Decline of a cryptic desert bird, the Thick-billed Grasswren, in the northern Flinders Ranges, South Australia

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ABSTRACT – The El Niño-Southern Oscillation (ENSO) determines climatic conditions across continental Australia and is known to drive a cycle of boom and bust population dynamics in Australian native fauna in the arid interior. When applying management regimes for threatened and often cryptic wildlife the true causes of population decline can be difficult to determine. We report a decline in observations of the Flinders Ranges Thick-billed Grasswren *Amytornis modestus raglessi*. We correlated climate data from the Bureau of Meteorology and count data from field surveys over the last decade to analyse relationships between rainfall, extreme heat and abundance. We infer that the decline may not be readily explained by normal fluctuations in ENSO but by increasing climatic extremes resulting from an intensification of ENSO associated with climate change. Other factors, such as excessive grazing pressure by overabundant macropods might have contributed. Annual rainfall appears to be the primary driver of abundance but a striking increase in the number of days exceeding 45° C during this period is thought largely responsible for the dramatic fall in numbers of grasswrens through its lethal influence. Temperatures that were above 28° C at 1500 h had a negative effect on grasswren detection. Our results show that climatic extremes can have severe impacts on populations of native fauna and put them at risk of extinction.

INTRODUCTION

The Thick-billed Grasswren *Amytornis modestus* comprises five extant subspecies: *Amytornis modestus raglessi, A. m. curnamona, A. m. indulkanna, A. m. obscurior and A. m. cowarie* and two extinct subspecies, *A. m. inexpectatus and A. m. modestus* (Black 2016). Three extant subspecies were listed as Vulnerable under the *Environment Protection and Biodiversity Conservation Act 1999* and all five are now included among Australia's threatened or near threatened taxa (Garnett and Baker 2021).

Thick-billed Grasswrens once occurred patchily between central Australia and inland eastern New South Wales (Schodde 1982; Black 2011). It is thought that the species declined rapidly early last century due to a reduction in habitat quality resulting from excessive grazing by domestic livestock and rabbits, drought, and possibly predation (Threatened Species Scientific Committee 2016; Woinarski *et al.* 2018; Garnett and Baker 2021). The species is now possibly entirely restricted to South Australia and north-west New South Wales (Black and Reid 2021).

The subspecies *Amytornis modestus raglessi* occupies a restricted range around the northern Flinders Ranges (Black 2011; Black *et al.* 2011a) (Figure 1) and is susceptible to stochastic events and threatening processes due to its limited extent of occurrence (Hanski 1982; Gilad 2008; Skroblin and Murphy 2013). They are typically found in dense low chenopod shrublands dominated by Blackbush *Maireana pyramidata*, Low Bluebush *M. astrotricha*, Cottonbush *M. aphylla* and Spiny Saltbush *Rhagodia spinescens* with shrubs of 25 cm or higher covering at least 6% of the surface and with less than 60% bare ground (Black *et al.* 2011a).

Witchelina Nature Reserve, a former pastoral station, was purchased by the Nature Foundation (formerly known as Nature Foundation SA) in 2010 for the conservation of biodiversity. The reserve covers 421,900 hectares of the north-west spur of the Flinders Ranges and adjacent plains between Leigh Creek and Marree. It comprises portions of several distinct landforms, including sand dunes with *Acacia* spp. and *Dodonaea* spp. shrublands in the south, undulating and alluvial plains with chenopod low shrublands in the centre, and rocky hills and ranges with River Red Gum *Eucalyptus camaldulensis* lined creeks and chenopod low shrublands in the north. The reserve has significant biodiversity values; 23 mammal species, 165 birds, 56 reptiles, three frogs and one fish have been recorded to date (Launer *et al.* 2012; Commonwealth of Australia 2010).

Since 2010, a group of Birds SA volunteers has conducted bird surveys on the reserve about annually, chiefly between mid-August and late November. It was apparent during initial surveys that a very substantial population of Thick-billed Grasswrens was present, and all grasswren observations were recorded wherever identified. Yet soon after the initiation of grasswren research through Flinders University (Black *et al.* 2011b; Louter 2016; Slender *at al.* 2017; Slender 2018) in 2012, opportunistic grasswren observations declined (M. Louter pers. comm.; AB pers. obs.). Deteriorating habitat condition due to below average rainfall was considered a likely contributing factor and the decline appeared to be exacerbated following severe drought conditions in 2018 and 2019. Rainfall did not exceed 25 mm during the latter year, raising suspicion that the decline was not simply part of a natural boom and bust cycle but might be a response to an intensification of drought conditions and increased temperature extremes due to climate change. Another factor considered was excessive grazing by overabundant kangaroos, resulting in a reduction in habitat quality and an indirect negative impact upon available resources, as recently documented on another South Australian arid zone conservation reserve (Gilmore 2018).

