

Could biodiversity loss have increased Australia's bushfire threat

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1 **Could biodiversity loss have increased Australia’s bushfire threat?**

2
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17 these).

18
19 **Abstract**

20 Ecosystem engineers directly or indirectly affect the availability of resources through
21 changing the physical state of biotic and/or abiotic materials. Fossorial ecosystem engineers
22 have been hypothesised as affecting fire behaviour through altering litter accumulation and

23 breakdown, however, little evidence of this has been shown to date. Fire is one of the major
24 ecological processes affecting biodiversity globally. Australia has seen the extinction of 29
25 of 315 terrestrial mammal species in the last 200 years and several of these species were
26 ecosystem engineers whose fossorial actions may increase the rate of leaf litter breakdown.
27 Thus, their extinction may have altered the rate of litter accumulation and therefore fire
28 ignition potential and rate of spread. We tested whether a reduction of leaf litter was
29 associated with sites where mammalian ecosystem engineers had been reintroduced using a
30 pair-wise, cross fence comparison at sites spanning the Australian continent. At Scotia (New
31 South Wales), Karakamia (Western Australia) and Yookamurra (South Australia)
32 Sanctuaries, leaf litter mass (-24%) and percentage cover of leaf litter (-3%) were
33 significantly lower where reintroduced ecosystem engineers occurred compared to where
34 they were absent, and fire behaviour modelling illustrated this has substantial impacts on
35 flame height and rate of spread. This result has major implications for fire behaviour and
36 management globally wherever ecosystem engineers are now absent as the reduced leaf litter
37 volumes where they occur will lead to decreased flame height and rate of fire spread. This
38 illustrates the need to restore the full suite of biodiversity globally.

39

40 **Introduction**

41 Ecosystem engineers directly or indirectly affect the availability of resources through
42 changing the physical state of biotic or abiotic materials and, as such, they modify, maintain
43 or create habitats either autogenically or allogenicly (Jones, Lawton and Shachak, 1994).
44 Beavers *Castor spp.* do this through their role in dam building, which affects geomorphology
45 and ecology, and ultimately protects rare species (Bartel, Haddad and Wright, 2010). White
46 rhinoceros *Ceratotherium simum* create grazing lawns that alter fire size and heterogeneity

47 (Waldram, Bond and Stock, 2008). Plain's viscacha *Lagostomus maximus* promote fire
48 heterogeneity by gathering vegetation for nesting sites, which ultimately alters vegetation
49 patterns (Hierro *et al.*, 2011). Fossorial ecosystem engineers influence bioturbation and alter
50 water infiltration, capture organic matter and increase nutrient cycling (Eldridge *et al.*, 2015,
51 Fleming *et al.*, 2014).

52 The services provided by ecosystem engineers is frequently specific to individual
53 species (James *et al.*, 2011, Machicote, Branch and Villarreal, 2004) suggesting functional
54 redundancy is rare. Consequently, the extinction of ecosystem engineers means that the
55 ecological function they provide is unlikely to be replaced by surviving species. The plethora
56 of studies on the functions performed by ecosystem engineers reflect their importance within
57 ecosystems, however to date we know of no study that has illustrated the role fossorial
58 mammalian ecosystem engineers play in regulating fire, despite this being hypothesised
59 previously (Jones, Lawton and Shachak, 1996). In this study, we illustrate the role that
60 fossorial ecosystem engineers play in leaf litter breakdown and how that translates to fire
61 behaviour.

62 Uncontrolled wildfires cause enormous damage. For example, the total cost of 23
63 major wildfires in Australia between 1967 and 1999 was greater than \$AUD2.5 billion with
64 an additional human cost of 223 deaths and 4185 injuries (Australian Institute of
65 Criminology, 2004). In the USA, the 1998 Florida wildfire produced economic impacts of at
66 least US\$600 million (Butry *et al.* 2001) and fire suppression in the USA now exceeds \$US1
67 billion per annum (Calkin *et al.*, 2005). Despite improvements in communications and
68 technology, massive wildfires are still a common event in Australia, and with climate change,
69 increasingly so (Marris, 2016).

70 Wildfire is a major conservation and land management issue globally with 179
71 mammal, 262 bird, 146 reptile, 300 amphibian and 974 plant species threatened by fire and
72 fire suppression (IUCN, 2015). Leaf litter is the major source of combustible material to
73 allow fire to spread, especially in mallee eucalypt communities (Bradstock, 1990), and
74 fossorial species have the potential to reduce litter fuel loads (Nugent, Leonard and Clarke,
75 2014). Australia has suffered the loss of 29 medium-sized, ground-dwelling mammal species
76 (Johnson, 2006, Short and Smith, 1994, Woinarski, Burbidge and Harrison, 2012), while
77 numerous others are now restricted to offshore islands and so are extinct on the mainland
78 (Burbidge, Williams and Abbott, 1997, McKenzie *et al.*, 2007, Woinarski *et al.*, 2012).
79 Hence, the loss of these species in Australia means there is a high likelihood of cascading
80 impacts that extend to fire regimes.

