

## RESEARCH ARTICLE

Functional Ecology



# Bioturbation by bandicoots facilitates seedling growth by altering soil properties

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## Abstract

1. Animals that forage for food via bioturbation can alter their habitat, influencing soil turnover, nutrient cycling and seedling recruitment, effectively acting as ecosystem engineers. Many digging mammals forage for food by digging small pits and creating spoil heaps with the discarded soil. We examined how small-scale bioturbation, created by the foraging actions of an ecosystem engineer, can alter soil nutrients and subsequently improve growth of plants.
2. We investigated the microbial and chemical properties of soil disturbed by the foraging of an Australian marsupial bandicoot, quenda (*Isoodon fusciventer*). Soil was collected from the base of 20 recent foraging pits (pit), the associated spoil heaps (spoil) and adjacent undisturbed soil (control) and analysed for nutrients (phosphorus, potassium, sulphur, organic carbon and conductivity) and microbial activity. Soil cores were collected from the same locations and seeds of the dominant canopy species, tuart (*Eucalyptus gomphocephala*), added to the soil under glasshouse conditions. The growth of seedlings was measured (height, maximum growth, basal stem width, shoot and root biomass) over a 4-month period and arbuscular mycorrhizae (AM) fungi colonisation rates of seedling roots investigated.
3. Soil from the spoil heaps had the greatest levels of conductivity and potassium. Both the spoil and undisturbed soil had greater amounts of microbial activity and organic carbon. In contrast, the pits had less nutrients and microbial activity.
4. Seedlings grown in spoil soil were taller, heavier, with thicker stems and grew at a faster rate than seedlings in the pit or control soil. Colonisation with AM fungi was greatest for seedlings grown in pit soil. The best predictors of seedling growth were greater amounts of potassium, electrical conductivity and microbial activity. The best predictor of higher colonisation rates of AM fungi was less phosphorus.
5. Bioturbation by ecosystem engineers, like quenda, can alter soil nutrients and microbial activity, facilitating seedling growth. We propose this may be caused by enhanced litter decomposition beneath the discarded spoil heaps. As the majority of Australian digging mammals are threatened, with many suffering substantial population and range contractions, the loss of these species will have long-term impacts on ecosystem processes.

## KEYWORDS

arbuscular mycorrhizal fungi, bandicoot, digging mammals, ecosystem engineer, plant–animal interactions, plant–animal–microbe interactions

## 1 | INTRODUCTION

Bioturbation by animals that dig, burrow or displace soil while searching for food can influence their environment in many ways (Whitford & Kay, 1999). Digging animals alter the physical and chemical properties of soils, modify resource pathways and alter the availability of resources for other species; and, consequently, many digging animals are considered ecosystem engineers (Coggan, Hayward, & Gibb, 2018; Davidson, Detling, & Brown, 2012). Species that dig when foraging for food create small-scale disturbances that may be quite ephemeral in nature; however, small-scale bioturbation actions may cumulatively impact ecosystems (Darwin, 1881). When digging animals are numerous, the foraging pits they create can be plentiful and subsequently influence environmental processes (Alkon, 1999; Eldridge, Koen, Killgore, Huang, & Whitford, 2012). Here, we examine how foraging pits created by quenda, *Isoodon fusciventer*, an Australian digging marsupial, may alter soil nutrients and consequently facilitate seedling growth.

By foraging in the soil, animals break through the soil crust, often mixing soil types and horizon layers (Alkon, 1999). In arid environments, breaking the soil crust can reduce soil hydrophobicity, while simultaneously allowing moisture to infiltrate the top layer of soil (Garkaklis, Bradley, & Wooller, 1998; Valentine et al., 2017), at least initially. The pit created often acts as a sink for organic matter, trapping sediment, litter and seeds, altering soil fertility at local scales (Eldridge & Mensinga, 2007; Garkaklis, Bradley, & Wooller, 2003; Hagenah & Bennett, 2013; James, Eldridge, & Hill, 2009). When a foraging pit is created, it usually has an associated spoil heap of evacuated soil, also known as ejecta mounds (Whitford & Kay, 1999). The combination of digging and discarding soil disrupts the microhabitat layer by exposing soil at the digging site, and burying organic matter and litter under the spoil heap; subsequently altering surface litter composition and potentially contributing to litter decomposition (Valentine et al., 2017). The burial of litter is an important component in litter decomposition (Austin, Araujo, & Leva, 2009; Beare et al., 1992) and the digging or raking activities of some animals, such as heteromyid rodents, the short-beaked echidna (*Tachyglossus aculeatus*) and malleefowl (*Leipoa ocellata*) enhance litter decomposition in arid environments (Eldridge et al., 2012; Smith, Avitabile, & Leonard, 2016; Travers & Eldridge, 2016).

The engineering activities of animals that enhance litter decomposition can facilitate a change in soil nutrients (see Platt, Kolb, Kunhardt, Milo, & New, 2016 for review), although these are often inconsistent, varying among organisms, bioturbation type and intensity of digging (Yu et al., 2017). For example, the burrows of mole-rats (Bathyergidae) have more nitrogen compared to undisturbed soil (Hagenah & Bennett, 2013), while mounds of pocket gophers

(*Thomomys talpoides*) are predominantly associated with lower levels of nitrogen (Yurkewycz, Bishop, Crisafulli, Harrison, & Gill, 2014). Foraging pits created by badgers (*Meles meles*) have more potassium (Kurek, Kapusta, & Holeksa, 2014) as do those made by burrowing bettongs (*Bettongia lesuer*) and greater bilbies (*Macrotis lagotis*) (James et al., 2009), although there appears to be no effect on potassium or phosphorus levels in foraging pits created by the woylie (*B. penicillata*) (Garkaklis et al., 2003).

As many nutrients (e.g., nitrogen, phosphorus and potassium) are essential for adequate plant growth, burrowing or foraging that encourages litter decomposition may subsequently lead to enhanced seedling recruitment and/or growth. Greater seedling recruitment was observed in areas with digging marsupials (James, Eldridge, & Moseby, 2010) and in experiments using artificial diggings compared to undisturbed areas (Valentine et al., 2017). Glasshouse trials also indicate that when grass seedlings are grown in the soil of foraging tracks created by echidna, the seedlings grew taller than seedlings grown in undisturbed soil, especially under challenging conditions (Travers, Eldridge, Koen, & Soliveres, 2012). Furthermore, the composition of many vegetation communities is considered to be influenced by the presence (or the removal) of digging animals (Davidson et al., 2012; Whitford & Kay, 1999).

Digging activities of animals are also linked to changes in soil microbial communities, with foraging activities of echidnas influencing ecosystem function, measured by enzyme concentrations, compared to undisturbed soils (Eldridge, Delgado-Baquerizo, Woodhouse, & Neilan, 2016). Digging mammals can also be key dispersers of mycorrhizal fungi, via consumption of the fruiting bodies and subsequent defecation of viable spores (Johnson, 1996; Tay et al., 2018). Mycorrhizae are specialised structures arising from the association of plant roots and fungi that allow plants greater access to limited soil nutrients (e.g., nitrogen and phosphorus) and water (Smith & Smith, 2011), with an estimated 72% of vascular plants forming symbiotic associations with arbuscular mycorrhizae (AM) (Brundrett & Tedersoo, 2018). Indeed, the presence of small mammals positively influenced AM colonisation of roots in semiarid Chilean shrubland (Aguilera et al., 2016), while in Western Australia woodlands mycorrhizal communities differ in areas with abundant digging mammals (Dundas et al., 2018).

