The Threats to Malleefowl, *Leipoa ocellata*: An Appraisal of the "Usual Suspects", i.e., Predation by Foxes, Competition with Introduced Herbivores and Changed Fire Frequency.

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Abstract

Stated threats to Malleefowl *Leipoa ocellata* include loss of habitat, predation by the introduced Red Fox *Vulpes vulpes*, competition with introduced herbivores, and a lack of mature mallee due to an increase in fire frequency.

This paper examines the relative significance of the three latter threats by reviewing particular studies undertaken in New South Wales and South Australia. Most of the studies involved monitoring the fates of captive-reared Malleefowl, each fitted with a radio transmitter, released into disturbed and undisturbed habitats, some of the former being subjected to intensive fox control. Predation, chiefly by the fox, was the most significant cause of death of captive-reared Malleefowl released into all the habitats in question. Death due to predation was greater than 90% of the total number of birds released; at least 13% by raptors, and at least 54% by foxes and cats. Death directly due to a lack of food is known for only one individual, indicating that Malleefowl can find sufficient food to survive despite the presence of exotic herbivores. However, in the absence of fox control, the mean survival period of Malleefowl in grazed habitat was markedly less than that occurring in mallee where exotic herbivores had been excluded, suggesting the effect of herbivores and predators acting in concert is greater than the sum of the individual effect of each.

The premise that Malleefowl prefer long unburnt mallee as breeding habitat was tested by examining the distribution of active mounds in a wheatbelt mallee remnant. The remnant had areas of mallee regrowth, mostly less than 10-years old, interspersed with blocks of mature (i.e., > 50-years old) mallee. Although the regrowth resulted from eucalypt leaf and broombush harvesting, mallee age in the remnant is treated as a surrogate for mallee age resulting from fire. Contrary to what was expected, Malleefowl frequently nested in areas subjected to eucalypt-leaf or broombush harvesting, mostly on a five-to-ten- year cycle. Over a 14-season period, 147 active mounds were recorded; 12% occurred in mature stands of mallee, 35% wholly within regrowth mallee (27% in mallee 5-10 years old, 8% in mallee 10-20 years old), and almost 53% at or within five metres of the boundary between regrowth and mature mallee (37% on the mature side of the boundary, 16% on the regrowth side). Overall, 42% of active mounds were in mallee less than 10-years old.

Introduction

The Malleefowl, *Leipoa ocellata*, is a ground-nesting bird that was once common throughout its range in the southern states of mainland Australia (Blakers *et al*. 1984). Nationally it is regarded as *Vulnerable,* and in the Northern Territory and all the states where it is found (i.e., Western Australia (WA), South Australia (SA), Victoria and New South Wales (NSW)) it is *Threatened* (Benshemesh 2007). The suspected causes of decline are 1) loss and fragmentation of habitat; 2) predation by the introduced European Red Fox *Vulpes vulpes*; 3) increase in fire frequency and 4) competition with introduced herbivores (Benshemesh 2007). However, the amount of research in evaluating those last three threats, as indicated by the number of relevant publications, has not been uniformly distributed amongst them. Over 46%, of publications (i.e., journal papers, conference proceedings, thesis studies and reports) concerning the four stated threats to Malleefowl have examined the role of predation by the fox in the decline of Malleefowl. In contrast less than 12% deal with competition with herbivores while 23% have been concerned with time-since-fire in relation to Malleefowl.

This paper reviews the latter three of the threats referred to above in the light of several studies on Malleefowl undertaken in New South Wales and South Australia (Priddel and Wheeler 1994, 1996, 1997, 1999, 2003, 2005; Priddel *et al.* 2007). No discussion of the first listed threat, namely *loss and fragmentation of habitat,* is required as its significance is self-evident. The best mallee habitats for Malleefowl tended to be on the more fertile soils and received relatively high rainfall (Frith 1962), but these have been extensively cleared, up to 93% and 80%, respectively, in WA and the eastern states (Frith 1958; Saunders *et al*. 1993; Glanznig 1995; Parsons *et al*. 2008). The major cause of decline of Malleefowl in NSW has been "the wholesale destruction of habitat for agricultural purposes" (Frith 1962).

