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Assessing the Distribution, Density and Ecological Impacts of Feral Deer in Urban and Peri-Urban Areas of Lake Macquarie, New South Wales, Australia

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ABSTRACT

Feral deer are associated with a range of environmental impacts including overgrazing and trampling of native vegetation, increased insolation, ringbarking, creation of wallows, erosion and stream degradation. Consequences of invasive deer impacts can threaten vulnerable ecological communities and have the potential to alter long-term vegetation dynamics if deer populations are left uncontrolled. Studies of feral deer impacts in Australia to date have mostly focused on forested natural areas and agricultural lands; however, deer also pose a threat to the environment and property in urban and peri-urban areas. In this study we investigated the impacts of feral deer (fallow and possibly red deer) in urban and peri-urban habitats using faecal pellet counts and vegetation browsing assessments at 29 sites throughout western Lake Macquarie. Deer were found to have a patchy distribution; however, where present, significant impacts were observed. Browsing impacts were significantly greater in plots containing faecal pellets. There was a significant relationship between the number of faecal pellets detected and browsing intensity. Forested wetland had the highest browse rate of all vegetation types at 35%, with dry sclerophyll at 10% and wet sclerophyll at 20%. This study provides insights into the study of feral deer impacts in urban and peri-urban areas. We provide recommendations for researchers conducting future studies in such habitats to quantify ecological impacts and to overcome access difficulties experienced in this study.

1 | Introduction

Deer have been one of the most successful invasive mammals in Australia since their introduction in the mid-1800s (Bennett and Coulson 2012; Burns et al. 2021; Davis et al. 2016). Deer were deliberately brought into Australia through European settlements and acclimatisation societies for commercial deer farms, landscape aesthetics and hunting sports (Moriaty 2004; Claridge et al. 2016; Kelly et al. 2023). An estimated 29 species or sub-species of deer were imported but only six species were able to naturalise and become invasive (English 2007; Kelly et al. 2023). These six species are chital deer (*Axis axis*), fallow deer (*Dama dama*), hog deer (*Axis porcinus*), rusa deer (*Rusa timorensis*), red deer (*Cervus elephus*) and sambar deer (*Rusa unicolor*) (Strahan 1995).

In the Western Lake Macquarie Region of NSW, Australia, three deer species have been recorded, Fallow deer (*Dama dama*) have been recorded near the localities of Cooranbong, Martinsville and Mandalong in the southwest of the Lake Macquarie Local Government Area (DPI 2022a, 2022b; Deerscan 2023). Sambar (*Cervus unicolour*) and red deer (*Cervus elephus*) have been recorded in the adjoining Cessnock Local Government Area (DPI 2022a, 2022b).

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Implications for Managers

- Feral deer have significant impacts on native vegetation in urban and peri-urban areas.
- Browsing impacts in plots were proportional to faecal pellet counts.
- Monitoring and control of deer in areas with private land tenure may be challenging and require significant public outreach.

Feral deer are associated with a range of environmental impacts and are a Key Threatening Process to biodiversity in NSW (Davis et al. 2016; NSW Scientific Committee 2004) and at a national level under the Environment Protection and Biodiversity Conservation Act 1999 (Coté et al. 2004; Hampton and Davis 2020). Deer impacts include overgrazing and trampling of native vegetation, ringbarking, creation of wallows, erosion and stream degradation (Clarke et al. 2000; NPWS 2002; Keith and Pellow 2025; Chollet et al. 2016; Burns et al. 2021; Comte et al. 2022; Wills et al. 2023). These impacts can result in the degradation of ecosystem productivity, facilitation of weeds, increased resource competition with native species, soil erosion, creating paths in vegetation that increase the movement of introduced carnivores, reduced abundance and species richness of small mammals and the impairment of seed germination and bushfire recovery (Claridge et al. 2016; Davis et al. 2016; Giljohann et al. 2017; Burns et al. 2021; Hampton and Davis 2020; Hartley et al. 2022; Hertzog and Bateman 2021; Gallagher et al. 2022; Kelly et al. 2023). Cumulative impacts include changes to ecosystem function in natural and agricultural ecosystems (Augustine and Decalesta 2003; Coté et al. 2004; Davis et al. 2016) and the extirpation of threatened ecological communities (Chollet et al. 2016; Burns et al. 2021).

Over grazing also elevates the risk of forests fires by increasing insolation (Davis et al. 2016; Cadiz et al. 2020). Deer are attracted to regrowth in burnt areas thus inhibiting regrowth of burnt areas (Forsyth et al. 2012; Hampton and Davis 2020).

In addition to environmental impacts, feral deer also present a threat to public safety and community amenity. Deer are known to browse on garden and street plantings and are a significant source of motor vehicle and rail accidents (Local Land Services 2020; Comte et al. 2022).

Legislation in NSW and Victoria requires land managers to mitigate threats to threatened ecological communities (TECs) and protect vulnerable biodiversity (Claridge et al. 2016; Burns et al. 2021). However, the paucity of research differing invasive herbivory from native herbivory hinders effective management in Australia (Hartley et al. 2022). Early signs of a deer population and their environmental impacts are often difficult to detect due to their cryptic nature, allowing them to remain undetected for prolonged periods (Mark and Baylis 1982; Rackham 2003). Thus, identifying early stages of deer invasion and population density is critical for land managers to mitigate ecological impacts. Deer management in Australia is hindered by the limited number of published datasets available, with many studies (Claridge et al. 2016) and land managers (NFDAP 2023; DPI 2022a, 2022b) relying on anecdotal observations of presence/absence data and insufficient quantitative records. While these observations are important, providing 90% of available data (Claridge et al. 2016), they do not allow for precise monitoring or the development of accurate predictive models.

Studies of deer impacts have predominantly focused on Southern regions of Australia (Giljohann et al. 2017; Ward-Jones et al. 2019; Hartley et al. 2022; Burns et al. 2021; Bennett et al. 2021; Hampton et al. 2022; Comte et al. 2022; Wills et al. 2023). Despite recent investigation of feral deer in peri-urban landscapes (Comte et al. 2022), most studies have focused on forested lands with few insights on peri-urban areas. Regions with detailed studies are concentrated in natural areas of Victoria's Yarra Ranges National Park or Alpine National Park (Bennett et al. 2021; Hampton et al. 2022; Comte et al. 2022; Wills et al. 2023), which are in close proximity to NSW's Kosciuszko National Park studies (Giljohann et al. 2017; Ward-Jones et al. 2019; Hartley et al. 2022; Burns et al. 2021). There is thus a pressing need for more studies of deer impacts to the north of previously studied habitats and in urban and peri-urban areas.