In this paper we explore the possible causes of decline in observed numbers of Thick-billed Grasswrens in the context of climate variability and climatic extremes. We analyse the opportunistic observations of grasswrens during Birds SA surveys (2010-2019) and report the results of two fixed width transect surveys in 2011 and 2019. We investigate factors potentially influencing counts obtained during surveys, potential causes of decline, implications for conservation management and topics for future research.

METHODS

This study has been conducted at Witchelina Nature Reserve which extends between 29° 44′ S and 30° 34′ S and between 137° 39′ E and 138° 11′ E. The reserve homestead is located 23 km west of Farina and 42 km south-west of Marree. The climate is arid, with an average annual rainfall at the reserve homestead (1939-2019) of 151.4 mm, and is influenced by monsoonal weather patterns with 51.1 mm on average falling in the summer months December to February. The mean daily maximum temperature at Marree is 37° C in summer and 21° C in winter (Bureau of Meteorology BOM); temperature data at the reserve homestead have not been recorded.

Opportunistic records

Grasswren observations were recorded during surveys undertaken by Birds SA members in each year from 2010 to 2019, except for 2017. Surveys were conducted between mid-August and late November, except in 2018 when the survey was in June. Typically, each survey took place over four days throughout the duration of daylight. While travelling between formal survey sites, all opportunistic observations of grasswrens were recorded and their localities documented using GPS. For analysis, each day's travel was considered a transect. Observations were recorded over a total of 46 survey days with an average of 85.2 km driven per day. An encounter rate (n/100 km) for each survey was calculated by dividing the number of opportunistic observations by the number of kilometres travelled. The encounter rate is a surrogate for abundance and was the primary indicator of decline and the impetus for further investigation.

Fixed width transects

Black *et al.* (2011b) conducted a fixed width transect survey at three localities on the reserve in December 2011 and repeated the survey in September 2019 (Figure 2). At each locality, three observers walked 100 m apart through vegetation containing shrubland habitats considered likely to be suitable for Thick-billed Grasswrens, which were detected by scanning up to 100 m ahead, listening for calls and stopping every 100 m or so to play their calls or give high pitched squeaks to elicit responses. The observers noted each grasswren detected within 50 m on either side and recorded their locality using a hand-held GPS unit. Each transect was therefore 300 m in breadth but varied in length, depending on the extent of evidently suitable vegetation. A return transect was then undertaken parallel with the initial transect, but with at least 200 m separating the two, to minimise the likelihood of recording the same bird in both transects.

Thick-billed Grasswrens are thought to occupy territories throughout the year, chiefly as breeding pairs but occasionally with additional birds as helpers (Rowley and Russell 1997). It was therefore considered that mapping individuals could provide information on territory and population sizes, and that groups of three or four birds were pairs with helpers or young, and two birds seen less than 200 m apart represented a pair. Density estimates were calculated by dividing the number of grasswrens observed at a transect by the area of that transect that lay within suitable habitat, and abundance was derived by applying that figure to the total area of suitable habitat at the site.

