



Livestock and kangaroo grazing have little effect on biomass and fuel hazard in semi-arid woodlands

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ARTICLE INFO

Keywords:

Cattle
Fire hazard
Fire management
Fuel load
Ordinal logistic regression
Sheep

ABSTRACT

Using livestock grazing as a tool to manage biomass and reduce fuel hazard has gained widespread popularity, but examples from across the globe demonstrate that it often yields mixed, context-dependent results. Grazing has potential to deliver practical solutions in systems where grazing reduces not only biomass but also reduces fuel hazard by altering vegetation connectivity or composition. We assessed the extent to which recent rainfall, rabbit and kangaroo grazing and recent and historic livestock grazing alters and accounts for variation in above-ground biomass, biomass composition and fuel hazard ratings across three broad communities in eastern Australia. We used nested linear models to assess biomass in three vertical vegetation strata, that matched the strata assessed in the Overall Fuel Hazard Assessment guide (i.e. litter/surface fuel; groundstorey vegetation/near surface fuel; and midstorey vegetation/elevated fuel) and Ordinal Logistic Regression to assess categorical fuel hazard ratings. Only recent kangaroo grazing reduced groundstorey biomass across all communities. Kangaroo grazing altered litter mass and significantly reduced surface fuel hazard in one community. Recent livestock grazing did not reduce fuel hazard, and despite significantly reducing half of our measures of biomass, these were not practical reductions. For instance, livestock grazing significantly reduced litter mass, however our model predicts that doubling our assessment of livestock grazing intensity only reduces total litter mass by 0.8%, or 8 kg per hectare in landscapes where average litter loads ranged from 3600 to 12,600 kg per hectare. Furthermore, long-term livestock grazing increased shrub biomass and in one community this increased elevated fuel hazard. There were few effects of rabbits. The effects of rainfall on biomass were up to an order of magnitude greater than any effects due to grazing, despite sampling during relatively average rainfall conditions. Our data suggest that management practices that seek to use livestock grazing to reduce biomass or its connectivity in these systems will not achieve practical reductions in biomass and or fuel hazard.

1. Introduction

Weather, grazing and fire interact to structure many of Earth's ecosystems by regulating the production and consumption of plant biomass (Bond and Keeley, 2005). Under modern agricultural practices, fire and grazing have largely become decoupled, with fire management strategies focussed on the safety of people and property and therefore preventing and suppressing fire (Fuhlendorf and Engle, 2001; Starns et al., 2019). Globally, many billions of dollars are spent each year to manage and mitigate the ecological, social and economic impacts of wildfire, with over US\$2 billion spent in 2015 in the United States alone

(Doerr and Santin, 2016). Consequently, cost-effective practices that deliver practical solutions to managing fuel loads and the risk of wildfires are a high priority for governments and resource management agencies. Apart from hazard reduction burning, livestock grazing is a strategy that has been used widely to manipulate plant biomass and composition across large areas in order to reduce the frequency, size and severity of fires and has a large body of research underpinning it (Zimmerman and Neuenschwander, 1983; Starns et al., 2019). The adage that 'grazing reduces blazing' has gained widespread popularity and political currency in several countries (Diamond et al., 2009; Leonard et al., 2010), but the few studies that have assessed the role of

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<https://doi.org/10.1016/j.foreco.2020.118165>

Received 24 February 2020; Received in revised form 14 April 2020; Accepted 16 April 2020

Available online 20 April 2020

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grazing in reducing fuel loads (i.e. reducing the vegetative components that contribute to fire spread and flame height; Hines et al., 2010), have found mixed, context-dependent results (Leonard et al., 2010; Bailey et al., 2019). Understanding the circumstances under which livestock grazing could be an ecologically and cost-effective tool for managing fuel loads and hazard is critical as we move towards a hotter, drier climate with more extreme weather events and wildfires.

Effective use of livestock to reduce fuel loads and fuel hazard by altering plant biomass generally requires substantial knowledge of plant ecology, foraging behaviour and livestock nutrition (Davies et al., 2017; Diamond et al., 2009). When successful it obviates the need to use more costly mechanical, chemical, and prescribed fire treatments (Bailey et al., 2019). However, livestock grazing can sometimes lead to increases in both biomass and subsequently, fuel hazard (a combined risk of fuel load and its connectivity, composition and dryness; Hines et al., 2010), in circumstances where, for example, livestock grazing results in high levels of standing dead material (Leonard et al., 2010; Williamson et al., 2014). It is imperative to consider the net and long-term impacts of livestock grazing, as it can have severe negative consequences for ecosystem composition, functions and services by triggering irreversible changes in stable states and decoupling numerous ecosystem processes (Fuhlendorf et al., 2009; Starns et al., 2019).

Drylands make up about 70% of the Australian land area, experience high inter-annual variability in rainfall and therefore high variability in biomass production (Poulter et al., 2014). Consequently, these drylands may be amenable to the use of grazing (*sensu* Bailey et al., 2019) to minimise fuel hazard. Although shifts in biomass do not necessarily equate to shifts in fuel load or fuel hazard, the most important circumstances in which grazing could be a viable management option is where it reduces both biomass and fuel hazard. Despite repeated calls for an assessment of the importance of grazing for managing fuel loads and fuel hazards in systems beyond grasslands and savannahs (Leonard et al., 2010; Starns et al., 2019), few studies have evaluated the feasibility of using grazing in woodlands. Given the extent and range of conditions under which grazing occurs in Australia's semi-arid woodlands, it is prudent to know the specific contexts and vegetation communities under which livestock grazing could be used to reduce biomass to reduce fuel load and fuel hazard. In systems dominated by native vegetation, it is imperative to consider the role of native and introduced free-ranging herbivores in removing plant biomass as their foraging preferences, feeding abilities and behaviours differ substantially from that of livestock (Leonard et al., 2010). Also, we are not aware of any studies which compare the effects of recent and historic livestock grazing on biomass and fuel hazard. Here we report such a study.