In this study, we investigated the impacts of feral fallow and possibly red deer in urban and peri-urban habitats of western Lake Macquarie, New South Wales, Australia. Fallow deer have been detected in urban and peri-urban areas of the western regions of Lake Macquarie City Council 2015 Local Government Area (LMCC) while red deer have been recorded in parts of Cessnock City Council adjoining the western boundary of LMCC (DPI 2022a, 2022b).

Sightings of deer recorded around Lake Macquarie City (DPI 2022a, 2022b) and information provided by residents suggest a gradual expansion across western LMCC. Despite concern as to impacts on ecology and residential amenity, precise impacts have not previously been determined.

The aims of this project were to:

i. Identify the current distribution of fallow and potentially red deer in Western LMCC.

ii. Understand the relationship between vegetation browsed and pellet presence in proportion to deer density.

2 | Methods

2.1 | Study Area

The study area for this project was the western side of Lake Macquarie City Council in New South Wales, Australia. The city comprises a total area of 648 km^2 (LMCC 2025). The study area was chosen using occurrence records from the Atlas of Living Australia (ALA 2023), the citizen science database DeerScan (2023), State Forest recreational hunting returns (DPI 2022a, 2022b) and sightings reported by LMCC residents.

The average annual rainfall for the Lake Macquarie City region is 1148.6 mm with a monthly mean of 157.6 mm in March and a lowest monthly mean of 58.7 in August. Annual average

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maximum and minimum temperatures are 23.9°C and 11.5°C. The warmest monthly average is 28.6°C in January and coolest is 5.1°C in July (BOM 2026).

2.2 | Site Selection

Preliminary site investigations were conducted throughout June 2023 and July 2023 to determine the accessibility and suitability of 45 potential sites, including LMCC reserves, Landcare sites, State Conservation Areas, State Forests and private landholdings. Preliminary sites were derived from the satellite perspective on google maps. Multiple sites of interest were constrained by inaccessible private land or slopes too steep to traverse. A total of 29 sites (see Supporting Information) were selected for transect surveys (Figure 1). Density and distribution of deer were assessed via faecal pellet indexing (FPI) (Forsyth 2005) and vegetation assessments (Bennett et al. 2021). Method has demonstrated the relationship between faecal pellet counts and deer density to be positive, and approximately linear (Forsyth et al. 2007).

2.3 | Faecal Pellet Indexing

Sampling was conducted at 29 individual sites throughout western Lake Macquarie City. At each site, faecal pellet counts (FPC) were recorded along a linear 150-m transect comprising 30 individual 1-m radius circular plots, separated by 5-m intervals (Forsyth 2005). This transect method has demonstrated the relative relationship between faecal pellet counts and deer density to be positive and approximately linear (Forsyth et al. 2007).

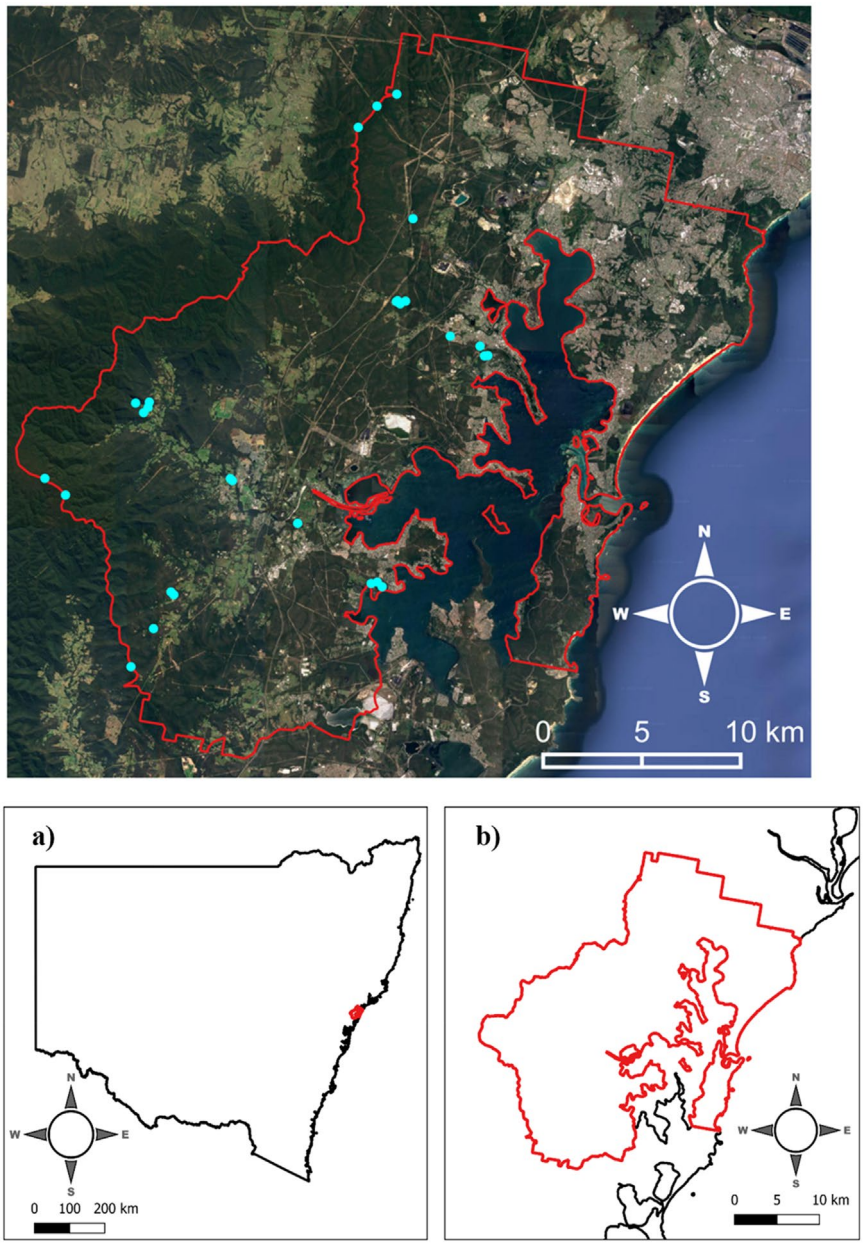


FIGURE 1 | Map of Lake Macquarie City Council (LMCC), New South Wales, Australia. The redline indicates the boundary of LMCC. Blue dots indicate the location of individual sampling transects. Map generated in QGIS (2023).

