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Curtailment as a successful method for reducing bat mortality at a southern Australian wind farm

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Abstract Wind energy is a rapidly expanding renewable technology with massive global investments; however, operating turbines are associated with bat strikes globally, and evidence suggests that without intervention, wind farm collisions could drive some common species to extinction. One widely regarded method for reducing strike mortality is operational mitigation, or curtailment, where turbine operation is restricted at low wind speeds. Despite an increasing number of studies in the Northern Hemisphere demonstrating curtailment effectiveness, no empirical studies have yet been conducted in Australia. This paper reports the findings of a curtailment study implemented at the Cape Nelson North wind farm in southwest Victoria, Australia. Conservation detection dog teams conducted mortality surveys between January and April in 2018 (before; pre-curtailment) and 2019 (after; during curtailment). Results were consistent with similar studies in the USA and Europe, as curtailment significantly reduced pooled species mortality by 54%. Bat calls did not decline during the study period, and thus were not an explanation for the reduction in fatalities. This study demonstrates that curtailment is a valid method for reducing bat turbine collision in south-eastern Australia. Consideration should be given to curtailment as a means to reduce bat turbine impacts in Australia, particularly at sites with known endangered and threatened populations, as we act to reduce anthropogenic climate change and its time-sensitive negative consequences.

Key words: bat fatality monitoring, mitigation, southern bent-wing bat, white-striped free-tailed bat, wind energy.

INTRODUCTION

Wind-generated power is being increasingly incorporated into the global energy portfolio due to its potential to substantially reduce anthropogenic climate change and the associated long-term negative environmental impacts (Pasqualetti *et al.* 2004; DeCarolis & Keith 2006; Arnett *et al.* 2007; Arnett *et al.* 2011; Chu & Majumdar 2012; Hayes *et al.* 2019); however, wind energy facilities can adversely affect wildlife through turbine collision, a phenomenon reported worldwide (Arnett *et al.* 2016; Thompson *et al.* 2017). Bats are particularly susceptible to collisions with operating turbines, with fatalities estimated to be in the hundreds of thousands per year in the United States and Canada alone (Arnett & Baerwald 2013; Smallwood 2013).

Population-level empirical data is lacking for many bat species worldwide (O'Shea *et al.* 2016), but this level of fatality is considered unsustainable due to the distinctive slow life history of bats that limits their ability to recover from population declines (Barclay & Harder 2003). Increasing evidence is thus illustrating that without intervention, wind farm collisions could drive some common bat species to extinction (Frick *et al.* 2017; Friedenberg & Frick 2021). Investigations into the contributing factors of bat fatalities at wind farms is a topic of much research in the Northern Hemisphere, with a plethora of studies on mitigative procedures (Arnett & Baerwald 2013; Arnett *et al.* 2016; Hein & Schirmacher 2016; Behr *et al.* 2017; Thompson *et al.* 2017; Rodhouse *et al.* 2019). From this work, it is widely agreed that curtailment is the most successful method of reducing turbine-associated fatalities.

Curtailment involves operational restriction of turbines at low wind speeds (often lower than 6 ms^{-1}) between dusk and dawn during periods of high bat activity, generally from summer to autumn (Arnett *et al.* 2008, 2009, 2011, 2016; Arnett & Baerwald 2013; Rodrigues *et al.* 2015; Hein & Schirmacher 2016; Behr *et al.* 2017; Martin *et al.* 2017; Thompson *et al.* 2017; Hayes *et al.* 2019; Rodhouse *et al.* 2019; Adams *et al.* 2021; Whitby *et al.* 2021).

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Despite this evidence regarding the effectiveness of turbine curtailment, it has not yet been trialled in Australia, where turbine-associated bat fatalities were first reported five decades ago (Hall & Richards 1972), and more recently in the past 20 years as the wind energy industry has developed in Australia (Hull & Cawthen 2013). Additionally, although a small player in the global wind energy portfolio, wind energy capacity in Australia has increased 67% over 4 years, with many more developments underway (WWEA 2020).

The main objective of this study was thus to evaluate curtailment as a method of reducing bat fatalities at the Cape Nelson North wind farm in southwest Victoria, Australia. This study was proposed following the reporting of six fatalities of the critically endangered southern bent-wing bat (*Miniopteris orianae bassanii*) during the initial two-year monitoring period for bird and bat impacts associated with the wind farm. In line with Northern Hemisphere counterparts of this study type, we predicted that bat fatalities would be significantly higher at fully operational turbines than those with increased turbine cut-in speeds (Arnett *et al.* 2011). Although the reasons behind why bats collide with turbines are still being debated (Hein & Schirmacher 2016), techniques for minimizing such impacts must be investigated, particularly when threatened species are involved. Considering the time-sensitive implications of a warming planet, it is vital we understand the environmental impact of any alternative energy sources to ensure we can reduce the now inevitable critical effects of anthropogenic climate change, whilst ensuring low environmental cost.