81 Herbivory is well documented as affecting fire regimes by removing fuel on plants
82 and that can fall as leaf litter (Ingram, Doran and Nader, 2013, Leonard, Kirkpatrick and
83 Marsden-Smedley, 2010). Bioperturbating species, such as bower birds and lyrebirds, alter
84 litter volume and distribution, and thereby reduce fire likelihood (Carvalho *et al.*, 2011,
85 Mikami *et al.*, 2010, Nugent *et al.*, 2014). Here, we aimed to determine whether the
86 extinction of members of Australia's critical weight range mammal fauna (Burbidge and
87 McKenzie, 1989), has led to an increased accumulation of fuel that would potentially affect
88 the rate of fire spread. This is timely given the directives of Australian state governments and
89 Royal Commissions (Government of Victoria, 2011) regarding the area of control burns
90 necessary to reduce the risk of life and property threatening bushfires, despite the findings
91 that this would only reduce bushfire risk by half (Price and Bradstock, 2011). It was
92 originally proposed that 5% of all Crown Estate in Victoria would be burnt annually on a 20
93 year rotation (Recommendation 56 of the 2009 Bushfires Royal Commission (Government of
94 Victoria, 2011)), which is well below levels that would allow 'old growth' vegetation to form

95 and provide habitat for old growth dependent fauna (Clarke, 2008, Clarke *et al.*, 2010, Kelly
96 *et al.*, 2011, Taylor *et al.*, 2012) and would negatively impact biodiversity (Giljohann *et al.*,
97 2015).

98

99 **Methods**

100 A pair-wise, fence-line comparison was replicated at three of the Australian Wildlife
101 Conservancy's (AWC) faunal restoration sites spanning the Australian continent: Karakamia
102 (284 ha in Western Australia's jarrah forest), Scotia (64,654 ha in far-western New South
103 Wales) and Yookamurra (5108 ha in South Australia's Murrayland region; Fig. 1).
104 Karakamia receives 883 mm, Scotia 246 mm and Yookamurra 275 mm of rain per year
105 (AWC *unpubl. data*). Scotia and Yookamurra are dominated by mallee eucalypt communities
106 on linear dunes at Scotia and on thin soils overlaying calcrete at Yookamurra, while
107 Karakamia supports jarrah forest. All sites have large fenced areas that exclude introduced
108 predators (red foxes *Vulpes vulpes* and cats *Felis catus*) and competitors (European rabbits
109 *Oryctolagus cuniculus* and livestock) and from where such species have been eradicated.
110 Karakamia was fully-fenced in 1994, Scotia in 2002 and 2006 (two separate 4000 ha areas),
111 and Yookamurra in 2007. There have been no domestic herbivores on the properties since
112 acquisition by AWC and large grazing macropod numbers are controlled within the fenced
113 areas.

114 The vegetation at Scotia is generally in better condition than surrounding national
115 parks due to a shorter pastoral history (Westbrooke, 2012, Westbrooke, Miller and Kerr,
116 1998). Karakamia and Scotia are situated within a matrix of largely intact vegetation, so
117 human-impacts on fire regimes are considered minimal (Archibald *et al.*, 2010), in contrast to
118 Yookamurra, which sits partially within an agricultural landscape. In semi-arid areas, rainfall

119 and soil moisture are limiting and limit litter decomposition rates, and the digging pits created
120 by fossorial species are sources of higher humidity that promote litter breakdown, water
121 infiltration and seed germination (Travers and Eldridge, 2012a, Travers and Eldridge, 2012b).

122 Six previously extinct species (bilby *Macrotis lagotis*, boodie *Bettongia penicillata*,
123 bridled nailtail wallaby *Onychogalea fraenata*, greater stick-nest rat *Leporillus conditor*,
124 numbat *Myrmecobius fasciatus* and woylie *B. penicillata*) have been reintroduced to Scotia
125 (Finlayson, 2010, Hayward, Herman and Mulder, 2010a, Hayward *et al.*, 2010b), four to
126 Karakamia (woylie, southern brown bandicoot *Isoodon obesulus*, tammar wallaby *Macropus*
127 *eugenii* and western ringtail possum *Pseudocheirus occidentalis*) and four of these have also
128 been reintroduced to Yookamurra (bilby, boodie, numbat and woylie). Most of these species
129 are considered as ecosystem engineers and their turnover of soil and litter could be expected
130 to increase the rate of leaf litter breakdown (Garkaklis, Bradley and Wooller, 2004, James
131 and Eldridge, 2007, James, Eldridge and Hill, 2009, James *et al.*, 2011). There is no
132 difference in the arboreal folivore communities inside and outside the fenced areas as the
133 fences are permeable to them, so any differences in litter volumes are unlikely to be driven by
134 browsing effects.