Many of the world's digging mammals are threatened (Davidson et al., 2012). The loss of these ecosystem engineers may lead to a subsequent loss of the ecological processes they perform and important plant–animal interactions. Globally, conservation efforts include reintroductions of threatened species, increasingly not only for the conservation of species themselves, but also in attempts to restore lost ecosystem functions (e.g., Law, Gaywood, Jones, Ramsay, & Willby, 2017); and greater understanding on the role of digging mammals in ecosystem function is therefore required (Coggan et al.,

2018). Australia has the world's highest record of mammal extinction in the last 200 years (Woinarski, Burbidge, & Harrison, 2015), and a large proportion of extant digging marsupials are threatened or have suffered severe range contractions (Fleming et al., 2014). Many of these species are within the critical weight range category (35–5,500 g) and are highly susceptible to predation by introduced red foxes (*Vulpes vulpes*) and feral cats (*Felis catus*), in addition to habitat loss and inappropriate fire regimes (Johnson & Isaac, 2009; Woinarski et al., 2015).

We examined the role of quenda foraging in facilitating plant growth. Previous research indicates this species is an important ecosystem engineer, with an individual quenda creating ~45 pits each night and displacing nearly four tonnes of soil annually per individual (Valentine, Anderson, Hardy, & Fleming, 2013). The foraging pits of quenda can also reduce soil water repellency, increase soil moisture and reduce litter size within a few months of creation (Valentine et al., 2017). In addition, seedling recruitment of co-occurring native tree species (e.g., *Eucalyptus gomphocephala* and *Acacia saligna*) is greater in artificially dug soil compared to undisturbed soil (Valentine et al., 2017). Our research further explores the role of quenda in manipulating soil and plant properties by examining: (a) whether soil nutrients are different between recently created quenda foraging pits (both the foraging pit and associated spoil heap) and undisturbed soil; (b) difference in growth of seedlings and AM fungi colonisation of seedling roots grown in quenda-manipulated soil and undisturbed soil; and (c) whether soil nutrients and microbial activity can predict seedling growth and AM colonisations.

## 2 | MATERIALS AND METHODS

The quenda is a medium-sized (weighing 800–1,200 g) omnivorous marsupial that searches for food (e.g., invertebrates, tubers and fungi) by digging foraging pits (Valentine et al., 2013). Previously considered a subspecies of the threatened southern brown bandicoot (*Isodon obesulus*) (Travouillon & Phillips, 2018), the quenda has similarly suffered population decline, principally as a result of introduced predators and habitat loss, throughout its range in south-western Australia. The quenda persists in forest remnants and peri-urban reserves where vegetation cover is sufficient to provide protection from predators (Bryant, Kobryn, Hardy, & Fleming, 2017), although these small metapopulations are vulnerable to disturbances (Ramalho et al., 2018). While digging for food, quenda creates conical-shaped foraging pits (~100 mm across and 70 mm deep), with soil ejected from the pit forming a spoil heap (ejecta mound) that covers the undisturbed ground surface and any litter present (Valentine et al., 2013).

Yalgorup National Park (32°50'54.52''S; 115°40'08.72''E) within the Swan Coastal Plain bioregion (Thackway & Cresswell, 1995) in south-western Australia supports a naturally occurring population of quenda. The region has a Mediterranean-type climate with hot, dry summers and mild, wet winters with average annual rainfall of 864 mm (Bureau of Meteorology, station # 009679). Our work was

conducted on the Spearwood Dune system (predominantly yellow-phase Karrakatta sands) where the habitat was open woodland dominated by *E. gomphocephala* (tuart), with scattered *E. marginata* (jarrah) and *Corymbia calophylla* (marri) and a midstorey *Banksia* spp. (for detailed vegetation description, see Valentine et al., 2013, 2017). The dominant eucalypt, tuart, has been the focus of restoration trials within sections of Yalgorup National Park (see Ruthrof, Bader, Matusick, Jakob, & Hardy, 2016). South-western Australian soils are old, leached and nutrient deficient (Henderson & Johnson, 2016; McArthur & Bettenay, 1960), and consequently, mycorrhizal fungi play an important role in maintaining plant health.

### 2.1 | Soil nutrients

We identified 20 recent foraging pits created by quenda, within the previous 1–2 months, at Martin's Tank, Yalgorup National Park (29 October 2012). Samples from three locations along the foraging pit profile were collected as follows: (a) the base of the foraging pit (hereafter called pit), (b) the spoil heap or ejecta mound (spoil) and (c) adjacent undisturbed ground, located within 0.5 m of the foraging pit (control). From each location, we collected soil samples (~150 g) for nutrient analyses. Standard soil nutrient analyses, undertaken by CSBP Soil and Plant Analysis Laboratory (Bibra Lake, Western Australia), examined nutrient quantities that may be important for plant growth: nitrate nitrogen (mg/kg), ammonium nitrogen (mg/kg), phosphorus (mg/kg; Colwell), potassium (mg/kg; Colwell), sulphur (mg/kg; KCl 40), organic carbon (carbon, %; Walkley-Black), as well as electrical conductivity (dS/m; which provides an indication of the level of nutrient salts present (Landis 1989) and pH level (CaCl<sub>2</sub> and H<sub>2</sub>O).

### 2.2 | Microbial activity

To estimate the overall microbial activity in each sample, we undertook a fluorescein diacetate (FDA) hydrolysis assay, which measures the enzyme activity (including lipases, esterases and proteases) of microbial populations (using methods following: Schnürer & Rosswall, 1982; and Adam & Duncan, 2001). We collected soil samples (~5 g) from the top 5 cm of soil from the three locations: pit, spoil and control. Activity of the enzymes results in the hydrolytic cleavage of FDA (colourless) into fluorescein (fluorescent yellow-green). Enzyme activity is quantified by assessing the intensity of colour using spectrophotometry (490 nm). A range of fluorescein dilutions was used ( $n = 5$ ) to generate a standard curve and optical densities converted to  $\mu\text{g}$  fluorescein produced per gram of soil.

### 2.3 | Plant growth and colonisation of arbuscular mycorrhizal fungi

To examine growth of seedlings, we collected 60 soil cores from the three locations (pit, spoil and control from 20 replicate foraging pits) using a cylindrical corer (plastic PVC pipe inner diameter: 27 × 10 cm L × W) and carefully transferred the soil to standard, free-draining pots of similar dimensions to the corer with minimal disturbance

of soil. Pots were placed in a glasshouse, seeded with 10 *E. gomphocephala* seeds into each pot (3 November 2012) and watered automatically once daily. Germination was successful with all pots containing seedlings (median 8 seedlings per pot) and was thinned to the largest single seedling per pot (at 7 weeks, 21 December 2012). We measured seedling height (cm) every 7–12 days, with a total of 13 measurements over a 3-month period. Prior to harvesting (25 March 2013), we measured the final height and stem width (mm, using digital callipers, 1 cm from the soil surface). Shoots were harvested using secateurs to cut the shoot off at 5 mm from the soil surface and were dried at 70°C for 3 days, before weighing (g).

To collect root material, we gently removed roots from the pots and washed the root mass to remove excess soil and then gently dried with paper towels. Fine roots were identified using visual inspection, and a small sample (~0.5 g) was carefully removed into a fine sieve (0.5 mm) to examine AM colonisation. Fine root samples were stored in 70% ethanol, with remaining root material dried at 70°C for 3 days before weighing (g). Fine roots (<1 mm in diameter) were later fixed in formalin acetic acid (FAA) solution (13 ml formalin + 5 ml acetic acid + ethyl alcohol) and cut into 1-cm-long segments. Mycorrhizal colonisation was assessed according to methods described by Brundrett, Piche, and Peterson (1984). The root segments were washed with water and placed in 20-ml vials containing 10% KOH solution and incubated for 30 min at 90°C. Roots were washed with water and dyed with 0.05% trypan blue solution (lactic acid:glycerol:distilled water = 1:2:2) and maintained at 50°C overnight. Ten randomly selected root segments per plant replicate were mounted on each of three microscope slides and examined for mycorrhizal colonisation under an Olympus BX50 transmitted light bright field microscope (Olympus, Japan). The number of colonised root sections was counted and summed across the three slides and converted to a proportion of the 30 root sections examined.