METHODS

Study design

The study was a before:after designed experiment, with mortality surveys and bat call monitoring conducted in both 2018 ('before'; before curtailment) and 2019 ('after'; during curtailment, Table 1). Curtailment began at sunset on the 31st December 2018, and was maintained until sunrise on the 1st May 2019. Mortality surveys were conducted by experienced dog-handler teams from: (i) 19th January to 28th April 2018 and (ii) 5th January to 27th April 2019 (Table 1). All 11 turbines of the wind farm were surveyed for fatalities each survey day in both years, for a total of 319 surveys over 29 days in 2018 and 352 surveys over 32 days in 2019. Bat acoustic data were collected as a proxy of bat activity on site using four ultrasonic bat call detectors from a subset of locations within the wind farm footprint (Fig. 1). Bat calls were recorded from dusk to dawn from: (i) 19th January to 15th April, 2018 and (ii) 7th January to 29th April, 2019 (Table 1) for a total of 86 and 112 nights, respectively (Appendix S3).

Table 1. Parameters for a curtailment experiment at a wind farm in southwest Victoria, Australia

Curtailment status	Month	Mortality survey days	Acoustic survey nights
Before	Jan	4	13
	Feb	8	28
	Mar	9	31
	Apr	8	15
	Total	29	87
After	Jan	7	25
	Feb	8	28
	Mar	9	31
	Apr	8	29
	Total	32	113

Acoustic data were taken as proxy for the number of bats onsite during any one night. Curtailment occurred from the 31st December, 2018 to the 1st May, 2019.

Fig. 1. Wind turbine (red circles) and Songmeter sound recorder (yellow stars) locations in a curtailment-effects experiment at the Cape Nelson North wind farm in southwest Victoria, Australia from 2018 to 2019.

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Wind farm location

The Cape Nelson North Wind farm (38°21′8.74″S, 141°35′14.4″E) is located 5 km southwest of Portland in Victoria, Australia (Fig. 1). The site is part of the Portland Wind Energy Project and operated by Pacific Hydro (Melbourne, Australia). The wind farm consists of 11 Senvion MM92 2.05-megawatt (MW) turbines with three blades, a rotor hub height of 80 m, rotor diameter of 92.5 m, rotor swept area of 6722 m^2, and a maximum rotor speed of 15 revolutions per minute. The site is situated primarily on cleared agricultural land with varying conditions of grass and pasture. Areas to the immediate south and west are well-covered in coastal native vegetation, and the site is adjoined in part by the Discovery Bay Coastal Park and Portland H46 Bushland Reserve.

The study area is in a temperate climatic zone; between January and April, precipitation typically averages from 32.4 to 45.7 mm per month, mean monthly temperatures range from 12.3 to 21.4°C, and mean daily wind speed ranges from 1.26 ms^{-1} (April) to 5.48 ms^{-1} (February, 1995–2021 averages; Bureau of Meteorology, Australian Government 2021).

Two megabats are known to occur in this area: the grey-headed flying fox (*Pteropus poliocephalus*) and little red flying fox (*Pteropus scapulatus*), and 13 microbats: yellow-bellied sheath-tail bat (*Saccolaimus flaviventris*), southern bent-wing bat (*M. orianae bassanii*), eastern falsistrelle or false pipistrelle (*Falsistrellus tasmaniensis*), large-footed myotis (*Myotis macropus*), Gould's long-eared bat (*Nyctophilus gouldii*), lesser long-eared bat (*Nyctophilus geoffroyi*), chocolate wattled bat (*Chalinolobus morio*), Gould's wattled bat (*Chalinolobus gouldii*), large forest bat (*Vespadelus darlingtoni*), little forest bat (*Vespadelus vulturnus*), southern forest bat (*Vespadelus regulus*), white-striped free-tailed bat (*Austronomus australis*, formerly *Tadarida australis*), and the southern free-tailed bat (*Ozimops planiceps*).