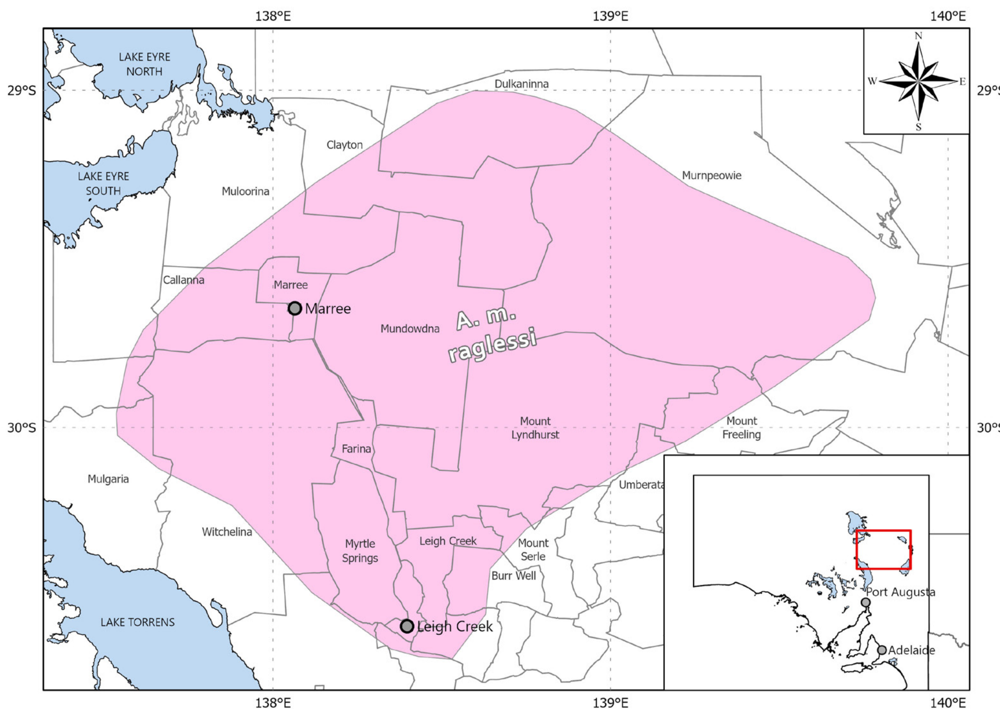

Figure 1. Thick-billed Grasswren *Amytornis modestus raglessi*: estimated extent of occurrence in South Australia.

Data analysis for opportunistic records

Data exploration was carried out following the protocol described by Zuur *et al.* (2010) on the variables thought to influence abundance and the probability of detection (Table 1). Rainfall was included in the analysis due to its importance in driving production, habitat condition and resource availability. Rainfall in the previous calendar year and rainfall in the calendar year test for a lag in the response of grasswrens to rainfall. Distance travelled during surveys tests the influence of survey effort on counts. The number of days with maxima above 40° C but under 45° C in the previous calendar year and current calendar year, and the number of days above 45° C in the previous and current calendar year, all test for effects on counts of extreme heat, which is assumed to influence survivability of birds or their insect prey. The temperature at 1500 h (as an indication of daily maximum temperature) and wind speed at 1500 h on the day of the survey test for the effect of temperature and wind on the probability of detection. Rainfall data from Witchelina Homestead were used; gaps in records were filled using the corresponding data from the nearest weather station (Farina, 23 km to the east). Temperature and wind data were obtained from the Marree weather stations. Kangaroo density, derived from approximately two-monthly spotlighting surveys covering the entire reserve, tests the negative effect of high kangaroo numbers on habitat and indirectly on grasswren counts.

To avoid compromising model performance we inspected our data for outliers (unusual observations) and collinearity (when independent variables correlate with one another) using appropriate visual tools (Cleveland dotplots and pairplots). Multipanel

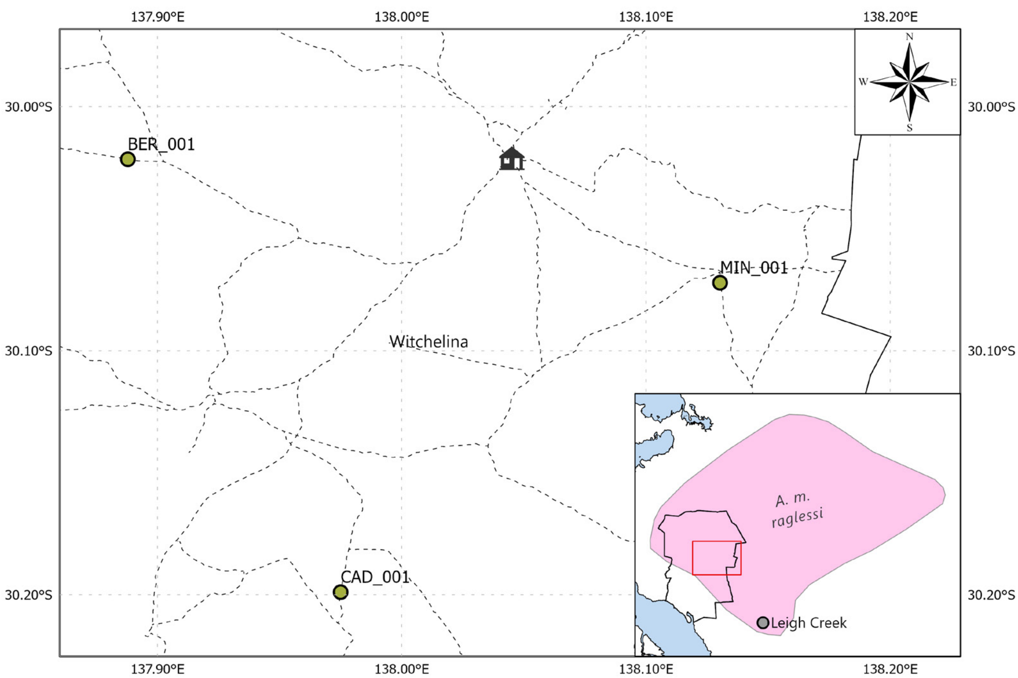

Figure 2. Survey site locations for fixed width transects. House symbol indicates location of Witchelina Homestead. BER = Berlina transect, CAD = Cadnawitina transect, MIN = Minagoona transect.

Table 1. Predictor variables used for modelling Thick-billed Grasswren counts during opportunistic surveys.