## 2.4 | Statistical analyses

Individual seedling trajectories were fitted by modelling seedling height using a Gamma distribution as a smooth function of time since sowing via the `GAMM4` package (Wood & Scheipl, 2013) in R (R Core Team, 2016). The resulting smoothed model trajectories were used to calculate rate of maximum growth for each seedling (mm/day). We used a hierarchical mixed modelling approach to examine the strength of the effect of the foraging pit location (pit, spoil, control) on both soil characteristics (conductivity, nutrients and FDA) and the plant growth response variables. The variables final height, max growth, dry shoot biomass, dry root biomass and stem width were modelled using a gamma distribution, and the proportion of AM in roots were modelled using a binomial distribution based on the 30 observations. As soil characteristic variables were used as predictors of the plant growth response variables in subsequent analyses (see below), they were transformed (where necessary) to optimise spread across the predictor range and improve scaling relationships. The nutrients phosphorus, potassium and sulphur were natural log-transformed, FDA was cube-root (`cbrt`)-transformed

and conductivity was square-root (`sqrt`)-transformed. Following transformations, all soil characteristic variables were modelled via a Gaussian distribution. Each variable was modelled using a GLMM, including foraging pit identifier as a random intercept to account for nonindependence of the three locations (pit, spoil and control) sampled at each foraging pit replicate. Initial models were fit using the function `glmer` from the `lme4` library (Bates, Maechler, Bolker, & Walker, 2015) in R, with resulting model output used to calculate AICc and a pseudo  $R^2$ . Equivalent models were fit in a Bayesian context based on uninformative priors using the `INLA` package (Lindgren & Rue, 2015) in R and the `inla.posterior.sample` used to generate 95% credible bounds for model parameters that were used to interpret significant differences among locations. Two models were fitted for each variable: the null model including only an intercept and the foraging pit identifier and a model including foraging pit location (pit, spoil, control). Differences in the AICc and pseudo  $R^2$  values between the location and null models were used to evaluate the strength of the effect of foraging pit location for each variable.

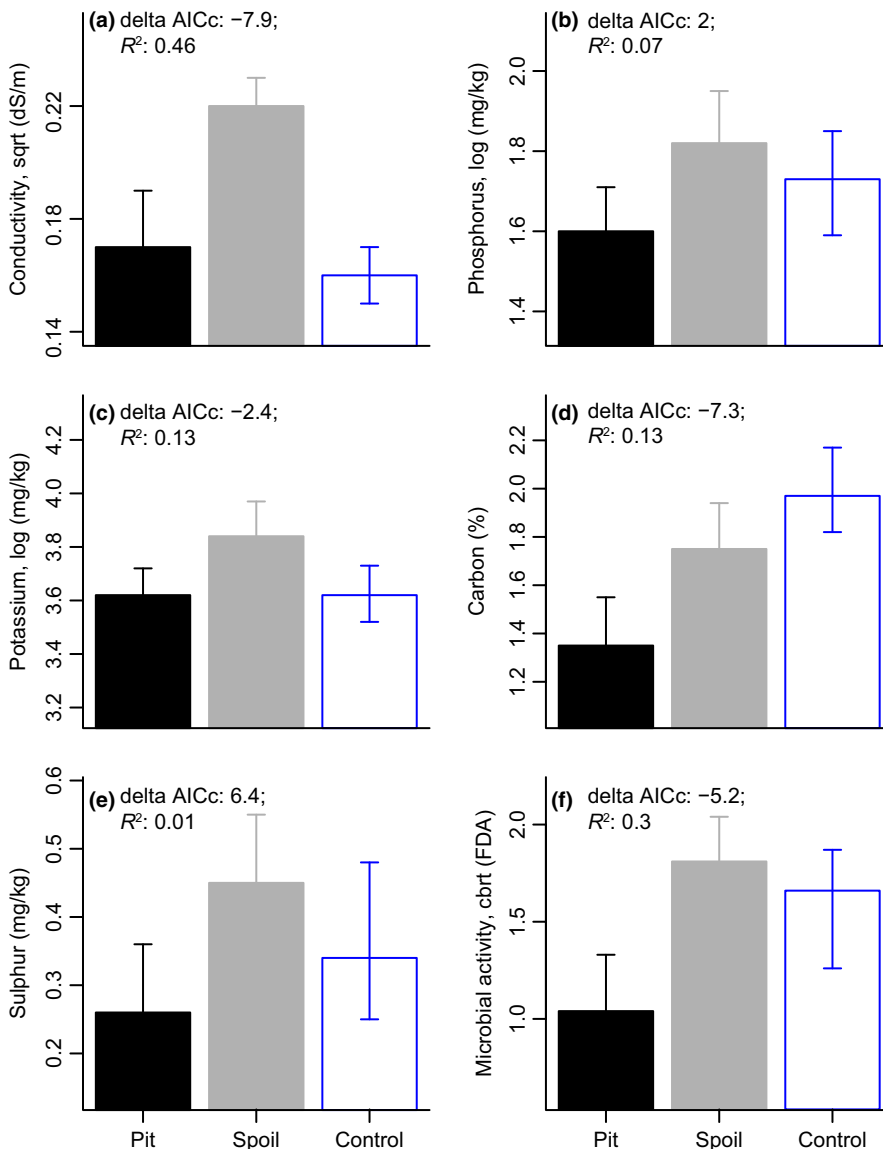
Differences in the growth trajectories of seedlings among the three foraging pit profile locations were assessed using generalised additive mixed models (GAMMs) based on a Gamma distribution with a log link function, with foraging pit identifier included as a random intercept term as in the GLMM above, but an additional seedling identifier random intercept to account for repeated measurement on individual seedlings over time.

We explored the relative importance of the relationship among the soil characteristics [phosphorus (mg/kg), potassium (mg/kg), sulphur (mg/kg), carbon (%), pH ( $\text{CaCl}_2$ ), electrical conductivity (dS/m) and FDA ( $\mu\text{g}$  hydrolysed FDA/g of dry soil)] as predictors of the plant growth variables [response variables: final height (mm); stem width (mm); maximum growth (cm/day); dry shoot biomass (g); dry root biomass (g); AM colonisation (%)] using a full subsets GAMM approach via the function `full.subsets.gam` described in Fisher, Wilson, Sin, Lee, and Langlois (2018) in R using the default argument settings, with the exception that maximum model size was limited to two simultaneous predictors. This approach constructs a complete model set excluding any models containing correlated >0.28 Pearson correlation and compares these using Akaike information criterion (AICc), Bayesian information criterion (BIC) and AIC weight ( $\omega_i$ ) values (Burnham & Anderson, 2002). The simplest model within two AICc of the model with the lowest AICc was assumed to be the optimal model, with the relative importance of each predictor across the whole model set calculated as summed model weights. All models were fit using GAMMs, via the `gamm4` function from the `GAMM4` package (Wood & Scheipl, 2013) in R using the appropriate statistical distribution and random structure as described for the GLMs above.