135 Paired samples were taken from one m to the north of eucalypt trees growing 30 m
136 inside and 30 m outside the fences at each of 21 locations at Scotia and 20 locations at
137 Yookamurra and Karakamia spaced one km apart. These paired sites had similar vegetation,
138 topography, fire ages and the trees selected all exceeded 0.2 m diameter at breast height.
139 Areas beneath canopies are the major sites of litter accumulation in the mallee (Eldridge *et*
140 *al.*, 2012). Each sample consisted of leaf litter collected in a 22 x 22 cm quadrat. This
141 material was then sieved through one mm sieves and air dried for a month. At Scotia, we
142 also compared the number of animal digging pits and logs inside and outside the fences by

143 counting them 1 m either side of a 50 m long transect, while percentage cover of cryptogamic
144 crust cover, bare ground cover and vegetation cover were estimated visually by two
145 observers.

146 Paired differences in leaf litter between fenced and unfenced plots were analysed
147 using a linear mixed effect model in the *lme4* package (Bates *et al.*, 2013) in R (R Core
148 Development Team, 2008) with site as a random effect. As absolute leaf litter levels varied
149 strongly by site, relative change in levels in the unfenced plots was analysed. Ninety-five
150 percent (95%) confidence intervals for the relative differences were estimated using profile
151 likelihood. Linear regression models were used to determine whether there was a difference
152 in ground cover inside and outside the fences at Scotia. We also ran paired *t*-tests on
153 individual site data.

154 Finally, to assessed how changes in leaf litter caused by reintroduced mammals might
155 affect fire behaviour, we used mean fuel-load inputs from Scotia with conditions based on
156 those experienced during a wildfire in September 2012 to run the McArthur Mk5 Forest Fire
157 Behaviour model (Noble, Gill and Bary, 1980). This model is widely used by fire services
158 worldwide to predict the probability of fire starting, its rate of spread, intensity and
159 suppression difficulty according to data on temperature, humidity, wind and drought
160 conditions. On the day of the fire, maximum temperatures reached 37.5°C, relative humidity
161 was 28% and winds reached 57 km hr⁻¹ (data from Bureau of Meteorology online). We ran
162 the models with drought conditions 5 and with a 0 ground slope following Nugent *et al.*
163 (2014) and present data on both flame height as a measure of fire intensity and severity
164 (Alexander and Cruz, 2012, Byram, 1959), and rate of spread. We present means \pm 1 S.E.

165

166 **Results**

167 Overall, the linear mixed effect model estimated a statistically significant 24%
168 decrease (95% CI 6-43%) in leaf litter mass in the fenced plots compared to the unfenced
169 plots across sites. Scotia had significantly more leaf litter than Yookamurra and Karakamia
170 (Fig. 2). The mass of leaf litter found inside the fences was significantly less at Karakamia
171 (23 ± 2 g cf 41 ± 2 g; paired $t_{19} = -6.586$, $p < 0.001$), Scotia (155 ± 21 g cf 223 ± 35 g; paired
172 $t_{20} = -2.158$, $p = 0.043$) and Yookamurra (24 ± 1 g cf 55 ± 3 g; paired $t_{19} = -2.158$, $p = 0.046$;
173 Fig. 2).

174 The linear model showed there was no significant difference in percentage ground
175 cover inside and outside fences at Scotia, however there were significant differences in
176 ground cover types, as well as an interaction between fencing and cover type (Table 1). There
177 was significantly less leaf litter cover inside Scotia's fenced areas compared to outside (Wald
178 $\chi^2 = 13.495$, d.f. = 1, $p < 0.001$), but significantly more logs (Wald $\chi^2 = 37.432$, d.f. = 1, $p <$
179 0.001) and pits (Wald $\chi^2 = 29.272$, d.f. = 1, $p < 0.001$) inside fenced areas (Fig. 3). Leaf litter
180 covers only 3% less area inside fences, but is 37% less in volume (dry weight) compared to
181 sites outside the fences.

182 The McArthur fire behaviour model predicted flame heights during the September
183 2011 fire at Scotia to reach 1.41 m outside the fences compared to 0.37 m inside the fences.
184 This model also predicted the fire to spread faster outside the fences (0.18 km hr^{-1}) compared
185 to 0.12 km hr^{-1} inside the fences. This equates to a 74% reduction in flame height and a 33%
186 reduction in the rate of fire spread.