Perceived Threat

1) Predation

Survival of Captive-reared Malleefowl Released into a Wheat-belt Remnant, Yalgogrin, NSW (see Priddel and Wheeler 1994):

Much of the native bush on fertile soils in southern NSW east of the Lachlan River was cleared in the 1950s for wheat production and stock grazing, principally by sheep *Ovis aries* (Frith 1962; Short 2004). Native bush survived in small and isolated remnants either because the local soil was too stoney for wheat cropping, or the bush was used as a source of eucalyptus oil or it was set aside for conservation (Frith 1962; Hardinge and Payne 1989; Short 2004). One such remnant is a 558-ha patch of mallee near Yalgogrin in southern NSW. Mallee in this area has a high diversity of shrub species and is regarded as high-quality habitat for Malleefowl (Frith 1962). The remnant contained a small and declining population of Malleefowl (16 breeding pairs in 1985, five in 1998; Priddel and Wheeler 2003). The site is surrounded by agricultural crop and pasture lands, and is regularly grazed by sheep and cattle *Bos taurus*. The area had not been burnt since at least 1940 (Priddel and Wheeler 1994) and from the 1930s, patches of it have been harvested regularly to provide eucalypt leaves for the distillation of oil (Hardinge and Payne 1989). Broombush is also harvested for use in the construction of brush fences. Approximately 40% of the remnant is subject to eucalypt and broombush harvesting resulting in patches of regenerating coppice of mostly 0-10-years growth interspersed with mature vegetation (Priddel and Wheeler 2003). Average annual rainfall recorded at the nearest weather station (40 Km to the east) was 487 mm spread evenly over the year (Commonwealth Bureau of Meteorology database).

Seventeen Malleefowl, aged between eight and 127 days, were released into the remnant in March 1988. Fifteen of these birds were killed by predators: five by raptors, three by foxes, one by a cat *Felis catus*, two by either a fox or cat, and four left insufficient clues as to the predator responsible (Priddel and Wheeler 1994). This release was followed up in June with another, this time of 15 birds aged between 100 and 184 days. Fourteen of these 15 Malleefowl were killed by predators within 11 days of release: 11 by foxes and three by raptors. The fifteenth bird was also killed by a fox sometime between days 11 and 98. Of the 32 birds released, at least 22 were dead after 11 days, and none survived longer than 107 days. In all, 94% of Malleefowl were killed by predators: 26-39% by raptors, and 55-68% by introduced predators, principally foxes. Corpses were recovered from all habitat types, including mature mallee, ironbark forest, dense broombush, and regenerating mallee coppice. No relationship was evident between habitat and cause of death or predator type.

Survival of Captive-reared Malleefowl Released into a Large Nature Reserve in the Absence of Fox Baiting: Yathong NSW (see Priddel and Wheeler 1996):

Yathong Nature Reserve covers 107,000 hectares, slightly more than 50,000 hectares of which is mallee. The reserve is located in central NSW, 160 km south of Cobar. The quality of mallee in the reserve is marginal for Malleefowl (Frith 1962). Much of the mallee contained a dense and diverse understorey of shrubs dominated by Broombush *Melaleuca uncinata* and Malleefowl feed plants such as *Acacia rigens*, *A. wilhelmiana* and *Eremophila glabra* (Harden and Priddel 1996). Interspersed amongst this habitat were expanses of mallee with an open understorey dominated by spinifex, *Triodia irritans*. Mean annual rainfall at Cobar is 344 mm (Weather Records Database, Bureau of Meteorology). Rainfall during the period of this study (1990-1992) was below average. The region encompassing the study site was officially declared to be in drought from September 1991 to August 1992 (Drought Area Declarations, Hillston Rural Lands Protection Board). The reserve has a long history of frequent fires and heavy infestations of goats *Capra hircus* and European Rabbits *Oryctolagus cuniculus*. Most mallee habitats within the reserve were burnt by wildfire in 1957, 1974–75 and 1984 (Priddel and Wheeler 1996).

In April 1990, 24 captive juveniles (3-5 months old) and 10 captive sub-adults (14-28 months old) were released into a 19,200-hectare block of mallee in the north-west section of Yathong Nature Reserve. Juveniles were found dead from the first day after liberation, and at least 50% of the juveniles had died by the seventh day; only one juvenile was confirmed to have survived in the wild longer than 36 days; it died sometime between day 37 and day 104. Seven days after liberation at least two sub-adult Malleefowl were dead but four sub-adults were confirmed to have survived longer than 36 days, and three of these survived longer than 428 days.

Of the 24 juveniles that were released, at least 21 were killed by predators; between 50% and 92% of juveniles had succumbed to foxes. Of the 10 sub-adults that were released, seven were killed by predators: six by foxes and one by either a fox or cat.

Survival of Captive-reared Malleefowl Released into Yathong Nature Reserve with Partial Fox-baiting (see Priddel and Wheeler 1997):

A grid system of tracks in the 19,200-ha block of mallee referred to above made it practical to systematically bait the whole block, or part of it, with baits containing Compound 1080 targeting foxes. In winter 1990, 24 Malleefowl (6-9 months old) were released into the mallee block; 12 in the baited western third, 12 in the non-baited eastern third. Baits were placed every 100 metres along 48 km of track every two weeks which resulted in the continuous availability of bait at a density of 7.5 baits km^{-2}. Five of the 12 birds (41%) released into the baited section survived for more than three months however, despite the intensive baiting undertaken, at least 83%, possibly 92%, of the release was killed by foxes. Ten baiting sessions over five months resulted in 4,830 baits being set around and within 6,400 hectares (i.e., the western third of the mallee block). Almost 1,300 of these baits were taken by foxes.

