous (Howes et al., 2014). Further, the noisy miner has been recorded directly competing with two critically endangered woodland bird species, the regent honeyeater (*Anthochaera phrygia*) and swift parrot (*Lathamus discolor*) (Crates et al., 2019; Saunders & Heinsohn, 2008). On the basis of these impacts, overabundant noisy miners are listed as a Key Threatening Process under Australia's national biodiversity Act (Environmental Protection and Biodiversity Conservation Act 1999), and separately in the states of New South Wales (Threatened Species Conservation Act 1995) and Victoria (Flora and Fauna Guarantee Act 1988).

Lethal control of noisy miners has been trialed in a series of small to larger-scale interventions intermittently over the past three decades. The common proximate objective was to suppress noisy miner density at the treatment site, with the ultimate objective to achieve an increase in abundance or richness of other woodland birds. The requirement for a removal permit depends on the state or territory and the purpose of the removal, as with translocation of noisy miners. Translocation is not recommended as the birds are not readily assimilated into resident populations of noisy miners in the new locations and can travel long distances to return to the capture site (Clarke & Schedvin, 1996). No consensus has yet emerged as to whether lethal control of noisy miners is an effective management action for woodland bird conservation. At least some small-scale (3–8 ha) removals appear to have reduced noisy miner density in the long-term, and facilitated the return of small birds (Debus, 2008; Grey, Clarke, & Loyn, 1997; Grey, Clarke, & Loyn, 1998). Yet, larger-scale (16–49 ha) removals have had mixed results. Some have resulted in no significant reduction of noisy miner density (Beggs et al., 2019; Davitt, Maute, Major, Mcdonald, & Maron, 2018), while others successfully suppressed the population with measurable benefits for a species of conservation concern (Crates et al., 2018; Crates et al., 2020). Several removals have occurred without legal permits in place, one of which was reported to have been successful (Debus, 2008), but most are not reported in the literature.

The aim of our study is to answer the question "What characteristics of a noisy miner removal event influence the likelihood of its success?" We focus on identifying factors that affect the likelihood of achieving both proximate (noisy miner reduction) and ultimate (woodland bird increase) objectives. We hypothesized that noisy miner density would be more likely to remain low following the removal at sites where shrubs were present, as previous studies have found a negative association between noisy miner abundance and the presence of shrubs. We also hypothesized that an increase in the occurrence of small birds would be more likely at sites with greater woody vegetation cover within 1 km of the treatment site, as isolated treatment sites could be less accessible for other woodland birds to disperse into following the removal. We compiled published and unpublished data from noisy miner removals to build a comprehensive dataset of environmental and methodological factors as well as noisy miner and woodland bird response. We analyzed this dataset to identify ecological and methodological factors associated with reduction in noisy miner density, and/or subsequent increase in small bird abundance and richness. Based on our findings, we identify critical knowledge gaps in our understanding of what results in effective noisy miner removals. This information is important for considering and designing future control activities, to ensure practitioners have the best chance of conducting ethical and efficient management of this problem species. The use of a standard protocol for data collection of future noisy miner control activities will help provide the evidence needed to evaluate their use as a tool for woodland bird conservation.

## 2 | METHODS

### 2.1 | Study area

The temperate and subtropical woodlands of eastern Australia are primarily dry, open, *Eucalyptus*-dominated vegetation, with some woodlands dominated by *Allocasuarina*, *Acacia*, and *Callitris spp*. This woodland zone supports a diverse community of birds, within which over 40 species are listed as threatened under state and national legislation. Over 50% of temperate woodland and over 40% of subtropical woodland has been cleared from this zone for agriculture (Bradshaw, 2012; Fraser, Simmonds, Kutt, & Maron, 2019), resulting in a mosaic of small remaining woodland habitat areas, open agricultural mosaics, and increased edge habitat that is suitable for noisy miners (Maron et al., 2016; Mortelliti et al., 2016; Thomson et al., 2015).

## 2.2 | Overview of data and analysis

We collated data from published and unpublished noisy miner removal studies, as well as from the experiences of landholders who had undertaken noisy miner removals on their properties, to create a collective database describing all known removal events. These data included ecological context information describing the site of the removal and its surrounding landscape, the methodological approach used to do the removal, and the conservation goals of the removal. These data were analyzed to identify whether any ecological or methodological factors, which varied between removals, correlated with the likelihood of successfully reducing noisy miner density and/or increasing the occurrence of small woodland birds at the treatment site post-removal.

We collated all published peer-reviewed and grey literature describing lethal removals of noisy miners from woodland habitat and extracted the associated methods and results described in the text to a collective dataset. We contacted authors of the publications for additional information where it was not already available. This information included noisy miner density before and after the removal event, site context and environmental information, the timescale over which the removal was conducted, and the timing of pre- and post-removal data collection (Table 1). Time between prior bird survey data collection and the removal varied between removals, as did the time between the removal and post-removal bird survey data collection. If there were multiple before and/or after surveys, the first bird survey data collected before removals (average = 8.07 months, range = 0.25–13 months), and the most-recent bird survey data (average = 8.36 months, range = 1–24 months) were used in these analyses. There were a range of bird survey methods used including the 20-min 2-ha method, multiple stationary 5-min point count methods within a 50 m radius, and 25-min 0.3-ha counts. All survey data were converted to birds detected per hectare. We refer to these noisy miner removals conducted under permits and research approvals as "official removals."