Variable	Description
year	Year of survey (explanatory variable)
distance.km	Kilometres travelled on day of survey
rainfall.prevyr	Annual rainfall in the previous calendar year (proxy for vegetation condition and productivity)
rainfall	Annual rainfall in year of survey (proxy for vegetation condition and productivity)
temp	Temperature at 1500 h on day of survey
days..40.45C.prevyr	Number of days with temperature maxima between 40° C and 45° C in the previous calendar year
days..40.45C	Number of days with temperature maxima between 40° C and 45° C in the calendar year
days..45C.prevyr	Number of days with temperatures of 45° C or above in the previous calendar year
days..45C	Number of days with temperatures of 45° C or above in the calendar year
kang.d	Density of kangaroos (animals/km^2) in previous year
wind	Wind speed at 1500 h on day of survey

scatterplots used to visualise relationships revealed that several were non-linear. For this reason, a Generalised Additive Model (GAM) was applied to test the effects of covariates thought to influence abundance and the probability of detection of grasswrens (Table 1).

Overdispersion, when empirical variance in the data exceeds the nominal variance under a presumed model (Dean and Lundy 2016), was not present and so a GAM with Poisson distribution and a log link function was applicable (see equation below). The log link function ensures positive fitted values, and the Poisson distribution is typically used for count data.

Of variables listed in Table 1, fixed covariates that showed strong statistical correlation were annual rainfall (continuous), days above 45° C in the previous year (continuous), and day temperature at 1500 h (continuous). An equation was derived from these variables, as below.

$$Count_i \sim Poisson(\mu)$$

$$\log(\mu_i) = \alpha + f(rainfall_i) + f(days..45C.prevyr_i) + f(temp_i) + \varepsilon_i$$

The GAM function from the 'mgcv' R package (Wood and Wood 2015) was used to fit the model in the equation. Model assumptions were verified by plotting residuals versus fitted values, versus each covariate in the model.

Climate variability

Temperature and rainfall data were compiled from the Marree and Marree Aero weather stations, the nearest long term weather station with complete data sets, *ca* 42 km NE Witchelina Homestead (BOM) from 1940 to 2019. The long-term average annual rainfall at Marree is 160.9 mm compared with a long-term average at Witchelina Homestead of 151.4 mm. Long-term climatic trends were analysed using GAMs from the ‘mgcv’ R package (Wood and Wood 2015) in the software package R Studio (RStudio Team 2020). The dependent variables were in this case the total number of *days above 40° C* and *days above 45° C* in the calendar year, and *annual rainfall*, with the explanatory variable being *year*.

RESULTS

Opportunistic records

In total, 88 independent grasswren observations were made during nine surveys over a 10-year period. In 2010 and 2011, grasswrens were at their most abundant and were regularly detected on or near the tracks with 9.50 and 9.62 grasswrens observed every 100 km. In 2012 and 2013 there was a decline in grasswren encounter rate to 0.50 and 1.50 per 100 km. Observations increased to 4.3 per 100 km in 2016 and declined again in 2018 and 2019 to 2.0 and 0.57 per 100 km (Figure 3).

Generalised Additive Modelling

We found no significant relationship between grasswren counts and kangaroo density, rainfall in the previous year, wind speed, days between 40° C and 45° C in either year, or days above 45° C in the year of survey. Several outliers that contributed to misspecification of the model were removed. The statistically significant variables were rainfall ($p = <2e-16$), days above 45° C in the previous year ($p = 0.00152$) and temperature at 1500 h ($p = 7.973e-08$).

Examination of the effects of each variable on grasswren counts showed that annual rainfall in the year of survey had the strongest effect during the 10-year period. Grasswren counts increased moderately with annual rainfall up to 250 mm and then rose sharply with higher rainfalls (Figure 4). Daily temperature had the second strongest effect, suggesting that grasswren activity declines once the daily temperature at 1500 h exceeds 28° C resulting in fewer observations. Finally, the number of days above 45° C in the previous calendar year had an almost linear negative correlation with grasswren counts (Figure 4).

Fixed width transects

During the fixed width surveys, the three observers walked 37 km (Minagoona 20 km, Cadnawitina 13 km and Berlina 4 km), and counted grasswrens detected in suitable habitat, an estimated 1,048 hectares of a total of 3,139 ha.