Of the 12 Malleefowl released into the non-baited eastern third of the block, two (i.e., 17% of the release) survived longer than three months, and foxes were responsible for 58-67% of the deaths.

Survival of Captive-reared Malleefowl Released into Yathong Nature Reserve with Extensive Ground Baiting (see Priddel and Wheeler 1997):

In April 1991 baiting was extended to fully cover the 19,200 ha of the mallee block by placing bait stations every 200 metres along 112 km of track. Baiting continued throughout the study. On average, baits were laid at a density of 1·5 km^{-2}, or one bait per 68 ha, per fortnight. Twenty-four

Malleefowl (4-5 months old) were released here in June 1991. Of those Malleefowl released, 25% were still alive three months later, but fox predation remained a significant cause of Malleefowl mortality, accounting for 41-58% of all deaths.

Some foxes dug up baits but did not eat them. This regularly happened at specific bait stations which suggests particular foxes in the mallee block were bait-wary, perhaps after receiving a sub-lethal dose of poison.

Survival of Captive-reared Malleefowl Released into Undisturbed Habitat in South Australia (see Priddel et al. 2007)

Malleefowl breeding densities in undisturbed habitat can be high and apparently stable despite the presence of foxes (Frith 1962; Benshemesh 1992, 1997). However, much of the research on Malleefowl survival in NSW has been conducted in habitats that have been degraded by frequent fire and large numbers of feral goats (e.g. Yathong Nature Reserve, Priddel and Wheeler 1996, 1997) or grazing by stock, harvesting of Broombush and extraction of eucalyptus oil (e.g. Yalgogrin, Priddel and Wheeler 1994). The existence of long-undisturbed Malleefowl habitat in SA provided the opportunity to examine the relationship between Malleefowl survival and habitat age, integrity and structure.

Bakara Conservation Park, SA

Bakara Conservation Park, situated approximately 30 km east of Swan Reach, encompasses an area of 1,031 ha and is contiguous with two blocks of privately owned remnant vegetation totalling 1,300 hectares. The dominant land use of the region is wheat cropping and sheep grazing. Mean annual rainfall is approximately 250 mm (Brandle 1991). There have been no known fires in the area now covered by the park since early in the 20th century (Brandle 1991). The understorey in Bakara was sparse and dominated by hummock grass and spinifex, and, with <30% foliage cover (Priddel *et al*. 2007) is classified as sparse (Specht 1972). No fox baiting had been undertaken in the park prior to nor during the study.

Ferries-McDonald Conservation Park, SA

Ferries-McDonald Conservation Park is located approximately 60 km south-east of Adelaide. As far as is known, the last bushfire in the area now covered by the park occurred sometime during the 1950s (Department of Environment and Natural Resources 1996). Mean annual rainfall is approximately 375 mm (Commonwealth of Australia 2006). The understorey, with a foliage cover of 30–70% (Priddel *et al*. 2007), is classified as mid-dense (Specht 1972). Like Bakara, it was free of large exotic herbivores and did not have a fox-control programme in place, but unlike Bakara, its understorey structure was denser and dominated by shrubs.

Malleefowl Release

Three (20%) of 15 birds (approximately 3-6 months old) released into Bakara were killed by Foxes within 11 days. Only four individuals (27%) survived longer than 100 days. Four (27%) of the 15 birds released into Ferries-McDonald died within 11 days; all were killed by Foxes. Five individuals (33%) survived for longer than 100 days. Fox predation was the prime known cause of Malleefowl mortality, accounting for at least 30%, and possibly as much as 96%, of all deaths (Priddel *et al*. 2007).

The number of captive-reared Malleefowl that survived at least three months after release into these two reserves was nine, (30% of the total release). Thus, compared to the releases of captive-bred Malleefowl into the NSW sites where the habitat was far more disturbed, Malleefowl released at Bakara and Ferries-McDonald survived better than those released in the absence of any fox control, and about as well as those released when localised fox control was undertaken.

Bakara and Ferries-McDonald contained mallee canopies of similar species and density. The understorey, however, differed greatly between reserves. In Bakara, the understorey was open and consisted mostly of scattered clumps of spinifex. The area was easy to walk through and Malleefowl could generally be seen from at least 20 m away. In Ferries-McDonald the understorey was denser, dominated by tall, woody shrubs, and was difficult to negotiate. It was often impossible to glimpse sight of a radio-tagged Malleefowl walking just a few metres ahead. However, there was no discernible difference between the survival of captive-reared Malleefowl released into Bakara and the survival of those released into Ferries-McDonald. Predators killed 73% of birds released into Ferries-McDonald and 47–73% of those released into Bakara. It seems that the denser understorey in Ferries-McDonald did not afford Malleefowl any significant level of increased protection from predators. Although dense understorey (>70% foliage cover; Specht 1972) in mesic habitats may help protect some prey species from fox predation (Short 1998), it seems that the moderately dense understorey of Ferries-McDonald is not sufficient to provide Malleefowl a similar level of protection.