## 2.3 | Questionnaires

We also contacted relevant government liaison officers to facilitate collection of data about permit-based noisy miner removals that were not part of the published removal studies. We requested they contact individuals who had been formally issued permits to remove noisy miners from private property, and invite them to provide information through an anonymized phone questionnaire that described these removals. Through the networks of the authors and land managers, individuals known to have conducted unofficial noisy miner removals were also invited to provide information through an anonymized phone questionnaire (Appendix 1). All phone questionnaires followed protocol approved by the Human Ethics Committee of the primary institution (HEA Approval #2019000450). We refer to these noisy miner removals that were undertaken by private landholders without specific permissions as "unofficial removals."

## 2.4 | Response variables

We modeled several response variables as surrogates of the success of noisy miner removals, with the aim of identifying environmental and methodological predictors of successful removal events. We separately analyzed both the full dataset, with modifications to the variables to allow inclusion of subjective estimates from the phone surveys, and the subset of the data involving only official removals. For the subset of data from official removals, for which before and after bird survey data were available ($n = 37$ removals), the response variables were the percentage change of noisy miner density following removal, calculated as the difference between the number of noisy miners observed per hectare before versus after the removal, and whether each of small bird abundance and richness increased by at least 25% following the removal (Table 2). Originally, a response variable describing successful or unsuccessful reduction of noisy miner density to below the critical threshold described by Thomson et al. (2015) of 0.6 birds $ha^{-1}$ was selected. Analysis from hundreds of sites across southeastern Australia where noisy miners were not managed, found that small birds were excluded from sites where noisy miner density was above this threshold. However, only three removals we identified reduced densities to below this value.

When analyzing the full dataset, we modeled three different response variables describing removal outcomes to allow for some data being subjective, coarse, or not well replicated. These were: estimated or measured reduction of noisy miner density by 50% or greater; and estimated or measured increase in each of small bird species richness and abundance of at least 25%, as opposed to raw continuous survey data. These percentages were selected as they were considered to be thresholds that would be sufficiently different to

TABLE 1 Ecological and methodological predictor variable descriptions and source information

| Predictor | Description | Inclusion criteria |
|---|---|---|
| Location | Anonymized, general GPS coordinates of removal sites, obtained from authors of removal studies in questionnaire participants.[a,b] | Spatial autocorrelation factor to identify multiple removal sites that were within the same study area, used as a random effect in model. |
| Treatment area | The area over which noisy miners were removed in hectares.[a,b] | Methodological context which implicates colony extent. Removal of noisy miners from a larger area may reflect the majority of a noisy miner colony was removed, whereas removal of noisy miners from a small area may reflect a portion of a colony was removed. |
| Percentage cover of woody vegetation | Woody vegetation cover extracted from National Vegetation Information System data in ArcGIS using 1 km buffers surrounding the center of the removal location (%) (Department of the Environment 2018).[a,b] | Proxy for decolonization sources in the landscape surrounding the removal site (Dow, 1979). |
| Presence of shrubs | Presence or absence of shrubs in treatment area (0/1).[a,b] | The density of noisy miners is negatively correlated with shrub density (Eyre et al., 2009; Howes & Maron, 2009; Val et al., 2018); thus, we might expect reduced decolonization by noisy miners of a removal site with shrubs. |
| Prior density of noisy miners | Density of noisy miners (birds/ha$^{-1}$) at the treatment site prior to removal as indicated by bird survey data[a] or subjective Likert scale data (0–5, where 0 indicates no noisy miners present and 5 indicates the greatest density of noisy miners that interviewees were familiar with).[b] | Implications to the extent of overabundance of noisy miners at the removal site, and what that might mean temporally for how effective a removal will be. |
| Time between first and final removal | Time between the first and final cull conducted across the treatment area (months, 0 indicates only one cull was conducted).[a,b] | Indicates temporal effort in removal, to explore how suppression of noisy miners over time could influence the likelihood of achieving the proximate and ultimate objective. |
| Total number of culls | Total number of repeat culls conducted across the treatment area.[a,b] | Indicates removal effort, to explore how consistent removal actions could influence the likelihood of achieving the proximate and ultimate objectives. |
| Change in noisy miner density | The difference in noisy miner density (birds/ha$^{-1}$) between the prior density of noisy miners and the density recorded after the removal.[a] | Post-removal data used to identify whether noisy miners needed to be reduced below the critical threshold to be successful. |

[a]Variables represented by the subset of official removals.
[b]Variables represented by the full dataset.

observers not conducting formal bird counts. As such, participants were asked in the questionnaire whether they did observe or did not observe these differences. Formal bird survey data of the official removals were then converted to a binary successful/unsuccessful reduction of noisy miners by 50% or greater and increased small bird species richness and abundance by 25% or greater variables, so that all data could be analyzed collectively as the full dataset.

## 2.5 | Predictor variables

For the full dataset, the ecological context predictor variables available for all removals were: presence or absence of shrubs at site of removals and extent of woody vegetation cover within 1 km of the treatment site (Table 1). We also included methodological predictors: treatment area, number of separate culls conducted, time between the first and final cull, and the density of noisy miners removed