We examined the extent to which grazing reduces and accounts for variation in above-ground biomass and its composition, and assessed its effect on fuel hazard ratings across three broad semi-arid forests and woodlands with variable levels of biomass and grazing. We also assessed the relative effects of recent rainfall, which is known to drive biomass and fuel loads and therefore fuel hazard. To determine the scenarios under which grazing may alter biomass or fuel hazard, we separately assessed the effects of recent and historic grazing by domestic livestock, and recent grazing by free-roaming native (kangaroo) and introduced (rabbit) herbivores on each component of biomass and fuel hazard. Fuel hazard was measured according to the Overall Fuel Hazard Assessment guide (McCarthy et al., 1999), an approach widely used in Australia (McColl-Gausden et al., 2019; Volkova et al., 2016), and analogous to those used by resource managers globally (e.g. Morrow et al., 2008; Rollins 2009). Biomass was independently measured in three strata equivalent to those used in the guide where litter beds are surface fuel, groundstorey vegetation is near-surface fuel, and shrubs and saplings are elevated fuel (McCarthy et al., 1999; Hines et al., 2010). As communities vary inherently in their structure and composition, we expected them to differ in their biomass, and therefore, in their response to grazing and rainfall. We expected that high

levels of historic livestock grazing would increase shrub biomass, consistent with the shrub encroachment literature (Eldridge and Soliveres 2014) and the results of previous studies at these sites (Travers et al., 2018, 2019). Finally, we expected rainfall to be the strongest of all our drivers, by affecting both biomass and therefore fuel hazard across all three communities. Our approach will help identify whether livestock could be used as a tool for minimising the intensity and spread of high-severity wildfires by extending the time and area over which standard fire-fighting equipment and techniques remain effective in these systems (McDonald and McPherson, 2011).

2. Materials and methods

2.1. Study sites

The 451 sites in our study spanned a large area (0.5 M km²) of eastern Australia (−31.84 to −36.09, 141.54 to 148.25; Fig. A). Average annual temperatures are stable across this region (−18 °C). Average annual rainfall varies from east (460 mm yr^{−1}) to west (385 mm yr^{−1}) and its seasonality varies from winter-dominated in the south to evenly throughout the year in the north. Sites were distributed among three broad semi-arid forests and woodlands dominated by either River red gum (*Eucalyptus camaldulensis* Dehnh.; 150 sites), Black box (*Eucalyptus largiflorens* F. Muell.; 150 sites), or Cypress pine (*Callitris glaucophylla* F. Muell.; 151 sites). River red gum forests line the deep clay rich soils of the lower terraces of major river systems and their tributaries. Their understorey species are driven by flood frequency and duration. Black box woodlands occur on soils high in silt and clay on the outer banks of inland rivers, lakes and swamps that are flooded infrequently (10–40 years; Smith and Smith, 2014). The understorey vegetation is variable, driven by rainfall, grazing and flood histories (Keith, 2004). The Cypress pine woodlands occur on dry slopes, alluvial sandhills, rocky hills and peneplains. Soils are typically gradational, consisting of Quaternary colluvium and aeolian deposits with understorey species driven by soil, rainfall and disturbance history (e.g. fire, grazing).

We sampled from early spring 2013 to late summer 2014 across a range of land tenures including conservation reserves, state forests (actively and historically grazed by livestock), travelling stock reserves (grazing reserves along roads) and town commons. Sites spanned a range of grazing histories and recent grazing intensities, with sites positioned between 50 m and 2 km from livestock watering points (e.g. earthen dam). For most sites, the time since last fire was unknown, however we avoided sampling sites where there was clear evidence of recent fire.

2.2. Data collection and preliminary analyses

Each site consisted of a 200 m transect parallel to (i.e. not radiating from) the nearest watering point with five 25 m² (5 m × 5 m) 'large quadrats' at 50 m intervals (0, 50, 100, 150, 200 m). Within each large quadrat we centrally nested a 0.25 m² (0.5 m × 0.5 m) quadrat ('small quadrat').

We assessed grazing intensity by identifying and counting faecal pellets to estimate short to medium term grazing pressure (Bahamonde et al., 2017). We counted dung events within the large quadrat for cattle (*Bos taurus*) and faecal pellets within the small and large quadrats for three groups of herbivores: (1) kangaroos (*Macropus* spp., *Osphranter* spp., *Wallabia bicolor*); (2) rabbits (*Oryctolagus cuniculus*, including hares, *Lepus europaeus*); and (3) sheep (*Ovis aries*, including goats *Capra hircus*; further details in Eldridge et al., 2017). Small quadrats were easier to search but were too small to capture the spatial distribution of large faecal events (e.g. cattle, rabbit latrines). We sampled dung from every site to calculate the oven dried mass per hectare of each herbivore from each quadrat. All quadrats were used to generate an average site level mass per hectare per herbivore. We summed sheep and cattle data

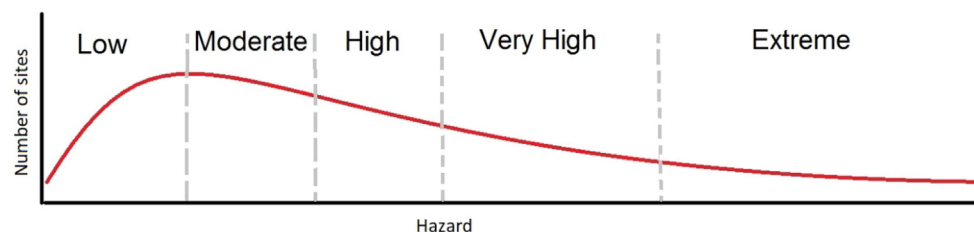
to give a single site-level measure of recent livestock grazing. We assessed historic livestock grazing by measuring the width and depth of all livestock tracks crossing the 200 m transect to derive a summed cross-sectional area (cm^2 ; Pringle and Landsberg, 2004). Livestock tracks develop from repetitive trampling by hard-hooved, large bodied animals, and persist in the landscape for many decades (Trimble and Mendel 1995).

All surface litter was collected once per site within the 50 m small quadrat to minimise bias. Litter was oven-dried, divided into the following six components and weighed separately: overstorey leaves (shrubs and trees), groundstorey leaves, reproductive structures (seeds, flowers, capsules, nuts), woody components (sticks, bark), animal derived material (invertebrates, dung), and frass (< 2 mm diameter). Data for each component were converted to tonnes per hectare as our measures of litter composition and total litter mass (sum of all components). Animal-derived material was omitted from our analysis as it mostly comprised dung and therefore was not independent of our grazing measures.

To assess groundstorey biomass, all five small quadrats at a site were photographed at a 45° angle about 1 m above the quadrat. After photographing we clipped, oven-dried and weighed all vegetative material rooted within the 50 m small quadrat (451 sites by one quadrat). Once all field surveys were completed two trained observers used the 2255 photographs (451 sites by five quadrats) to estimate standing biomass for all quadrats at all sites, calibrating their estimations against a series of photographs from previous studies of known biomass. We used the sample from the 50 m small quadrat to assess their accuracy in estimating biomass at each site. It was highly correlated (Pearson's R^2 were 0.69, 0.71 and 0.86 for Cypress pine, Black box and River red gum respectively). Therefore, the observer's estimates were averaged and scaled, across quadrats at a site, to generate a site-level assessment of groundstorey biomass as tonnes per hectare.