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Intervals and plots were measured by a string that was exactly 5 m long with knots and flagging tape at 1-m intervals for the radius identification of 1-m and 5-m plots. A surveyor and assistant were on opposite ends of the string, with the surveyor always in front of the assistant to prevent trampling on pellets and only proceeding when the plot was completed (Forsyth 2005). The same surveyor conducted all pellet and plant observations to ensure consistency.

Transects were selected based on the presence of established animal trails and nearby water sources likely to be utilised by deer (Harmsen et al. 2010; Gormley et al. 2011). The date, location, transect number, bearing and site coordinates were recorded prior to the commencement of sampling each transect (Forsyth 2005). Where impassable obstacles (such as bluffs or watercourses) were encountered, 90° was added or subtracted to the bearing in the unobstructed direction, and sampling continued along this new bearing until the obstacle was avoided and the transect was realigned with the original bearing (Forsyth 2005). If a return to the original bearing was not possible, sampling continued along the new bearing until the transect was completed (Forsyth 2005).

2.4 | Vegetation Assessment and Faecal Pellet Counts

Vegetation assessments followed the protocol of Bennett et al. (2021) protocol to simultaneously assess and differentiate deer from sympatric species responsible for foraging within a plot. Sympatric species include wallaby (*Wallabia bicolour*), eastern grey kangaroo (*Macropus giganteus*), red-necked wallaby (*Notamacropus rufogriseus*), common wombat (*Vombatus ursinus*) and European rabbit (*Oryctolagus cuniculus*) (Burns et al. 2021).

In each transect 60 plants were measured with four plants measured at every second plot (i.e., every 10 m) within a 5-m radius, focusing on native forbs, ferns and shrubs (Bennett and Coulson 2012; Bennett et al. 2021). Each 5-m radius plot was divided into, four quadrants were; North-east, South-east, South-west and North-west and browsing impacts assessed using the methods of Bennett et al. (2021) Browsing impacts were classified by a rapid assessment scale of 0–4, observing the percent of defoliation inflicted (Table 1). Further examination of deer faecal pellets and browsing impacts was conducted through an increased transect belt of 20 m, 10 m on both sides of the transect.

Browsing impacts of native sympatric species cannot be easily distinguished from deer if the plant is below 1 m, hence plants were assessed both below 1 m and above 1 m but below 3 m (Bennett et al. 2021). For a plant individual under 1-m to be assessed, it must be greater than 10 cm in height, thinner than 10 cm diameter at breast height (DBH) classified as a young tree or woody shrub (Bennett et al. 2021).

Faecal pellets were assessed in individual plots and overall transects, whereas vegetation impacts were examined according to the browsing presence, intensity and vegetation type. Impacted vegetation types where deer scat was present were identified by a state vegetation type map (SVTM) (NSW OEH 2017) with 5 m^2 cells. SVTM data was spatially extracted along transects (with a 20 m buffer), and vegetation type was selected based on the most prevalent vegetation occurring over the area. Vegetation types were classified into four groups; dry sclerophyll forests (13 transects), wet sclerophyll forests (11 transects), forested wetlands (3 transects) and modified (2 transects), where modified vegetation corresponds to 'not classified' in the SVTM.

TABLE 1 | Rapid assessment scores for categorising deer impact via defoliation and damage on understorey vegetation.

Score	Impact	Description
0	No impact	No damage
1	Low impact	1%–25% foliage browsed
2	Low-moderate impact	25%–50% foliage browsed, stem breakage or rubbing damage
3	Moderate-high impact	51%–75% foliage browsed, multiple stem breakage or severe rubbing damage
4	High impact	76%–100% foliage browsed or extreme rubbing damage

Note: Scores range from 0 to 4, where 0 indicates no impacts and 4 indicates heavily impacted (Bennett et al. 2021).

2.5 | Data Analysis

Using the ordinal records of damage to individual plants, counts of plants showing any level of browsing damage and numbers of pellets were summarised at transect level ($n = 29$). The proportion of plants with browsing damage was then calculated using the total numbers of plants recorded for each transect. This dataset was used to test if the proportions and numbers of plants browsed (1) differed between transects where scats were detected or not (two-level categorical factor), (2) if there was any relationship with the numbers of pellets detected (ln transformed continuous), or (3) if there were differences among vegetation types (four-level categorical factor). For (3), the proportion of plots along each transect where browsing was detected, and the proportion of plots where scats were found was used as a response in two separate models.

For models using a proportion as a response, generalised linear models (GLMs) with a binomial error structure were used, and GLMs with a Poisson error structure for models of counts, with observations weighted for the total abundance of plants per transect. All models were fitted in R (R Core Team 2023). Model effects, 95% confidence intervals, and comparisons between pairwise combinations of levels of categorical factors (vegetation type models) were estimated using emmeans (Lenth 2024), and term significance was assessed using likelihood ratio tests in car (Fox and Weisberg 2019).

3 | Results

A range of browsing and rubbing impacts were observed on transects within the study area.

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Approximately 0.4 plots across all transects (36 of 870) contained faecal pellets (Figure 2a), indicating that 4% of plots contained scats, with deer pellets averaging 10 pellets within those plots (Figure 2b) and that, where present, deer occurred in low density.

In transects where scats were detected, significantly more plants showing browsing were found ($\chi^2 = 16.302$, DF = 1, $p = 0.0001$; Figure 3a), and significantly higher numbers of plants were browsed ($\chi^2 = 13.980$, DF = 1, $p = 0.0002$; Figure 3b). Browsing rates were relatively low at 10% in the absence of pellets with an average of three plants browsed per transect (Figure 3). Conversely, where pellets were present, the browse rate averaged 13 plants and forage activity increased to almost 40% (Figure 3). In three plots with pellet presence, close to 80% of plants or up to 30 individual plants were browsed, while in nine of the 20 transects showing an absence of pellets, no browsing was detected. In contrast, only one of the nine transects with scats detected showed no browsing.