**TABLE 2** Response variable descriptions and source information

| Response variable | Description | Inclusion criteria |
|---|---|---|
| Percentage change in noisy miner density | The difference in the density of noisy miners (birds/ha) converted to a percentage value, between prior density of noisy miners, and the density of noisy miners after the final removal, for the subset of official removals. | Relative change in the density of noisy miners at a site indicates how effective the removal was in achieving the proximate objective, highlighting the extent of decolonization by noisy miners after the removal. Exploring what ecological and methodological predictor variables were significant factors contributing to these response variables indicates what may influence desirability of a site for neighboring noisy miners. |
| Successful reduction of noisy miner density by 50% or greater | A binary (0/1) variable describing whether the difference in the density of noisy miners (birds/ha) between prior density of noisy miners and the density of noisy miners after the final removal was 50% or greater (1) or less than 50% (0). A 50% change in noisy miner density was considered easily identifiable to interviewees who had not collected formal bird survey data. Bird survey data collected in the official removals were converted to this binary form for a full dataset analysis. | |
| Successful increase in small bird species richness by 25% or greater | A binary (0/1) variable describing whether the difference in the number of different small bird species increased following the removal event by 25% or greater. A 25% change was considered easily identifiable to interviewees who had not collected formal bird survey data. Bird survey data collected in the official removals were converted to this binary form for a full dataset analysis. | An increase in the occurrence of small birds following the removal event indicates the effectiveness of the removal in achieving the ultimate objective. Exploring what ecological and methodological predictor variables were significant factors in these response variables may indicate the desirability of the site for colonizing small birds. |
| Successful increase in small bird abundance by 25% or greater | A binary (0/1) variable describing whether the difference in the abundance of small bird species increased following the removal event by 25% or greater. A 25% change was considered easily identifiable to interviewees who had not collected formal bird survey data. Bird survey data collected in the official removals were converted to this binary form for a full dataset analysis. | |

(Table 1). The density of noisy miners prior to the removal was included for the subset of official removals, and converted to a Likert scale (between 0 and 5) for the full dataset to be comparable with the unofficial removals. For the unofficial removals, interviewees were asked to provide a value of the prior density of noisy miners on a scale from 0 to 5, where 0 = no birds and 5 = highest density of birds they were familiar with (Table 1). For example, in one case, the density of 9.3 noisy miners per hectare was converted to a Likert value of 4.4, based on the range of values observed during bird surveys for the official removals.

## 2.6 | Statistical analysis

Prior to analysis, we tested for collinearity between predictor variables using a Pearson correlation test. No predictors were significantly correlated. We also assessed diagnostic plots to check the assumptions of linear models including normality of residuals and equality of variances. We standardized predictor variables to lie between 0 and 1, to allow direct comparisons of the parameter estimates. We then used generalized linear mixed models with binomial error distributions and a logit-link function to model each of the response variables for both the subset dataset of official removals and the full dataset. We used a linear mixed model to model percentage change in noisy miner density from before to after the removal for the subset of official removals. We used an all-subsets method of multimodel inference, extracting a 95% confidence set of models (based on Akaike information criterion weight adjusted for small sample size) from alternative models of all linear combinations of predictor variables of the global model. Model averaged coefficient estimates were calculated across the 95% confidence set, and the relative importance of the predictor for each response type calculated by summing the cumulative Akaike weight for that predictor for all models of the 95% confidence set. We also explored whether sites that had a noticeable reduction of noisy miner density by at least 50% following the removal were more likely to have an increase in each of small bird species richness and abundance of at least 25% by performing a Chi-square test for independence.

## 3 | RESULTS

In total, we compiled data on 45 removals (Figure 1): 29 from published, official removal studies; six from unpublished, official removal studies; two from permit-based removal events, and eight from unofficial removal events. Noisy miner removal events varied substantially in the methodological approach and ecological conditions under which removals were conducted (Table 3). For example, some removals were single events while others involved multiple removal events conducted over a 60-month period. Some removals were conducted over a fraction of 1 ha, while some involved persistent culling across several hundreds of hectares. Most removals used direct lethal control (e.g., by shooting all noisy miners present), whereas some trapped or netted the noisy miners and released them at distant locations (26%). Additionally, some removals used audio playback recordings to attract birds for trapping or shooting.