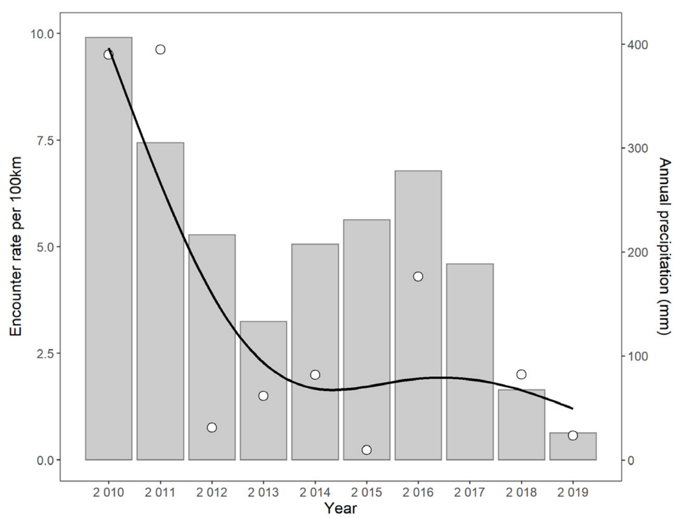

Figure 3. Thick-billed Grasswren encounter rate (circles) and annual rainfall (bars) at Witchelina Homestead. The line represents a smoothed regression using a generalised additive model where y = grasswren count/100 km and x = year.

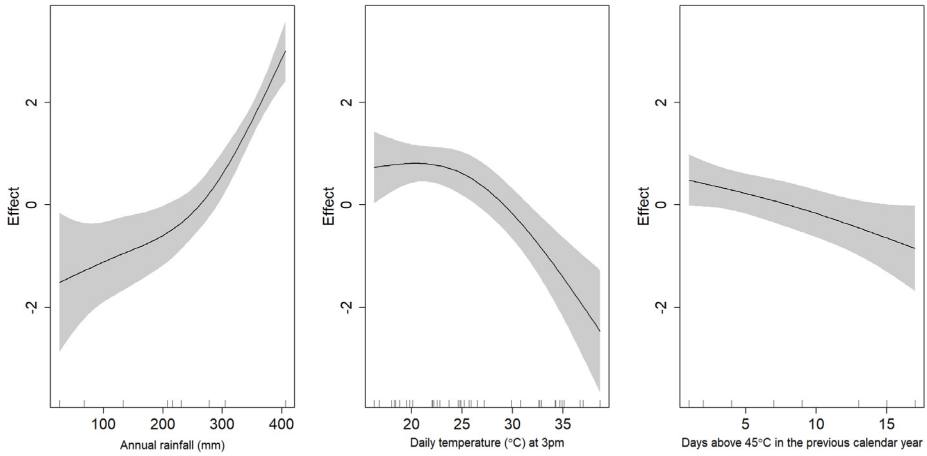

Figure 4. The effect of annual rainfall, daily temperatures at 1500 h, and days above 45° C in the previous year on Thick-billed Grasswren counts at Witchelina Nature Reserve, showing the fitted generalised additive model and 95% confidence intervals based on standard errors.

Table 2. Estimated density and abundance of Thick-billed Grasswrens within fixed width transect surveys. The estimated density for each site is n = number of birds observed divided by the area of suitable habitat surveyed. The estimated abundance (Total) applies this density across the total area of suitable habitat at the site.

			2011			2019		
Locality	**Area surveyed (ha)**	**Total Area (ha)**	**n**	**Density**	**Total**	**n**	**Density**	**Total**
Minagoona	596	2,275	51	0.086	195	0	0	0
Cadnawitina	334	742	47	0.141	104	1	0.003	2
Berlina	118	122	9	0.076	9	1	0.008	1
	1,048	3,139	107		308	2		3

In 2011, 107 Thick-billed Grasswrens were recorded across the three sites, with a total estimated population of 308 individuals (Table 2). The most abundant site was Minagoona with an estimated 195 individuals over 2,275 hectares of suitable habitat comprising extensive Cottonbush shrubland. The most densely populated area was the Cadnawitina site with 0.141 birds per hectare albeit over a smaller area of suitable habitat. The Cadnawitina site differed, with more variable habitat of shrublands, including Blackbush, Cottonbush, Low Bluebush, Spiny Saltbush, *Acacia* spp. and *Eremophila* spp. There, grasswrens were largely confined to denser vegetation along drainage lines that accounted for less than 25% of the total area (742 ha) (Black *et al.* 2011b). The Berlina site was an area of more limited habitat suitability comprising predominantly Blackbush and Low Bluebush.

The survey was repeated in September 2019 after five years of roughly average rainfall followed by two of severe drought. No grasswren was detected on the Minagoona transect and only one was seen on each of the Cadnawitina and Berlina transects.

Climate

During the period 1940-1959 the average number of days per year when the maximum daily temperature at Marree reached 40° C was 26.85. It has risen slowly since, and during 2000 to 2019 it reached 43.2, a 61% increase (Table 3). More striking is the change in days per year with a temperature of 45° C or above, from 2.30 in 1940-1959 to 3.88 in 1960-1979, a 69% increase, and to 7.36 in the 2000-2019 period, an overall increase of 220% (Table 3). Trending differently, the mean annual rainfall increased by 20% between the periods 1940-1959 and 1960-1979 and has remained stable through subsequent periods (Table 3). The dissimilar trends in temperature and rainfall are shown in Figure 5.