187

188 Discussion

189 This study highlights the benefits of reintroducing ecosystem engineers for the
190 services they offer to fire management that have been lost from the majority of Australia's

191 environment. These species probably play similar roles globally given the widespread
192 distribution of fossorial species and the ubiquitous role that turning litter plays in speeding its
193 breakdown. Such reintroductions may reduce the need for fire suppression and control in
194 numerous fire-prone environments, which are costly and dangerous practices. The fossorial
195 nature of the reintroduced marsupials has increased the rate of leaf litter breakdown
196 compared to introduced fossorial species as native species dig deeper and wider pits than
197 introduced rabbits *Oryctolagus cuniculus* due to the larger amount of litter and soil they turn
198 over (Eldridge *et al.*, 2012, James and Eldridge, 2007, Pollock, 2006). This in turn increases
199 the return of nutrients into the soil (Eldridge *et al.*, 2012, Elliot, Hunt and Walker, 1988).
200 However, the reduction in available leaf litter also reduces fire spread as leaf litter is the
201 biggest factor driving this (Bradstock, 1990). With reduced leaf litter, the risk of fire ignition
202 is also reduced. Ultimately, a reduction in fire frequency is likely to slow the rate of carbon
203 released into the atmosphere compared to current rates, because of the more rapid and
204 complete release of carbon during fire than in the slow carbon pool driven by litter
205 breakdown (Bond-Lamberty *et al.*, 2007).

206 This is a global issue given reviews show that 447 mammalian genera spanning the
207 globe have fossorial species that may significantly disturb the soil and leaf litter (Kinlaw,
208 1999) and many of these are likely to be threatened or locally extinct. Some taxa obviously
209 turn over litter to increase decomposition rates. For example, Philippine porcupines *Hystrix*
210 *pumila* are listed as vulnerable (IUCN, 2015) and, as fossorial rodents, are likely to affect
211 litter decomposition (Bragg, Donaldson and Ryan, 2005). The rooting of suids clearly
212 increases the rate of decomposition (Sandom, Hughes and Macdonald, 2013) and several of
213 these are threatened including the Palawan bearded pig *Sus ahoenobarbus*, bearded pig *S.*
214 *barbatus*, Visayan warty pig *S. cebifrons*, Oliver's warty pig *S. oliveri*, Philippine warty pig
215 *S. philippensis* and the Javan warty pig *S. verrucosus* (IUCN, 2015). Fire is a major

216 environmental problem in the range states of many of the species discussed above (Page *et*
217 *al.*, 2002).

218 A wildfire at Scotia provided additional support for the hypothesised ecosystem
219 services provided by fossorial reintroduced fauna on fire behaviour. The fire burnt out rapidly
220 where reintroduced ecosystem engineers were present, but continued to burn for several
221 hours where they were absent (for further details see Appendix). While the relationship
222 between leaf litter and bushfire is complex and each of our study sites is likely to respond
223 differently to fire, we believe this anecdote illustrates the impact of the altered leaf litter
224 cover and volume on fire behaviour.

225 It is important to point out the limitations of this study. There are potential differences
226 between the inside and outside of the fences beyond the presence of ecosystem engineers
227 including the presence of introduced herbivores (rabbits and goats *Capra hircus*), potential
228 local rainfall variation and the reintroduced species within the fences may be at artificially
229 high densities in the absence of dingoes *Canis lupus* and this may enhance the fuel
230 differences. Future studies should investigate how the change in leaf litter cover and volumes
231 that we found affects fire behaviour in the field. Nugent *et al.* (2014) did this using a
232 chronosequence approach with superb lyrebirds *Menura novaehollandiae* and was able to
233 model the impact on fire behaviour. Given the intensive fire management implemented by
234 AWC at fenced reintroduction sites, there is scope to investigate this experimentally.
235 Furthermore, the relationship between litter breakdown and the number of diggings is also
236 worth investigating.

237 The broad-scale declines and localised extinctions of Australia's marsupial ecosystem
238 engineers (Woinarski *et al.*, 2012) are likely to have impacted a vast array of ecological
239 features, including fire regimes. Altered fire regimes are a threat to numerous species of

240 biodiversity, and in New South Wales alone this includes 14 endangered ecological
241 communities, 39 threatened plant species, four birds and ten mammals (NSW Scientific
242 Committee, 2012), highlighting that the loss of functionally unique species undermines entire
243 ecosystems (O'Gorman *et al.*, 2011). Yet the most fire-prone forested environments of
244 eastern mainland Australia are bereft of numerous species of critical weight range mammals
245 and ecosystem engineers (e.g. Tasmanian bettongs *Bettongia gaimardi*, eastern barred
246 bandicoots *Perameles gunni*, potoroos *Potorous spp.*, etc). Their value in reducing the
247 impact and spread of fires may be further evidence of the need to restore them to the
248 environment. Tasmania retains an intact herbivore fauna, but still experiences devastating
249 fires suggesting forest type may interact with ecosystem engineers to affect leaf litter
250 breakdown or fire behaviour, and that, even in the presence of these fossorial species,
251 extensive wildfires will still occur in Australia (albeit at a lesser frequency).