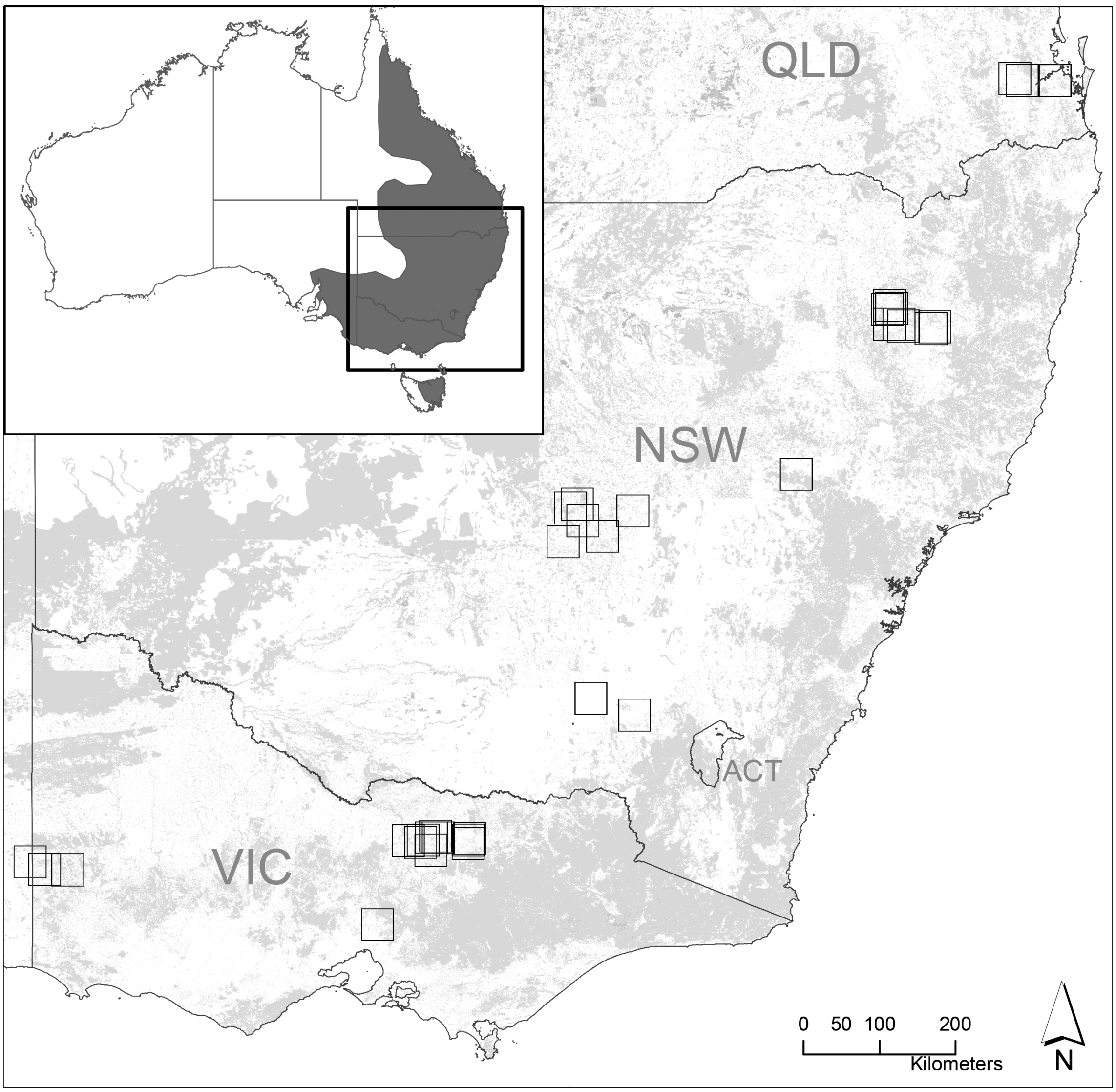


FIGURE 1 Distribution of all known noisy miner removals across southeastern Australia. Remaining woodland habitat is in light-grey (data derived from Department of the Environment (2018)—downloaded from National Vegetation Information System data products). Inset Map: Context of removal locations within Australian continent and indicative, broad distribution of noisy miners (BirdLife International [2020]—Species factsheet: *Manorina melanocephala*. Downloaded from http://www.birdlife.org on October 1, 2020)

**TABLE 3** Summary of methodological and site context data, and the range of responses identified for removal events for the subset of official removals and for the full dataset (official and unofficial removals)

| | Mean | Range |
|---|---|---|
| *Site context variables* | | |
| Treatment area ($ha^{-1}$) | 30.7 | 0.5–430.0 |
| Woody vegetation cover within 1 km radius of treatment site (%) | 28.8 | 0–100.0 |
| % Sites with shrubs present | | 66.7 |
| **Method variables** | | |
| Prior density of noisy miners; official removals subset (birds $ha^{-1}$) | 6.0 | 1.5–19.0 |
| Prior density of noisy miners; unofficial removals subset (0: none through to 5: extremely high) | 4.2 | 3–5 |
| Density of noisy miners removed (birds $ha^{-1}$) | 28.1 | 0.4–250.0 |
| Density of noisy miners removed (birds $ha^{-1}$); official removals subset | 13.7 | 0.4–48.5 |
| Number of repeat culls | 3.0 | 1–6 |
| Time between first and final cull (months) | 10.0 | 0–60 |
| *Response variables* | | |
| Change in noisy miner density following removal; official removals (%) | −25.1 | −91.5 to +87.2 |
| | | **% Sites** |
| % Sites with successful reduction of noisy miner density below the critical threshold (Thomson et al., 2015); official removals subset | | 8.3 |
| % Sites with successful reduction of noisy miner density >50% | | 40 |
| % Sites with >25% increase in small bird species richness | | 82.2 |
| % Sites with >25% increase in small bird abundance | | 80 |

## 3.1 | Official removals

No single ecological or methodological parameter was consistently associated with the various response variables across multiple response types (Tables 4 and 5, Appendices 2–5). For the official removals, the "best" model for the response variable percentage change in noisy miner density contained all predictor variables, yet the confidence intervals of the estimates of each individual predictor included zero when averaged across the 95% confidence set (Table 4). Where the response variable was a successful increase in small bird species richness for the official removals, the "best" models tended to include the density of noisy miners prior to removal (birds $ha^{-1}$) (Table 4); however, this predictor was nonsignificant (Appendix 5). The inclusion of methodological and ecological context variables appeared to have no significant influence on modeling successful increase in small bird abundance (Table 4).

## 3.2 | All removals

When the data from the eight unofficial removals were included, the "best" models for successful reduction of noisy miner density by 50% or greater included the time between first and final cull (months) and the density of noisy miners removed (birds $ha^{-1}$) (Table 5). Although there was some evidence that models including these variables performed better than the null model, only time between first and final cull had an averaged coefficient estimate whose 95% confidence intervals did not include zero, with a significant positive effect on the likelihood of a removal reducing noisy miner density by 50% or more (Figure 2). Inclusion of methodological and ecological context variables appeared to have no significant influence on modeling successful increase in one of small bird species richness or abundance (Figure 3, Table 5).

## 3.3 | Effects of noisy miner reduction on small birds

Even though more than 91% of sites did not see noisy miner reductions below the critical threshold of 0.6 birds $ha^{-1}$ (Thomson et al., 2015) after the removals, over 80% of sites had increases in small birds (Table 3). Sites in which noisy miner density was reduced by at least 50% by the removal ($n = 18$) were more likely to have increased post-removal small bird species richness ($\chi^2_1 = 6.501$, $p < .05$). However, the same reduction (at least 50%) of noisy miner density at these sites was not significantly associated with increased small bird abundance post-removal ($\chi^2_1 = 1.488$ $p > .05$).

