# KANGAROOS AND CONSERVATION

## ASSESSING THE EFFECTS OF KANGAROO GRAZING IN LOWLAND GRASSY ECOSYSTEMS

MARCH 2018

**Melissa Snape, Peter Caley, Greg Baines and Don Fletcher**

Conservation Research

Technical Report

ISBN 978-1-921117-58-9

Published by the Environment, Planning and Sustainable Development Directorate, ACT Government

Visit the EPSDD Website

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**This publication should be cited as:**

Snape M, Caley P, Baines G, Fletcher D (2018). Kangaroos and Conservation: Assessing the effects of kangaroo grazing in lowland grassy ecosystems. Environment, Planning and Sustainable Development Directorate, ACT Government, Canberra.

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Front cover (left to right): Common Dunnart discovered during reptile surveys with young in the pouch (K Nash), staff measuring pasture structure at the quadrat scale, and a Spotted-back Skink (M Snape).

**Technical Report**

# Kangaroos and Conservation:

# Assessing the effects of kangaroo grazing in lowland grassy ecosystems


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Conservation Research

Environment Division

Environment, Planning and Sustainable Development Directorate

March 2018

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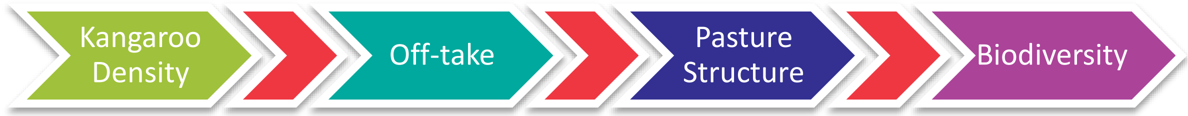
# EXECUTIVE SUMMARY

Eastern Grey Kangaroos are managed in the ACT to protect natural values within the conservation estate. The policy for kangaroo management and reference to the relevant scientific literature can be found in the ACT Kangaroo Management Plan (ACT Government, 2010) and more recent Eastern Grey Kangaroo: Controlled Native Species Management Plan (ACT Government, 2017b). A summary of the most recent scientific literature can also be found at the EPSDD Website by searching for 'kangaroo research'. This report presents a study that involved a detailed assessment of the relationships between kangaroo density, pasture off-take (i.e. grazing pressure), grassy layer structure and measures of biodiversity, with the aim to improve kangaroo management decisions. The ecological relationships investigated can be summarised as:




The red arrows indicate the stages of statistical analysis undertaken to describe relationships between different ecological processes. Data were collected according to a stratified design across a range of sites and kangaroo densities.

Under the 'average' rainfall conditions experienced between 2012 and 2015, this study showed that

- Pasture growth rates were a strong driver of off-take by kangaroos
- Off-take decreased markedly under high herbage mass conditions
- Off-take increased with kangaroo density where common native grasses dominated
- Grass association (i.e. the dominant grass species) and canopy cover class (grassland or open woodland) were key drivers of pasture structure (average grass height, grass height variability and proportion of bare ground)
- Off-take was not related to measures of spring pasture structure at the one hectare scale
- Reptile abundance (the number of individual reptiles per unit area) increased with average grass height and was higher in open woodland than grassland plots
- Reptile diversity (the number of reptile species adjusted for rarity) increased with the proportion of bare ground and was also higher in open woodland than grassland plots
- Floristic richness (the number of vascular plant species) increased with grass height variability, and differed between grass associations and canopy cover classes.
- Floristic value score was negatively related to average grass height and differed between grass associations.
- Non-grass habitat features (e.g. logs, rocks, litter and shrubs) interacted with grass structure to significantly affect biodiversity.

The results of this study will allow the future development of a statistical model to better predict appropriate kangaroo densities for individual sites. Such predictions would need to consider long range weather forecasts (and thus predict pasture growth), current pasture condition and reserve-specific management objectives. The importance of differences between grass associations in terms of habitat function and management responses across the broader landscape is a key result of this study. Given the small size and isolated nature of habitat fragments within Canberra Nature Park, future management of these threatened grassy ecosystems should consider such local characteristics.

# ACKNOWLEDGMENTS

We thank the many casual employees, contractors and volunteers who contributed to this research on kangaroos. For personal security reasons it has become policy not to name individuals involved with kangaroo policy, research or management. If you are such a person, please know that your efforts and support are very much appreciated and it has been a pleasure working with you all. We would also like to thank both internal and external reviewers for providing comments on an earlier draft of this document.

# GLOSSARY

Average grass height: The mean measured height of grass blades within a quadrat, e.g. if half of the measured area has grass 4 cm tall, and half of the area has no grass, the average grass height will be 2 cm. Height measures exclude flowering stems. At the plot scale, average grass height is the mean of grass heights measured from 15 individual 1 $m^2$ quadrats. Used to reflect the 'amount' of grass in a sampling unit.

Bare ground: Bare ground in this study is defined as areas where soil can be directly observed. That covered by litter, lichen, overhanging grass or which is made up of rock does not constitute bare ground. See also 'Proportion of bare ground'.