Long-term monitoring data of the Malleefowl populations in Bakara and Ferries-MacDonald show that these populations are declining at a similar rate to that for the Yalgogrin remnant (Priddel *et al*. 2007) although the SA reserves are basically undisturbed in contrast to the heavily disturbed Yalgogrin site. The lack of disturbance (i.e., from fire and grazers) in the SA reserves appears to have extended the period of Malleefowl survival but not to an extent that would slow the overall rate of population decline.

The Fox as a Predator

These experimental releases of captive-reared Malleefowl showed that predation by foxes is not restricted to fragmented remnants of mallee vegetation scattered amongst agricultural land but extends into and throughout the larger expanses of remaining habitat (Priddel and Wheeler 1994, 1996, 1997). Significant fox predation is also not confined to habitats degraded by fire and exotic herbivores but also occurs in relatively undisturbed habitats (Priddel *et al*. 2007).

The fox is an extremely efficient predator; Kinnear *et al*. (2002) describe it as a biocontrol agent because of its high searching ability, its mobility and because it is a generalist in regard to niche use and dietary requirements.

The fox may also engage in surplus killing of prey (Short *et al*. 2002), i.e., killing more prey than it is inclined to eat. Surplus killing may have happened during one of the releases at Yalgogrin. Foxes, or one fox, killed 11 of the 15 released Malleefowl within the first 11 days post release. Several carcasses, usually headless although one was intact with only the telltale wounds from a canine bite to indicate that it was killed by a fox, were found on the ground surface or buried.

In a review of predator-removal programmes, Lavers *et al*. (2010) report that bird productivity increased 18.3% following the control or removal of foxes. Ominously, most of the relevant literature in this review related to bird species in the Northern Hemisphere, where the fox is native. Australian marsupials like the Brush-tailed Bettong *Bettongia penicillata* are vulnerable to the fox partly because their anti-predator defences have evolved in response to their native predators, and these defences do not necessarily protect prey from the depredations of a recently introduced exotic species (Short *et al*, 2002). Similarly, the lack of co-evolution between the Malleefowl and foxes may place the Malleefowl at a comparable disadvantage. Foxes occur throughout the current and former range of the Malleefowl so it is likely that foxes are a major factor in the decline of Malleefowl throughout the bird's range. To quote Kinnear *et al.* (2002) "the impact of the fox would be more fully appreciated if it were recognised for what it really is—an exotic predator, pre-adapted to assume the role of a biocontrol agent."

The Effectiveness of Fox-control Programmes

The two baiting regimes referred to above involved more frequent (fortnightly) and more intensive baiting (7.5 baits km^{-2} over 6,400 ha and 1·5 baits km^{-2} over 19,200 ha) than that commonly employed to control foxes. Although both baiting regimes enhanced the survival of Malleefowl, neither managed to eliminate fox predation as a major cause of Malleefowl mortality. In 1993, in addition to baiting the boundary of Yathong Nature Reserve and internal roads, the reserve was baited from the air at a density of 5 baits km^{-2}. A subsequent release of captive-reared Malleefowl resulted in 75% of the release surviving for at least six months (Priddel and Wheeler 1999), approximately a three-fold increase of what had been achieved with intensive ground baiting alone. Even under such extensive baiting, 10 to 15% of deaths in the first six months after release were attributed to foxes. The benefit of small scale and/or infrequent baiting to protect Malleefowl is questionable; the Recovery Plan for Malleefowl (Benshemesh 2007) states "baiting for foxes in and around Malleefowl habitat is only recommended where it can be conducted at scale (ideally hundreds of km^2), intensity (2-5 baits per km^2) and frequency (2-4 times per year)….." Even such a baiting protocol does not necessarily guarantee protection for Malleefowl. Some foxes will not take baits typically used in control programmes possibly due to aversion to a particular bait type developed after ingesting a bait containing a sub-lethal concentration of 1080 (Priddel and Wheeler 1997). Therefore, for a baiting programme to be effective, it must not only be extensive, intensive and frequent as set out in the recovery plan (Benshemesh 2007) it should also vary the type of bait used to reduce the likelihood of foxes becoming bait-shy.