252 There have been questions about the efficacy of control burning in reducing bushfire
253 risk (Bradstock, 2003, Brewer and Rogers, 2006, Pinol, Beven and Viegas, 2005). Fuel
254 reduction burns theoretically reduce fuel loads and make fire suppression more feasible
255 (Cheney, 1994), however post-fire leaf fall rapidly replenishes this source of fuel (Travers
256 and Eldridge, 2012b). Also other factors, such as ambient weather and recent rainfall, affect
257 fire behaviour (Price and Bradstock, 2011). This is the first study that identifies the potential
258 fire suppressive effect of native mammalian fauna via the increased breakdown of leaf litter
259 to reduce fuel loads. This is a fascinating issue as the decline of critical weight range fauna
260 in Australia has been linked to altered fire regimes (Carwardine *et al.*, 2011, Fitzsimons *et al.*,
261 2010, Woinarski *et al.*, 2010), however there may be a feedback loop relationship occurring
262 with native fauna reducing fuel loads and thereby reducing their risk of increased predation
263 following fire (McGregor *et al.*, 2014).

264 While this study focuses on the benefits of the restoration of Australian fossorial
265 species, it has direct relevance to wildlife restoration and fire management globally.
266 Throughout the world, mammals are declining and fossorial ecosystem engineers are no
267 exception (Davidson, Detling and Brown, 2012). Thus, this study provides more evidence of
268 the value of conserving these species and restoring them to sites where they have been
269 extirpated, to avert the functional homogenisation of the planet (Clavel, Julliard and Devictor,
270 2010). Furthermore, restoring ecosystem engineers is a practice that reduces fuel loads while
271 maintaining the integrity of the soil, and thereby yields cascading benefits to local ecosystems
272 (Dombeck, Williams and Wood, 2004).

273

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278

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457

458 **Table 1. Generalised linear model results of the percentage ground cover at**
 459 **Scotia. Wald *post-hoc* tests revealed no effect of fencing on the area covered by any of**
 460 **the ground cover types at Scotia (bare earth, cryptogamic crust, leaf litter, logs, animal**
 461 **digging pits or vegetation).**

Source	Wald χ^2	d.f.	Probability
Intercept	745.975	1	< 0.001
Fenced/unfenced	0.001	1	0.974
Ground cover type	326.629	5	<0.001
Interaction	344.594	11	<0.001