Biodiversity: The variety of plant and animal life present in a particular ecosystem. Maximisation of biodiversity particularly that of native species, is a common aspiration for conservation land management.

Canopy cover class: The plot level strata based on canopy cover, classified as either 'Grassland' or 'Open Woodland'. See also definitions for these terms.

Climate: The combined influences of local temperature, rainfall, humidity and other meteorological variables which can influence parameters such as thermoregulation of animals and plant growth rates.

Ecology: The study of how organisms interact with their environment (including others of their species) and how this determines their abundance and distribution across environmental gradients.

Floristic value score (FVS): A condition score for Natural Temperate Grasslands which considers native species richness and abundance with an additional weighting for 'rare' native species.

Grassland: Environments characterised as having less than 2% tree canopy cover.

Grass association: The quadrat or plot level strata defined based on the most dominant grass species (by dry herbage mass) in the sampling unit. Six grass associations were defined for this study (see Table 1).

Grass height variability: The coefficient of variation from 15 individual measurements of average grass height sampled from across a plot; calculated as the mean divided by the standard deviation and expressed as a proportion. Used to reflect the structural variability in grass heights across a sampling unit.

Grazing pressure: A term used to describe the amount of pasture being removed by herbivores (see also 'off-take').

Heterogeneity: A term used to describe habitat variability. A heterogeneous grass structure, for example, might include a mixture of long and short grasses with both tussock and prostrate growth forms, and include variable inter-tussock spaces or patches or bare ground. Consideration of scale (e.g. whether a given level of variability is observed across a 1 $m^2$ quadrat or a 100 ha site) is a critical in describing heterogeneity.

Herbage mass: The above ground component of pasture, including both living and (attached) dead parts of plants.

Kangaroo density: The counted number of kangaroos per unit area, e.g. if 340 kangaroos were detected in a 100 ha site, the density of kangaroos would be said to be 3.4 per hectare.

Floristic richness: The number of vascular plant species detected within a sampling unit, e.g. if 75 plant species are observed on a plot, the plot is said to have a total floristic richness of 75. This measure is also reported for *native* and *exotic* plants separately. Unlike 'diversity', this measure is not corrected for rarity.

Off-take: The rate at which pasture is removed by herbivores, measured as the amount removed per unit area per day (dry kg/ha/day). Off-take is measured by comparing the amount of pasture remaining in caged *versus* uncaged quadrats after a period of six months.

Open woodland: Environments characterised as having between 2% and 20% tree canopy cover.

Pasture: Ground layer vegetation, in this study exclusively that of grass species, which is potentially or actually subject to grazing by herbivores.

Pasture growth: The rate of herbage mass accumulation (dry kg/ha/day) in the absence of herbivory. Measured by comparing the herbage mass in quadrats before and after they are caged against herbivory for a period of ~6 months.

Pasture structure: A term used to describe the combined influences of specific elements on overall ground layer habitat composition. In this research, the specific elements of 'pasture structure' which are considered include *average grass height*, *grass height variability,* and the *proportion of bare ground*. The presence of logs, rocks, shrubs and litter are also considered for some analyses. When considered together, these individual elements assist in describing 'pasture structure'.

Proportion of bare ground: The proportion of the ground which fits the description of 'bare ground' (see above). Where the proportion is 1 all of the ground is considered to be bare.

Reptile abundance: A count of the number of individual reptiles present, e.g. if 34 reptiles were detected in the plot, the reptile abundance for the plot was 34. Multiple captures of the same species of reptile under the same tile on successive visits were considered to be the same animal. A tile was recorded as having captured two or more individuals of a given species only if they were observed simultaneously within a single visit.

Reptile diversity: Diversity is used to describe the number of different species detected, with some adjustment for the frequency with which each is observed such that areas which contain 1 rare and 3 common species are given a higher diversity index than those with 4 common species. Shannon's diversity index is used in this report for reptiles.

Standing crop: This term is used to describe the average *herbage mass* measured in the uncaged quadrats, based on that measured at the start and at the end of the six month sampling period. It aims to represents the average herbage mass which was available to herbivores throughout the period for which *off-take* was measured.

Stratification: The breaking up of sampling effort into *strata* to improve accuracy and precision of estimates. The inherent variability between measurements *within* strata is likely to be less than that detected *between* strata. For example, ten measures of herbage mass all taken within a grassland might be more similar to one another compared with ten measures taken from a mix of grassland and open woodland environments. Stratification (here based on two strata reflecting 'canopy cover' and six strata reflecting 'grass association') reduces the background 'noise' in data allowing more accurate predictions to be made without an increase in sampling effort.

*NB. Terms coloured blue refer to measured variables or strata used in the experimental design.*

# INTRODUCTION

## GRASSY ECOSYSTEM CONSERVATION

Natural Temperate Grassland (NTG) and Yellow Box/Red Gum Grassy Woodland (YBRG-GW) ecosystems are listed nationally as endangered ecological communities, having been reduced to less than 5% of their original distribution across south-eastern Australia (ACT Government, 2004, 2005; Yates and Hobbs, 2000). The ACT represents a stronghold in the protection of NTG and YBRG-GW ecosystems, with a number of conservation reserves having been established within the lowland urban matrix (Figure 1). The protective management of these ecosystems, and the native species within, remains a priority for the ACT Government in the face of an increased human population and the continuing spread of urban development. Local universities, ParkCare groups and other not-for-profit organisations also play significant roles in the management, study and restoration of these important communities (Shorthouse et al., 2012).