## 3 | RESULTS

### 3.1 | Soil nutrients

Many of the soil physiochemical properties (e.g., conductivity, Figure 1a and potassium, Figure 1c) were significantly greater in the



**FIGURE 1** Conductivity (dS/m), nutrient levels (mg/kg) and microbial activity (FDA) of soil collected from different locations of a foraging pit created by quenda (*Isoodon fusciventer*). Means ( $\pm 95\%$  credible intervals, based on estimated Bayesian posterior parameter estimates) are plotted. Delta AICc and  $R^2$  values show the difference in AICc and  $R^2$  values between GLMMs based on location and null models, respectively (e.g., location model AICc - null model AICc). Negative delta AICc values indicate that the model containing location was a better fit than the null model (i.e., the AICc value of the location model was less than the AICc of the null model)

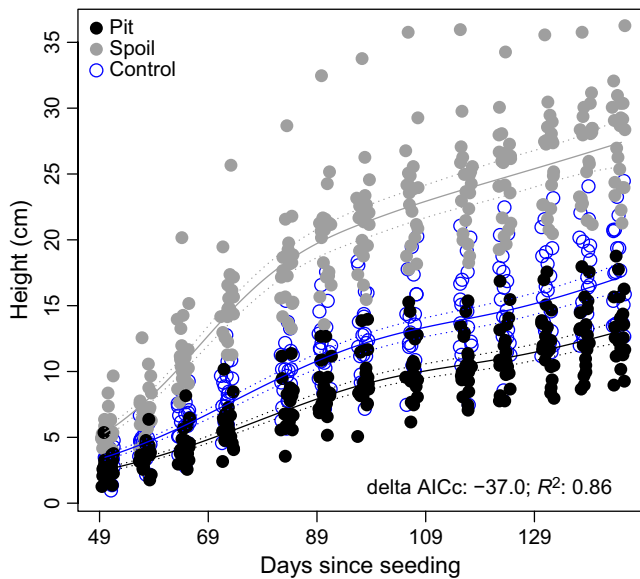
spoil soil than either the pit or control soil. Carbon was least in the pit compared to either spoil or control soil (Figure 1d). Soil location significantly influenced conductivity, potassium and carbon, with models including foraging pit location having substantially smaller AICc values than the null models (Figure 1). Although there was a trend for higher levels of phosphorus and sulphur in the spoil compared to pit soil (based on 95% CI; Figure 1b,e), the AICc, models including location had very little support, indicating that differences were not strong. The pH level (both  $\text{CaCl}_2$  and  $\text{H}_2\text{O}$ ) did not vary among the foraging pit locations and is not considered in any further analyses (not shown in Figure 1).

### 3.2 | Soil microbial activity

There was more microbial activity in the spoil and control soil, indicating the pit soil was comparatively sterile, and soil microbial activity, indicated by hydrolysed FDA (Figure 1f), showed strong support for the inclusion of soil location in a model.

### 3.3 | Plant growth and colonisation of arbuscular mycorrhizal fungi

There was no difference in the number of seedlings that germinated among foraging pit locations at seven weeks postsowing in pots in the glasshouse trial (location mean seedlings  $\pm 95\%$  CI; pit =  $7.8 \pm 1.1$ ; spoil =  $7.8 \pm 0.7$ ; control =  $7.5 \pm 0.8$ ). Location along the foraging pit had a strong influence on seedling growth over time with seedlings grown in the spoil soil taller than seedlings grown in pit or control soil (location model AICc: 2778.3 vs. null model AICc: 2815.3; Figure 2). Seedlings in the spoil soil were already slightly taller than seedlings in the pit soil at the first measurement (49 days since sowing) and by the third measurement (62 days since sowing) differences in the heights of seedlings among foraging pit locations were distinct (Figure 2). Seedlings grown in the spoil soil grew more rapidly than seedlings grown in either the pit (2.8 times faster) or control ( $\sim 2$  times faster) soils (Figure 3b), especially in the first 40 days of measurements (Figure 2). At the time of harvest (142 days since



**FIGURE 2** Growth of seedlings over time grown in soil collected from different locations of a foraging pit (pit, spoil and control) created by quenda (*Isoodon fusciventer*). Solid lines show GAMM fits for each treatment, and dotted lines indicate estimated 95% confidence limits

seeding), seedlings from the spoil soil were double the height of pit seedlings and 1.5 times taller than the control seedlings (Figure 3a). At harvest, seedlings grown in the spoil soil had the greatest shoot biomass (four times heavier than seedlings from the pit; Figure 3c), stem width (Figure 3d) and root biomass (3.5 times heavier than seedlings from the pit; Figure 3e). By contrast, seedlings grown in the pit soil were consistently the shortest seedlings (Figures 2 and 3). Seedlings in the pit soil had the narrowest stems (Figure 3d) and smallest shoot biomass (Figure 3c), while their root biomass was not different to the seedlings grown in the control soil (Figure 3e). The seedlings grown in the pit soil, despite being typically the smallest seedlings observed, exhibited the greatest proportion of AM colonisation (four times greater than for seedlings from the pit; Figure 3f).

### 3.4 | Predictors of seedling growth

Potassium, phosphorus, FDA and electrical conductivity were the strongest predictor variables for the six seedlings response variables examined (Figure 4). For each seedling response variable, there was only one preferred model (all other models had  $\Delta\text{AICc} > 2$ ), with each model for the seedling response variable containing two predictor variables (Table 1). Seedling final height, stem width and root biomass were positively correlated with the amount of potassium in soil samples. Maximum growth per day and shoot biomass of seedlings were positively correlated with the amount of electrical conductivity of the soil (Table 1; Figure 4; Supporting Information Figure S1). The percentage colonisation of AM was negatively influenced by the amount of phosphorus in the soil (Table 1; Figure 4; Supporting Information Figure S1). All seedling response variables were correlated with FDA readings, with bigger seedlings tending to

have greater levels of FDA (Table 1; Figure 4; Supporting Information Figure S1).

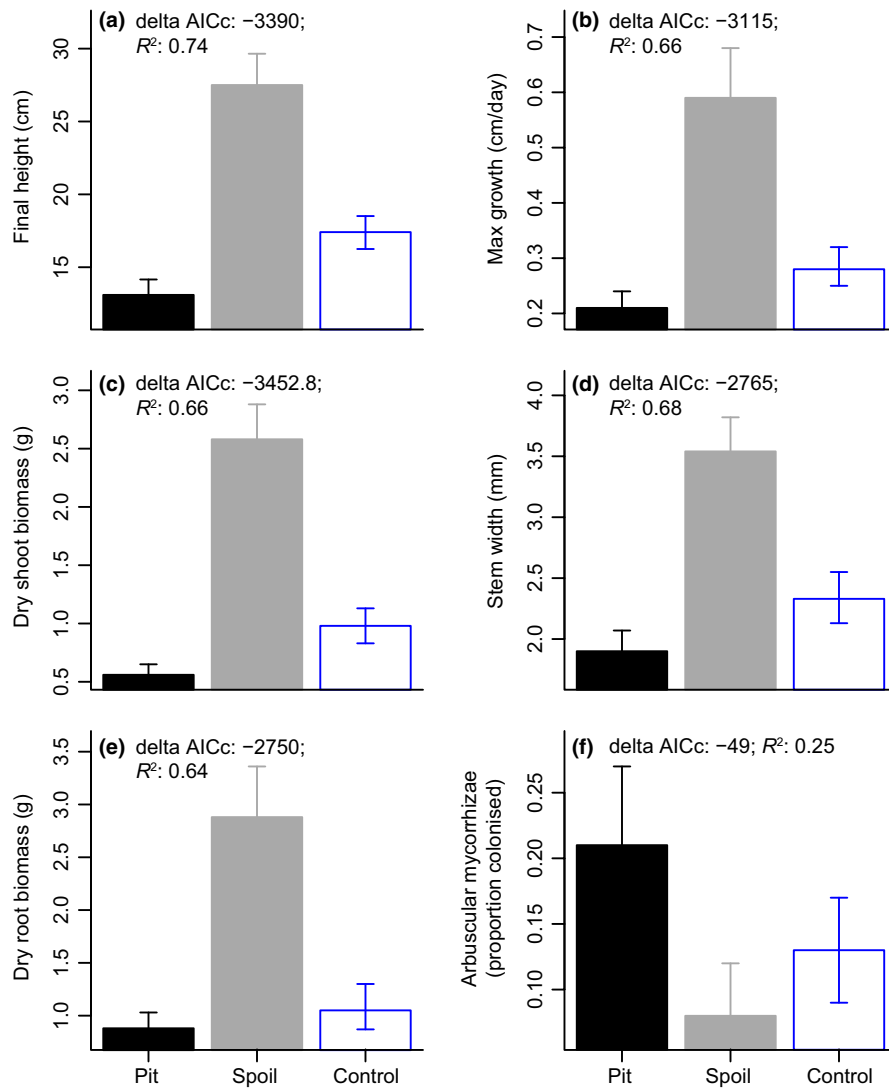
## 4 | DISCUSSION

We have demonstrated that foraging activities of quenda alter soil properties, including nutrient concentrations and microbial activity, which facilitates greater plant growth of young seedlings. The differences in soil properties were most evident in spoil soils (the soil ejected from the foraging pits) where the subsequent growth of seedlings was 1.5–2 times greater than seedlings grown in control (undisturbed) or foraging pit soils. Seedling growth response variables were best predicted by greater amounts of microbial activity and some soil nutrients (potassium and electrical conductivity), which were often greatest in the spoil soils. While it has been demonstrated that quenda foraging alters the heterogeneity of soil properties at microscales, such as increasing water infiltration and decreasing hydrophobicity (Valentine et al., 2017), our current results illustrate that digging activities of quenda also significantly increase native plant growth.