462

463

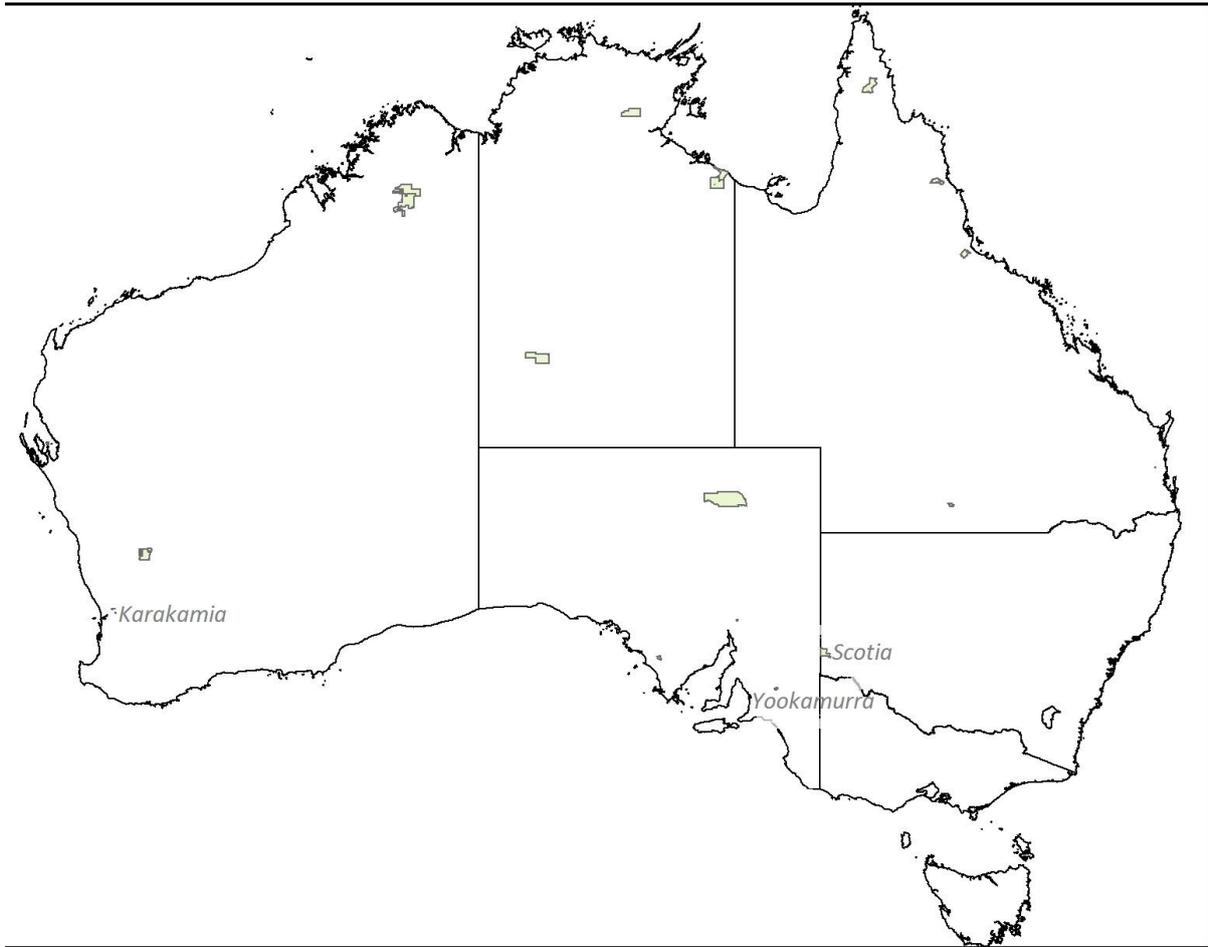
464 **Figures**

465 Fig. 1. Location map of the Australian Wildlife Conservancy's sanctuaries showing
466 Karakamia, Scotia and Yookamurra.

467 Fig. 2. Mean (± 2 S.E.) mass of leaf litter inside and outside fences at the Australian Wildlife
468 Conservancy's Karakamia, Scotia and Yookamurra Sanctuaries.

469 Fig. 3. Mean (± 2 S.E.) percentage ground cover of bare earth, cryptogamic crust, leaf litter,
470 logs, animal digging pits and vegetation inside and outside fences at the Australian
471 Wildlife Conservancy's Scotia Sanctuary. Significant differences based on Wald's χ^2
472 test are shown with asterisks (***) denoting significance at $p < 0.001$.

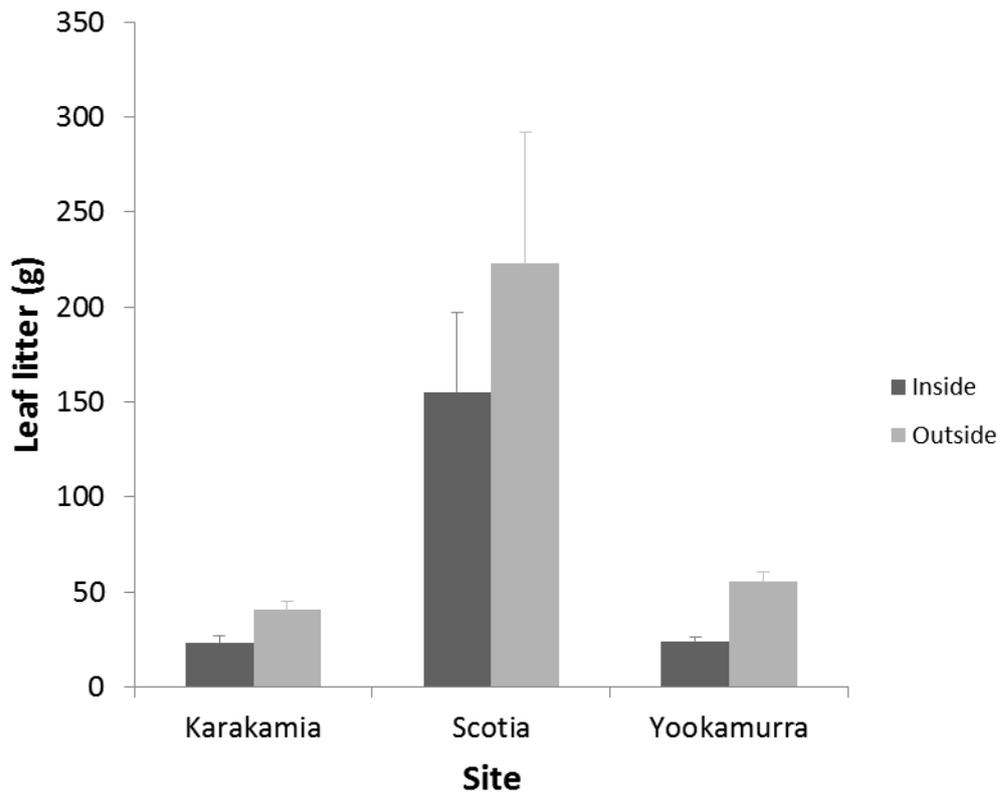
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475 Fig. 1