Like any ecosystem, a suite of microbial, fungal, plant and animal functional groups are critical to maintaining the health of lowland grassy ecosystems (Prober and Thiele, 2005). Historically, herbage mass in these ecosystems was managed by a combination of indigenous fire regimes and grazing, predominantly by macropods (Lunt, 1991). Soil turnover, resulting from diggings by bettongs, bandicoots, echidnas and other fauna, would have spread fungal spores, improved soil structure and encouraged plant germination and invertebrate and microbial activity (McIntyre et al., 2004; Shorthouse et al., 2012). Herbivore abundance was probably limited historically by the ebb and flow of climate-dependent landscape productivity (i.e. food resources), as well as predation by dingoes, quolls, monitor lizards, pythons, birds of prey and humans (Glen and Dickman, 2014).

Nowadays, much of the original native fauna of the region are in serious decline or have become extinct as a result of a loss of habitat and the introduction of foxes and cats (Glen and Dickman, 2014; Short and Smith, 1994). Floristic values are similarly threatened by a change in soil composition (including the addition of agricultural fertilisers), competition with weeds, and increased grazing pressure by large native or introduced herbivores (Dorrough et al., 2012; McIntyre et al., 2010). Changes in nutrient cycling, the flow of water throughout the landscape and the microbial and fungal components of the ecosystem are also both contributors to, and effects of, changes to local flora and fauna ecology (Bennett et al., 2009; McIntyre et al., 2004).

## DRIVERS OF GRASSY ECOSYSTEM FUNCTION

It is widely accepted that flora and fauna dependent on the grassy ground layer vegetation (hereafter ‘pasture’) are strongly influenced by pasture structure (e.g. Dorrough et al., 2012; James, 2003; McIntyre et al., 2010). Heterogeneity of pasture structure, and the subsequent provision of a multitude of microhabitat conditions, is an aspiration of conservation land managers (e.g. ACT Government, 2017a) where a variable pasture structure is assumed to better meet the needs of a range of flora and fauna in regards to the provision of shelter and appropriate food resources (Prober and Thiele, 2005). Attaining a variable pasture structure is dependent on a large number of environmental and climatic factors (Schultz et al., 2011), not all of which can be measured within the scope of a single project. An expansive literature exists on ecosystem function in grassy communities (see review by Bennett et al., 2009), which combined with the use of surrogate measurements, can help untangle the many interacting environmental variables which contribute to ecosystem wellbeing.

Figure 1 Many of Canberra's remnant threatened lowland grassy ecosystems are protected within the urban matrix as part of Canberra Nature Park. High speed roads, suburb edges and other anthropomorphic features provide isolating barriers from adjacent reserves for a range of plant and animal species.


Weather is the main factor determining pasture productivity (and thus herbage mass) in grassy ecosystems. Temperature, rainfall and the relative timing of these two climatic variables have a strong influence in pasture growth models, in both dry (Bayliss and Choquenot, 2003; Caughley, 1987; Owen-Smith, 2002) and temperate (Clark et al., 2000; Cullen et al., 2008; Fletcher, 2006) environments. The rate of pasture growth is additionally influenced by soil characteristics (Cullen et al., 2008), which in itself can be dependent on a range of ecological and anthropogenic processes; and by the composition, cover and condition of existing pasture (Brougham, 1956). The density of over-storey (i.e. woody) canopy cover, which can vary ten-fold between areas classified as grasslands (< 2%) and grassy woodlands (2 – 20%) will

also affect pasture productivity, pasture structure, and the related flora and fauna species assemblages (Dorrough et al., 2012; Schultz et al., 2011; Figure 2).

Figure 2 Canopy cover can impact on pasture productivity and structure. This image illustrates the structural complexity of wooded areas (logs, litter, shade and patchy grass) compared to the more homogeneous grassland structure beyond.

Grass species typical of the ACT's grassy ecosystems (both native and exotic) possess a variety of growth forms, ranging from small clumped tussocks (< 4 cm; e.g. *Rytidosperma carphoides*) to larger arching tussocks over a meter high (e.g. *Rytidosperma pallidum*); and from prostrate grasses which grow low along the ground (e.g. *Bothriochloa macra*) to those which form larger, more dense swards *(e.g. Themeda triandra*; Eddy et al., 1998; Figure 3). Assuming similar effects of any given management tool on each of these different associations would likely be a vast oversimplification of grassy ecosystem functional diversity (Lunt, 1995). Grasses which tolerate shallow or nutrient poor soils (e.g. *Rytidosperma* spp.) are often associated with inter-tussock bare ground or a low density of similarly resilient native forbs (ACT Government, 2005; McIntyre et al., 2010), and require little disturbance to maintain a diverse structure and species assemblage (Lunt, 1995). Particularly high nutrient levels in soil, for example as a result of carcass decomposition (Barton et al., 2016) or a historic use of fertilisers (McIntyre et al., 2010), may result in patches of bare ground amongst nutrient intolerant native flora or else a localised sward of nutrient-loving exotic species. The structure of the latter can require significant management intervention to disrupt; especially where it occurs in association with highly productive soil or beneficial climatic conditions (Bakker et al., 2006).