To estimate midstorey biomass, shrubs and juvenile trees up to 3 m tall were identified and counted within a 200 m transect of variable width (between 1 and 10 m depending on density). Each individual plant was assigned to one of two height classes (0.5–1.5 m or 1.5–3.0 m). We estimated biomass for each individual plant using their height and a combination of published species-specific and universal allometric relationships used to estimate biomass (e.g. Harrington, 1979; Paul et al., 2016; see Appendix B). Individual plant data were summed and scaled to tonnes per hectare for each site.

Our fuel hazard assessment followed protocols described in McCarthy et al., (1999) and was undertaken once per site. This method assesses biomass, its connectivity and the proportion of material that contributes to a fire's rate of spread and flame height (Hines et al., 2010). The assessment process considers four vertical strata of fuel (surface, near surface, elevated and bark; Fig. C) and includes empirical measurements and visual estimates of litter, plant and bark features (McCarthy et al., 1999; Table C). From these data, four stratum-level fuel hazard ratings and an overall fuel hazard rating are derived as one of five categories: low, moderate, high, very high or extreme. Bark fuel hazard was calculated but omitted from our analyses as it is unlikely to be affected by grazing.



i.e. the odds of a site being low compared to being moderate or above; the odds of a site being moderate or below compared to being high or higher, etc. This generates a separate prediction (coefficient) for each model term for each threshold between categories and highlights where there may be disproportionate effects on hazard ratings. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

We obtained site-level rainfall data for the periods of 1, 2, 3, 6, 9 and 12 months prior to field surveys using Bureau of Meteorology (BOM) databases. Preliminary analyses using Variance Inflation Factors (VIF) confirmed high collinearity existed among these lags. A stepwise process of elimination led us to select rainfall in the past three months for two of the three assessments of biomass and two of the five assessments of litter loads. We therefore used it as our measure of rainfall for all models. There was no collinearity among measures of grazing or rainfall in the past 3 months. Rainfall in the three months prior to surveys ranged from 20.1 mm to 217.3 mm which is within average conditions for these areas.

2.3. Biomass and litter composition analyses

We assessed midstorey and groundstorey biomass, total litter mass and each litter component (overstorey leaves; groundstorey leaves; sticks and bark; reproductive structures; frass) in separate linear models. We used nested models to assess the variance explained by each measure of grazing (recent livestock, rabbit and kangaroo; historic livestock) and rainfall. We accounted for differences among communities with a two-way interaction between each model term and community. All biomass, grazing and rainfall data were natural log transformed, i.e. $\log_e(x + 1)$, prior to inclusion to linearize the x-y relationship and remove skewness from the residuals. We assessed the significance of each term using Type III sums of squares as this removes the need to consider the order of model terms.

We assessed the variance explained by each model term using a stepwise process to assess model fit on all possible linear combinations of terms. Each "step" included the addition of a term plus its interaction with community (Appendix D). We assessed how model fit changed with increasing model complexity by calculating and plotting three assessments of model fit for all nested models: residual sums of squares (RSS), log likelihood, and corrected Akaike's Information Criterion (AICc).

2.4. Fuel hazard analysis

To assess the impacts of grazing on the fuel hazard ratings (i.e. surface, near surface, elevated, and overall) we used a Generalized Ordered Logistic Regression (GOLR; See Appendix D). The GOLR was structured such that hazard ratings followed a cumulative distribution, representing a latent continuous measure of hazard with a logistic distribution (Fig. 1), and flexible thresholds among categories (Bürkner and Vuorre, 2019). Again, we assessed the effects of our four measures of grazing and rainfall and their two-way interactions with community. Within the model we tested for category specific effects, generating a coefficient for each model term for each threshold between fuel hazard categories, as we expected disproportionate effects of grazing and rainfall on the chances of a site having specific fuel hazard rating (Bürkner and Vuorre, 2019). Our GLOR models were constructed in R within the Bayesian package 'brms' (Bürkner, 2017). Models were run using four chains each with 20,000 iterations, including 4000 warm up iterations and 50 thins. Chain mixing was visually assessed, and

Fig. 1. Theoretical model of fuel hazard categories from the overall fuel hazard assessment. The ordered categories reflect a continuous underlying increase in hazard. We assumed a logistic distribution (red line) as more sites occur at lower hazard categories. Generalized Ordered Logistic Regression models with category specific effects model the odds around thresholds between each category (grey dashed lines),