There was a significant relationship between greater numbers of scats being detected and greater proportions of plants showing browsing signs ($\chi^2 = 24.705$, DF = 1, $p = 0.0001$; Figure 4a). This effect was also observed for the number of plants browsed, with more plants showing browsing where more pellets were found ($\chi^2 = 21.410$, DF = 1, $p = 0.0001$; Figure 4b).

Browsing damage was detected in 30% of plots across all transects (browsed and unbrowsed) (Figure 5a). Within browsed transects, an average of 70% of plants per plot were browsed, with many plots displaying browsing rates of 50%–100% of plants (Figure 5b). The average number of plants browsed per plot was under two where browsing was detected within a plot (Figure 5c).

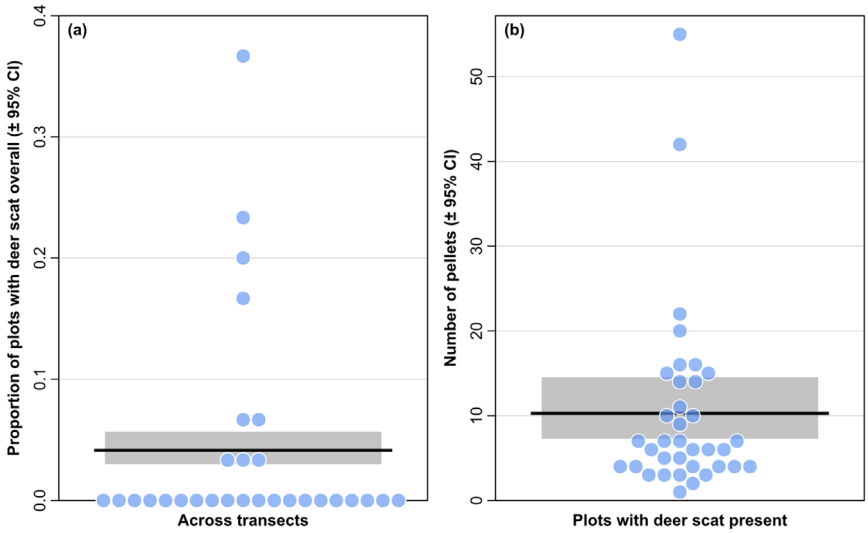


FIGURE 2 | Bee swarm plots of (a) the proportion of plots across all transects with deer scat present, and (b) the mean numbers of pellets where scat was detected. The horizontal black line is the model estimated mean, grey shading the 95% CI, and blue points are observations.

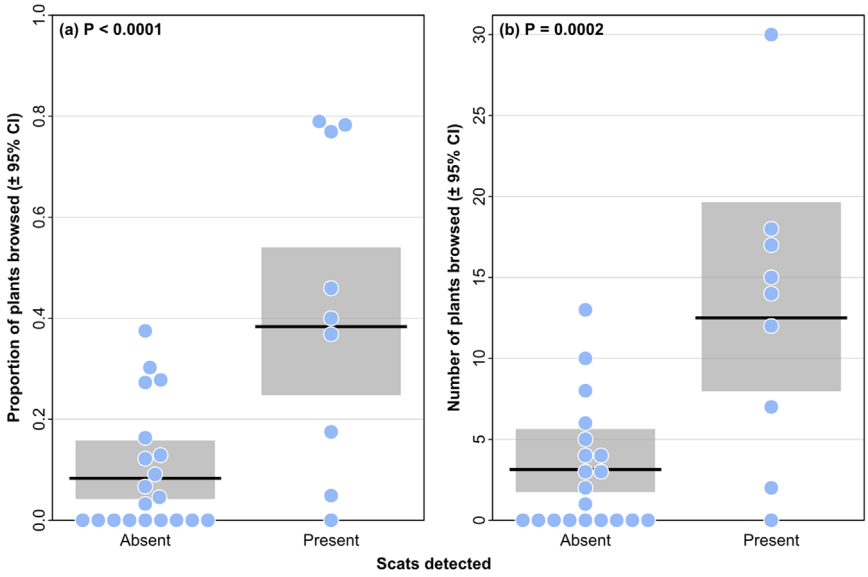


FIGURE 3 | Proportion of plants browsed (a) and/number of plants browsed (b) by transect by deer presence or absence (scat detected vs. not detected). The horizontal black lines are the model estimated means, grey shading the 95% CIs, and blue points are observations. Model *p*-values are shown at top left.

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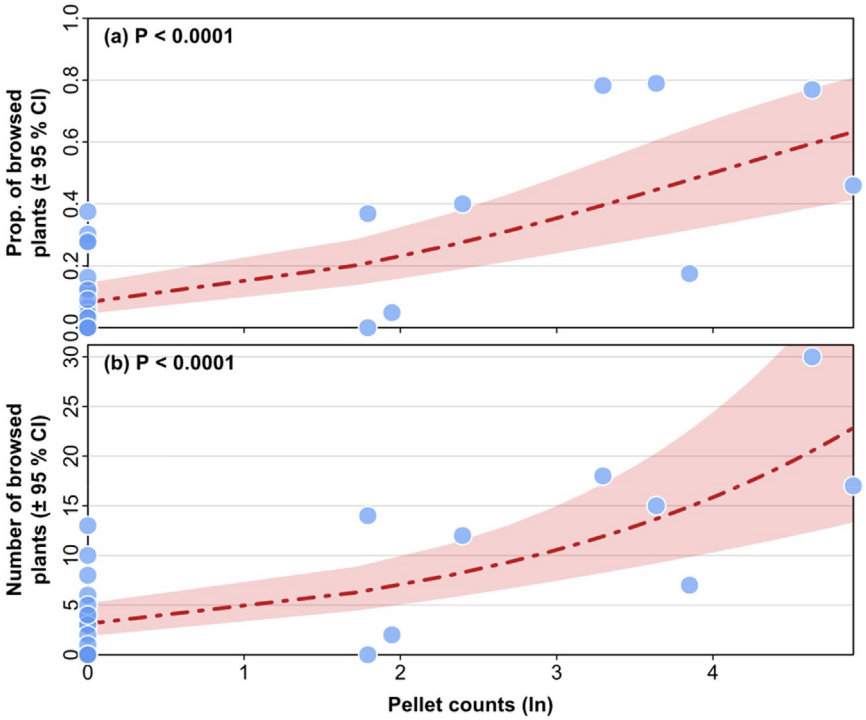


FIGURE 4 | Proportion of browsed plants (a) and number of browsed plants (b) by pellet counts, summed across plots within transects. Blue points are observations, and the broken red line the line of best fit from the models. Model *p*-values are shown at top left. Shaded areas indicate the 95% confidence interval.