Soil disturbance by animals that dig or burrow can have a great impact on soil chemical properties (Platt et al., 2016; Yu et al., 2017), with most studies comparing soil from burrows or mounds with nearby undisturbed soil (Coggan et al., 2018). Far fewer studies examine the more ephemeral foraging pits, although in Australia there has been some research in this field (e.g., Garkaklis et al., 2003; James et al., 2009; Travers et al., 2012). Our study is the first to compare soil nutrients at different locations along the foraging pit profile, and our findings clearly show that digging animals are creating significant nutrient patchiness at a microsite scale.

Our study demonstrated that the spoil soil of quenda foraging had greater levels of electrical conductivity and potassium than either the undisturbed soil or the pit themselves. Similarly, the burrow spoils of wedge-tailed shearwaters (*Puffinus pacificus*) were greater in electrical conductivity than soil from the bird colonies or surrounding undisturbed vegetation mounds (Bancroft, Garkaklis, & Roberts, 2005). Although not an active dig, hip holes created by Australian kangaroos (*Macropus* spp.) while they rest, have greater electrical conductivity, which decreases with distance from the hip hole (Eldridge & Rath, 2002). Very little is known about how electrical conductivity affects tree species, although seedlings seem sensitive to small changes (Allen, Chambers, & Stine, 1994). Growth of container-grown seedlings of *Pinus resinosa* from north-eastern North America was greatest at electrical conductivity between 1.8 and 2.2 dS/m; followed by toxicity at 2.5 dS/m (Timmer & Parton, 1984). The ancient, low-nutrient soil of south-western Australia typically has low levels of electrical conductivity (Henderson & Johnson, 2016), and small changes in these amounts, such as those observed in this study (e.g., control soil = 0.16 dS/m *c.f.* spoil soil = 0.22 dS/m), may facilitate seedling growth in the early establishment phase.

In our study, potassium was one of the best predictors of seedling growth. Changes in soil potassium levels have been observed

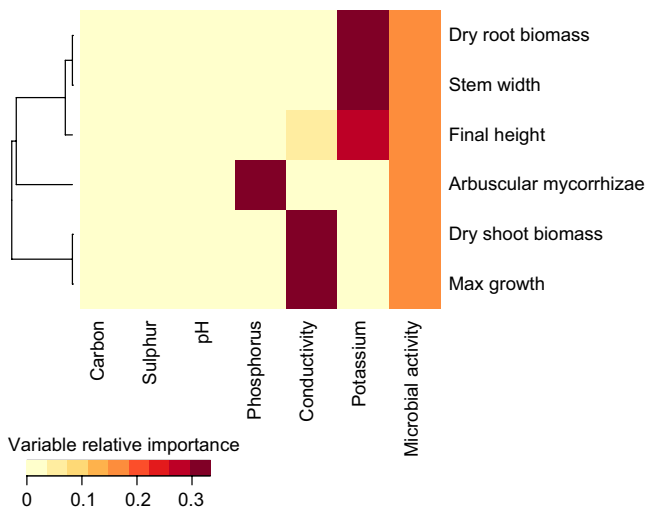


**FIGURE 3** Seedling response variables and proportion of arbuscular mycorrhizal (AM) fungi colonisation on roots from seedlings grown in soil collected from different locations of a foraging pit created by quenda (*Isoodon fusciventer*). Plotted are means ( $\pm 95\%$  credible intervals, based on estimated Bayesian posterior parameter estimates). Delta AICc and  $R^2$  values show the difference in AICc and  $R^2$  values between GLMMs based on location and null models, respectively (e.g., location model AICc - null model AICc). Negative delta AICc values indicate that the model containing location was a better fit than the null model (i.e., the AICc value of the location model was less than the AICc of the null model)

in the burrows created by many digging animals (see Platt et al., 2016 for review), although there is little consistency in the direction of change. For example, burrows created by badgers and foxes had more potassium (Kurek et al., 2014), while mounds of pocket gophers (*T. talpoides*) had less potassium than undisturbed surface soil (Mielke, 1977). In contrast, potassium quantities at foraging pits created by woylies were similar to undisturbed soil (Garkaklis et al., 2003), and the intensity of digging by plateau pika (*Ochotona curzoniae*) did not modify potassium levels (Yu et al., 2017). Potassium plays a key role in plant growth and development through the movement of water, nutrients and carbohydrates in plant tissue (Marschner, 1995). Potassium is considered to be an essential nutrient that can significantly ameliorate plant abiotic stress (Marschner, 1995); and previous studies have associated greater levels of potassium with increases in tree growth, wood production, leaf gas exchange, stomatal sensitivity to water deficit and water use efficiency (Battie-Laclau et al., 2016). The addition of potassium to soil can also result in a positive effect on the growth of tropical forest seedlings (Santiago et al., 2011), while potassium deficiency can result in reduced plant growth (Marschner, 1995). Our research is one of the

first studies that demonstrate a clear relationship between animal foraging activities, changes in nutrient levels and subsequent plant growth. Given that potassium is highly mobile and readily leached in soils, for the nutrient deficient soils of south-western Australia (Henderson & Johnson, 2016; McArthur & Bettenay, 1960), even small increases in potassium (such as those created in the wake of quenda digging activities) could make a difference to early seedling development.

Microbial activity (FDA) was significantly less in pit soil than for spoil and control soil. The depth of the foraging pit may contribute towards this observation, as microbial activity declines with increasing soil depth (Taylor, Wilson, Mills, & Burns, 2002). Quenda digs at Yalgorup National Park have a depth of  $\sim 70$  mm (range 35–135 mm; Valentine et al., 2013). Consequently, the bottom of the pit (where pit soil was sampled) may have been below the level of high microbial activity. Previous research has indicated that burrowing by invertebrates (e.g., earthworms, Aira, Lazcano, Gomez-Brandon, & Dominguez, 2010) can also increase FDA levels, but, this is the first study to show an increase in FDA through the digging actions of mammals. Further research examining the influence of digging on



**FIGURE 4** Heat-map indicating the relative importance (summed AICc weights/number of models) of each predictor variable (FDA, potassium, electrical conductivity, phosphorus, pH, sulphur and carbon) in contributing towards each seedling response variable (maximum growth, shoot biomass, AM colonisation, final height, stem width and root biomass) of seedlings grown in soil from different locations of a foraging pit created by quenda (*Isoodon fusciventer*). Dendrogram shows a Euclidian hierarchical cluster analysis (complete linkage) of the seedling response variables based on the relative importance of the different predictor variables

the composition and function of microbial communities and how they impact seedling germination and establishment, would be valuable.

Mycorrhizal mutualisms are particularly important for plant growth; specifically, these fungi increase the ability of plants to take up phosphorus, nitrogen and micronutrients, and are a defence against plant pathogens (see review by Smith & Smith, 2011). We found that AM colonisation was greater in seedlings grown in the pit soil and that low levels of soil phosphorus were a predictor of high AM colonisation. Phosphorus is an important nutrient for plant growth, but can be challenging for plants to take up; AM fungi-plant mutualisms are an effective pathway for plants

to acquire phosphorus, which can assist in root growth (Smith, Jakobsen, Gronlund, & Smith, 2011). The seedlings grown in the pit soil had ~one-third of the root biomass compared to seedlings grown in the spoil heap, and it is possible that this greater root biomass reduced the ratio of AM root colonisation to noncolonisation (Smith & Smith, 2011). In addition, it is unclear how the differences in AM colonisation of roots would affect seedling growth over longer time frames.