DISCUSSION

We have recorded a decline in Thick-billed Grasswren counts on Witchelina Nature Reserve between 2010 and 2019, derived from opportunistic observations and fixed width transect surveys. Abundance appears to have been most strongly influenced by rainfall during the year of observation, followed by the number of days above 45° C in the previous calendar year, with the maximum temperature on the day of survey significantly influencing grasswren detection. Importantly, the decline was not restricted to Witchelina Nature Reserve but occurred more widely among the subspecies (anecdotal reports to AB from 2012), for example between 1-3 March 2020 only two grasswrens were recorded from 23 known sites on Mount Lyndhurst Station (AB and K. Jones unpublished observations).

Rainfall

Two climatic phenomena, the El Niño-Southern Oscillation (ENSO) and the Indian Ocean Dipole, influence rainfall and temperature patterns and long-term climate variability across much of continental Australia (Letnic and Dickman 2006; Collins *et al.* 2010; Wang and Cai 2020). ENSO typically operates on a time scale of two to seven years where the eastern Pacific Ocean climate varies between cold La Niña and warm El Niño conditions (Collins *et al.* 2010). Sustained changes in the difference in sea surface temperatures between the tropical western and eastern Indian Ocean are known as the Indian Ocean Dipole or IOD. An El Niño event and a positive IOD are often associated with one another resulting in below average rainfall across much of the Australian continent. These weather patterns result in a sequence of booms and busts in wildlife populations across arid Australia (Letnic and Dickman 2006). During boom times plentiful food resources provide favourable conditions for population expansion of small mammals, birds, and other fauna, and with drought comes scarcity and decline. Rainfall therefore plays a significant role in regulating populations of fauna (White 2008).

Our analyses suggest that mean annual rainfall during the study period has remained relatively stable, only experiencing a 1% decline in the years 2000 to 2019 compared with the previous 20-year period, although there have been large annual fluctuations. The beginning of the study period saw a strong La Niña with record rainfall (95th percentile) in 2010 and the end saw a drought with record rainfall deficit (5th percentile) in 2019. Thick-billed Grasswren observations have shown a strong response to rainfall in the calendar year of a survey. This is consistent with many species in arid regions that initiate breeding in response to increased food availability due to rainfall (Immelmann 1971; Zann *et al.* 1995; Hau *et al.* 2004; Saunders *et al.* 2013).

We suspect the background boom and bust cycle driven by ENSO will continue to regulate population dynamics in arid Australia with periods of La Niña providing some relief in offsetting the negative impacts of increasing periods of extreme heat. Climatic trends suggest that rainfall across northern Australia has increased and may continue to increase under all but the worst climate scenarios (Bureau of

Table 3. Climate variability since 1940, Marree weather station (Bureau of Meteorology).

Period	**Mean annual rainfall (mm)**	**% change from previous period**	**Mean days above 40° C**	**% change**	**Mean days above 45° C**	**% change**
1940-1959	138.03		26.85		2.30	
1960-1979	165.43	+20%	32.10	+20%	3.88	+69%
1980-1999	163.14	-1%	37.40	+17%	3.27	-16%
2000-2019	161.24	-1%	43.20	+16%	7.36	+125%
Overall change		+17%		+61%		+220%