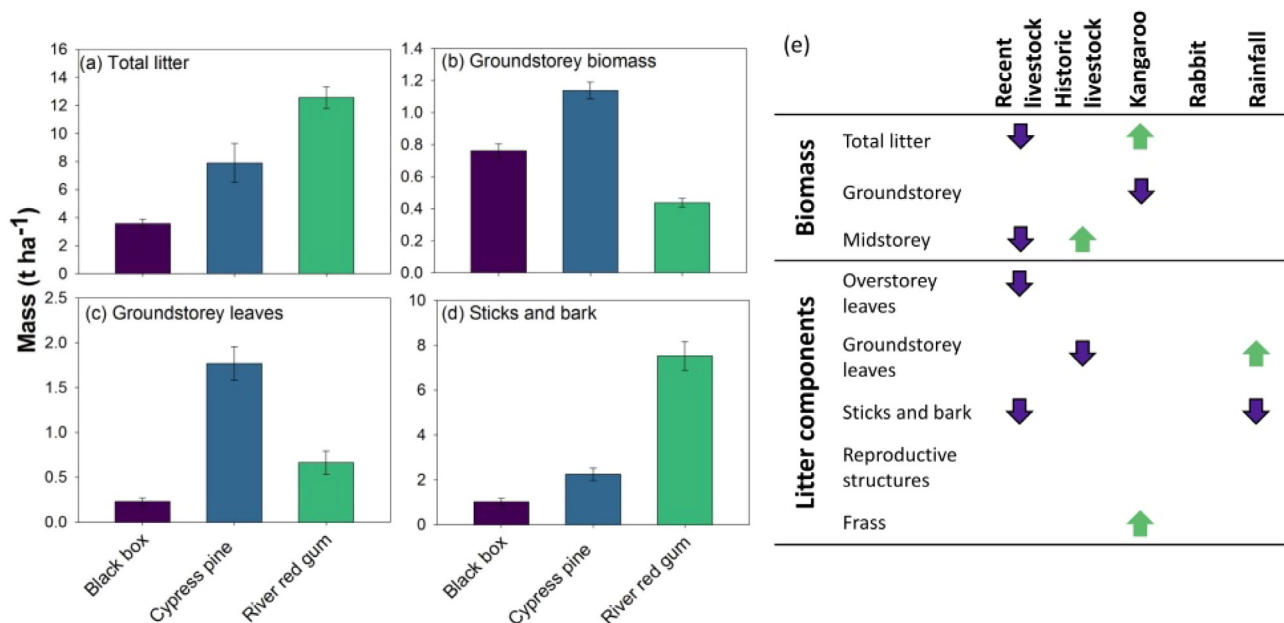


Fig. 2. Summary of significant main effects of community on (a) total litter mass, (b) groundstorey biomass, (c) groundstorey leaves (d) sticks and bark; and (e) significant main effects of grazing and rainfall. Arrows indicate direction of the significant effects. Full results in Appendix E.

significance of each term was assessed using 95% credible intervals.

3. Results

3.1. Community-level effects on biomass and litter components

Our three communities differed significantly in their biomass and litter components for half of our measures. Average litter mass was 3.6-times greater in River red gum and 2.2-times greater in Cypress pine than in Black box ($F_{2,433} = 8.88$; $P < 0.001$, Fig. 2a). Groundstorey biomass in Cypress pine was 1.7-times greater than in Blackbox and 3.1-times greater than in River red gum ($F_{2,433} = 8.18$; $P < 0.001$; Fig. 2b). Groundstorey leaf mass was also highest in Cypress pine ($F_{2,433} = 11.49$; $P < 0.001$, Fig. 2c). The mass of sticks and bark in River red gum was 3.3-times greater than in Cypress pine, and 7.4-times greater than in Black box ($F_{2,433} = 3.21$; $P = 0.041$; Fig. 2d), despite no significant differences overall in midstorey biomass among communities (Tables E.1, E.2).

3.2. Grazing effects on biomass and litter components

Grazing had relatively few significant effects on biomass or litter composition, with only nine significant main effects out of a possible 64 (Fig. 2e). Grazing explained little variance, and rarely improved model fit for most measures of biomass and litter components. Our three assessments of model fit (ΔAICc , ΔRSS , $\Delta\text{Log likelihood}$) showed consistent trends across all measures (Fig. F.1, F.2) and therefore we only present ΔAICc data (Fig. 3).

Recent livestock grazing significantly reduced midstorey biomass, overstorey leaves and sticks and bark ($F_{2,433} \geq 6.81$, $P \leq 0.009$; Fig. 2b), and generally improved model fit for these measures irrespective of model complexity (Fig. 3b, 3c, 3f, F.1, F.2). Recent livestock grazing also significantly reduced total litter mass overall (Fig. 2e) but did not improve model fit, suggesting that it was a poor explanatory measure (Fig. 3a). Reductions in midstorey biomass were restricted to the Cypress pine community ($F_{2,433} = 8.32$, $P < 0.001$ Fig. 4a), but for all other measures the effects of livestock varied little among communities. Despite statistically significant results, the practical implications were negligible for all significant effects. For instance, our models show

that doubling our assessment of recent livestock grazing would reduce litter mass by 0.8%, midstorey biomass by 1%, overstorey leaves by 1.7% and sticks and bark by 0.8% (Tables E.1, E.2).

Historic livestock grazing had mixed effects, increasing midstorey biomass overall ($F_{2,433} = 14.8$, $P < 0.001$; Fig. 2e), most strongly in Cypress pine ($F_{2,433} = 7.8$, $P < 0.001$; Fig. 4b), but reducing groundstorey leaf mass in the litter across all communities ($F_{1,433} = 4.97$; $P = 0.026$; Fig. 2e; Tables E.1, E.2). Increasing historic livestock grazing also strongly reduced overstorey leaves in the litter in the Black box community but increased it in the River red gum community ($F_{2,433} = 5.07$, $P = 0.007$; Fig. 4c). Again, these statistically significant effects equated to negligible practical implications, with our models showing that a doubling of historic livestock grazing leads to a 0.22% increase in midstorey biomass and a 1.7% decline in groundstorey leaves in the litter (Tables E.1, E.2). Including historic livestock grazing in our models significantly improved model fit for midstorey biomass and overstorey leaves, irrespective of model complexity (Fig. 3c, 3d).

We found no overall effect of increased rabbit grazing on any biomass or litter components (Fig. 2e), but rabbit grazing significantly reduced midstorey biomass in the Cypress pine community ($F_{2,433} = 3.18$, $P = 0.042$; Fig. 4d; Table E.1). Including the effects of rabbit grazing and its interaction with community in our models only improved model fit for midstorey biomass (Fig. 3c), but almost all other models had substantially poorer fit when rabbit grazing and its interaction with community was included at any Level of model complexity (i.e. $\Delta\text{AICc} < 0$; Fig. 3).

Across all communities, increasing kangaroo grazing significantly reduced groundstorey biomass but increased total litter mass and frass ($F_{1,433} \geq 4.05$; $P \leq 0.045$; Fig. 2e). However, these significant effects had little practical implication, with a doubling of kangaroo grazing leading to a 4.5% increase in litter, a 2.8% increase in frass and a 0.3% reduction in groundstorey biomass. Except for frass, kangaroo grazing generally did not improve model fit for biomass or litter components (Fig. 3), and its ability to explain deviance in the frass model diminished with increasing model complexity (Fig. 3h).