The growth form of some grass species can also vary with season and in response to different levels of grazing pressure (Milchunas et al., 1988). Such intrinsic effects should be accounted for in a research design through stratification, such that statistical modelling of ecosystem processes can take into consideration the similarities within and differences between different grass associations, canopy cover and seasons (Schultz et al., 2011). The short-term effects of grazing on the occurrence and structure of an

association at a given time of year will also depend on the relative availability of alternative food resources within the landscape (Halpern and Underwood, 2006). This latter effect is difficult to account for without detailed maps of the relative distribution of grass associations across the landscape, which can change temporally with varying climatic conditions and which are not currently available for all ACT lowlands.

Figure 3 Grass association has a pronounced effect on small and large scale ground layer structure. This image shows the ecotone between a *Themeda/Bothriochloa* grass association on the left, and a *Rytidosperma/Austrostipa* grass association on the right at Crace Nature Reserve. The patchy distribution of native and exotic grass associations can also be detected through the patchy colouration on the hillsides in the background.

Grass is not the only source of structure within grassy ecosystems. Woody elements such as logs, shrubs and litter and non-vegetative elements such as rocks also provide structural heterogeneity across multiple scales (Barton et al., 2011; Fischer et al., 2004; Garden et al., 2010; Tongway et al., 1989). In damp areas, non-grass monocot species such as sedges and rushes may provide a grass-like structure which persists under heavy grazing due to the low relative palatability of these species compared to grasses (Davis et al., 2008; Figure 4). Similar habitats where soil is disturbed or higher in nutrients may instead contain exotic pasture species, although at high herbage mass these are also generally unpalatable to kangaroos. Large grass tussocks, such as *Rytidosperma palladium* provide significant grazing-resistant structure in wooded environments due to their retention of unpalatable dead material (McIntyre et al., 2010). Their grassland equivalents, such as *Poa labillardieri*, are rarely observed within Canberra's lowland grassy ecosystem reserves (ACT Government, 2005).

# THE ROLE OF KANGAROOS

The Eastern Grey Kangaroo (*Macropus giganteus*, hereafter 'kangaroo') is the largest indigenous mammal in the ACT, both individually (males up to 100 kg) and in terms of their biomass (up to 25 tonnes of kangaroo/ha). They are a common, iconic species commonly known to Canberra residents. As the overwhelmingly dominant herbivore in lowland grassy ecosystems, kangaroos

Figure 4 Coarse woody debris, water logged areas and a variety of sedge and rush species provide a varied pasture structure amongst short grass in this heavily grazed grassland of Mulligans Flat Nature Reserve. The purple flowers of Fairy Aprons (*Utricularia dichotoma*) can be seen thriving amongst Common Box Sedge (*Schoenus apogon*) to the right of the log.

also occupy a central place in the ecology of such ecosystems (Fletcher, 2006) due to a strong preference for feeding on grass and other monocotyledonous species (Billing, 2007; Davis et al., 2008; Jarman and Phillips, 1989). In some situations they are 'ecosystem engineers' as defined by Jones *et al*. (1997) and Wilby *et al*. (2001) due to their ability to modify both their own habitat and that of other species. Kangaroos are preyed upon by wedge-tailed eagles (*Aquila audax*, Fuentes et al., 2007), introduced red foxes (*Vulpes vulpes*; Fletcher, 2006; Jarman and Wright, 1993; Robertshaw and Harden, 1989), and dingoes (*Canis lupus*) in the non-urban environment, and their carcasses provide food for a diversity of scavengers (Barton et al., 2013a; Barton et al., 2013b; Barton et al., 2011). Kangaroos graze selectively and, in places, heavily enough to have a negative effect on biodiversity by depleting habitat for birds (Neave and Tanton, 1989), reptiles (Dorrough et al., 2012; Howland et al., 2014; Manning et al., 2013), invertebrates (Barton et al., 2011) and plants (McIntyre et al., 2014; Meers and Adams, 2003; Neave and Tanton, 1989). Their occasional browsing or trampling of *Eucalyptus* and *Acacia* seedlings appears to help maintain secondary grasslands against re-establishment of forest and woodland (Webb, 2001). As a result of these various roles, kangaroo management is a key element of grassy ecosystem protection and restoration. The role of kangaroos in the economic, social and environmental fabric of the ACT is broadly appreciated by the Canberra community, as is the need for their management (Micromex, 2008, 2011, 2015).