Because of the success of this 1993 release, thrice-yearly aerial baiting was instigated at Yathong in 1996. In 2001, 85 Brush-tailed Bettongs, including 33 fitted with radio-transmitters, were re-introduced into Yathong (Priddel and Wheeler 2004). However, the re-introduction failed to establish this mammal in the reserve due to predation, chiefly by the cat, but also involving birds of prey. Over the 13 months that Bettongs were present in Yathong there is no evidence of predation by the fox. The success of the baiting programme in controlling fox numbers may have benefited cats as there is evidence that cat numbers or activity may increase three-fold when foxes are removed (Risbey *et al.* 2000).

If cats increase in number in response to a reduction in the fox population then perhaps the cat can prevent Malleefowl benefiting from fox control. Cats kill young Malleefowl (Priddel and Wheeler 1994, 1997) and, more alarmingly, they kill breeding adults (Katherine Moseby personal communication). The evaluation of any fox-control programme should consider the effect fox control has on cat numbers and, in turn, the effect cats have on Malleefowl numbers.

2) Competition with Introduced Herbivores

Frith (1962) reported that the breeding density of Malleefowl in areas heavily grazed by sheep ranged from 9% to 16% of that in undisturbed mallee. He concluded that because sheep ate the shrubs that also supply Malleefowl with food then grazing by sheep had led to the decline in Malleefowl numbers, probably because the chicks do not survive. Unfortunately, Frith did not provide data to compare the amount of food available in the various habitats he examined, either directly by sampling each habitat or indirectly by, for example, measuring the laying interval between successive eggs which can gauge relative food availability (Frith 1959). At Yalgogrin, which is grazed by sheep and cattle, the mean interval between successive Malleefowl eggs was 6.4 ± 1.1 days (range 3–12 days) (Priddel and Wheeler 2005). As a newly laid egg is about 10% of the female's body weight (Frith 1959), it does not appear that the average female adult Malleefowl at Yalgogrin was under nutritional stress.

Most captive-reared Malleefowl released at Yalgogrin also found ample food to survive. Of the ten Malleefowl captured and weighed six days after release in March, eight differed little from their release weight: -5 to +23 grams, mean increase of 6.0 grams or 3.1% of the weights at release. Two birds still surviving after six days had decreased markedly in weight since release. Individual no. 211

lost 37 grams (10.8% of body weight at release) during the first six days but by day 38 had increased its weight to 438 grams, 96 grams (28.1%) more than its weight at release. Individual no. 206 had lost 71 grams (21.5% of body weight at release) and was in an obviously weakened state and was removed from the experiment but regarded, for all intents and purposes, as dead from starvation (Priddel and Wheeler 1994).

The limited effect exotic-herbivore grazing had on the adult females and captive-reared young at Yalgogrin may be due to the intensity of that grazing. Although sheep and cattle were present in the remnant, their grazing pressure could not be regarded as "heavy", the term used by Frith to describe the grazing he witnessed. However, the same cannot be said of Yathong Nature Reserve. As well as being marginal habitat for Malleefowl (Frith 1962), Yathong also has a large goat population (and has had it for decades), was burnt by wildfire in 1957, 1974-1975 and 1984, had below-average rainfall in 1990 to the first half of 1991 and was in drought from the second half 1991 to August 1992; all conditions that should impose severe limitations on the availability of food for Malleefowl. Yet predators were involved in the deaths of all 79 captive-reared Malleefowl released in the reserve between 1990 and 1991; starvation was not attributed to any deaths. Fourteen birds lived for more than three months, four for more than a year including through the 1992 drought. Twelve captive-reared Malleefowl released in 1993 in conjunction with the aerial baiting were caught and weighed eight months after release (Priddel and Wheeler unpublished data). Age at capture ranged from 421 to 460 days, weights were between 1520 to 1970 grams, average 1813 grams; four similarly aged (417 – 492 days) birds kept in captivity on site and fed seed (millet, canary, panicum and rapeseed), green vegetable and mealworms, weighed between 1716 and 1848 grams (average 1788 grams). Captive-reared Malleefowl living in the highly disturbed mallee at Yathong were heavier than birds living the relatively easier life in captivity where food and water was supplied. The body condition of birds caught was also noted as good or very good. Crop contents retrieved from two of these birds subsequent to them being killed by foxes included over 40 wattle seeds in one, and more than 27 wattle seeds and in excess of 40 lerps in the other.

The Malleefowl released into Yathong Nature Reserve did not starve as a result of direct competition against herbivores for food. However, the detrimental effect of herbivores may be subtler. Large exotic herbivores were absent from the two South Australian reserves where Malleefowl had been released (Priddel *et al.* 2007). The Malleefowl still fell victim to foxes but not as rapidly as had happened in NSW (Priddel and Wheeler 1994, 1996). If grazing does lessen food availability it is also likely to increase the time that Malleefowl spend foraging, thus lengthening the period of their exposure to predators (Priddel and Wheeler 1990).