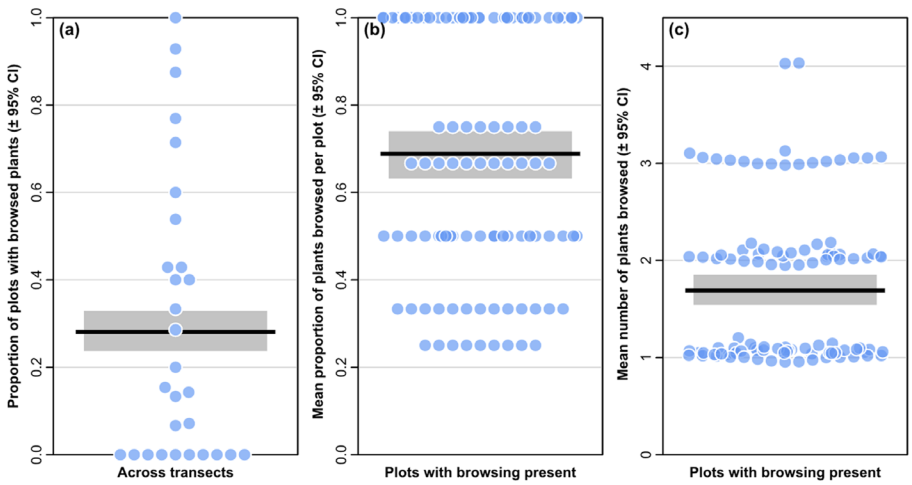


FIGURE 5 | Proportion of plots across all transects ($n = 29$) with browsing detected (a), mean proportion of plants browsed per browsed plot (b) and mean number of plants browsed per browsed plot (c). The horizontal black line is the model estimated mean, grey shading the 95% CI, and blue points are observations.

Deer browsing preferences can be connected to different vegetation types in forests, to understand vegetation with a greater likelihood of being browsed. Among the four vegetation types surveyed, no significant differences were found in the proportion of plots with browsed plants ($\chi^2 = 3.505$, DF = 3, $p = 0.3$; Figure 6a), and though a significant difference in counts of browsed plants ($\chi^2 = 7.882$, DF = 3, $p = 0.049$; Figure 6b). Pairwise tests found Forested Wetlands had significantly higher counts of browsed plants relative to Dry Sclerophyll, while Wet Sclerophyll and the human modified habitat type did not differ significantly among themselves or with Dry Sclerophyll and Forested Wetlands (Figure 6b). No significant differences were found for the proportions of plots with scats detected ($\chi^2 = 3.551$, DF = 3, $p = 0.3$; Figure 7a), or for the counts of scats per transect ($\chi^2 = 2.804$, DF = 3, $p = 0.4$; Figure 7b).

4 | Discussion

The limited number of sites in which faecal pellets were detected indicates that deer have a fragmented and patchy distribution across western Lake Macquarie. Indeed, there was only a 5%

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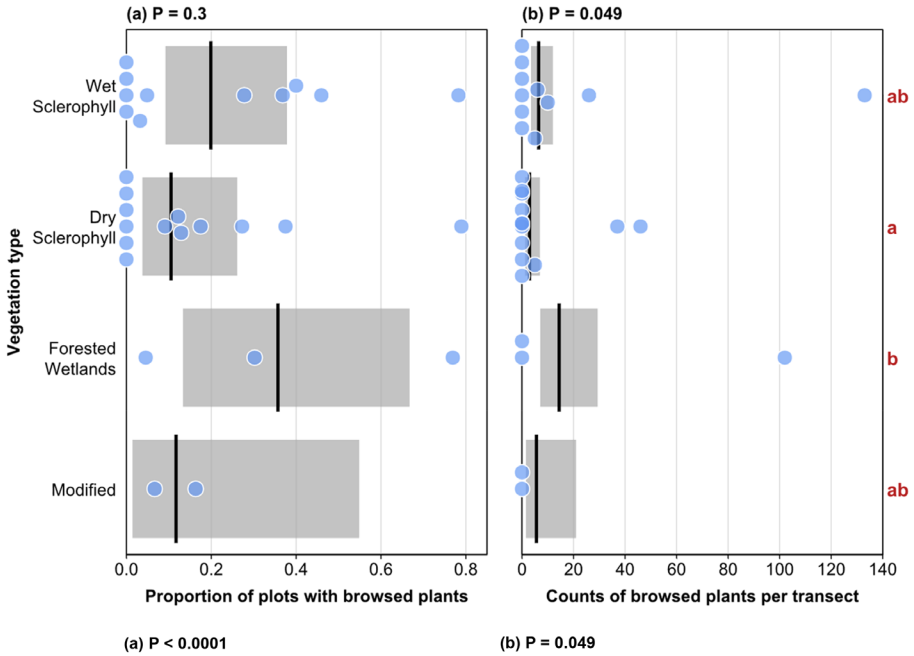


FIGURE 6 | Proportion of plots across all transects with browsed plants (a) and mean count of browsed plants per transect by vegetation type (b). The vertical black lines are the model estimated means, grey shading the 95% CIs and blue points are observations. The *p*-values for the models are shown at top left. Red letters on the right margin of (a) indicate the pattern of significant pairwise differences.