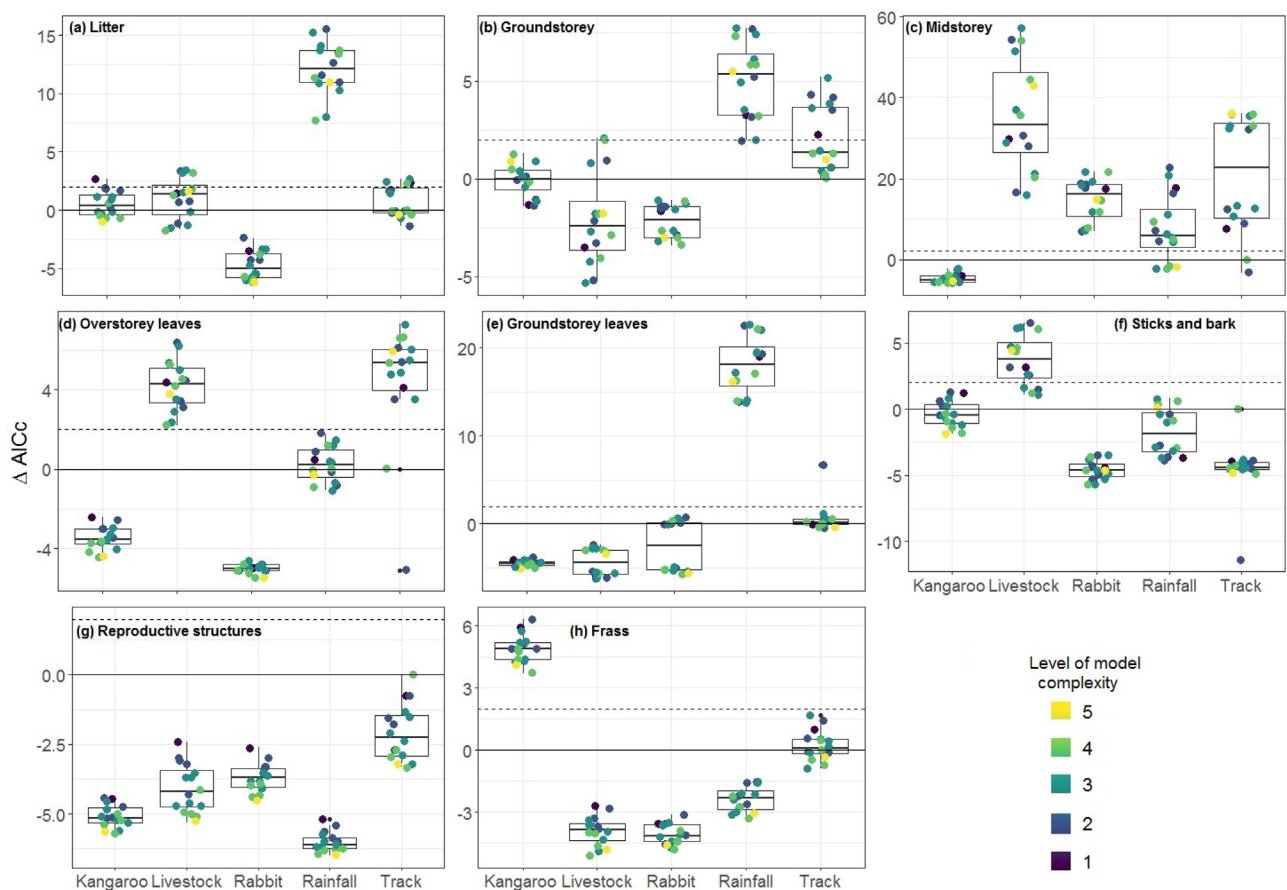


Fig. 3. Changes in corrected Akaike's Information Criterion ($\Delta AICc$) indicate the variance explained by the addition of each model term (x-axis) for (a) litter mass, (b) groundstorey biomass, (c) midstorey biomass, (d) canopy leaves, (e) groundstorey leaves, (f) sticks and bark, (g) seeds and flowers and (h) frass. The y-axis represents a change in model fit $\Delta AICc$, where a model (Model 2) is compared with a nested model which did not include the term (or the term and its interaction with community) on the x-axis (Model 1). We coined $\Delta AICc$ such that an increase in $\Delta AICc$ indicate an increase in model variance explained by the additional term i.e. $\Delta AICc = -1 * (\text{Model } 2_{AICc} - \text{Model } 1_{AICc})$. Coloured points indicate the Level of complexity of the most complex model in each comparison, such that Level 1 is one term and its interaction with community and Level 5 is the full model with all five model terms and each of their interactions with community (see Appendix D). We considered a model term important if it consistently explained substantial model variance (i.e. $\Delta AICc \geq 2$, dashed line) and its explanatory power did not diminish with increasing model complexity (i.e. as happens with all terms in subplot g). Points below zero (solid line), indicate that the model fit was substantially worsened. Note that y-axes vary among plots.

3.3. Effects of rainfall on biomass and litter components

Increasing rainfall altered litter composition across all communities by reducing the mass of sticks and bark and increasing groundstorey leaves ($F_{2,433} \geq 5.08$; $P \leq 0.025$; Fig. 2b). Increasing rainfall led to strong reductions in groundstorey biomass and groundstorey leaf mass in Cypress pine only (Fig. 4e, 4f), and reductions in total litter mass in Cypress pine and River red gum only ($F_{2,433} \geq 5.93$; $P \leq 0.003$; Fig. 4g). Our models show that doubling rainfall would lead to a 9.4% increase in groundstorey leaves and a 2.0% reduction in sticks and bark. Rainfall and its interaction with community significantly improved model fit for the total litter mass, groundstorey biomass and groundstorey leaves (Fig. 3a, 3b, 3e, $F_{1,1}$, $F_{2,2}$) and this did not diminish with increasing model complexity. Rainfall also improved model fit for midstorey biomass, but this diminished as models became more complex.

3.4. Effect of grazing and rainfall on biomass and fuel hazard

Across stratum assessments, more than 51% of sites in each community were of low or moderate hazard rating (Fig. 5), supporting our model assumption of an underlying logistic distribution (Fig. 1). For surface, elevated, and overall fuel hazard, less than 2% of sites were of very high rating and no sites were extreme (Fig. 5a, c, d). For near

surface fuel hazard 18% of sites were rated high or higher, largely due to the River red gum community.

Grazing and rainfall had few effects on fuel hazard ratings with only six significant results (Table G) out of 234 possible effects and no consistent effects across communities. These effects were mostly in River red gum, and mostly corresponded to differences between low and moderate hazard ratings. Greater historic livestock grazing increased the probability of the overall fuel hazard rating being low in the Cypress pine community only ($b = -0.61$; 95%-CI = $[-1.04, -0.04]$, Fig. 6a). However greater historic livestock grazing increased elevated fuel hazard rating in River red gum by increasing the chances of a site having a moderate or higher hazard rating (c.f. low; $b = 0.35$; 95%-CI = $[0.00, 0.69]$, Fig. 6b). Increasing kangaroo grazing reduced surface fuel hazard in River red gum, by increasing the chances of a low hazard rating ($b = -0.55$; 95%-CI = $[-0.09, 0.00]$; Fig. 6c).