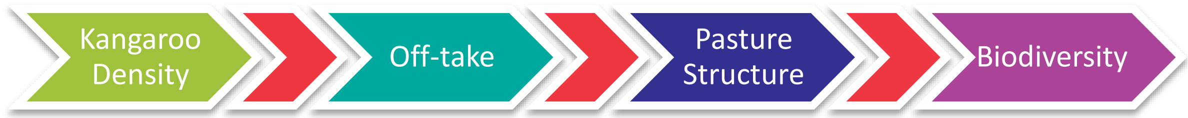
# ACT KANGAROO MANAGEMENT PLAN

The ACT Kangaroo Management Plan (ACT Government, 2010) includes a policy [5.3.1 (g) on p 110] to moderate the density of Eastern Grey Kangaroos in order to protect two endangered ecological

communities of the ACT lowlands (ACT Government, 2004, 2005). This policy was based on the best scientific evidence available at the time of publishing, and has been validated since by a range of local studies relating to the effects of kangaroo grazing on a range of organisms (e.g. Barton et al., 2011 for beetles; Howland et al., 2014 for reptiles; Manning et al., 2011 for reptiles; McIntyre et al., 2014 for plants). The need for a more detailed understanding of the numerical and temporal relationships between kangaroo density and biodiversity was emphasised in the more recent Eastern Grey Kangaroo: Controlled Native Species Management Plan (ACT Government, 2017b). Such research would assist in providing quantitative guidelines for the management of kangaroos for conservation across their environmental gradient (Morellet et al., 2007). A multi-faceted investigation was initiated in 2012 by the Conservation Research Unit of the (then) Environment and Sustainable Development Directorate of ACT Government to address these research questions. Over four years, this project measured kangaroo density, off-take, pasture structure and indicators of grassy-layer biodiversity (plants and reptiles). This document describes the relationships between these measures based on analyses performed to date. The capacity for these data to be used in further analyses of ecosystem function should not be understated.

# RESEARCH DESIGN

This research was designed to evaluate the step-wise process linking kangaroo density to biodiversity outcomes, according to the following model:




The hypotheses behind this study were that 'kangaroo density' would influence 'off-take' (i.e. grazing pressure), different levels of 'off-take' would influence 'pasture structure', and that 'pasture structure' was an important driver of local measures of 'biodiversity'. These assumptions are based on common relationships observed across a range of herbivore species in diverse ecosystems on multiple continents (e.g. Caughley and Sinclair, 1994). The individual analyses performed in this study are represented in the schematic above by the red arrows between variables. Data collected for each ecological element ('kangaroo density', 'off-take', 'pasture structure' and 'biodiversity') were collected under local climatic and environmental conditions and sampling units were stratified according to 'grass association' and 'canopy cover' as appropriate. Sampling across a range of kangaroo densities (necessary to establish the relationship between kangaroo density and off-take) was achieved via both spatial and temporal variation in the positioning of research quadrats, and involved both natural and managed kangaroo populations. Measurements of 'pasture growth' were considered to provide a surrogate measure for the influences of soil, land use history and climate on pasture productivity (Dorrough et al., 2006; McIntyre et al., 2010).

Results presented are based on sampling at three spatial scales: 'site' (> 100 ha), 'plot' (1 ha), and 'quadrat' (1 $m^2$). Plot level attributes reflect a pooling of data from multiple quadrats, and there were generally multiple plots per site. The 'grass association' (● annuals; ● exotic perennial; ● small tussock, ● medium tussock; ● native tuft) and 'canopy cover' (● grassland; ○ open woodland) strata of each data point is shown within all figures for interest, regardless of the significance of the strata in the model presented. When variables are referred to in the text of the following sections, they are highlighted in blue to aid in the recognition measured parameters.

# RELATIONSHIPS BETWEEN KANGAROO DENSITY AND GRAZING PRESSURE

## INTRODUCTION

The first stage of this project aimed to assess the relationship between kangaroo density and grazing pressure, measured as off-take (dry weight of grass removed in kg/ha/day).


The relationship between kangaroo density and off-take is complicated by a range of co-occurring ecological processes driven by climate, pasture growth patterns, preferential grazing of palatable species and herbivore population dynamics (Caughley et al., 1987; Clark et al., 2000; Mysterud, 2006). Weather, for example, has been shown to drive pasture growth in temperate environments (Clark et al., 2000; Fletcher, 2006) resulting in grass species-specific differences in pasture productivity between seasons and across years. The rate of off-take relative to the rate of pasture growth determines the overall rate of herbage mass accumulation or loss. This in turn will feed back to influence both pasture growth (Brougham, 1956) and structure (Howland et al., 2014; Figure 5). The palatability of a given grass species within a site reflects the relative availability of nutritious green growth between species (Billing, 2007; Halpern and Underwood, 2006; Figure 6).

Kangaroo density has been shown to be negatively related to herbage mass at the site scale (Howland et al., 2014; McIntyre et al., 2014; Figure 6). The nature of the relationship between kangaroo density and instantaneous off-take (i.e. the short term effect of kangaroo density on pasture) is however poorly defined for the lowland temperate environment (but see Fletcher, 2006). In order to understand the likely effects of a given kangaroo population density on pasture condition at a specific site, an understanding of the relationships between kangaroo density, pasture growth and current herbage mass ('standing crop') is required across a range of grass associations (Ungar and Noy-Meir, 1988). As such, the first aspect of this investigation utilises sites with different kangaroo densities (stable over the long-term) to assess the effects of each of these components on rates of off-take in multiple common grass associations of ACT lowland ecosystems.