3) Increase in Fire Frequency:

Evidence on the importance of mallee age (i.e., time since fire) is scant and contradictory. On the one hand some observations indicate that mallee older than 40 years (Benshemesh 1990, 1992, 2007) or even 60 years (Woinarski and Recher 1997) is the optimal breeding habitat for Malleefowl. For example, Benshemesh (1990, 1992) found breeding density at four sites 20-30 years post fire was only one third that in neighbouring sites that were at least 40 years old. Fire intervals of 20 years were estimated to reduce Malleefowl densities to 6% of potential maximum carrying capacity (Woinarski and Recher 1997). Another study (Clarke 2005 cited in Benshemesh 2007), related Malleefowl sightings to mallee of various ages, concluding that there was a strong preference by Malleefowl for mallee greater than 20 years old, and an avoidance of younger age-classes. However, Malleefowl populations are declining in many long-unburnt mallee communities in SA (Priddel *et al.* 2007) and have vanished from NSW reserves containing mallee greater than 50 years old (Priddel and Wheeler 1994; Garden 2012). Furthermore, Malleefowl are known to breed in mallee three to six years old (Benshemesh 1996; Benshemesh and Burton 1997; Benshemesh and Stokie 2018; Lill 2013:). Three years after a hot wildfire burnt 95% of Bronzewing Flora and Fauna Reserve (Victoria), including all the Malleefowl-monitoring grid (Schneider 2014) there were five active mounds in that grid compared to the 12-15 active mounds before the fire (Benshemesh and Stokie 2018). Benshemesh (2005) examined the breeding density at one site where the area was burnt in a mosaic pattern leaving areas of old-growth mallee dispersed amongst burnt areas. He found that the breeding density 16 years after the fire was 60% more than it was before the fire. However, this response has not been recorded in any other Malleefowl population (Benshemesh 2007).

Assuming breeding in mallee six years or younger is atypical (Benshemesh 2007; Benshemesh and Stokie 2018) and that mature mallee is preferred as breeding habitat, then the crucial habitat features that may favour old mallee over younger vegetation could be the availability of food and/or the degree of canopy cover (Frith 1962; Benshemesh 1992, 2007) and/or amount of leaf litter (Woinarski and Recher 1997; Benshemesh 2007; Parsons *et al*.2008).

Food Availability

The relationship between age of mallee and food availability was investigated in Nombinnie Nature Reserve, central NSW, by comparing the abundance of potential food resources in various age classes of mallee (Harlen & Priddel 1993). The age classes examined were 8-, 16-, 23- and 36-year-old mallee. Sampling was conducted in February, the month when food resources are most scarce, and therefore the time when Malleefowl are most vulnerable to food shortage (Harlen & Priddel 1996). The potential food resources examined were (a) the buds, flowers, fruit and seeds of shrubs, (b) herbs and (c) ground-dwelling invertebrates. Although the relative abundance of particular shrub species may have varied in the different age classes, there was no difference in the total density of food shrubs present in each of the various age classes sampled (e.g., the decrease in density of Acacia shrubs in the older classes was compensated by an increase in density of other shrubs, such as *Beyeria opaca*) (Harlen and Priddel 1993). The study at Nombinnie found the overall abundance of shrub-borne food items was not a function of mallee age, at least in mallee up to 36-years old and located in central NSW. The abundance of herbs, however, did decrease with age. Herb abundance in mallee, regardless of the age of that mallee, plummets in late spring or early summer, and for much of the year (including the period when chicks are emerging from mounds) herbs are not a major food resource for Malleefowl (Harlen and Priddel 1992). Consequently, a difference in herb abundance between young and old age classes is not as critical to Malleefowl as it may initially appear (Harlen and Priddel 1993). There was also no significant effect of time since fire on invertebrate abundance (time since fire was a determining factor in the abundance of less than 1% of the ground-dwelling invertebrates in the study area) (Harden and Priddel 1993). Whether mallee older than 36 years contains more or less food for Malleefowl cannot be gauged from this study.