## 4 | DISCUSSION

Our analysis of all known noisy miner removal data found that despite the overwhelming majority of removals (>91%) failing to suppress noisy miner density to below the critical threshold of 0.6 birds $ha^{-1}$ (Thomson et al., 2015), species

**TABLE 4** Models within two AICc values of the best model for each of percentage change in noisy miner density, and observed or not observed increase in small bird occurrence following removals for the official data set only ($n = 37$ removal sites)

| Response | Variables | AICc | ΔAICc | $\omega_i$ | *df* | logLik | $R^2$ |
|---|---|---|---|---|---|---|---|
| Percentage change in noisy miner density | Time between first and final cull + number of culls + prior density of noisy miners + density of noisy miners removed + presence of shrubs + woody vegetation cover + treatment area | 320.33 | 0 | 0.67 | 10 | −145.77 | .23 |
| | (Null) | 366.24 | 45.9 | 0 | 3 | −179.74 | .08 |
| Increase/no increase in small bird species richness (25% or greater) | Prior density of noisy miners | 36.02 | 0 | 0.09 | 3 | −14.64 | .29 |
| | Prior density of noisy miners + percentage change in noisy miner density | 27.09 | 1.07 | 0.05 | 4 | −13.90 | .35 |
| | Prior density of noisy miners + woody vegetation cover | 37.15 | 1.13 | 0.05 | 4 | −13.93 | .33 |
| | Prior density of noisy miners + number of culls | 37.30 | 1.27 | 0.05 | 4 | −14.00 | .33 |
| | (Null) | 39.83 | 3.81 | 0.01 | 2 | −17.73 | 0 |
| Increase/no increase in small bird abundance (25% or greater) | (Null) | 42.50 | 0 | 0.0 | 2 | −19.07 | 0 |

Abbreviation: AICc, Akaike information criterion weight adjusted for small sample size.

**TABLE 5** Models within two AICc values of the best model for each of successful/unsuccessful reduction of noisy miner density >50%, and observed or not observed increase in small bird occurrence following removals for full dataset (official and unofficial removals, $n = 45$ removal sites)

| Response | Variables | AICc | ΔAICc | $\omega_i$ | *df* | logLik | $R^2$ |
|---|---|---|---|---|---|---|---|
| Successful/unsuccessful reduction of noisy miner density (50% or greater) | Time between first and final cull + density of noisy miners removed | 56.73 | 0 | 0.11 | 4 | −23.86 | .482 |
| | Time between first and final cull + density of noisy miners removed + number of culls | 57.01 | 0.28 | 0.10 | 5 | −22.73 | .409 |
| | Time between first and final cull + density of noisy miners removed + treatment area | 57.23 | 0.50 | 0.09 | 5 | −22.85 | .482 |
| | Time between first and final cull + density of noisy miners removed + number of culls + treatment area | 57.67 | 0.95 | 0.07 | 6 | −21.73 | .454 |
| | Time between first and final cull + density of noisy miners removed + presence of shrubs | 58.53 | 1.80 | 0.05 | 5 | −23.49 | .533 |
| | (Null) | 64.50 | 7.77 | 0 | 3 | −28.96 | .131 |
| Increases/no increase in small bird species richness (25% or greater) | Prior density of noisy miners | 45.93 | 0 | 0.07 | 3 | −19.67 | .13 |
| | (Null) | 46.41 | 0.48 | 0.05 | 2 | −21.06 | 0 |
| | Prior density of noisy miners + density of noisy miners removed | 46.58 | 0.65 | 0.05 | 4 | −18.79 | .21 |
| | Prior density of noisy miners + woody vegetation cover | 46.63 | 0.70 | 0.05 | 4 | −18.82 | .19 |
| | Prior density of noisy miners + time between first and final cull | 47.33 | 1.40 | 0.03 | 4 | −19.17 | .17 |
| | Woody vegetation cover | 47.45 | 1.52 | 0.03 | 3 | −20.43 | .05 |
| Increase/no increase in small bird abundance (25% or greater) | Treatment area + density of noisy miners removed | 47.53 | 0 | 0.07 | 3 | −19.27 | .79 |
| | Density of noisy miners removed | 47.74 | 0.21 | 0.06 | 3 | −20.58 | .66 |
| | Treatment area + density of noisy miners removed + presence of shrubs | 48.59 | 1.06 | 0.04 | 5 | −18.53 | .84 |
| | Density of noisy miners removed + time between first and final cull | 48.61 | 1.08 | 0.04 | 4 | −19.80 | .70 |
| | Density of noisy miners removed + presence of shrubs | 48.7 | 1.18 | 0.04 | 4 | −19.85 | .74 |

(Continues)

**TABLE 5** (Continued)

| Response | Variables | AICc | ΔAICc | $\omega_i$ | *df* | logLik | $R^2$ |
|---|---|---|---|---|---|---|---|
| | Treatment area + density of noisy miners removed + woody vegetation cover | 48.76 | 1.23 | 0.04 | 5 | −18.61 | .78 |
| | (Null) | 49.32 | 1.79 | 0.03 | 2 | −22.52 | 0 |
| | Treatment area + density of noisy miners removed + time between culls | 49.51 | 1.98 | 0.03 | 5 | −18.98 | .77 |