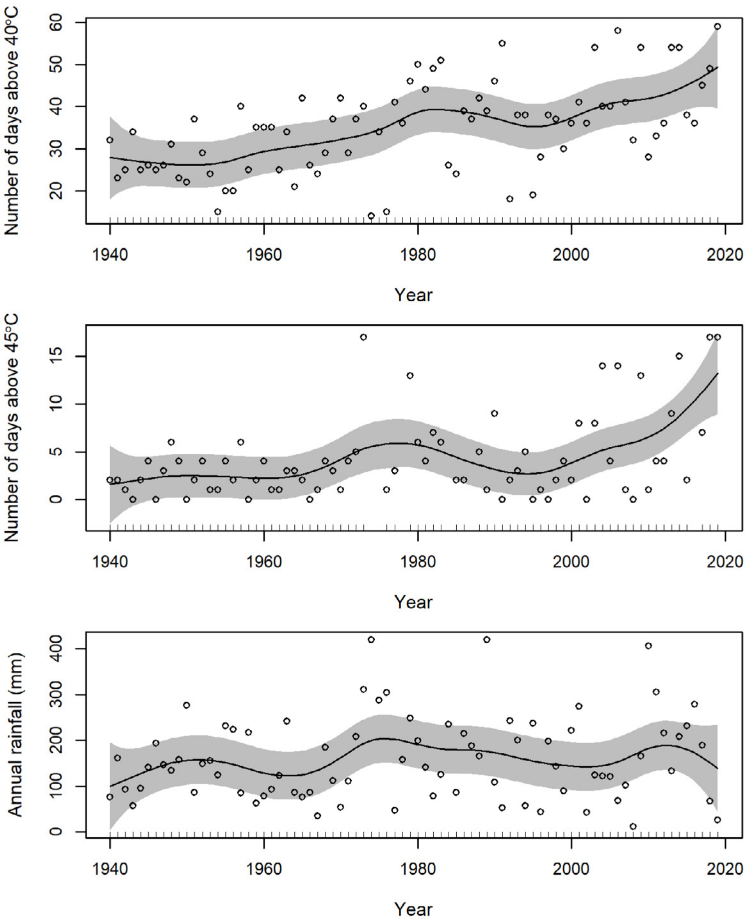

Figure 5. Climate variability since 1940, Marree weather station (BOM), showing the fitted generalised additive model and 95% confidence intervals based on standard errors.

Meteorology 2020; IPCC 2021). The extent to which this trend will extend south towards Witchelina is unclear but may mean the reserve experiences an increase in summer rainfall and a decline in winter rainfall. Our concern is that during periods of severe drought and increasing periods of extreme heat, populations may decline so dramatically that they are unable to recover during wetter cooler periods. Another serious threat, not explored in this paper, is the potential decline in habitat structure and condition caused by severe drought resulting in loss of long-lived perennial shrubs.

Extreme temperatures

Present and anticipated changes in global climate predict a shift towards increased frequency and intensity of climatic extremes (Collins *et al.* 2010; Boucek and Rehage 2014), which are defined as rare, intense events that deviate significantly from background climatic variability (Boucek and Rehage 2014; Harris *et al.* 2018) and may result in conditions that abruptly exceed an organism's adaptive capacity (Gutschick and BassiriRad 2003). Extreme weather events can have a range of ecological impacts including mass mortality, catastrophic and abrupt changes to ecosystems or systems pushed beyond thresholds of dynamic equilibrium towards novel systems (Jentsch *et al.* 2007; Kreyling *et al.* 2011).

We investigated climatic trends in the region and the influence of several heat parameters on counts of Thick-billed Grasswrens. The yearly number of days above 45° C has more than doubled since 1999 and we show that such days in the preceding year had a significant effect on grasswren counts. We infer that an increase in extreme heat, in conjunction with low rainfall or drought, has had a significant negative effect on grasswren abundance. Noteworthy was the record-breaking summer of 2012-13, followed by the even more exceptional years of 2018-19 which were the driest and hottest consecutive years since record keeping began at Marree in 1940. The summer of 2012-13 had five consecutive days exceeding 45° C (Bureau of Meteorology 2013), while the years 2018 and 2019, with a combined rainfall of only 84.6 mm, experienced 34 such days that included 6 separate events when temperatures exceeded 45° C for 4 to 6 consecutive days (BOM climate data online). The combination of these conditions increases water requirements in birds (150-200% in small birds) resulting in lethal dehydration or hyperthermia (McKechnie and Wolf 2010; McKechnie *et al.* 2012; Conradie *et al.* 2020). While we are not aware of studies specifically investigating thermal tolerance in any grasswren species, we predict that Thick-billed Grasswrens are likely to be affected similarly.

Another serious threat to the long-term survival of Thick-billed Grasswrens and many other insectivorous birds is the impact that increasing periods of extreme maximum daily temperatures have on the abundance of insects. The direct effects of extreme climate events on insects include mortality through loss of motor control when the maximum thermal tolerance is exceeded (Filazzola *et al.* 2021). If not fatal, extreme heat can reduce fecundity and negatively affect behaviour and development (Hamblin *et al.* 2017; McCauley *et al.* 2018; Zhu *et al.* 2019).

Daily temperature

Surveys were conducted throughout the day and temperature at the time of observation was not recorded so we could not correlate grasswren activity directly with temperature. However, an indirect correlation was made by using daily temperature at 1500 h, which had a significant non-linear effect on grasswren counts (Figure 4). The activity of grasswrens declined when daily temperatures were greater than about 28° C, suggesting the optimal time to conduct surveys is when temperatures are less than 28° C. It also suggests the advisability of avoiding the hottest months for future surveys, thus maximising the probability of detection.

Other potentially contributing factors

The strong correlations between low rainfall and periods of extreme heat with reduced grasswren counts make it likely that both were major contributing factors in the inferred decline in abundance over the 10-year period. There are other factors that may have contributed directly or indirectly. A reduction in habitat suitability caused by overgrazing is likely to further exacerbate the impact of drought and heat stress. Louter (2016) reported an absence of grasswrens in areas close to waterpoints where long term grazing had reduced habitat complexity.