Curtailment parameters

Curtailment began in the second year of the study at sunset on the 31st December, 2018, and was maintained until sunrise on the 1st May, 2019, following completion of mortality surveys on the 28th April, 2019. This time of year (summer to autumn) was chosen as bat activity is highest during the warmer months of the year in temperate Australia (October–March, Lumsden & Bennett 1995) when wind speed and temperatures are favourable and there is greater insect activity (Sanderson & Kirkley 1998; Milne *et al.* 2005; Turbill 2008). In the Northern Hemisphere, the summer to autumn period is when most bats are killed at wind energy facilities (Arnett *et al.* 2008), and similar results have been reported in Tasmania, Australia (Hull & Cawthen 2013). Consistent with this, the previous 2 years of mortality monitoring at Portland found that approximately 80% of all bat strikes occurred during January to April (data not shown). As such, conducting the study in this period maximized the likelihood of detecting fatalities to test curtailment effectiveness. From dusk until dawn during the curtailment period, the cut-in speed of all 11 turbines was revised from 3.0 to 4.5 ms^{-1} as a voluntary commitment by Pacific Hydro.

Mortality surveys

Experienced conservation detection dog teams that had previously demonstrated consistent detection rates of >95% (data not shown) were employed for mortality surveys. Dogs were chosen to maximize the likelihood of carcass detection (Paula *et al.* 2011; Mathews *et al.* 2013; del Valle *et al.* 2020; Smallwood *et al.* 2020). The same survey teams were used in both years and survey methods remained consistent during the study. Furthermore, searcher efficiency for dog-handler teams is consistently high across all sites in Victoria (~84% regardless of the time of year), with a smaller overall variance in detection than human-only search teams (Stark & Muir 2020). As they search by scent, weather and vegetation also has less of an impacting factor on dog-handler teams than human-only searchers (del Valle *et al.* 2020); therefore, adjustments for searcher efficiency were not considered within the scope of this study (Mathews *et al.* 2013; Smallwood & Bell 2020).

Transect surveys of all 11 turbines were conducted twice weekly to a radius of 60 m. This radius covers >99% of the fall zone for bats for a rotor height of 80 m (Hull & Muir 2010). Surveys were spaced three to 4 days apart, commenced at sunrise each day, and took approximately 4 h. Mortality surveys in 2019 were conducted slightly earlier in the year to coincide with the beginning of curtailment on the 1st January, and thus an additional three survey days (i.e. an extra three surveys per turbine) were undertaken in the second year of this study. This difference is considered in the statistical analysis by calculating the total fatalities per survey day across all 11 turbines before and during curtailment ('before' and 'after', respectively).

When a carcass was located, survey teams recorded: GPS location, time of find, species, sex, life stage (adult/juvenile, where possible), turbine number, surrounding habitat characteristics, and estimated time of death (e.g. <1 day, 2 days, etc.). Carcasses were placed in plastic bags and removed from plots, and stored in a car freezer prior to long-term freezer storage (−20°C). Approximately 96% of the total survey area was searched, with some reductions necessary due to safety issues, for example young calves in paddocks or elevated snake interaction risk in hot weather.

Bat activity

Four ultrasonic bat call detectors (Songmeter SM4 model operated in zero crossed mode; Wildlife Acoustics, Maynard, MA, USA) were placed at representative locations within the wind farm to record all bat activity (Fig. 1). Detectors were tied approximately 1.2 m off the ground on fence posts, and were placed in the same position each year. Detectors were not placed close to turbines themselves to prevent noise interference and locations were constrained by farming activity, with areas fenced off from cattle chosen to prevent equipment damage; however, all four detectors were spatially separated from each other whilst within 200 m of turbines (Fig. 1). Data cards were replaced as necessary, with no data lost due to full cards.

Whilst uncertainty exists regarding the use of bat call activity as a proxy for the number of individuals onsite

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(Sherwin *et al.* 1998; Barclay 1999), it remains the least invasive and most reliable method for quantifying bat activity levels, especially over a longer period, such as that in this study (Milne *et al.* 2004; Peterson *et al.* 2021). It is possible high-flying species were missed with ground-based detectors; however, the Cape Nelson North windfarm mostly occupies cleared agricultural land, and ground-based detectors can accurately account for bat activity to a height of at least 30 m in these environments (Menzel *et al.* 2005; Collins & Jones 2009). We were also constrained in achieving extra height with existing infrastructure whilst avoiding interference from turbines and high wind noise. Furthermore, the aim was to record general bat activity across the windfarm to test for any significant difference between the years, which if detected could mean any lower bat mortality may be explained by lower bat activity, and thus it was not a priority to record all possible species on site.

Data preparation

Prior to analysis, data were cleaned and standardized as follows (full details can be found in Appendix S1): for mortality surveys, species names were given consistent labels, and records of carcasses found in multiple pieces were merged. Bat acoustic data were analysed with Anascheme (Gibson & Lumsden 2003) and AnaBat Insight Software (Titley Scientific, Australia). Any call files initially identified by AnaScheme as a low frequency bat species (e.g. white-striped free-tailed bat and yellow-bellied sheath-tail bat) or as unknown were further analysed in Anabat Insight to distinguish between noise and valid bat calls. Any of these sound files Anabat Insight classified as valid calls were retained, whilst those not classified as such were discarded. Calls identified by AnaScheme as higher frequency species (e.g. lesser long-eared bat or large-footed myotis, Milne 2002) were considered valid and retained. Each valid call was considered an individual count.