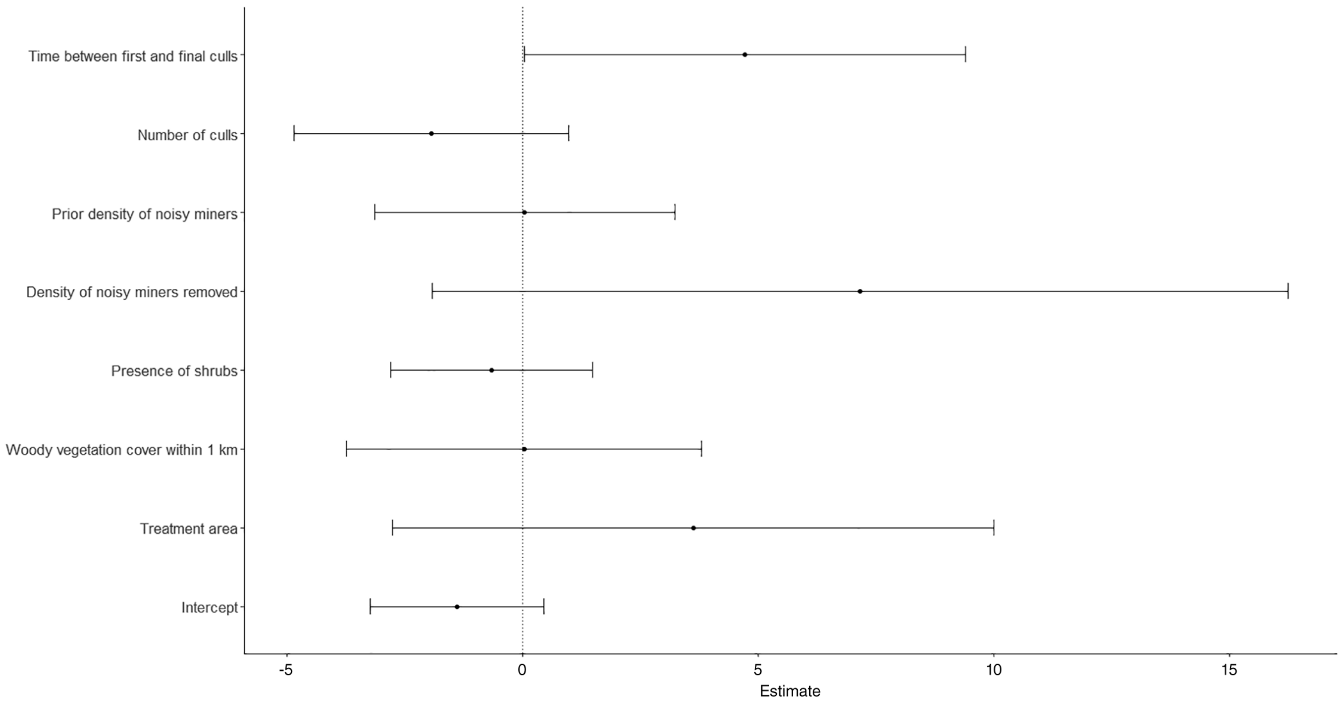


**FIGURE 2** Coefficient estimates of standardized predictor variables averaged across the ±95% confidence interval set of models for the response variable successful reduction of noisy miner density by 50% or greater, for the full removal dataset. [Correction added on 15 October 2021, after first online publication: Figure 2 was revised.]

richness and abundance of small woodland birds increased at most sites following removals. This suggests that the critical threshold identified is not necessarily the only useful target for management to allow a positive change in the woodland bird community. The only significant predictor of any of the measures of success was time between first and final cull which was positively related to the likelihood of the removal reducing noisy miner density by 50% or more. The relatively small number of sites analyzed in this study may limit the statistical power in our regression analyses, and as such fail to identify some real relationships between predictor and response variables as significant.

## 4.1 | Limited effectiveness in reducing noisy miner density

Despite high removal effort at many of the treatment sites, and many concluding that all or almost all noisy miner present at the time were removed, we found that the density of noisy miners remained, on average, much higher (4.4 birds ha$^{-1}$) than the critical threshold of 0.6 birds ha$^{-1}$ (Thomson et al., 2015). This could potentially be the result of failure to remove all of the noisy miners that were inhabiting the site; however, this seems unlikely based on reported observations by those conducting the removals and the use of audio playback to attract birds, to which noisy miners are highly responsive. Furthermore, there were repeated removal events at many sites and the majority of removals (the official removals) were undertaken by experienced shooters.

An alternate, more plausible explanation could be that once noisy miners were removed from the treatment site, a neighboring noisy miner colony/ies expanded into this “vacuum.” Given that noisy miners exhibit intraspecific competition as well as interspecific competition (Dow, 1975), the removal of birds from a territory that they previously defended could enable rapid establishment by neighboring