Canopy Cover

Malleefowl are susceptible to predation by birds of prey (Korn 1986; Priddel and Wheeler 1990. 1994, 1996, 1997, 1999) and "show a very swift reaction and escape into the scrub when birds of prey fly over" (Frith 1962) so it is not surprising that extensive canopy cover is strongly associated with high breeding density (Benshemesh 1992, 2007). However, Frith (1962) recorded active Malleefowl mounds in regenerating mallee which had been rolled less than 18 months before and was consequently less than 60 cm high. At Yalgogrin, out of 147 records of active mounds from 1985/86 to 1998/99 (Priddel and Wheeler 2003), 40 or 27% were in areas completely devoid of canopy cover, the surrounding vegetation being two metres or under in height due to the harvesting of eucalypt leaf and broombush on a five to 10-year cycle. An additional 23 active mounds (15% of those recorded) were also in harvested areas but within 5 metres of the mature (i.e., greater than 50 years old) mallee, and 11 (8%) were in dense regrowth mallee 10-20 years old (i.e., 50% of the active mounds were in mallee that was less than 20-years old). Only 18 records (12%) were from deep within the mature mallee community, with a further 55 (38%) on the mature side of the boundary between the two age classes. Although the proportion of active mounds in mature and younger mallee (50:50) is approximately the proportion of mature mallee to younger mallee in the remnant, this should not be viewed as birds being forced to use the younger mallee because the mature mallee was fully occupied by breeding Malleefowl. Towards the end of the Yalgogrin study the breeding population of Malleefowl was less than one third of that recorded in the beginning (16 pairs in 1985/86, five pairs in 1998/99); mounds in the mature mallee had ceased being used and their resident pairs had disappeared from the population (Priddel and Wheeler 2003). Although sections of the mature mallee were now vacant, birds continued to breed in the younger (canopy-less) mallee, forgoing the opportunity to move into the supposedly optimal habitat of long-unburnt mallee.

Although Malleefowl at Yalgogrin and in Frith's study site constructed mounds in areas free of canopy cover, canopy cover may still be a crucial factor in determining Malleefowl population size because Malleefowl in open habitat are vulnerable to birds of prey (Priddel and Wheeler 1997). The length of the survival period for captive-reared Malleefowl released at Yathong during the extensive baiting that took place in 1991 was related to the degree of vegetative cover. Mallee at the southern end of the release area was largely unbroken; the habitat surrounding the northern release sites was more open and discontinuous. Five Malleefowl were killed in the north by birds of prey compared to two deaths attributable to birds of prey in the south (Priddel and Wheeler 1997). Malleefowl released in the south of the mallee block survived much longer than those released in the north (medians: 140 days and 5 days respectively).

Canopy cover does not appear to be essential if birds are to build mounds, but it may be important in protecting Malleefowl from birds of prey. If so, then this does not explain why mallee needs to be 60 years or older to be optimal Malleefowl habitat (Woinarski and Recher 1997). Frith (1962) noted that mallee allowed to regenerate after clearing less than 30 years before was "indistinguishable from virgin scrub". In WA, mallee developed a substantial canopy after 20-25 years (Parsons and Gosper 2011) and in the Murray Mallee of south-eastern Australia, canopy cover was near to maximum extent in about 35 years (Haslem *et al*. 2011). Therefore, if the degree of canopy cover is the crucial factor determining the size of the Malleefowl population, then mallee at 30-years old should be just as conducive to Malleefowl survival as mallee twice that age.

Leaf Litter

Approximately one cubic metre of leaf litter is required for an active mound (Brickhill 1980). The amount of ground surface covered by leaf litter was measured at four age classes (8-, 16-, 23- and 36- years post fire) in Nombinnie Nature Reserve (Harlen and Priddel 1993) and it was found to increase with time since fire up to the 23-year-old age class after which it remained stable. Likewise, other studies (Haslem *et al*. 2011; Parsons and Gosper 2011) have shown leaf litter to obtain maximum or near maximum value at approximately 25 years. Therefore, 25-year-old mallee is not markedly different to that of 60-years in respect to the amount of leaf litter present. The age at which mallee contains enough leaf litter for a mound will depend on factors such as season and severity of the most-recent fire, and the rate of plant growth (which will be influenced by factors such as soil type and climatic conditions). The amount of leaf litter available for a mound is also a function of the distance from the mound that the birds are prepared to rake in the litter. The existence of active mounds in 18-month old mallee (Frith 1962) or in 5-year-old mallee at Yalgogrin does not suggest the minimum age mallee needs to be before it contains adequate leaf litter for mound construction. In the former case, the mounds were constructed amongst rolled mallee so presumably there would have been ample leaf litter available. In the latter case, mallee coppice was mechanically cut to ground level and removed from the site for distilling but the spoil, that is, the dried leaves, was returned to, and dispersed over, the area from which it was harvested. However, active mounds in mallee three to six-years old (Benshemesh 1996; Benshemesh and Burton 1997; Benshemesh and Stokie 2018; Lill 2013;), whether they are typical or not, suggests mallee can be significantly younger than 25 years to have enough leaf litter available to enable the construction of active mounds.