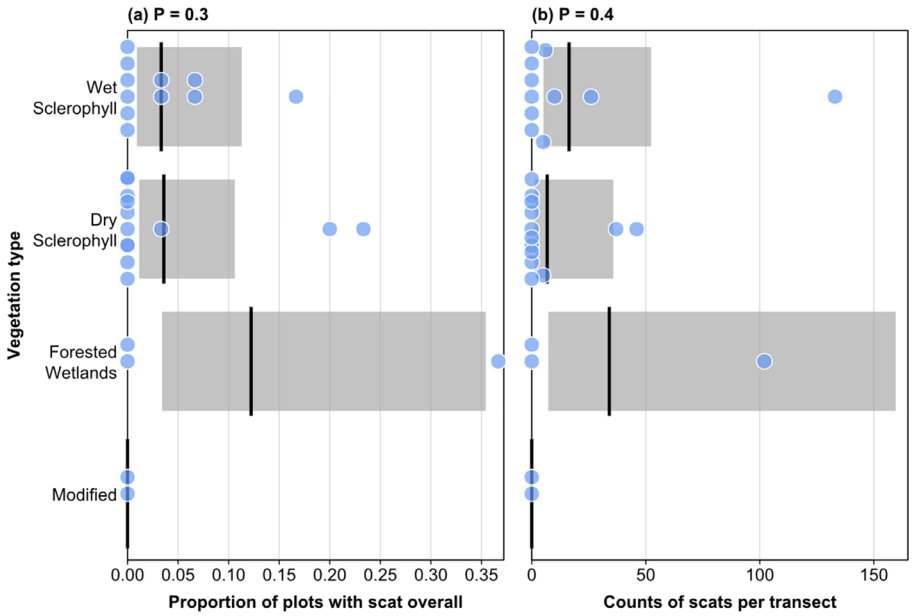


FIGURE 7 | Proportion of plots across all transects with deer scat present (a), and mean count of scats per transect by vegetation type (b). The vertical black lines are the model estimated means, grey shading the 95% CIs and blue points are observations. *p*-values for the models are shown at top left.

chance of detecting deer within the sampled transects (Figure 2). Nevertheless, where deer occur, their impacts are evident through higher levels of browsing and other damage where scats are present, in tandem with a proportional rise in pellet counts (Figures 2–4). Deer impacts were clearly discernible through a higher proportion of plots showing browsing damage above 1 m, closely associated with regions of elevated browsing intensity (Figures 5). This indicates that plants with minimal damage below 1 m are also prone to more severe damage above 1 m.

Based on published records (ALA 2023; Deerscan 2023; DPI 2022a; DPI 2022b) as well as observations and images provided by local residents, we are able to conclude that deer present at sites in the South-west of the study area (Cooranbong, Martinsville and Mandalong localities) are fallow deer (*Dama dama*). We are not, however, able to definitively conclude the species of deer causing impacts detected at North-western sites (Sugarloaf SCA). These may be fallow deer; however, they may also be red deer (*Cervus elaphus*) which are present in parts of

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Cessnock LGA directly adjoining the Sugarloaf SCA (DPI 2023a; DPI 2023b). Further studies utilising camera trapping are required to confirm the species present in Sugarloaf SCA.

Although fallow deer are typically identified as grazers and prefer grassy vegetation, they have versatile diets and can shift in response to seasonal availability (Guy et al. 2024). As noted by Potts et al. (2014), *Dama dama* display broad habitat tolerance but favour forested areas interspersed with grassland. They were also found in arable lands, open grasslands, scrublands and subalpine vegetation (Potts et al. 2014). Additionally, fire disturbed openings undergoing regrowth are exploited by fallow deer, thereby inhibiting vegetation recovery (Forsyth et al. 2012; Hampton and Davis 2020) and potentially influencing vegetation dynamics over time (Potts et al. 2014). Similarly, Cunningham et al. (2022) concluded that a 'sleeper' population of fallow deer in Tasmania experienced rapid population growth as a result of native ground covers being replaced by introduced plant species, which provided a better food source.

Time and resource constraints in this study did not permit detailed study of the precise species of plants browsed by deer. We recommend further studies to provide an accurate picture of the impacts of deer on individual native species. This may provide valuable information to predict the presence and spread of deer in previously unknown areas. For example, the percentage of Wet Sclerophyll Forest is an important predictor of sambar deer distribution in Victoria (Gormley et al. 2011).

Deer in this study displayed a preference toward browsing in forested wetlands, relative to the dry and wet sclerophyll environments where deer pellets were discovered (Figure 7.) This notable discrepancy in browsing behaviour suggests that forested wetlands may offer a larger supply of palatable vegetation compared to their sclerophyll counterparts, thus enticing deer to consume a wider variety of plants. Furthermore, it's evident that deer exhibit a preference for browsing in the understorey (comprised of ferns and shrubs) as opposed to the overstory (trees) where a high proportion of ferns are browsed by deer. This conclusion should be tempered, however, by the limited number of forested wetlands that could be accessed in this study ($n = 3$) Further investigations are required to determine the relative ecological impacts of deer in differing vegetation communities.

The patchy and fragmented distribution of deer in Western Lake Macquarie coupled with significant impacts, where present, has important management implications. It points to the feasibility of implementing control measures in areas with isolated populations before deer become more widely distributed with concomitant spread of ecological impacts. Such measures may include culling and deer fencing to protect sensitive habitats (Nilar et al. 2019).

Whilst this project focussed on Western Lake Macquarie, the findings are applicable to adjoining Local Government Areas and peri-urban habitats generally. Further investigations should be targeted toward quantifying ecological impacts including exclosure studies to differentiate impacts on vegetation between areas accessible and inaccessible to deer (Forsyth et al. 2023; Forsyth 2023).

A key limitation of this study and one that is likely to apply to peri-urban habitats more generally, was the difficulty of gaining access to private landholdings. For example, we were able to access only three forested wetland sites. Future research in peri-urban areas should include a communication strategy targeted at landholders to facilitate access by management authorities to private lands. We also recommend the use of Species Distribution Models (SDMs) to identify likely spread and identify vulnerable ecological communities that may be at risk (Kelly et al. 2023).

Further research is also required to understand deer browsing preferences in peri-urban areas and thus the plant species and ecological communities likely to be at greatest risk. This should include germination of seeds from scats collected in the field (Claridge et al. 2016) and analysis of deer rumen (Forsyth and Davis 2011).

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

References

Atlas of Living Australia. 2023. "Atlas of Living Australia." Accessed 14 March–13 April 2023. https://doi.org/10.26197/5d7f2348165a0.