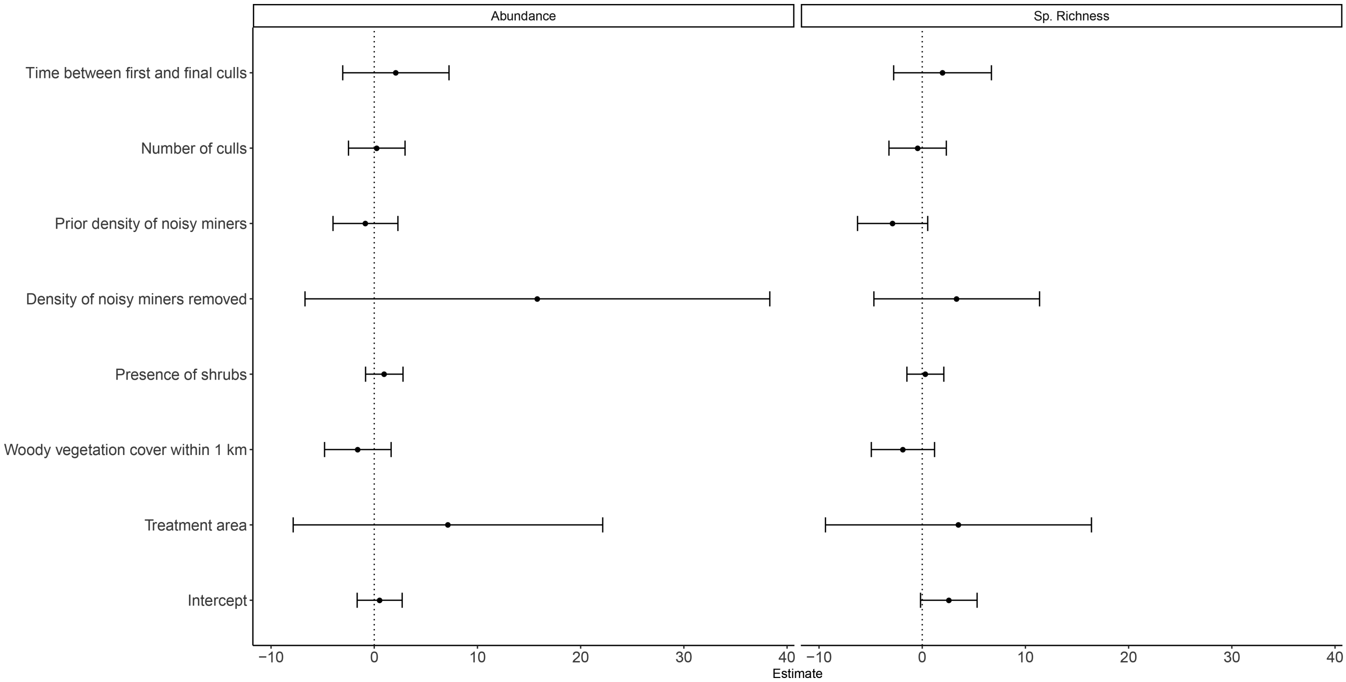


**FIGURE 3** Coefficient estimates of standardized predictor variables averaged across the ±95% confidence interval set of models for the response variables, observed increase in small bird species richness and observed increase in small bird abundance (by 25% or greater), for the full removal dataset

colonies, or parts thereof. Supporting this contention, many of the remnants targeted for noisy miner removal were in fertile agricultural land (Simmonds, VAN Rensburg, & Maron, 2017) which is likely prime habitat for noisy miners, as their density has been shown to be positively associated with site productivity (Oldland, Taylor, & Clarke, 2009). This may encourage rapid reestablishment where high-quality habitat becomes available to surrounding colonies.

Furthermore, a high density of noisy miners post-removal could indicate there were large numbers of individual birds in the landscape, unattached to existing colonies, which then expanded into the removal site. Noisy miners are communal breeders and young female noisy miners commonly disperse prior to breeding. If any remain in their natal territory past the onset of a breeding period, they rarely help in the provisioning tasks for other nests (Barati, Andrew, Gorrell, Etezadifar, & Mcdonald, 2018). This could suggest that these female birds actively prioritize seeking appropriate areas to establish a nest of their own. It is possible that once resident noisy miners were removed from the treatment sites, "scouting" dispersing females and any other individuals not part of a colony rapidly began establishing in this habitat. Vickers (2017) found that the age and sex of recolonizers following the Davitt et al.'s (2018) removals differed according to the time of year of the removal. Following the breeding season, dispersing immature noisy miners were the majority of recolonizers while before the breeding season, mature, disproportionately male, noisy miners from neighboring colonies were the majority of recolonizers. Thus, the timing of removals with respect to the breeding season could influence the source and extent of recolonizing noisy miners.

Immature individuals establishing at a removal site is also a common phenomenon observed when controlling invasive problem species. Removals of invasive problem species can even result in greater densities than were there before the removal under a process of overcompensation, whereby a reduced number of adult individuals fosters high survival rates of immature individuals (Grosholz et al., 2021). As such, specific strategies to manage reinvasion are often required (Banks, Byrom, Pech, & Dickman, 2018). The importance of managing reinvasions may be echoed in our study, as most of the noisy miner removal interventions analyzed included multiple removal events, some conducted over longer periods of time, and most removals benefited other woodland birds. Additionally, a positive effect between time between first and final culls and reduction in noisy miner density was the only significant predictor of any of the response variables. Therefore, suppression of noisy miners over time may be required to sustain these benefits.

## 4.2 | Increases in woodland bird richness post-removal

We expected that removals would have to result in reductions below the critical threshold 0.6 birds ha$^{-1}$ to benefit woodland birds (Thomson et al., 2015). This threshold is based on a synthesis of data from bird surveys at 2,128 transects from 23 studies, which revealed consistently reduced richness and abundance of small birds when noisy miner density was above this threshold. Our results suggest that removals can relieve local pressure on small woodland birds, at least for the short-term. For example, Crates et al. (2018, 2020) showed that removals allowed regent honeyeaters to breed successfully in habitat previously dominated by noisy miners and similarly, Grey et al. (1997, 1998) found that woodland bird richness was improved for at least 12 months following removals.