All data cleaning and analyses used the R statistical programming language (R Core Team 2021). Unless otherwise stated, all analyses and reporting were performed on the filtered dataset. Due to the overall low number of counts, all impacts of curtailment activity were considered using pooled species data.

Data analysis

Generalized linear models (GLMs) were used to test for any statistical differences, with the following explanatory variables: (i) 'before:after', that is before curtailment ('before', 2018 survey period) and during curtailment ('after', 2019 survey period); and, (ii) 'month' (January/February/March/April, Appendix S2). Response variables were fitted against these explanatory variables to investigate those that explain any changes in the data, if present. Models were fit and selected with the aid of the R 'MASS' package (Venables & Ripley 2002). Statistical significance was taken at the $\alpha \leq 0.05$ level for all tests. Further details of each specific model are reported below.

Bat fatalities GLM

An additional three survey days (i.e. three surveys per turbine) were conducted during curtailment ('after') compared to before (Table 1). To account for this additional survey effort, the response variable was standardized by using the total fatality count over a survey of the 11 turbines on a single day. A unit of data in this model was thus the tuple of (Finds, before:after, Month) aggregated over a full survey of the 11 turbines on a particular day. There were too few counts for species to be included as an explanatory variable. Time between surveys was not considered as a required factor due to the even spacing between surveys.

To test for significance, a Poisson regression model of the following form was fitted:

$$\log(\mu_i) = \beta_0 + \beta_1 \bullet \text{BeforeAfter}_i \times \beta_2 \bullet \text{Month}_i$$

where: μ_i is the mean of the Poisson distribution for observation i, and $\times$ signifies an interaction term, an additional effect on top of the 'main effect' of Month and before:after. AIC stepwise selection removed the interaction term and reduced the model to (Appendix S4):

$$\log(\mu_i) = \beta_0 + \beta_1 \bullet \text{BeforeAfter}_i + \beta_2 \bullet \text{Month}_i$$

Overdispersion was non-significant ($P > 0.1$, pseudo R^2 for final measure = 0.26); therefore, no negative binomial or 'quasipoisson' model was required. Zero-inflation was also tested for and found not to be required. The final set of model coefficients for the mortality model are presented in Table 2. An exponential transform was applied to the GLM formula to interpret the scale of change.

No carcass persistence adjustments were applied in the mortality modelling. Although this adds an assumption that scavenger activity was similar across the two survey years, this is supported by a Victoria-wide pooling study, which reported no seasonal difference in removal rate (Stark & Muir 2020). As such, some control for scavenger activity was provided given the same survey frequencies and methods were used across the study at the same time of year,

Table 2. Modelling coefficients for a final before:after mortality generalized linear model, generated as part of a curtailment-effects experiment conducted from 2018 to 2019 at a wind farm in southwest Victoria, Australia

	Estimate	Std. error	z value	pr(>|z|)
Intercept ('Jan', 'Before')	0.511	0.320	1.595	0.111
BEFORE_AFTERAfter	−0.783	0.312	−2.510	0.012
MonthFeb	−0.569	0.419	−1.356	0.175
MonthMar	−0.040	0.364	−0.110	0.913
MonthApr	−2.274	0.765	−2.973	0.003

Month and curtailment conditions ('Before', before curtailment, 2018; 'after', during curtailment, 2019) were held as explanatory variables. Coefficient estimates and standard errors are presented on a natural log scale.

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but ultimately scavenger rate was not included in this study as scavenger trials were not conducted.

Bat activity GLM

The bat activity survey period differed slightly from the mortality survey periods: in 2018, no acoustic data were collected for the final 13 days of mortality surveys, whilst in 2019, the acoustic survey period started and ended 2 days later than the mortality surveys (Table 1); however, the aim was to quantify the magnitude of the before:after change in each dataset (i.e. mortality and activity). The before:after change in nightly activity was thus analysed separately to contextualize the carcass findings in relation to bat activity, and how this may influence collision risk and thus mortality counts. As such, the slight differences in survey dates for the two datasets were not considered to hamper the proposed analysis approach.