Augustine, D. J., and D. Decalesta. 2003. "Defining Deer Overabundance and Threats to Forest Communities: From Individual Plants to Landscape Structure." *Écoscience* 10, no. 4: 472–486.

Bennett, A., and G. Coulson. 2012. "The Seedling Ratio Method for Determining Ungulate Impacts on Forest Understoreys: Utility in an Australian Ecosystem." *Ecological Management and Restoration* 13, no. 2: 198–201.

Bennett, A., M. Fedrigo, and J. Greet. 2021. "A Field Method for Rapidly Assessing Deer Density and Impacts in Forested Ecosystems." *Ecological Management & Restoration* 23, no. 1: 81–88.

14428903, 2026, 3, Downloaded from https://onlinelibrary.wiley.com/doi/10.1111/emr.70060 by University Of Technology Sydney, Wiley Online Library on [08/10/2026]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

Bureau of Meteorology. 2026. "Climate Statistics for Australian Locations." Australian Government, Canberra. Accessed 24 March 2026. https://www.bom.gov.au/climate/data.

Burns, H., P. Gibbons, and A. Claridge. 2021. "Quantifying Variations in Browsing Pressure Caused by Feral Deer for a Range of Threatened Ecological Communities and Plant Growth Forms." *Austral Ecology* 46, no. 7: 1156–1169.

Cadiz, G. O., J. G. Cawson, T. D. Penman, A. York, and T. J. Duff. 2020. "Environm Ental Factors Associated With the Abundance of Forest Wiregrass (Tetrarrhena Juncea), a Flammable Understorey Grass in Productive Forests." *Australian Journal of Botany* 68, no. 1: 37–48.

Chollet, S., S. Padié, S. Stockton, S. Allombert, A. J. Gaston, and J. Martin. 2016. "Positive Plant and Bird Diversity Response to Experimental Deer Population Reduction After Decades of Uncontrolled Browsing." *Diversity and Distributions* 22, no. 3: 274–287.

Claridge, A. W., R. Hunt, P. H. Thrall, and D. J. Mills. 2016. "Germination of Native and Introduced Plants From Scats of Fallow Deer (*Dama dama*) and Eastern Grey Kangaroo (*Macropus giganteus*) in a South-Eastern Australian Woodland Landscape." *Ecological Management & Restoration* 17, no. 1: 56–62.

Clarke, G. M., S. Grosse, M. Matthews, et al. 2000. *Environmental Pest Species in Australia*. Department of the Environment and Heritage, Australia: State of the Environment, Second Technical Paper Series No. 2 (Biodiversity), Paper 3, Canberra.

Comte, S., E. Thomas, A. J. Bengsen, et al. 2022. "Seasonal and Daily Activity of Non-Native Sambar Deer in and Around High-Elevation Peatlands, South-Eastern Australia." *Wildlife Research* 49, no. 7: 659–672.

Coté, S. D., T. P. Rooney, J. P. Tremblay, C. Dussault, and D. M. Waller. 2004. "Ecological Impacts of Deer Overabundance." *Annual Review of Ecology, Evolution, and Systematics* 35, no. 1: 113–147.

Cunningham, C. X., G. L. W. Perry, G. J. M. S. Bowman, et al. 2022. "Dynamics and predicted distribution of an irrupting 'sleeper' population: fallow deer in Tasmania." *Biological Invasions* 24: 1131–1147.

Davis, N. E., A. Bennett, D. M. Forsyth, et al. 2016. "A Systematic Review of the Impacts and Management of Introduced Deer (Family Cervidae) in Australia." *Wildlife Research* 43, no. 6: 515–532.

DeerScan. 2023. "Record Deer Activity in DeerScan." Accessed, 14 March–13 April 2023, https://www.feralscan.org.au/deerscan.

Department of Primary Industries. 2022a. "Summary of Species Present in State Forests; January, February, March 2022." NSW Government, pp. 7–8.

Department of Primary Industries. 2022b. "Summary of Species Present in State Forests; April, May, June 2022." NSW Government, pp.7–8.

English, A. W. 2007. "The Status and Management of Wild Deer in Australia." In *Pest or Guest: The Zoology of Overabundance*, edited by D. Lunney, P. Eby, P. Hutchings, and S. Burgin.

Forsyth, D., S. Comte, A. Bengsen, J. Hampton, and T. Pople. 2023. "Glovebox Guide to Managing Feral Deer." PestSmart Publication, The Centre for Invasive Species Solutions, Canberra, ACT. https://pestsmart.org.au/wp-content/uploads/sites/3/2023/10/CISS-Glovebox-Guide-Feral-Deer-final.pdf.

Forsyth, D. M. 2005. "Protocol for Estimating Changes in Abundance of Deer in New Zealand Forests Using the Faecal Pellet Index (FPI)." *Landcare Research Contract Report LC0506/027*. New Zealand Department of Conservation, Wellington, New Zealand.

Forsyth, D. M. 2023. "Using Exclusion Fencing to Manage Feral Deer Impacts in Australia." Produced by the NSW Department of Primary Industries, Orange, for the Centre for Invasive Species Solutions, Canberra, ACT.

Forsyth, D. M., R. J. Barker, G. Morriss, and M. P. Scroggie. 2007. "Modeling the Relationship Between Fecal Pellet Indices and Deer Density." *Journal of Wildlife Management* 71, no. 3: 964–970.

Forsyth, D. M., and N. E. Davis. 2011. "Diets of Non-Native Deer in Australia Estimated by Macroscopic Versus Microhistological Rumen Analysis." *Journal of Wildlife Management* 75, no. 6: 1488–1497.

Forsyth, D. M., A. M. Gormley, L. Woodford, and T. Fitzgerald. 2012. "Effects of Large-Scale High-Severity Fire on Occupancy and Abundances of an Invasive Large Mammal in South-Eastern Australia." *Wildlife Research* 39, no. 7: 555–564.

Fox, J., and S. Weisberg. 2019. *An R Companion to Applied Regression_*. Third ed. Sage.