This could be explained by the theory previously suggested by Mac Nally, Bowen, Howes, Mcalpine, and Maron (2012) and Davitt et al. (2018), that following the removal of some birds within a colony, noisy miners may need to expend more effort in behaviors associated with colony reformation or consolidation than in interspecific aggression. Furthermore, if the treatment site sees an influx of young female noisy miner dispersers and temporary helper males, the group of birds occupying a treatment site in the aftermath of a removal may not yet have the social bonds and intimate knowledge of a site that characterize an established colony, which are central to the cooperative exclusion of small birds.

Some management to enhance habitat quality for woodland birds has been carried out, including restoration and modified farming practices (Belder, Pierson, Ikin, & Lindenmayer, 2018; Lindenmayer et al., 2012; Smallbone, Matthews, & Lunt, 2014; Whytock et al., 2018). However, restoring woodland habitat is complex (Lindenmayer, 2020), can be costly (Schirmer & Field, 2000), involves considerable time lags (Belder et al., 2018), and the effectiveness of such actions is not always clear (Suding, 2011). Thus, removal interventions could be a useful management response to immediately reduce pressure on highly vulnerable small birds, as a complement to ongoing (and longer timescale) restoration endeavors. In particular, noisy miner removal could be important for targeted conservation efforts where immediate reduction to threatening processes is required, such as for critically endangered species like the regent honeyeater (Crates et al., 2018; Grey et al., 1997). As such, identifying conditions under which the benefits emerge is crucial for finding the best actions for the conservation of woodland birds.

## 4.3 | Conservation goals and what constitutes removal success

Objectives of the different removal events included suppressed noisy miner density, increased diversity and abundance of small birds, and reduced disruption to potential breeding opportunities of severely threatened species. As such, different studies had different definitions of success. For example, Davitt et al. (2018) determined success as significantly reducing noisy miner density at the treatment site immediately following the removal; Crates et al. (2018, 2020) considered removals successful if noisy miner density was suppressed for the breeding season of the critically endangered regent honeyeater for one season; and Debus (2008) described a successful removal which involved continued low level removal effort over time, coupled with revegetation activity at the treatment site.

Conservation interventions that aim to remove noisy miners do so not in order to reduce noisy miner density per se, but to benefit other species or bird communities of conservation concern. A reduction in noisy miner density is a means to this end, rather than the ultimate objective. We found increased richness of small birds in sites where noisy miner density was reduced by at least 50%—even though that was rarely enough to decrease density to below the critical threshold. This surprising finding highlights the importance of monitoring not only the target of a conservation intervention, in this case noisy miners, but also the biota that we ultimately seek to benefit—in this case, woodland birds.

## 4.4 | Management implications

Noisy miner removal must be justified with evidence before widespread use as a conservation intervention. More research is required to identify the duration of benefits to small woodland birds following removal events. Additionally, the implications (e.g., investment in ongoing or follow-up removal actions, and synergies with other interventions such as restoration) of managing this key threatening process long-term need to be well understood to ensure such action is feasible.

While noisy miner removal appears generally to facilitate a positive short-term woodland bird response, we still lack a full understanding of the extent and duration of this benefit, and of the environmental and methodological conditions under which removals are most likely to provide that benefit. Therefore, we argue for learning by drawing together data from multiple removal interventions to iteratively guide and refine future efforts to control this problem species. To support the development of this knowledge base, future removals must involve careful monitoring and reporting of standardized data before and after the interventions at the treatment site and matched control sites where possible, documenting the details of removal methods, site ecological context, and response of all birds. Vegetation surveys that at least described the vegetation structure (presence of shrubs) and density (woody vegetation cover) at both treatment and matched control sites would allow for more detailed assessment of the potential influence of site characteristics on the effectiveness of removal(s). Furthermore, noting the proximity of the treatment site to other noisy miner colonies could help in assessing its effect on the likelihood of reestablishment of the removal site.

Most noisy miner removal interventions analyzed in this study benefited other woodland birds. Most of these interventions involved multiple removal events, some of which occurred over longer periods of time; an important predictor in the likelihood of a removal having a reduction in noisy miner density by 50% or more. Thus, it is likely that future noisy miner control will also need to involve longer-term suppression efforts to sustain the benefits observed to small woodland birds during the period of disrupted social cohesion of recolonizing noisy miners. A research priority should be to first identify the duration of the benefits observed to small woodland birds following a removal event, to then use this information to help predict the frequency of suppression efforts likely required to sustain this benefit in critical conservation areas, potentially in the temporal context of noisy miner breeding activity.

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## CONFLICT OF INTEREST

The authors declare no potential conflict of interest.

## AUTHOR CONTRIBUTIONS

**Courtney B. Melton**, **Martine Maron**, **Jeremy S. Simmonds**, **April E. Reside**, **Paul G. Mcdonald**, and **Richard E. Major**: Conceived the manuscript, with input from all authors. **Martine Maron**, **Paul G. Mcdonald**, **Richard E. Major**, **Ross Crates**, **Carla P. Catterall**, **Mike F. Clarke**, **Merilyn J. Grey**, **Galen Davitt**, **Dean Ingwersen**, and **Doug Robinson**: Also shared data under data-sharing agreements for the purpose of this meta-analysis. **Courtney B. Melton**: Conducted the analyses and drafted the initial manuscript, and all authors contributed to writing and editing.

## DATA AVAILABILITY STATEMENT

Most of the datasets used in this meta-analysis are available by contacting the relevant authors. Data that were collected during interviews are only available in anonymized, per the requirements of the Human Ethics Approval.

## ETHICS STATEMENT

Human Ethics Approval was received from the primary institution to collect data via interviews describing unofficial noisy miner removals (Application Approval number: 2019000450).

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## SUPPORTING INFORMATION

Additional supporting information may be found in the online version of the article at the publisher's website.

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