For this model, the response variable was the count of bat calls in a single night over all four detectors. A negative binomial model of the following form was fitted:

$$\log(\mu_i) = \beta_0 + \beta_1 \bullet \text{BeforeAfter}_i \times \beta_2 \bullet \text{Month}_i$$

where μ_i is the expected call count for night i. This model structure correctly accounted for Poisson overdispersion (pseudo R^2 for final model = 0.02). Month coefficients were not significant; thus, AIC comparison reduced the model to:

$$\log(\mu_i) = \beta_0 + \beta_1 \bullet \text{BeforeAfter}_i$$

The final set of model coefficients for the mortality model are presented in Table 3.

Graphs and images

Graphs and images were generated in R and edited in Adobe Photoshop CC 2018 and Adobe Photoshop 2021 (Adobe Inc., San Jose, CA, USA). Editing was for clarity and formatting only and did not change the content.

RESULTS

Curtailment led to a significant reduction in mortality

In total, 46 bat carcasses were found during the study, with 30 found before curtailment and 16 found during curtailment ('after', Fig. 2a). Overall fatalities per daily survey of all 11 turbines decreased from 1.03 (± 0.24 SE) to 0.50 (± 0.16 SE) following curtailment implementation.

For a single observation unit (being 1 day of survey over all turbines), there was a significant decrease of 54% in the number of bat carcasses per survey day over all turbines, with 1.70 fatalities per daily survey in the January before curtailment (95% CI (0.84, 2.98)) and 0.76 carcasses found per day in the January after curtailment began (95% CI (0.39, 1.47), before:after coefficient $P = 0.012$, GLM). Visually, the month-by-month distribution of finds per turbine per survey appeared slightly higher before curtailment (Fig. 2b).

Evidence of the well-understood seasonal pattern in fatalities was observed (Fig. 2b, Arnett *et al.* 2008), with significantly less fatalities per day in April compared to January (baseline/intercept month) both before and during curtailment ($P = 0.003$, Table 2), whilst February and March were not significantly different in either period. The before:after change did not vary significantly month-to-month.

Taken together, these results suggest that, when holding Month as a fixed variable, applying curtailment results in a significant drop in bat mortality by 54%. This figure takes into consideration the increased search effort during curtailment relative to before curtailment.

White-striped free-tailed bats were the most common bat species found during mortality surveys

The carcasses of eight species were recorded during this study (Table 4): the white-striped free-tailed bat (*A. australis*, $n = 24$), southern forest bat (*V. regulus*, $n = 2$), lesser long-eared bat (*N. geoffroyi*, $n = 2$), large forest bat (*V. darlingtoni*, $n = 3$), Gould's wattled bat (*C. gouldii*, $n = 9$), eastern false pipistrelle (*F. tasmaniensis*, $n = 1$), southern bent-wing bat (*M. orianae bassanii*, $n = 3$), and the chocolate wattled bat (*C. morio*, $n = 1$), along with one unidentified species ($n = 1$).

For six species, fatalities decreased during curtailment, whilst for two species there was an increase in

Table 3. Modelling coefficients for a final before:after bat call generalized linear model (negative binomial), generated as part of a curtailment-effects experiment conducted from 2018 to 2019 at a wind farm in southwest Victoria, Australia

	Estimate	Std. Error	z value	pr(>|z|)
(Intercept)	6.453	0.081	80.054	<0.001
BEFORE_AFTERAfter	0.206	0.107	1.922	0.055

Curtailment conditions ('Before', before curtailment, 2018; 'after', during curtailment, 2019) were held as explanatory variables. Coefficient estimates and standard errors are presented on a natural log scale.