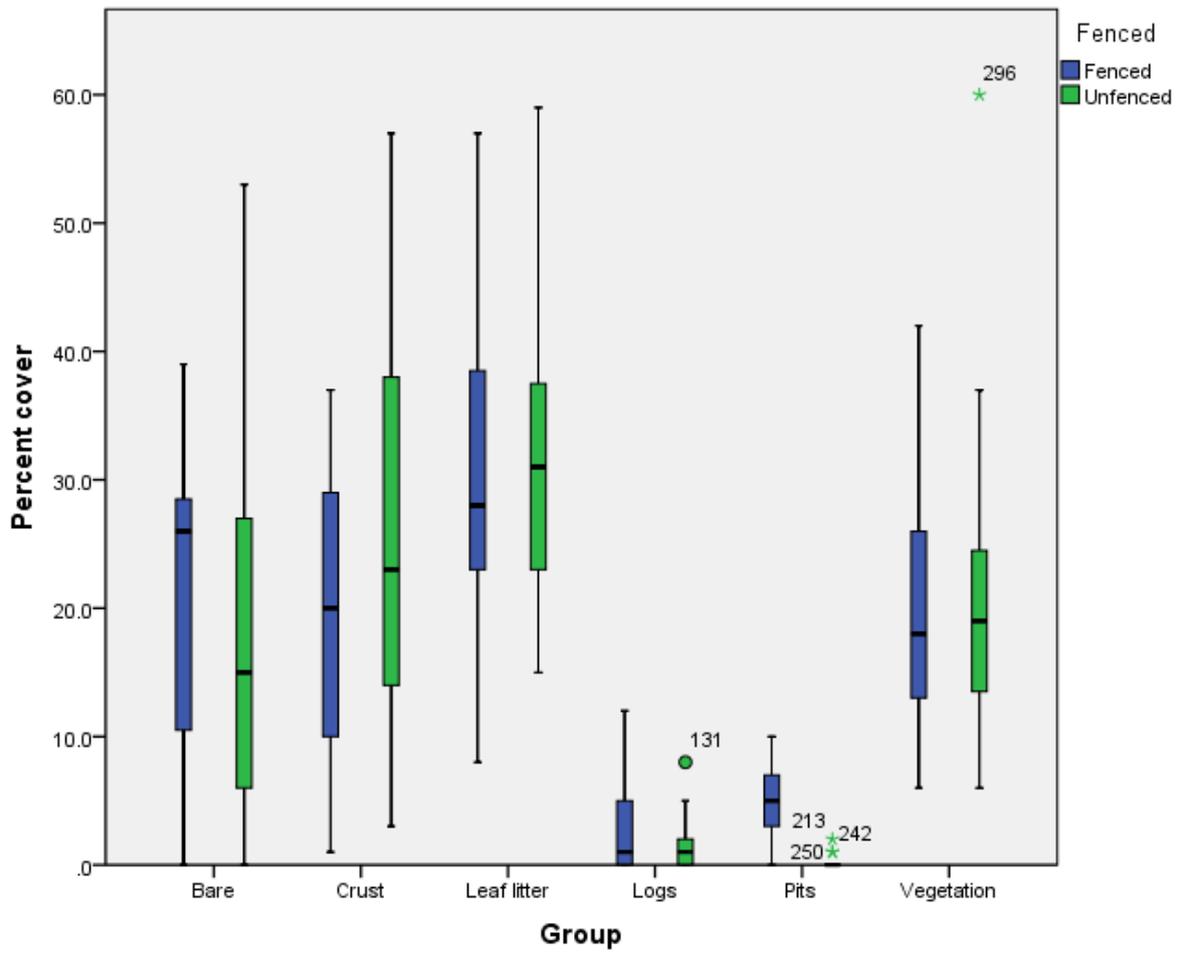
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478 Fig. 2

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484 Fig. 3.