Greater rainfall increased surface and near surface fuel hazard in the Red gum community only. It increased the chances of a being rated moderate or higher (c.f. low) for surface fuel loads ($b = 0.61$; 95%-CI = $[0.02, 1.22]$; Fig. 6d). For near surface fuels, rainfall increased the chances of moderate or higher rating (c.f. low; $b = 0.99$; 95%-CI = $[0.32, 1.71]$) and also increased the chances of a high or higher rating compared with a moderate or low rating ($b = 1.05$; 95%-CI = $[0.28, 1.86]$; Fig. 6e).

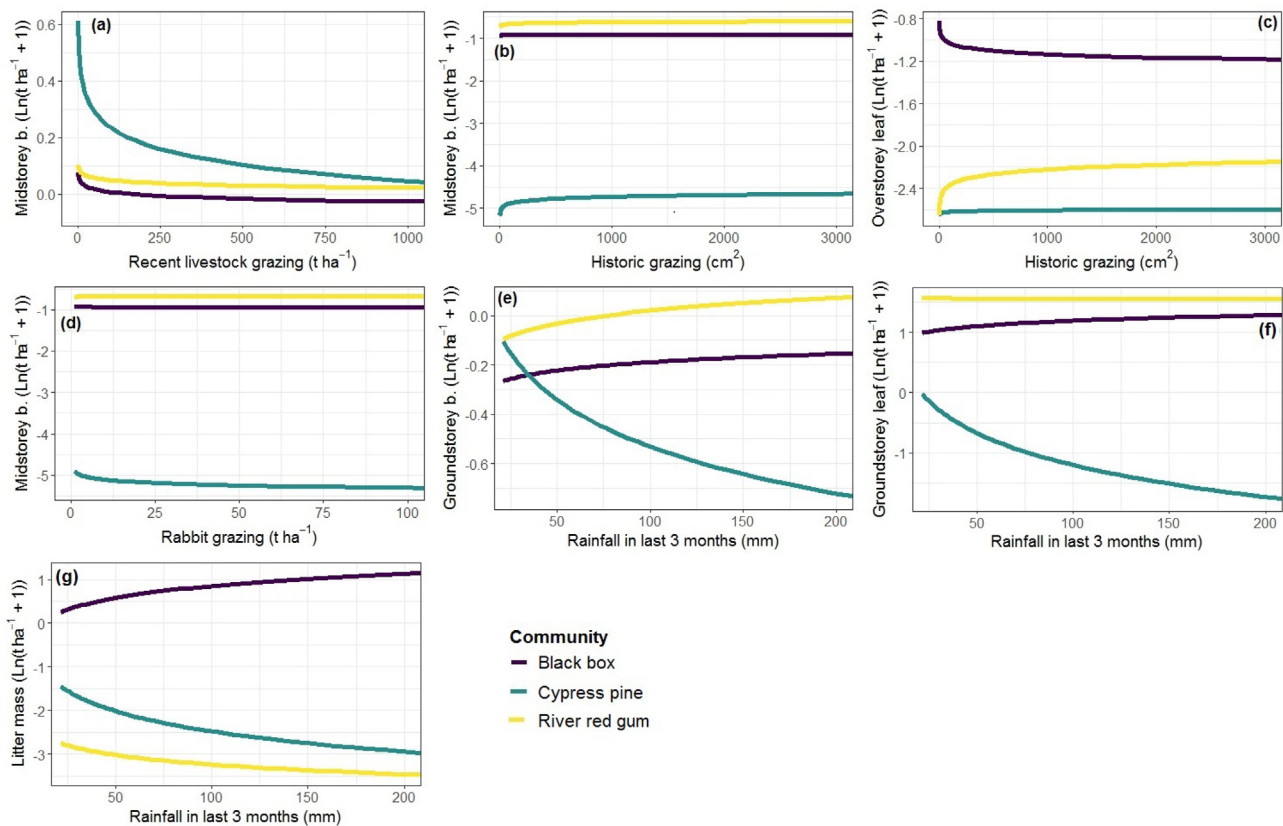


Fig. 4. Significant community by grazing or rainfall interactions for biomass and litter components: (a) recent livestock grazing effects on midstorey biomass; historic livestock grazing effects on (b) midstorey biomass, (c) overstorey leaf mass; (d) rabbit grazing effects on midstorey biomass; and rainfall effects on (e) groundstorey biomass, (f) litter mass and (g) groundstorey leaf mass. b. = biomass. Note axes vary among subplots.

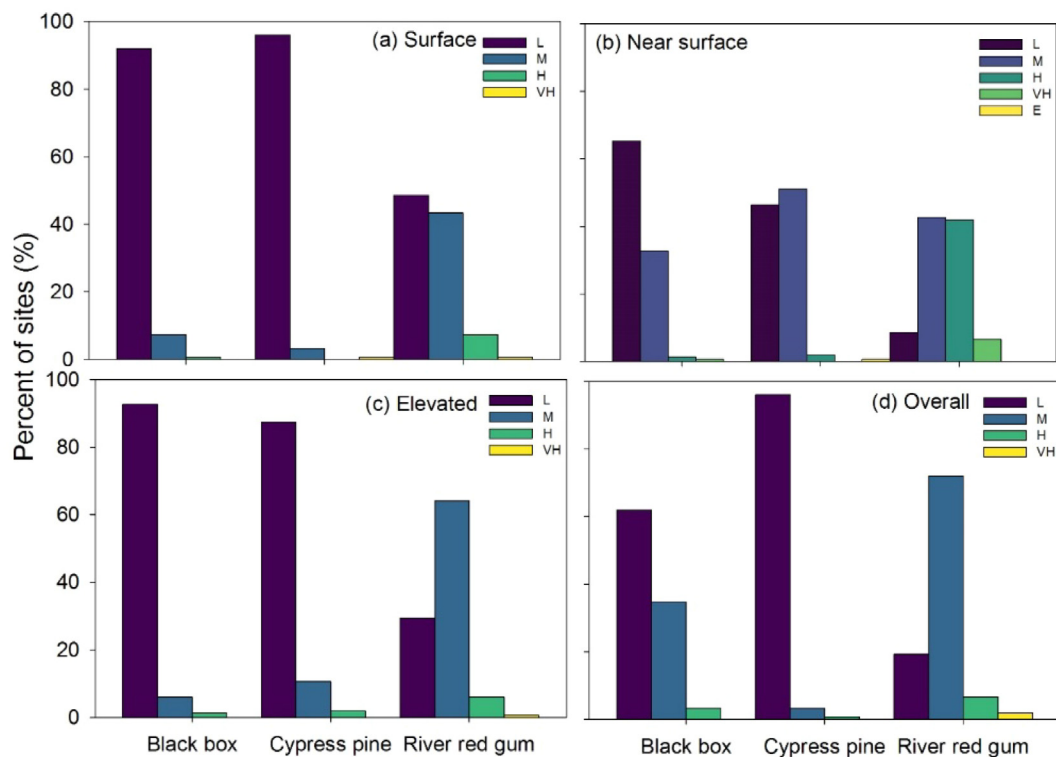


Fig. 5. Percentage of sites from each community in each hazard rating for (a) surface fuel hazard, (b) near surface fuel hazard, (c) elevated fuel hazard, (d) overall fuel hazard. Note near surface hazard rating has an extra hazard rating category. Overall fuel hazard ratings are indicated as follows: L = low, M = moderate, H = high, VH = very high, E = extreme.