#### 4.1 | Why does quenda digging facilitate seedling growth?

In our study, seedling growth was substantially greater for seedlings grown in soil from the spoil heap created by quenda than either the foraging pit or adjacent undisturbed soil. Potential reasons for enhanced seedling growth may be due to reduced bulk density of soil in the spoil heaps and altered litter decomposition rates. Although we did not measure bulk density among the soil treatments, previous research has identified that spoil heaps created by digging animals often have lower bulk density than undisturbed soils (reviewed in Platt et al., 2016). In manipulative experiments, lower soil bulk density positively affected many growth parameters of Scots pine (*Pinus sylvestris*) and European beech (*Fagus sylvatica*) seedlings (Kormanek, Banach, & Sowa, 2015). In addition to the potential changes in soil density, we propose that foraging by quenda created an environment conducive for litter decomposition in the spoil heap that subsequently returned nutrients to the soil, making them available for plant uptake and therefore facilitating seedling growth. The facilitation of seedling growth by animal digging activities has previously been demonstrated with Australian grass seedlings (*Dactyloctenium radulans*) grown in 18-month-old echidna foraging pits and undisturbed surface soil in a glasshouse experiment (Travers et al., 2012). Seedlings grown in the echidna foraging pit soils had greater biomass, greater proportional reproductive effort and growth rate than those growing on surface soils.

Litter decomposition is a major determinant of nutrient cycles for many terrestrial ecosystems, with decomposition returning nutrients

**TABLE 1** Top-ranking generalised additive mixed models (GAMM) for seedling response variables with soil nutrients and microbial activity predictor variables from seedlings grown in soil collected from different locations along the foraging pit profile created by the quenda (*Isoodon fusciventer*)

Response variable	Model	df	Adjusted-R <sup>2</sup>	AICc weight
Final height (mm)	Potassium + microbial activity	8.74	0.26	0.88
Max. growth (mm/day)	Conductivity + microbial activity	8.38	0.41	1
Shoot biomass (g)	Conductivity + microbial activity	8.07	0.24	1
Stem width (mm)	Potassium + microbial activity	8.45	0.19	1
Root biomass (g)	Potassium + microbial activity	8.07	0.15	1
Arbuscular mycorrhizae (proportion colonised)	Phosphorus + microbial activity	4.58	0.18	0.92

Note. Models included are the top-ranking model (i.e.,  $\Delta\text{AICc} = 0$ ) for each response variable.



(including potassium) captured in plant material to the soil (Aerts, 1997). Decomposition rates are influenced by climate, litter chemistry (Aerts, 1997), soil microbial and fungal communities (Beare et al., 1992) as well as litter position (above- vs. below-ground) and microhabitat characteristics (Austin et al., 2009). Buried litter decomposes faster than surface litter (Austin et al., 2009), potentially due to the increased exposure to microbial and fungal communities (Beare et al., 1992), with microbial communities varying in association with animal foraging activities (Eldridge et al., 2016).

Even though we collected the soil, and sampled the nutrients, when the foraging pits were still relatively fresh (within ~2 months of creation), the greater levels in the spoil soil we observed is likely to have occurred due to greater rates of litter decomposition (with the spoil heap containing surface litter that was buried by the spoil heap). During the glasshouse trial, the litter in the spoil soil may have continued to decompose (especially given the constant supply of water), adding nutrients to the soil, and potentially accounting for the relatively steep growth rate of seedlings grown in the spoil heaps within 2–3 months since seeding (Figure 1). In contrast, the pit had captured very little litter and had low levels of microbial activity potentially explaining the slow seedling development. In the field, we have observed the spoil heap partially degraded into the pit, and the foraging pits of digging mammals often become a reservoir that collects litter (and seeds) over time (James et al., 2010). The combination of increased nutrients, reduced soil bulk density and greater water infiltration (Valentine et al., 2017) provides important sites for seedling germination, establishment and growth.

## 5 | CONCLUSIONS

The microscale disturbances created by digging mammals may be incredibly important for ecosystem functioning, facilitating changes in soil nutrients, microbial activity and plant growth. Our study clearly shows that foraging by quenda can alter soil nutrient and microbial activity that subsequently influences plant growth. Of concern in Australian ecosystems, is that the vast majority of digging mammals are threatened (Fleming et al., 2014) and many landscapes no longer contain these ecosystem engineers, or if they do, the animals are in substantially reduced numbers. The loss of digging mammals goes hand-in-hand with the loss of their functional role in maintaining landscapes. Consequently, our understanding of the biotic and abiotic ecological interactions of Australian landscapes may be impoverished by not accounting for their presence. Further research is needed to understand the role of digging mammals in landscapes, as well as whether the return of such species may aid, or hinder, landscape restoration processes.

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## AUTHORS' CONTRIBUTIONS

L.E.V. and K.X.R. conceived the ideas and designed methodology; L.E.V., K.X.R. and R.F. collected the data; L.E.V. and R.F. analysed the data; L.E.V. and K.X.R. led the writing of the manuscript with contributions from G. J.E.H., R.J.H., R.F. and P.A.F. All authors contributed critically to the drafts and gave final approval for publication.

## DATA ACCESSIBILITY

Raw data used in this research article are accessible via the University of Western Australia Research Repository: <https://doi.org/10.4225/23/5b16364fb037e> (Valentine, et al., 2018).

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## REFERENCES

- Adam, G., & Duncan, H. (2001). Development of a sensitive and rapid method for the measurement of total microbial activity using fluorescein diacetate (FDA) in a range of soils. *Soil Biology and Biochemistry*, 33, 943–951. [https://doi.org/10.1016/S0038-0717\(00\)00244-3](https://doi.org/10.1016/S0038-0717(00)00244-3)
- Aerts, R. (1997). Nitrogen partitioning between resorption and decomposition pathways: A trade-off between nitrogen use efficiency and litter decomposability? *Oikos*, 80, 603–606. <https://doi.org/10.2307/3546636>
- Aguilera, L. E., Armas, C., Cea, A. P., Gutierrez, J. R., Meserve, P. L., & Kelt, D. A. (2016). Rainfall, microhabitat, and small mammals influence the abundance and distribution of soil microorganisms in a Chilean semi-arid shrubland. *Journal of Arid Environments*, 126, 37–46. <https://doi.org/10.1016/j.jaridenv.2015.11.013>
- Aira, M., Lazcano, C., Gomez-Brandon, M., & Dominguez, J. (2010). Ageing effects of casts of *Aporrectodea caliginosa* on soil microbial community structure and activity. *Applied Soil Ecology*, 46, 143–146. <https://doi.org/10.1016/j.apsoil.2010.06.001>