## METHODS

Relationships between kangaroo density and off-take were assessed at the site (> 100 ha) scale from August 2014 across six conservation areas managed by the ACT Government (Figure 8). 'Site' was identified as the minimum scale at which kangaroo density could be effectively and independently estimated and managed (Viggers and Hearn, 2005). Sites were chosen to represent both grassland (<2% canopy cover) and open woodland (2-20% canopy cover) canopy cover classes across a range of kangaroo densities (0-7 kangaroos per hectare). A preference was given to include sites where the kangaroo population was reasonably contained (e.g. by suburbs and high-speed roads) and where density had been stable over recent years and could be estimated using direct count methods. None of the kangaroo populations considered were food limited during this study (based on the absence of sub-adult 'die-off' events observed in wild, food limited populations).

Figure 5 Existing pasture herbage mass, or 'standing crop', affects both the absolute (kg/ha/day) and relative (% increase) pasture growth rates (Crawley, 1983; Thornley and Johnson, 1990). Different levels of standing crop are also associated with different ratios of new to older 'rank' grass.

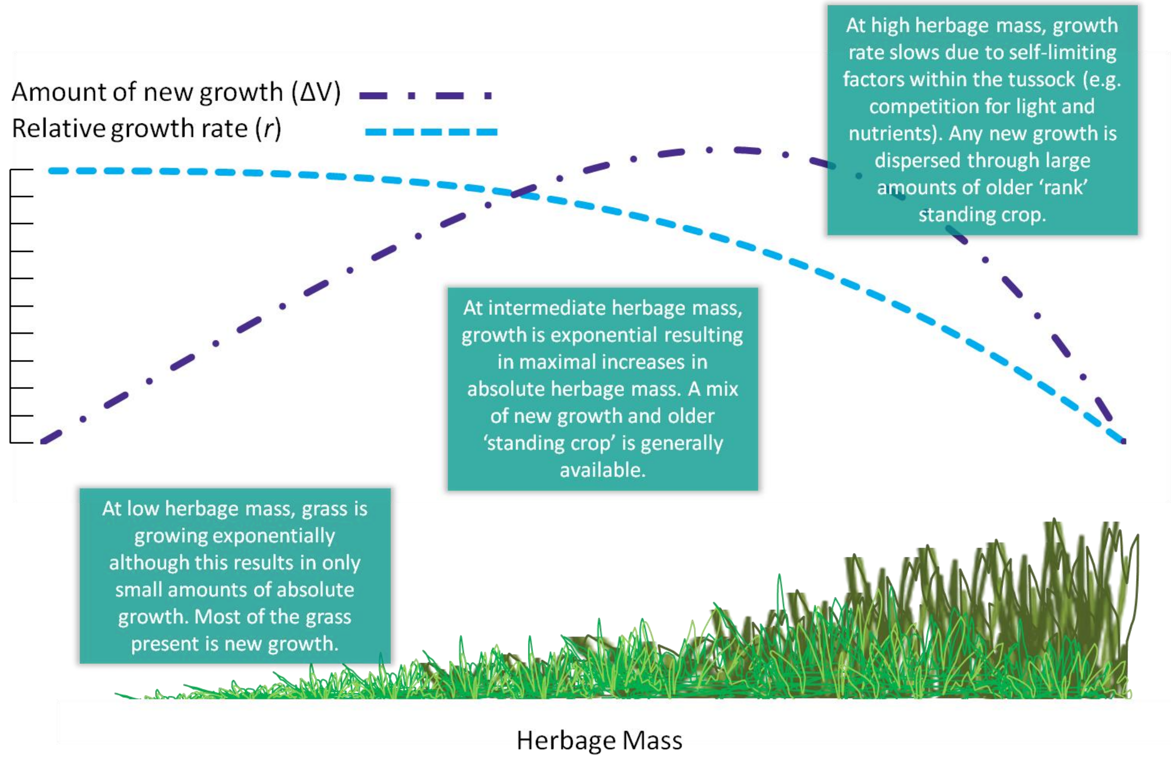
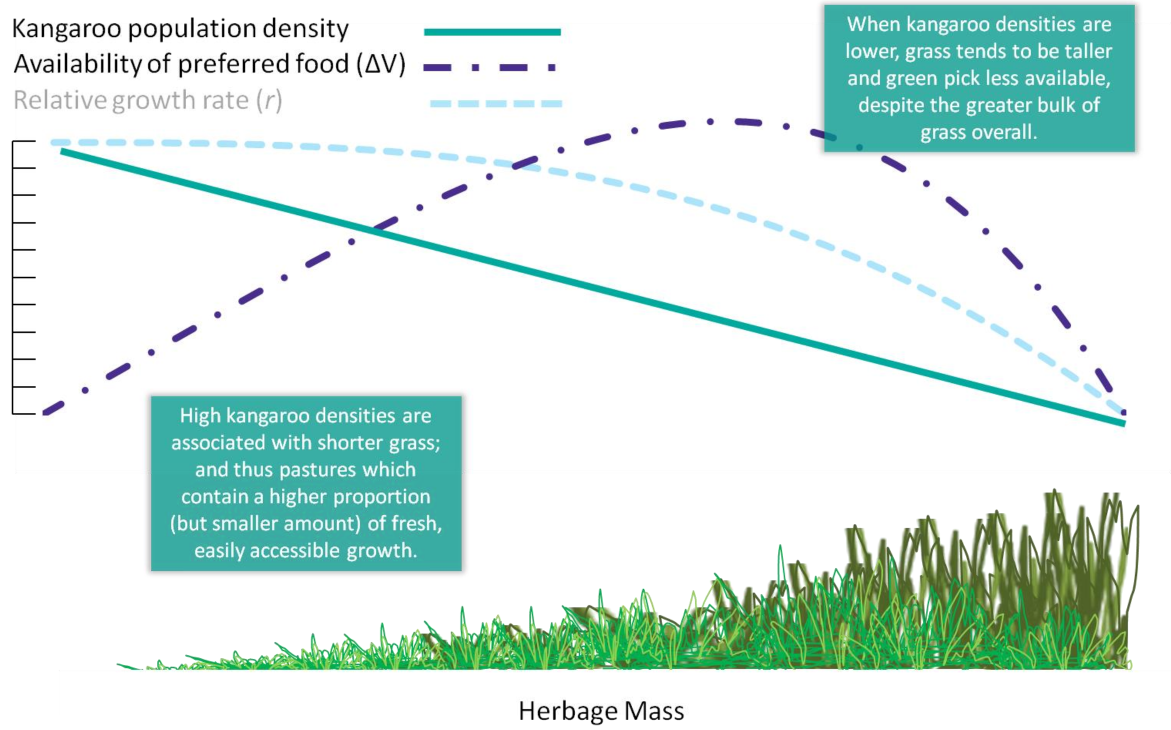