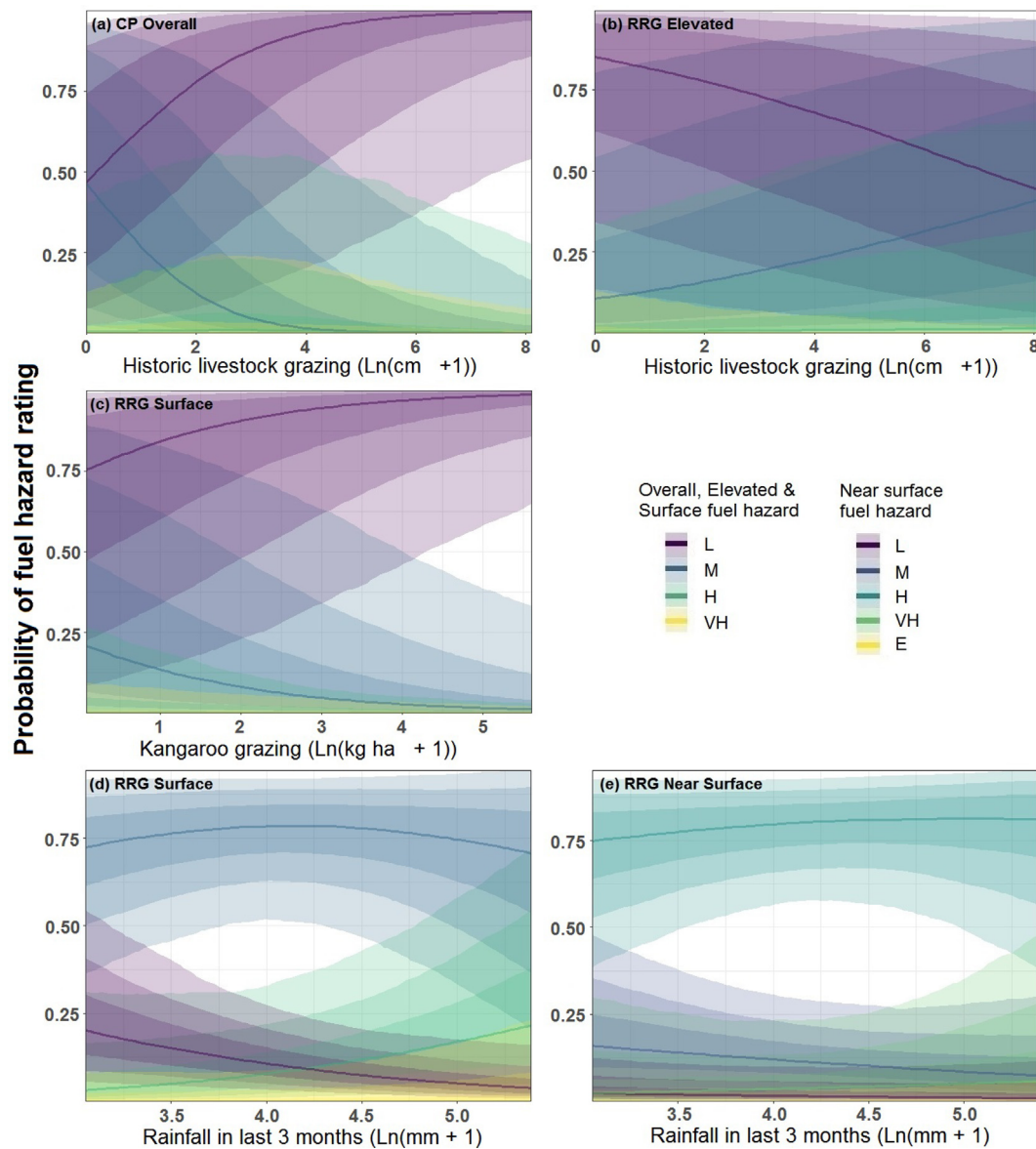


Fig. 6. Summary of significant interactions from the ordinal logistic regression between community and grazing or rainfall for historic livestock grazing effects on (a) overall fuel hazard in Cypress pine (CP) (b) elevated fuel hazard in River red gum (RRG); (c) kangaroo grazing effects on surface fuel hazard in River red gum; Rainfall in the past three months effects on (d) surface fuel hazard and (e) near surface fuel hazard in River red gum. The Y-axis shows the probability of a fuel hazard rating occurring, where L = low, M = moderate, H = high, VH = Very high, E = Extreme. The shading around each line represents the 50% (darkest), 80% and 95% (lightest) credible intervals. Note that Near surface fuel hazard rating has a separate legend to the remaining subplots. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

4. Discussion

Our study showed relatively few significant effects of grazing on biomass and fuel hazard in these semi-arid woodlands, with only 17 significant effects among the 294 cases examined.

However, these few significant results likely have little practical importance. For instance, our model shows that doubling livestock grazing pressure, from 2 to 4 tonnes per hectare of dung, did not reduce fuel hazard but significantly reduced litter mass, by only 0.8%. This is equivalent to a reduction of 8 kg of litter per hectare in landscapes where average litter loads ranged from 3,600 to 12,600 kg per hectare. Where recent grazing significantly reduced fuel hazard, the effects were community specific, and driven only by kangaroos. Furthermore, recent rainfall explained up to an order of magnitude more variability in biomass than grazing, despite being relatively average rainfall conditions for this region, with no extreme dry or wet conditions noted in the

12 months prior to sampling. Management practices that seek to use livestock grazing to reduce biomass in these systems are therefore likely to achieve negligible reductions in biomass and fuel hazard.