- Alkon, P. (1999). Microhabitat to landscape impacts: Crested porcupine digs in the Negev Desert highlands. *Journal of Arid Environments*, *41*, 183–202. <https://doi.org/10.1006/jare.1998.0481>
- Allen, J. A., Chambers, J. L., & Stine, M. (1994). *Prospects for increasing the salt tolerance of forest trees: A review*. Victoria, BC: Heron Publishing.
- Austin, A. T., Araujo, P. I., & Leva, P. E. (2009). Interaction of position, litter type and water pulses on decomposition of grasses from the semiarid Patagonian Steppe. *Ecology*, *90*, 2642–2647. <https://doi.org/10.1890/08-1804.1>
- Bancroft, W. J., Garkaklis, M. J., & Roberts, J. D. (2005). Burrow building in seabird colonies: A soil-forming process in island ecosystems. *Pedobiologia*, *49*, 149–165. <https://doi.org/10.1016/j.pedobi.2004.10.002>
- Bates, D., Maechler, M., Bolker, B., & Walker, S. (2015). *lme4: Linear mixed-effects models using Eigen and S4*. R package version 1.1-6. Retrieved from <http://CRAN.R-project.org/package=lme4>
- Battie-Laclau, P., Delgado-Rojas, J. S., Cristina, M., Nouvellon, Y., Bouillet, J. P., Piccolo, M., ... Laclau, J. P. (2016). Potassium fertilization increases water-use efficiency for stem biomass production without affecting intrinsic water-use efficiency in *Eucalyptus grandis* plantations. *Forest Ecology and Management*, *364*, 77–89. <https://doi.org/10.1016/j.foreco.2016.01.004>
- Beare, M. H., Parmelee, R. W., Hendrix, P. F., Cheng, W., Coleman, D. C., & Crossley, D. A. J. (1992). Microbial and faunal interactions and effects on litter nitrogen and decomposition in agroecosystems. *Ecological Monographs*, *62*, 569–591. <https://doi.org/10.2307/2937317>
- Brundrett, M., Piche, Y., & Peterson, R. (1984). A new method for observing the morphology of vesicular-arbuscular mycorrhizae. *Canadian Journal of Botany*, *62*, 2128–2134. <https://doi.org/10.1139/b84-290>
- Brundrett, M. C., & Tedersoo, L. (2018). Evolutionary history of mycorrhizal symbioses and global host plant diversity. *New Phytologist*. <https://doi.org/10.1111/nph.14976>
- Bryant, G. L., Kobryn, H. T., Hardy, G. E. S., & Fleming, P. A. (2017). Habitat islands in a sea of urbanisation. *Urban Forestry and Urban Greening*, *28*, 131–137. <https://doi.org/10.1016/j.ufug.2017.10.016>
- Burnham, K. P., & Anderson, D. R. (2002). *Model selection and multimodel inference: A practical information-theoretic approach* (2nd ed.). New York, NY: Springer.
- Coggan, N. V., Hayward, M. W., & Gibb, H. (2018). A global database an “state of the field” review of research into ecosystem engineering by land animals. *Journal of Animal Ecology*. <https://doi.org/10.1111/1365-2656.12819>
- Darwin, C. (1881). *The formation of vegetable mould through the action of worms with observations on their habits*. London: John Murray. <https://doi.org/10.5962/bhl.title.107559>
- Davidson, A. D., Detling, J. K., & Brown, J. H. (2012). Ecological roles and conservation challenges of social, burrowing, herbivorous mammals in the world's grasslands. *Frontiers in Ecology and the Environment*, *10*, 477–486. <https://doi.org/10.1890/110054>
- Dundas, S. J., Hopkins, A. J. M., Ruthrof, K. X., Tay, N. E., Burgess, T. I., Hardy, G. E. S. J., & Fleming, P. A. (2018). Digging mammals contribute to rhizosphere fungal community composition and seedling growth. *Biodiversity and Conservation*. <https://doi.org/10.1007/s10531-018-1575-1>
- Eldridge, D. J., Delgado-Baquerizo, M., Woodhouse, J. N., & Neilan, B. A. (2016). Mammalian engineers drive soil microbial communities and ecosystem functions across a disturbance gradient. *Journal of Animal Ecology*, *85*, 1636–1646. <https://doi.org/10.1111/1365-2656.12574>
- Eldridge, D. J., Koen, T. B., Killgore, A., Huang, N., & Whitford, W. G. (2012). Animal foraging as a mechanism for sediment movement and soil nutrient development: Evidence from the semi-arid Australian woodlands and the Chihuahuan Desert. *Geomorphology*, *157*–158, 131–141. <https://doi.org/10.1016/j.geomorph.2011.04.041>
- Eldridge, D. J., & Mensinga, A. (2007). Foraging pits of the short-beaked echidna (*Tachyglossus aculeatus*) as small-scale patches in a semi-arid Australian box woodland. *Soil Biology and Biochemistry*, *39*, 1055–1065. <https://doi.org/10.1016/j.soilbio.2006.11.016>
- Eldridge, D. J., & Rath, D. (2002). Hip holes: Kangaroo (*Macropus* spp.) resting sites modify the physical and chemical environment of woodland soils. *Austral Ecology*, *27*, 527–536. <https://doi.org/10.1046/j.1442-9993.2002.01212.x>
- Fisher, R., Wilson, S. K., Sin, T. M., Lee, A. C., & Langlois, T. J. (2018). A simple algorithm for complete subsets multiple regression in ecology with R. *Ecology and Evolution*. <https://doi.org/10.1002/ece3.4134>
- Fleming, P. A., Anderson, H., Prendergast, A. S., Bretz, M. R., Valentine, L. E., & Hardy, G. E. S. (2014). Is the loss of Australian digging mammals contributing to a deterioration in ecosystem function? *Mammal Review*, *44*, 94–108. <https://doi.org/10.1111/mam.12014>
- Garkaklis, M. J., Bradley, J. S., & Wooller, R. D. (1998). The effects of woylie (*Bettongia penicillata*) foraging on soil water repellency and water infiltration in heavy textured soils in southwestern Australia. *Australian Journal of Ecology*, *23*, 492–496. <https://doi.org/10.1111/j.1442-9993.1998.tb00757.x>
- Garkaklis, M. J., Bradley, J. S., & Wooller, R. D. (2003). The relationship between animal foraging and nutrient patchiness in south-west Australian woodland soils. *Australian Journal of Soil Research*, *41*, 665–673. <https://doi.org/10.1071/SR02109>
- Hagenah, N., & Bennett, N. C. (2013). Mole rats act as ecosystem engineers within a biodiversity hotspot, the Cape Fynbos. *Journal of Zoology*, *289*, 19–26. <https://doi.org/10.1111/j.1469-7998.2012.00958.x>
- Henderson, R., & Johnson, D. (2016). *The geology of Australia* (3rd ed.). Melbourne, Australia: Cambridge University Press. <https://doi.org/10.1017/CBO9781139923866>
- James, A. I., Eldridge, D. J., & Hill, B. M. (2009). Foraging animals create fertile patches in an Australian desert shrubland. *Ecography*, *32*, 723–732. <https://doi.org/10.1111/j.1600-0587.2009.05450.x>
- James, A. I., Eldridge, D. J., & Moseby, K. E. (2010). Foraging pits, litter and plant germination in an arid shrubland. *Journal of Arid Environments*, *74*, 516–520. <https://doi.org/10.1016/j.jaridenv.2009.09.016>
- Johnson, C. N. (1996). Interactions between mammals and ectomycorrhizal fungi. *Trends in Ecology and Evolution*, *11*, 503–507. [https://doi.org/10.1016/S0169-5347\(96\)10053-7](https://doi.org/10.1016/S0169-5347(96)10053-7)
- Johnson, C. N., & Isaac, J. L. (2009). Body size and extinction risk in Australian mammals: Back to the critical weight range. *Austral Ecology*, *34*, 35–40. <https://doi.org/10.1111/j.1442-9993.2008.01878.x>
- Kormanek, M., Banach, J., & Sowa, P. (2015). Effect of soil bulk density on forest tree seedlings. *International Agrophysics*, *29*, 67–74.
- Kurek, P., Kapusta, P., & Holeksa, J. (2014). Burrowing by badgers (*Meles meles*) and foxes (*Vulpes vulpes*) changes soil conditions and vegetation in a European temperate forest. *Ecological Research*, *29*, 1–11. <https://doi.org/10.1007/s11284-013-1094-1>
- Landis, T. D. (1989). Mineral nutrients and fertilization. In T. D. Landis, R. W. Tinus, S. E. McDonald, & J. P. Barnett (Eds.), *The container tree nursery manual, Agriculture Handbook 674*, Vol. 4 (pp. 1–67). Washington, DC: Department of Agriculture, Forest Service.
- Law, A., Gaywood, M. J., Jones, K. C., Ramsay, P., & Willby, N. J. (2017). Using ecosystem engineers as tools in habitat restoration and rewilding: Beaver and wetlands. *Science of the Total Environment*, *605*–606, 1021–1030. <https://doi.org/10.1016/j.scitotenv.2017.06.173>
- Lindgren, F., & Rue, H. (2015). Bayesian spatial modelling with R-INLA. *Journal of Statistical Software*, *63*, 1–25.
- Marschner, H. (1995). Functions of mineral nutrients: Macronutrients. In H. Marschner (Ed.), *Mineral nutrition of higher plants* (pp. 229–312). Adelaide, SA: Elsevier. <https://doi.org/10.1016/B978-012473542-2/50010-9>
- McArthur, W. M., & Bettenay, E. (1960). *The development and distribution of soils on the Swan Coastal Plain*. Swan Coastal Plain, WA: CSIRO Soil Publication.