The impact of domestic stock and feral animals on vegetation is generally well known (Pettit *et al.* 1995; James *et al.* 1999; Adler *et al.* 2001). Increasingly recognised also is the deleterious impact of over-abundant native herbivores such as kangaroos on habitat quality and ecosystem function, and consequently on a broad assemblage of Australian native flora and fauna, including arid zone birds (Neave and Tanton 1989; Howland *et al.* 2014, 2016; Gilmore 2018; Prowse *et al.* 2019; Mills *et al.* 2020; Braden *et al.* 2021).

A decrease in the quality and quantity of vegetation patches and an increase in bare ground are associated with reduced ecosystem function and abundance of arthropods (Louter 2016; Ludwig *et al.* 2004). In Thick-billed Grasswrens, the number of nest sites and feeding rate were both lower in habitats with less vegetation cover (Louter 2016). Thus, the impact of inappropriate total grazing pressure may be considered a significant factor in determining grasswren distribution and abundance.

Given that the Thick-billed Grasswren now occupies a reduced range compared with its pre-European distribution, with extinction of two subspecies, extant populations may be vulnerable to a range of threatening processes including extended periods of drought, extreme summer temperatures, predation, and habitat damage by over-abundant domestic, feral, and native herbivores. Localised extinction and inability to disperse between suitable patches of habitat may further exacerbate threats to their viability.

Future research will include expanding the study to examine other parts of the reserve and neighbouring pastoral properties, where Thick-billed Grasswrens have been recorded, and investigate the impact of different grazing regimes, including that of macropods, on habitat quality and resource availability. Other unanswered questions of importance in the long-term management of Thick-billed Grasswrens include their behavioural responses during periods of extreme heat and specific interventions to increase their survival. There is also scope to assess the frequency of functional genes associated with heat adaptation in different grasswren populations to better understand specific adaptations and develop long-term survival trajectories.

Ultimately, climate change mitigation must be addressed, but several shorter-term management interventions are recommended to build as much ecosystem resilience as possible. A buffer against the increased frequency of climate extremes will include managing total grazing pressure to retain optimal vegetative cover including dead material, promoting habitat complexity and assemblages of arthropods, and reducing predation pressure wherever possible.

ADDENDUM

Summary of grasswren observations on Witchelina since 2019

Two grasswrens were recorded during a Birds SA survey in October/December 2020 and two during the April 2021 survey, similar to figures of three in 2018 and one in 2019. Yet targeted surveys (methods and results to be reported) at 36 previously occupied grasswren sites during April 2021 confirmed their presence at 27 (AN personal data; G Carpenter pers. comm.). This is a detected occupancy of 75%, similar to finding grasswrens at 52 of 72 previous record sites (72%) during a more extensive targeted survey (Black *et al.* 2011a). Such surveys therefore appear able to detect most (at least 72% of) territory-occupying Thick-billed Grasswrens, and thus to have a Detection Probability (DP) of between 0.72 and 1.0.

Detection Probability, the likelihood of detecting a bird where it is known to be present (MacKenzie *et al.* 2002), can facilitate assessment of population size from presence/absence surveys. In a study assessing historical population decline in the Carpentarian Grasswren *Amytornis dorotheae*, Harrington and Murphy (2015) inferred a DP of around 0.25, much lower than reported here.

Reconciling these recent findings at Witchelina with earlier data is not straightforward but it is common experience that grasswrens will successfully avoid detection under certain, as yet incompletely determined circumstances. We have no estimate of their DP under less favourable conditions, but a much lower figure would explain the detection of only two birds in 2019 compared with 107 on the same transects in 2011. Grasswren counts through casual sightings made in transit will doubtless have a much lower DP than when targeted methods are employed.

We infer that grasswren numbers in the years 2010 and 2011 probably peaked at well above sustainable levels, the high numbers then present resulting from successive breeding events during a pluvial period but most birds failing to establish territories in subsequent years. That grasswren numbers declined subsequently is certain, but a finding of over 75% occupancy within 18 months of the 2019 survey suggests that the decline posed a lesser threat to the subspecies than implicit from earlier data.

The total rainfall at Witchelina Homestead during 2020 was 142.5 mm, below average but with important falls in February of 35 mm and in August and September of 21 mm and 26 mm respectively; a further 66.8 mm had fallen before the targeted surveys, including 49 mm in March 2021.

Active breeding was detected in April 2021 and might also have occurred in the previous year but we do not believe that a population explosion, the result of successful breeding, fully explains the disparity between results of differing survey methods. We find it likely that a basal resident population survived the worst of the drought but defied detection.

Future studies are planned to monitor grasswren numbers on Witchelina and elsewhere, using both targeted site surveys and fixed transects. The varied DP of Thick-billed Grasswrens under different circumstances is worthy of further analysis.

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