Small shifts in biomass did not reduce fuel hazard ratings overall or for any stratum. While our results are inconsistent with the results of studies from North American grasslands (Diamond et al., 2009; Davies et al., 2017) or African heathlands (Johansson and Granström, 2014) where livestock grazing has been used to manage fuel hazards, our data are consistent with several studies from Australia (Henderson and Keith, 2002; Leonard et al., 2010; Williamson et al., 2014) and Mediterranean systems in Spain (Calleja et al., 2019) showing that the effects of European livestock on biomass and subsequent fuel loads and hazard are highly context-dependent. Furthermore, we found livestock had few effects on litter composition. The heaviest recent livestock grazing occurred in areas with few woody plants (Travers et al., 2019), likely explaining the reduction in the mass of overstorey leaves, sticks and

bark by recent livestock grazing. High intensity livestock grazing is also known to have persistent and pervasive negative effects on ecosystem composition and structure by altering soils (Eldridge et al., 2016) vegetation (Prowse et al., 2019) and fire regimes (Hobbs, 1996).

We found no evidence that longer-term (historic) grazing intensity consistently reduces fuel hazard in these communities. Where sites had more intense historic grazing there was greater midstorey biomass, as we expected, supporting previous studies (Travers et al., 2019) and the substantial evidence demonstrating that overgrazing by livestock is a major driver of woody plant encroachment (Eldridge et al., 2011). In the River red gum community this led to significantly higher elevated fuel hazard. However, in Cypress pine, greater historic grazing significantly reduced the overall fuel hazard rating, despite increasing shrub biomass. Here, the reduced hazard likely ensues from altered fuel connectivity or composition, as many components of the biomass are unpalatable to livestock. Drylands dominated by dense shrubs rarely carry large wildfires because of the sparse, poorly connected ground cover (Klinger and Brooks, 2017). Fire behaviour depends heavily on spatial context, therefore the fuel loads in the surrounding areas are particularly relevant (Jenkins et al., 2016). Historic grazing also explained substantial variance in groundstorey and midstorey biomass, and overstorey leaves in the litter, irrespective of whether any or all measures of recent grazing or rainfall were included in our models. These results demonstrate that historic livestock grazing, which is unrelated to current management (Vermiere et al., 2018), affects current biomass and in some instances, fuel hazard. In turn this has severe negative consequences for vegetation, fauna and soil health in these systems (Eldridge et al., 2017; Travers et al., 2018, 2019; Val et al., 2018).

Only kangaroo grazing reduced groundstorey biomass across all communities, and this was likely due to their consumption of palatable grasses. Kangaroos, especially in high densities, are known to reduce the biomass of native vegetation (Prowse et al., 2019). Kangaroos selectively graze by removing the uppermost green foliage from a wide variety of plant species, particularly tussock grasses that contain substantial standing dead biomass, which livestock and rabbits generally avoid (Leonard et al., 2010; Dawson 1989). As kangaroos are unrestricted by fencing, they could potentially manage fuel loads with minimal management intervention (Leonard et al., 2010). Kangaroo grazing significantly reduced fuel hazard associated with surface litter, but only in the River red gum community. Although litter mass increased with greater kangaroo grazing, litter also became comminuted, which inhibits the spread of flames (Scarff and Westoby 2006) and therefore reduces fuel hazard (Hines et al., 2010). Larger litter loads may also be capable of retaining higher moisture, and therefore reducing their fuel hazard (Babl et al., 2019).

We acknowledge that a limitation of this study is that livestock we assessed were not under grazing regimes that aimed to reduce biomass or fuel hazard (Bailey et al., 2019). Given that we found that those sites with high or higher fuel hazard ratings occurred mainly in the River red gum community, where increasing historic livestock grazing increased fuel hazard ratings, intensive livestock grazing is unlikely to be an effective tool for reducing fuel hazard in the long term. Effective targeted grazing would be difficult to implement as plant phenology is understudied and large inter-annual variability in biomass occurs in these systems (Poulter et al., 2014). Our data show that recent rainfall is more likely to affect hazard than effects due to any measure of grazing. Our community-specific effects may mask underlying local environmental factors, such as soil and terrain, that have been found to be important fuel hazard predictors in more mesic areas of south eastern Australia (McCull-Gausden et al., 2019). The seasonality of plant growth and rainfall timing appears to be important, as increasing rainfall did not always lead to greater biomass (e.g. Cypress pine). It is feasible that longer rainfall lags may be important for initiating biomass production.

5. Conclusions

Grazing is used extensively to manage fire risk and there is a large body of research underpinning it (Starns et al., 2019; Bailey et al., 2019). Our study highlights the fact that grazing, when compared with recent rainfall, explains little variance and has minimal practical or ecological effects on biomass and fuel hazard in these semi-arid woodlands. Over longer time frames, livestock grazing has potential to increase fuel hazard, and therefore is likely to be an ineffective tool for managing fuel. Kangaroos were the only herbivores that altered fuel loads to reduce fuel hazard, and this occurred in only one community. Our community-specific fuel hazard results contribute to the growing body of evidence demonstrating the importance of context when applying broad management concepts such as 'grazing reduces blazing' (Leonard et al., 2010; Starns et al., 2019; Bailey et al., 2019). In the face of changing climate and its associated shifts in fire regimes and extreme weather events, alternative approaches to managing fuel hazard are required, particularly those that consider a ecosystems rate of fuel accumulation (Fernandes and Botelho, 2003) and balance both ecological and societal needs (Price and Bradstock, 2012).

Author contributions

This study was designed by DJE, TB, IO, JV, SKT; data were collected by JV, SKT, DJE; statistical analyses were designed by SKT, TB and conducted by ST; the manuscript was first drafted by ST with input from IO, DJE, JV. This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors. Data available from the Dryad Digital Repository <https://datadryad.org/stash/share/nmxwGJV4sUi2ffuyIaRlhY6rHgBrJi7f80Heqw7dYtE> <https://doi.org/10.5061/dryad.xgxd254c9> (Travers et al., 2020).

Acknowledgements

For project management, survey and analysis, we thank Mark Peacock, Ross McDonnell and Sarah Carr (NSW National Parks and Wildlife Service) the Department of Planning, Industry and Environment (DPIE; formerly Office of Environment and Heritage, OEH). The River Red Gum Scientific Advisory Committee for project guidance, and Forest Corporation NSW and landholders for allowing access to field sites. Marta Ruiz-Colmenero, James Glasier and staff from OEH, Umwelt and Ecology Australia collected and or entered field data. Ian Lunt, Peter Vesk and Libby Rumpf advised on data analysis. We particularly thank Sarah Carr and Greg Summerell for championing this research. This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Declaration of Competing Interest

The authors have no competing interests to declare.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.foreco.2020.118165>.

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