Gallagher, R. V., S. P. Allen, B. D. E. Mackenzie, et al. 2022. "An Integrated Approach to Assessing Abiotic and Biotic Threats to Post-Fire Plant Species Recovery: Lessons From the 2019–2020 Australian Fire Season." *Global Ecology and Biogeography* 31, no. 10: 2056–2069.

Giljohann, K. M., M. A. McCarthy, D. A. Keith, L. T. Kelly, M. G. Tozer, and T. J. Regan. 2017. "Interactions Between Rainfall, Fire, and Herbivory Drive Resprouter Vital Rates in a Semi-Arid Ecosystem." *Journal of Ecology* 105, no. 6: 1562–1570.

Gormley, A. M., D. M. Forsyth, P. Griffioen, et al. 2011. "Using Presence-Only and Presence–Absence Data to Estimate the Current and Potential Distributions of Established Invasive Species." *Journal of Applied Ecology* 48, no. 1: 25–34.

Guy, T. R., J. B. Kirkpatrick, C. X. Cunningham, et al. 2024. "Diet of Fallow Deer Suggests Potential for Invasion of Novel Habitats in Tasmania." *Wildlife Research* 51, no. 2: WR23124.

Hampton, J. O., A. J. Bengsen, A. Pople, M. Brennan, M. Leeson, and D. M. Forsyth. 2022. "Animal Welfare Outcomes of Helicopter-Based Shooting of Deer in Australia." *Wildlife Research* 49, no. 3: 264–273.

Hampton, J. O., and N. E. Davis. 2020. "Impacts of Introduced Deer in Victoria." *Victorian Naturalist* 137, no. 6: 276–281.

Harmsen, B. J., R. J. Foster, S. Silver, L. Ostro, and C. P. Doncaster. 2010. "Differential Use of Trails by Forest Mammals and the Implications for Camera-Trap Studies: A Case Study From Belize." *Biotropica* 42, no. 1: 126–133.

Hartley, R., W. Blanchard, M. Schroder, D. B. Lindenmayer, C. Sato, and B. C. Scheele. 2022. "Exotic Herbivores Dominate Australian High-Elevation Grasslands." *Conservation Science and Practice* 4, no. 2: e601.

Hertzog, C. J., and H. L. Bateman. 2021. "Using Trail Cameras to Document Meso and Large Mammal Use of Native and Nonnative Riparian Forest Types in Southeastern Arizona." *Western North American Naturalist* 81, no. 1: 71–86.

Keith, D., and B. J. Pellow. 2025. "Effects of Javan Rusa Deer (*Cervus timorensis*) on Native Plant Species in the Jibbon-Bundeena Area, Royal National Park, New South Wales." *Linnean Society of New South Wales* 126: 99–110.

Kelly, C. L., I. J. Gordon, L. Schwarzkopf, A. Pintor, A. Pople, and B. T. Hirsch. 2023. "Invasive Wild Deer Exhibit Environmental Niche Shifts in Australia: Where to From Here?" *Ecology and Evolution* 13, no. 7: e10251.

Lake Macquarie City Council (LMCC). 2015 2014-2015. "State of the Environment Report." LMCC.

Lenth, R. 2024. "emmeans: Estimated Marginal Means, Aka Least-Squares Means." R package version 1.10.0, https://CRAN.R-project.org/package=emmeans.

Local Land Services. 2020. "South East Regional Strategic Pest Animal Plan 2nd Version." LLS.

14428903, 2026, 3, Downloaded from https://onlinelibrary.wiley.com/doi/10.1111/emr.70060 by University Of Technology Sydney, Wiley Online Library on [08/10/2026]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

Mark, A. F., and G. T. F. Baylis. 1982. "Further Studies on the Impact of Deer on Secretary Island, Fiordland, New Zealand." *New Zealand Journal of Zoology* 5: 65–75.

Moriaty, A. 2004. "The Liberation, Distribution, Abundance, and Management of Wild Deer in Australia." *Wildlife Research* 31, no. 3: 291–299.

National Feral Deer Action Plan. 2023. "National Feral Deer Action Plan 2022-2027, Draft for Consultation." Government of South Australia, pp. 4–40.

Nilar, H., K. Moute, J. Dawson, R. Scarborough, J. Hudson, and B. Gooden. 2019. "Effectiveness of Different Herbivore Exclusion Strategies for Restoration of an Endangered Rainforest Community." *Forest Ecology and Management* 435, no. 1: 18–26.

NPWS. 2002. *Deer Management Plan for Royal National Park and NPWS Reserves in the Sydney South Region*. NPWS and the Royal National Deer Working Group.

NSW Office of Environment and Heritage. 2017. *The NSW State Vegetation Type Map: Methodology for a Regional Scale Map of NSW Plant Community Types*. NSW Office of Environment and Heritage.

NSW Scientific Committee. 2004. *Herbivory and Environmental Damage Caused by Feral Deer – Key Threatening Process Determination*. NSW Government.

Potts, J. M., N. J. Beeton, D. M. J. S. Bowman, G. J. Williamson, E. C. Lefroy, and C. N. Johnson. 2014. "Predicting the Future Range and Abundance of Fallow Deer in Tasmania, Australia." *Wildlife Research* 41, no. 8: 633–640.

QGIS Development Team. 2023. "QGIS Geographic Information System." Open Source. *Geospatial Foundation Project*. http://qgis.osgeo.org.

R Core Team. 2023. "R: A Language and Environment for Statistical Computing." R Foundation for Statistical Computing, Vienna, Austria. https://www.R-project.org/.

Rackham, O. 2003. *Ancient Woodland. Its History, Vegetation and Uses in England*. 2nd ed. Castlepoint Press.

Strahan, R., ed. 1995. *The Mammals of Australia*. Australian Museum and Reed Books.

Ward-Jones, J., I. Pulsford, R. Thackway, D. Bishwokarma, and D. Freudenberger. 2019. "Impacts of Feral Horses and Deer on an Endangered Woodland of Kosciuszko National Park." *Ecological Management & Restoration* 20, no. 1: 37–46.

Wills, T. J., R. W. Retallick, J. Greet, and A. Bennett. 2023. "Browsing by Non-Native Invasive Sambar Deer Dramatically Impacts Forest Structure." *Forest Ecology and Management* 543: 121153.

Supporting Information

Additional supporting information can be found online in the Supporting Information section. **Data S1:** Supporting Information

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