Figure 6 Herbage mass decreases with increasing kangaroo density. The maximum availability of palatable grass (accessible fresh growth) per kangaroo is likely to occur under intermediate herbage mass conditions, when medium length grass is growing almost exponentially and kangaroo density is not too high.



## KANGAROO DENSITY ESTIMATION

Kangaroo density was estimated annually in between April and September using one of three count methods: direct count, sweep count or walked line transect distance sampling (see Appendix 1 of ACT Government, 2010). Direct counts of individual animals were conducted from 2-3 vehicles coordinated by VHF radio, often with an observer positioned on a hill overseeing progress and monitoring the movement of counting vehicles and/or kangaroo groups. Sweep counts involved up to 30 surveyors spanning the site and moving as a line through the reserve tallying kangaroos as they pass into the counted area behind the line (modified from Coulson and Raines, 1985; Figure 7). Sites where kangaroo density was estimated by distance sampling (Buckland et al., 2007) involved the survey of kangaroos from approximately 40 km of transects per reserve, walked within three hours of first light over 10-15 consecutive mornings. Transects were parallel, aligned perpendicular to the winter morning sun to avoid impaired visibility and were spread evenly across the count area. As transects were surveyed, the distance and bearing to kangaroo groups was recorded using a laser rangefinder and voice recorder. The size of the kangaroo group and the GPS coordinates of the observer were also recorded when the observation was made. The GPS coordinates of kangaroo groups were subsequently calculated and observations were post-stratified by vegetation type ('open' or 'woody') prior to analysis using multi-covariate distance sampling models in Distance 6.2 (Thomas et al., 2010). Direct counts were restricted to sites considered to have reasonably contained populations (i.e. surrounded by high speed roads or suburbs; Figure 8) whilst distance sampling was employed to estimate population density in more continuous landscapes. All kangaroo counting procedures were approved under animal ethics permit CEAE 13/01.

Figure 7 Volunteers in high visibility vests spread across the reserve edge in preparation for a sweep count at Mt Painter Nature Reserve (left of image). A thin strip of rural lease (right of image) is checked for any kangaroos before the counters begin their ascent over Mt Painter. The distance between people in the counting line will vary as the count progresses to ensure visibility is maintained between participants such that all kangaroos are counted despite changes in topography and vegetation.

## OFF-TAKE MEASUREMENTS

Off-take was measured biannually (February and August) by comparing the dry herbage mass at an uncaged quadrat (0.25 $m^2$) with a matched quadrat which had been protected from grazing using a mobile herbivore exclusion cage made of 50 mm wire mesh (Cayley and Bird, 1996; Robertson, 1987a, b; t'Mannetje and Jones, 2000). The use of an additional set of hinge-joint cages (allowing herbivory by rabbits) was discontinued after lagomorph impact on off-take was found to be undetectable (data not shown). A random grid of 30 points was imposed across the site (Figure 9) to give the starting location for uncaged quadrats which were marked on the ground with an aluminium tag and peg. Caged and uncaged quadrats were positioned to be initially comparable in terms of herbage mass (estimated from average grass height; ACT Government, *unpublished data*), structural attributes (e.g. large *vs.* small tussocks, proportion of bare ground and presence of non-grass vegetation) and species composition. Paired quadrats were generally positioned within 2-5 m of one another. When revisited after approximately six months, measurements were repeated and grass was clipped to within 1 cm of soil level, oven dried ($70^oC$ over 24-48 hrs) and weighed on electronic scales to accurately determine dry herbage mass. The difference between caged and uncaged quadrats (divided by the number of days elapsed since set up) was calculated to give off-take (kg/ha/day). Pasture growth (kg/ha/day) was estimated based on the difference between herbage mass at the start (measured non-destructively) and end (clipped and weighed) of the six month period within the caged quadrat. 'Standing crop' (kg/ha) was the average of the start and end herbage mass values in the uncaged quadrat. Off-take and pasture growth measurements made in February are referred to as 'spring' measures whilst those made in August represent 'autumn' measures.