Mallee Age and Fire Management

A number of conservation management plans stress the need to manage mallee reserves so as to retain old mallee for the benefit of Malleefowl. The plan of management for Tarawi Nature Reserve in NSW, for example, states that Malleefowl "depend upon mature mallee for their survival" and "available data indicates that optimal fire frequency for Malleefowl conservation is likely to be in excess of 60 years". The plan of management for Yathong and Nombinnie nature reserves describes old mallee as "prime habitat for Malleefowl". However, the evidence for the association of Malleefowl with old mallee has been generated from a few studies which are "not of sufficient scope to adequately describe the habitat features that are important to Malleefowl across their range" (Benshemesh 2007). The high density of active mounds associated with old mallee may be due to other factors besides the age of the mallee. Factors such as the proportion of the Malleefowl population killed in the initial fire (Benshemesh 1990, 1992); the extent of unburnt patches or refuges remaining after the fire (Benshemesh 1990, 1992); the occurrence of drought in the aftermath of the fire (Priddel and Wheeler 2003; Benshemesh 2005, 2007); presence of large herbivores (Driscoll *et al*. 2008); reproductive capacity of the survivors (Priddel and Wheeler 2005); or difference in site factors (Driscoll *et al*. 2008, Driscoll *et al*. 2010) (e.g., soil type, fire history, climate) may all affect the rate of recovery. Higher breeding densities in old mallee may be due to nothing more complicated than the length of time the birds have had to increase in number.

The reliability of management plans formulated with limited empirical data can be poor (Clarke 2008; Driscoll *et al*. 2008; Taylor *et al.* 2013) and such plans may lead to undesirable outcomes or actions (Driscoll *et al.* 2008). Research needs to be undertaken to determine the optimal habitat factors required for Malleefowl, including the significance of mallee age, over the geographical extent of the bird. The National Malleefowl Monitoring Database can be used to relate mound presence to mallee age. However, there is a very important caveat that must be kept in mind. Malleefowl numbers have been declining for over a century (North 1917) and the general use by Malleefowl of one particular age category of mallee may mean that the mallee in question is more of a refuge than a representative of optimal habitat. Kinnear *et al*. (2002) cite cases where, after effective fox control commenced, *threatened* marsupials readily extended their range to include habitats which differed from their long-term refuges.

Conclusion

Malleefowl populations in Victoria, SA and NSW are in steep decline (Priddel & Wheeler 2003; Gates 2004; Benshemesh 2005). Decline is happening in long-unburnt mallee, in mallee frequently disturbed, in areas where large exotic herbivores are excluded as well as in areas where they are not, in remnant mallee of 100s of hectares surrounded by agricultural land and in large nature reserves of many 1000s of hectares remote from agriculture. The only listed threat to Malleefowl that all these locations have in common is the fox. Foxes prey on Malleefowl of all ages: eggs (Frith 1959; Brickhill 1987), chicks (Benshemesh 1992), juveniles (Priddel and Wheeler 1994, 1996), sub-adults (Priddel and Wheeler 1996), and adults (Booth 1985; Benshemesh 1992; Priddel and Wheeler 2003). No other suspected threatening process for Malleefowl has been studied as much as the interaction between foxes and these birds. Empirical studies which have directly examined the effectiveness of fox baiting in significantly reducing fox predation upon Malleefowl supports the recommendation in the National Recovery Plan for Malleefowl (Benshemesh 2007) that baiting needs to be over large areas, at a rate of 2-5 baits/km^2 and repeated 2-4 times per year. In general, baiting less than this may be fox baiting, but it is not necessarily fox-control.

The effect of herbivores, at least in Yathong Nature Reserve and the Yalgogrin remnant, is relatively minor compared to that of foxes. Apart from the malnourished captive-reared Malleefowl removed from the experimental release at Yalgogrin, grazing by exotic herbivores in this remnant did not have a direct impact on Malleefowl. Large herbivores at Yathong, similarly, were not directly significant to the survival of Malleefowl released there; captive-reared Malleefowl released into the reserve were heavier than birds of the same age that were held in captivity and supplied with food and water. The true significance of grazing by large herbivores is likely that the reduction in the amount of food results in Malleefowl spending more time looking for food, and the more time Malleefowl spend looking for food, the greater the likelihood that they will be seen by predators such as the fox. This explains why Malleefowl released into two reserves in SA where large herbivores were excluded, survived longer than those released into Yathong Nature Reserve in the absence of fox baiting.

Evidence concerning what mallee age is optimal for Malleefowl breeding is inconclusive and conflicting. Some studies have found mallee needs to be at least 40-years old to provide the best conditions for Malleefowl breeding but it is not known what environmental factors are responsible for the best conditions. Two which appear the most logical, namely extensive canopy cover and ample leaf litter, can be just as prevalent in mallee between 20 and 30-years old. Malleefowl, however, have bred in mallee that did not have any canopy cover even though they had ready access to mature mallee. Birds also breed in mallee three years after fire so very young mallee can have enough leaf litter to fuel active mounds. The significance of mallee age needs to be determined, especially considering various management plans have accepted the significance of old mallee unquestioningly. The National Malleefowl Monitoring Database has the potential to answer this question by comparing the breeding populations of various ages of mallee.

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