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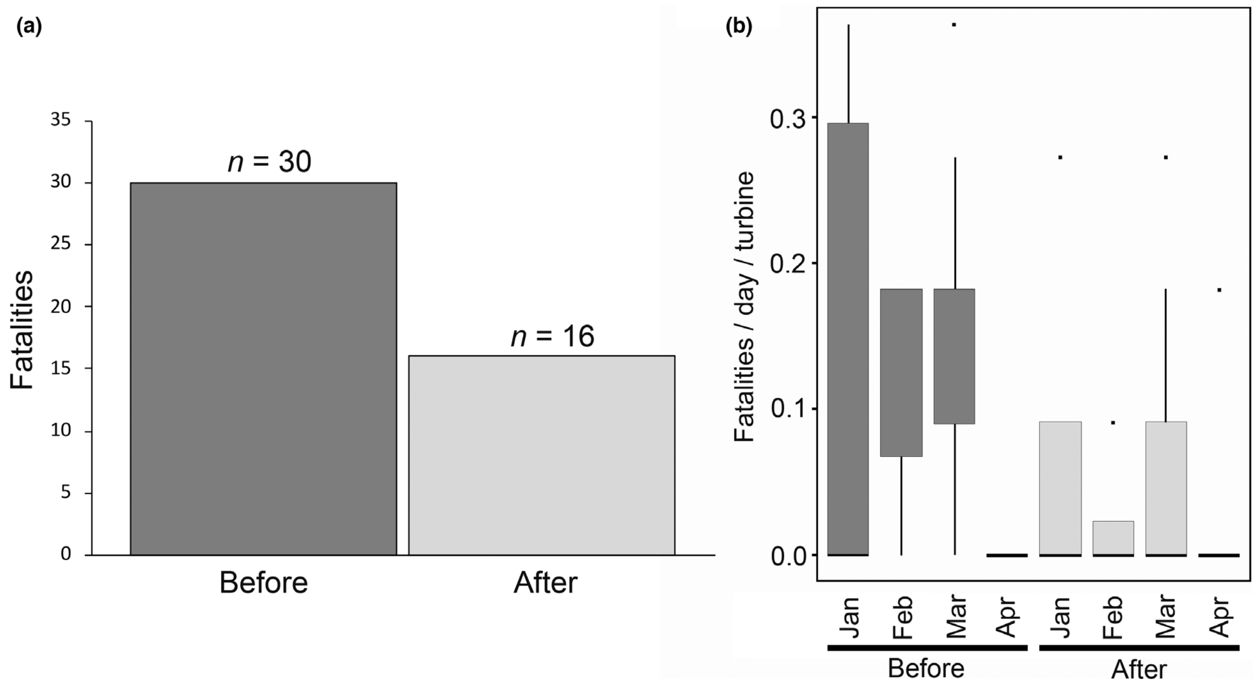

Fig. 2. Mortality survey findings from a curtailment-effects experiment at Cape Nelson North wind farm in Southwest Victoria, Australia, in 2018 and 2019. (a) Raw fatality counts during mortality surveys before (2018) and during (2019) curtailment. (b) Distribution of finds per turbine per survey presented as boxplot. The middle 50% of the data is contained within the box.

Table 4. Raw fatality counts of individual bat species found during mortality surveys in a curtailment-effects experiment conducted in 2018 (before curtailment) and 2019 (during curtailment) at a wind farm in southwest Victoria, Australia

Species	Before	After	Total
Chocolate wattled bat (*Chalinolobus morio*)	1	0	1
Eastern false pipistrelle (*Falsistrellus tasmaniensis*)	1	0	1
Gould's wattled bat (*Chalinolobus gouldii*)	2	7	9
Large forest bat (*Vespadelus darlingtoni*)	3	0	3
Lesser long-eared bat (*Nyctophilus geoffroyi*)	2	0	2
Southern bent-wing bat (*Miniopteris orianae bassanii*)	2	1	3
Southern forest bat (*Vespadelus regulus*)	0	2	2
White-striped freetail bat (*Austronomus australis*)	18	6	24
Unknown – bat	1	0	1
Total	30	16	46

Curtailment occurred from the 31st December, 2018 to the 1st May, 2019.

fatalities (Table 4). White-striped free-tailed bats were the most common carcass found before curtailment, with their carcass count during curtailment one-third that of pre-curtailment (Table 4).

Bat call activity did not decrease following curtailment

A GLM was fitted to the acoustic data to test if the significant decline in fatalities during curtailment could be explained by a background decline in activity. Across the 200 nights of recordings, there was a non-significant pattern of higher activity (i.e. a greater number of calls) during curtailment than before curtailment (before, $n = 55\,211$; after, $n = 88\,126$, $p = 0.055$, $\beta = 0.2$, 95% CI [−0.004, 0.5], GLM, Fig. 3).

A dominance of calls without species classification restricts the ability to comment on species-specific patterns. Only southern bent-wing bat calls were identified to a species level, of which 785 calls were recorded before curtailment, and 1251 recorded during curtailment.

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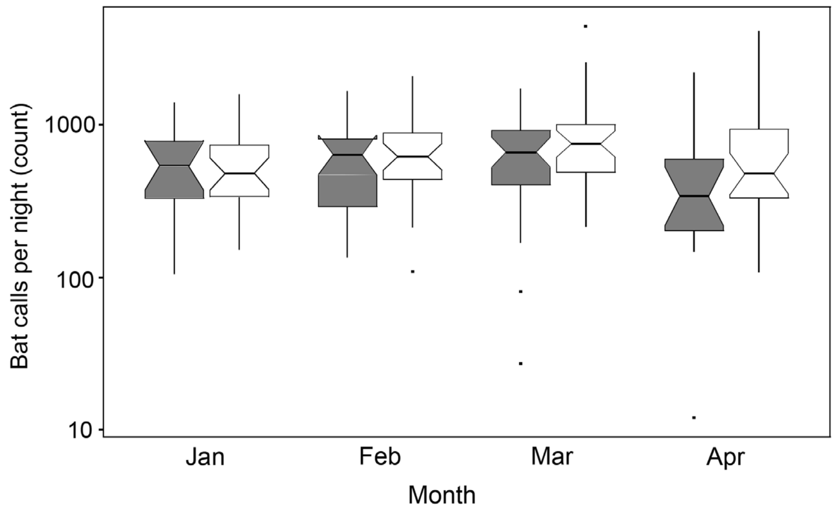