- Mielke, H. W. (1977). Mound building by pocket gophers (Geomysidae): Their impact on soils and vegetation in North America. *Journal of Biogeography*, 4, 171–180. <https://doi.org/10.2307/3038161>
- Platt, B. F., Kolb, D. J., Kunhardt, C. G., Milo, S. P., & New, L. G. (2016). Burrowing through the literature: The impact of soil-disturbing vertebrates on physical and chemical properties of soil. *Soil Science*, 181, 175–191. <https://doi.org/10.1097/SS.0000000000000150>
- R Core Team. (2016). *R: A language and environment for statistical computing*. Vienna, Austria: R Foundation for Statistical Computing. Retrieved from <http://www.R-project.org/>
- Ramalho, C. E., Ottewill, K. M., Chambers, B. K., Yates, C. J., Wilson, B. A., Bencini, R., & Barrett, G. (2018). Demographic and genetic viability of a medium-sized ground dwelling mammal in a fire-prone, rapidly urbanizing landscape. *PLOS ONE*, 13, e0191190. <https://doi.org/10.1371/journal.pone.0191190>
- Ruthrof, K. X., Bader, M. K. F., Matusick, G., Jakob, S., & Hardy, G. E. S. J. (2016). Promoting seedling physiological performance and early establishment in degraded Mediterranean-type ecosystems. *New Forests*, 47, 357–376. <https://doi.org/10.1007/s11056-015-9520-6>
- Santiago, L. S., Wright, S. J., Harms, K. E., Yavitt, J. B., Korine, C., Garcia, M. N., & Turner, B. L. (2011). Tropical tree seedling growth responses to nitrogen, phosphorus and potassium addition. *Journal of Ecology*, 100, 309–316.
- Schnürer, J., & Rosswall, T. (1982). Fluorescein diacetate hydrolysis as a measure of total microbial activity in soil and litter. *Applied and environmental microbiology*, 43, 1256–1261.
- Smith, A., Avitabile, S. C., & Leonard, S. W. J. (2016). Less fuel for the fire: Malleefowl (*Leipoa ocellata*) nesting activity affects fuel loads and fire behaviour. *Wildlife Research*, 43, 640–648. <https://doi.org/10.1071/WR16127>
- Smith, S. E., Jakobsen, I., Gronlund, M., & Smith, F. A. (2011). Roles of arbuscular mycorrhizas in plant phosphorus nutrition: Interactions between pathways of phosphorus uptake in arbuscular mycorrhizal roots have important implications for understanding and manipulating plant phosphorus acquisition. *Plant Physiology*, 156, 1050–1057. <https://doi.org/10.1104/pp.111.174581>
- Smith, S. E., & Smith, F. A. (2011). Roles of arbuscular mycorrhizas in plant nutrition and growth: New paradigms from cellular to ecosystem scales. *Annual Review of Plant Biology*, 62, 227–250. <https://doi.org/10.1146/annurev-arplant-042110-103846>
- Tay, N., Hopkins, A. J. M., Ruthrof, K. X., Burgess, T. I., Hardy, G. E. S., & Fleming, P. A. (2018). The tripartite relationship between a bioturbator, mycorrhizal fungi, and a key Mediterranean forest tree. *Austral Ecology*. <https://doi.org/10.1111/aec.12598>
- Taylor, J. P., Wilson, B., Mills, M. S., & Burns, R. G. (2002). Comparison of microbial numbers and enzymatic activities in surface soils and subsoils using various techniques. *Soil Biology and Biochemistry*, 34, 387–401. [https://doi.org/10.1016/S0038-0717\(01\)00199-7](https://doi.org/10.1016/S0038-0717(01)00199-7)
- Thackway, R., & Cresswell, I. D. (1995). *An interim biogeographic regionalisation of Australia: A framework for establishing the national system of reserves*. Canberra, ACT: Australian Nature Conservation Agency.
- Timmer, V. R., & Parton, W. J. (1984). Optimum nutrient levels in a container growing medium determined by a saturation aqueous extract. *Communications in Soil Science and Plant Analysis*, 15, 607–618. <https://doi.org/10.1080/00103628409367502>
- Travers, S. K., & Eldridge, D. J. (2016). Does litter decomposition vary between the foraging pits of two soil-disturbing mammal species? *Earth Surface Processes and Landforms*, 41, 669–676. <https://doi.org/10.1002/esp.3892>
- Travers, S. K., Eldridge, D. J., Koen, T. B., & Soliveres, S. (2012). Animal foraging pit soil enhances the performance of a native grass under stressful conditions. *Plant and Soil*, 352, 331–341.
- Travouillon, K. J., & Phillips, M. J. (2018). Total evidence analysis of the phylogenetic relationships of bandicoots and bilbies (Marsupialia: Peramelemorphia): Reassessment of two species and description of a new species. *Zootaxa*. <https://doi.org/10.11646/zootaxa.0000.0.0>
- Valentine, L. E., Anderson, H., Hardy, G. E. S. J., & Fleming, P. A. (2013). Foraging activity by the southern brown bandicoot (*Isodon obesulus*) as a mechanism for soil turnover. *Australian Journal of Zoology*, 60, 419–423.
- Valentine, L. E., Bretz, M., Ruthrof, K. X., Fisher, R., Hardy, G. E. S. J., & Fleming, P. A. (2017). Scratching beneath the surface: Bandicoot bioturbation contributes to ecosystem processes. *Austral Ecology*, 42, 265–276. <https://doi.org/10.1111/aec.12428>
- Valentine, L. E., Ruthrof, K. X., Fisher, R., Hardy, G. E. S. J., Hobbs, R. J., & Fleming, P. A. (2018). Data from: Bioturbation by bandicoots facilitates seedling growth by altering soil properties: dataset. *University of Western Australia Research Repository*, <https://doi.org/10.4225/23/5b16364fb037e>
- Whitford, W. G., & Kay, R. F. (1999). Bioperturbation by mammals in deserts: A review. *Journal of Arid Environments*, 41, 203–230. <https://doi.org/10.1006/jare.1998.0482>
- Woinarski, J. C. Z., Burbidge, A. A., & Harrison, P. L. (2015). Ongoing unraveling of a continental fauna: Decline and extinction of Australian mammals since European settlement. *Proceedings of the National Academy of Science*, 112, 4531–4540. <https://doi.org/10.1073/pnas.1417301112>
- Wood, S. N., & Scheipl, F. (2013) *gamm4: Generalised additive mixed models using mgcv and lme4*. R package version 0.2-2. Retrieved from <http://CRAN.R-project.org/package=gamm4>
- Yu, C., Pang, X. P., Wang, Q., Jin, S. H., Shu, C. C., & Guo, Z. G. (2017). Soil nutrient changes induced by the presence and intensity of plateau pika (*Ochotona curzoniae*) disturbances in the Qinghai-Tibet Plateau, China. *Ecological Engineering*, 106, 1–9. <https://doi.org/10.1016/j.ecoleng.2017.05.029>
- Yurkewycz, R. P., Bishop, J. G., Crisafulli, C. M., Harrison, J. A., & Gill, R. A. (2014). Gopher mounds decrease nutrient cycling rates and increase adjacent vegetation in volcanic primary succession. *Oecologia*, 176, 1135–1150. <https://doi.org/10.1007/s00442-014-3075-7>

## SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

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