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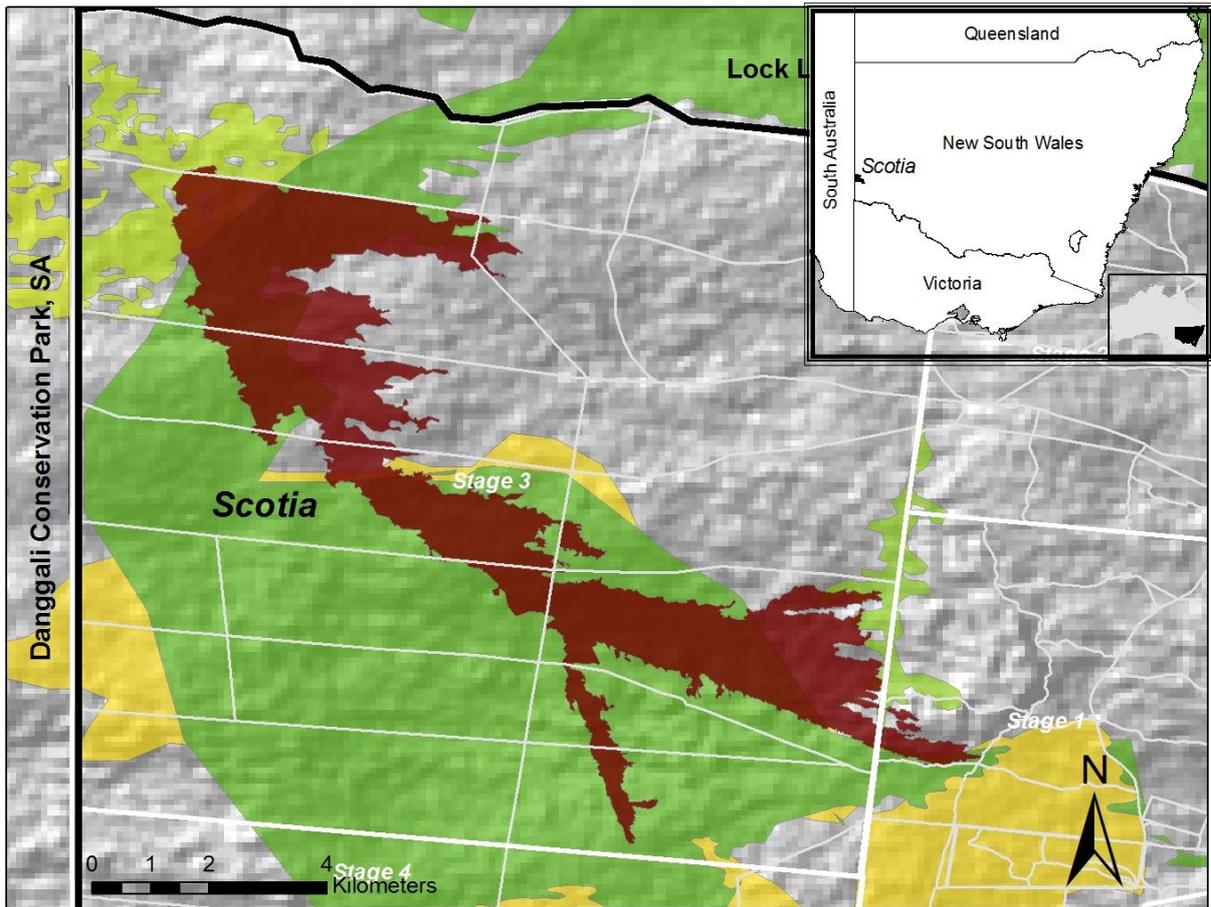
487 **Appendix**

488 A wildfire started from an overnight lightning strike in the north-western corner of Scotia in
489 September 2012 and burnt slowly to the south from when it was detected at 0830 am until
490 approximately 1300, when a strong wind change pushed it to the east (Fig. A1). The fire
491 crossed several potential fire breaks including vehicle tracks, an 8m cleared area along the
492 fence line protecting the reintroduced fauna, and fire breaks created earlier in 2011 and in
493 2010, to enter the fenced area around 1730. By 1900 hrs, the fire inside the fenced area where
494 reintroduced fauna occurred, had reached the extent shown in Fig. S1, however despite
495 weather conditions remaining fairly constant (and temperatures exceeding 30°C) it did not
496 progress further, while the fire continued to burn out the finger to the south for the rest of the
497 night (Fig. S1). Water was hosed on flames inside the fenced area where the fire was in reach
498 of vehicle tracks, however it is clear that large areas of long unburnt vegetation contiguous to
499 the fire and away from tracks did not burn (Fig. S1). Cool conditions arrived around 0500hrs
500 and the fire risk was largely alleviated via minor mopping up operations. We hypothesise that
501 the rapid cessation of fire in the fenced area was due to the reduced leaf litter caused by its
502 rapid breakdown by the actions of the ecosystem engineers that have been reintroduced there.
503 Whether this difference in fire behaviour was due to the reduced litter volumes inside the
504 fences or the reduced connectivity due to the lower percentage cover of leaf litter (or both) is
505 unknown. While the relationship between leaf litter and bushfire is complex and each of our
506 study sites is likely to respond differently to fire, we believe this anecdote illustrates the
507 impact of the altered leaf litter cover and volume on fire behaviour.

508

509 Fig. A1. Fire scar from the September 2012 wildfire at Scotia. The dark red polygon is the
510 boundary of the 2012 fire, while earlier fires are also shown (1985/6 in lime green;
511 1995-6 in bright green; 2010/11 controlled burn in pale green along the Stage 1/2
512 fenced boundary where native fossorial mammals have been reintroduced in 2002 and
513 2006 respectively). Uncoloured areas have not been burnt for over 40 years. The
514 2012 wildfire started from a lightning strike during a typical dry thunderstorm in the
515 north-western corner of the fire scar. Topography is shown in greyscale with darker
516 shades depicting higher elevations.

517



518

519 Fig. A1