Fig. 3. Distribution of bat calls per night before (2018, dark grey) and during (2019, white) curtailment each month during a curtailment-effects experiment at the Cape Nelson North Wind farm in southwest Victoria, Australia. January to March look within confidence of each other, whilst April 2019 appears to have slightly higher activity than April 2018. Data presented as a notched boxplot. Notches providing an approximate 95% confidence interval on the median.

The model has sufficient power to detect a change in bat activity, if present

Given a change in fatalities, but not activity, was found, a negative binomial GLM power analysis was run using previously reported methods (Lyles *et al.* 2007) to evaluate the probability that a significant change in before:after activity coefficients could be detected, if one was present. With mortality being assumed linear in respect to activity, the model tested if a similar activity decline of 54% following curtailment could be seen. Sufficient power existed for the GLM to detect a difference in bat activity 100% of the time if it were truly there (data not shown). Therefore, any measurable difference in fatalities is due to turbine curtailment and not a change in bat activity between study years.

DISCUSSION

Increasing turbine cut-in speed from 3.0 to 4.5 ms^{-1} from dawn to dusk at a southern Australian wind farm significantly reduced bat fatalities by 54%. Curtailment was the principle explanatory variable for reduced mortality, as bat call activity did not differ significantly between study years, but rather non-significantly increased during curtailment. These findings are consistent with the original hypothesis and a growing body of global evidence demonstrating curtailment as an effective method for reducing turbine-associated bat fatalities (Baerwald *et al.* 2009; Arnett *et al.* 2011; Rodrigues *et al.* 2015; Smallwood & Bell 2020; Adams *et al.* 2021; Whitby *et al.* 2021). In terms of impacts to annual generation in megawatts per hour and revenue at Cape Nelson North, the four-month curtailment trial resulted in an annual generational loss of 0.16% and a reduction of 0.09% in revenue (Pacific Hydro). These values are similar to other studies reporting on the costs of curtailment implementation (Baerwald *et al.* 2009; Arnett *et al.* 2011; Martin *et al.* 2017; Hayes *et al.* 2019).

Wind speed is a consistently reported weather variable related to bat mortality at wind farms, with lower speeds (<6 ms^{-1}) frequently associated with higher bat activity and subsequent fatalities (Arnett & Baerwald 2013; Cryan *et al.* 2014; Hein & Schirmacher 2016). As such, curtailment is the primary mitigation strategy undertaken in the Northern Hemisphere to reduce turbine-associated mortality (Arnett *et al.* 2008, 2016; Allison 2018; Adams *et al.* 2021). For example, Arnett *et al.* (2011) found 72 to 82% (95% CI: 44–86%, 52–93%) fewer fatalities occurred at curtailed turbines (cut-in speed: 5.0 or 6.5 ms^{-1}) than those that were fully operational (cut-in speed: 3.5 ms^{-1}), whilst Martin *et al.* (2017) reported 62% (95% CI: 34–78) fewer bat fatalities when turbine cut-in speed was increased from 4.0 to 6.0 ms^{-1}. A more recent meta-analysis reported a decrease in fatalities by 33% for every 1.0 ms^{-1} increase in cut-in speed, with a 5.0 ms^{-1} cut-in speed estimated to reduce bat fatalities by 62% (95% CI: (54%, 69%); Whitby *et al.* 2021). Consistent with these findings, this study illustrates curtailment is also an effective measure at the Cape Nelson North wind farm in Victoria, Australia.

White-striped free-tailed (WSFT) bats were the most impacted species in this study, with curtailment reducing their mortality by two-thirds. Why bats collide with turbines is still debated (Cryan *et al.* 2014; Arnett *et al.* 2016; Thompson *et al.* 2017); but one hypothesis includes turbines acting as a resource attractant. For example, Foo *et al.* (2017) reported food resources were regularly present at turbines, with the majority of stomachs of collected carcasses

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being full or partially full, indicating bats were likely killed whilst foraging. Unlike the tree-centred foraging behaviour of most other microbats, the WSFT bat, along with the southern free-tailed bat (*O. planiceps*), forage in cleared areas such as the agricultural land that the Cape Nelson North wind farm occupies (Lumsden & Bennett , 2005, 2010). This foraging behaviour may increase their susceptibility to turbine collision in these cleared environments, and indeed, WSFTs were the first turbine-associated bat fatalities reported globally five decades ago (Hall & Richards 1972), and have been more recently reported as the most frequent species impacted at wind farms in south-east Australia and Victoria (Smales 2012; Moloney *et al.* 2019; Stark & Muir 2020).

Similarly in the USA, three species comprise 72% of all wind farm reported fatalities: the hoary bat (*Lasiurus cinereus*), eastern red bat (*Lasiurus borealis*), and the silver-haired bat (*Lasionycteris noctivagans*; Allison & Butryn 2018). These three species are members of the Vespertilionid family that forms a clade with the Miniopteridae. The Molossidae family, which includes the southern free-tailed bat and WSFT bat, form a sister group to this Vespertilionid-Miniopteridae clade with divergence approximately 43–54 mya (Miller-Butterworth *et al.* 2007). Members of the Miniopteridae family, such as the critically endangered southern bent-wing, are aerial hunters particularly well-adapted to open-area foraging, and members of all three families can reach high speeds whilst hunting, which may mean they are also susceptible to collisions at wind farms in open agricultural land. Although we did not see similar levels of the southern free-tailed bats in this study, this could be due to their declining population (IUCN Red List).

Microbats are a critical component of Australia's native mammal assemblage (Lumsden & Bennett 2010), though they are often overlooked due to their cryptic nature and small size (Milne 2006). There is a paucity of knowledge on the populations and demographics of many of Australia's bat species; as such, the consequences of any turbine collision-driven population impacts are unknown, challenging evidence-based conservation (Rodhouse *et al.* 2019). A wait-and-see approach regarding the issue of bat population declines is not appropriate due to the slow life history of these mammals, meaning population recoveries may take decades, if they occur at all (Boyles *et al.* 2011). For example, in Europe, avoidance, or at least reduction to a minimum, of bat mortality is a priority for their conservation, as well as a legal obligation (Rodrigues *et al.* 2015).

It is critical concerted efforts are made to develop and use more effective methods for educating the public and policy-makers regarding the beneficial ecosystem services provided by bats. Foraging bats are voracious invertebrate predators, consuming up to half their body mass in a single night (Hill & Smith 1984; Turbill *et al.* 2003). These feeding levels likely have regulatory effects on many nocturnal insects, with potential health benefits for crops, tress, pastures, and revegetated areas (Lumsden & Bennett 2010), as well as economic and environmental implications for agricultural areas (McCracken 2004; Cleveland *et al.* 2006; Milne 2006; Federico *et al.* 2008; Boyles *et al.* 2011). It would be encouraging to see further curtailment measures implemented at wind farms in Australia, especially those characterized by high or moderately high bat fatalities, even with an absence of population data; however, consideration is required of the methodological variations that hinder comparisons.

This study found that curtailment at an Australian wind farm led to a reduction in bat fatality by 54%, with marginal annual power and revenue loss. Curtailment is recognized globally as an effective means to reduce bat fatalities at wind farms (Behr *et al.* 2017), and the findings presented here add further support to this. Increasing the cut-in speed at Australian wind facilities during periods of high bat activity will reduce fatalities. The curtailment employed was a relatively small adjustment, and as such, it would be of interest for future studies to compare higher curtailment parameters, such as 6.0 ms^{-1}, to contribute to our understanding of the relationship between cut-in speeds and bat fatality rates (Adams *et al.* 2021; Whitby *et al.* 2021). The authors hope this study encourages others to consider conducting further curtailment trials in Australia, given the significant gap in this research area compared to the Northern Hemisphere, and the promising results presented here.

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AUTHOR CONTRIBUTIONS

Emma M. Bennett: Conceptualization (lead); data curation (equal); funding acquisition (lead); methodology (equal); project administration (lead); writing – review & editing (equal). **Stevie Nicole Florent:** Writing – original draft (lead); writing – review and editing (equal). **Mark Venosta:** Formal analysis (equal); methodology (equal); validation (equal); writing – review and editing (equal). **Matthew Gibson:** Formal analysis (equal); methodology (equal); validation (equal); writing – review and editing (equal). **Alex Jackson:** Data curation (equal); formal analysis (equal); methodology (equal); writing – review and editing (equal). **Elizabeth Stark:** Data curation (equal); formal analysis (lead); investigation (equal); methodology (equal); writing – review and editing (equal).

CONFLICT OF INTEREST

The authors declare no conflicts of interest.

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SUPPORTING INFORMATION

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

Appendix S1. Data preparation and standardisation.

Appendix S2. Summary of mortality survey data.

Appendix S3. Summary of bat activity data.

Appendix S4. AIC table of mortality models.

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