After quadrats were revisited and grass was clipped, the uncaged quadrat was repositioned ~5 meters from the previous sampling position. A matching caged quadrat was also re-set to begin the next sampling period. Quadrats were first established at all sites in August 2014 and off-take measures were subsequently made in February and August 2015, and February 2016 (except at Mulanggari). Notes provided to field staff containing detailed data collection methods can be found in Appendix 1.

## STATISTICAL ANALYSIS

Data were inspected for outliers, collinearity, and influential observations and covariates according to the methods described in Zuur *et al.* (2009; 2014) prior to analysis using R version 3.3.1 (R Core Team, 2013). As anticipated, the dominant grass association in surveyed quadrats was an important factor in estimating the relationship between kangaroo density and off-take. As such, six grass association categories were defined based on growth habit, growth season, palatability and grazing tolerance of individual species (Mitchell, 2002) as well as in reference to the grass communities previously described as occurring within the ACT (ACT Government, 2005; Table 1). Grass association for each quadrat was assigned based on the most frequently occurring dominant grass observed at set up. For example, if the herbage mass at 9 of the 15 quadrats within a plot comprised predominantly of *Rytidosperma* spp., the plot was stratified as 'small tussock'. Annual grasses were only observed to dominate herbage mass during summer, thus plots stratified as 'annual' grass association are observed almost exclusively during autumn (Feb-Aug) data. Relationships between kangaroo density and off-take were found to differ between grass associations in preliminary analyses (data not shown) and so were analysed separately. Relationships for large tussock associations were not assessed due to insufficient data.

As previous research identified a functional response between kangaroo density and off-take (Fletcher, 2006) we chose to initially fit a generalised additive mixed model (GAMM; Wood and Scheipl, 2014) to allow loess smoothers (maximum 4 knots) to be fitted where non-linear relationships were expected

between response and explanatory variables. Two models for estimating off-take were examined according to an information theoretic approach. Each model considered kangaroo density, standing crop, pasture growth, and survey season as fixed effects (explanatory variables). Season was fitted either as an independent fixed effect, or as an interaction with pasture growth; except in annual dominated associations where season was not considered. A 'survey' within 'site' nested random component corrected for the non-independent nature of multiple sampling units per site (i.e. 30 quadrats linked to a single site-level estimation of kangaroo density) and their repeated sampling over time (i.e. quadrats being sampled every 6 months in a similar location, and annual estimations of kangaroo density). The best combination of fixed effects was chosen based on AICc (Barton, 2016) and inspection of residuals (Anderson, 2008).

Figure 8 Map showing the six sites (green shading) assessed for relationships between kangaroo density and off-take at the site scale across the ACT and surrounding land. A preference was given to sites surrounded by roads (grey lines) or other barriers to kangaroo movement. The thick grey line indicates the ACT border; blue indicates water bodies.

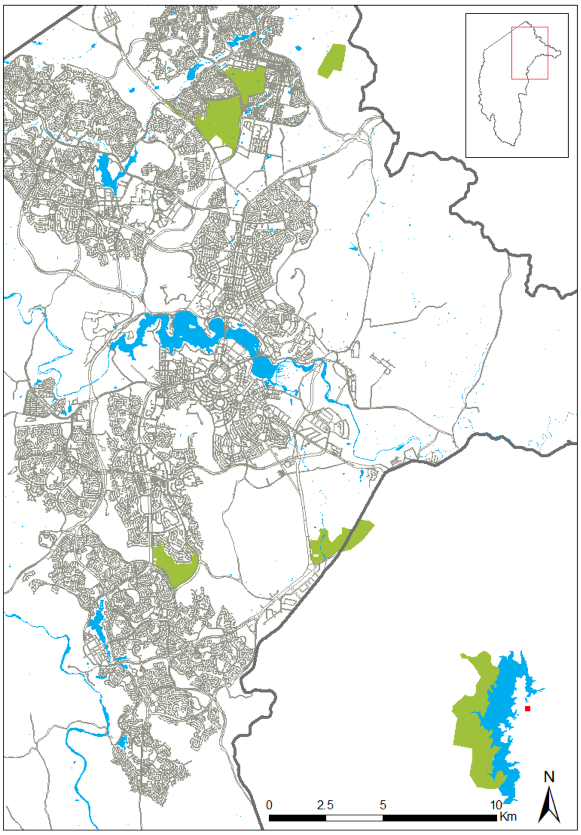



Figure 9 The position of 30 uncaged quadrats (white dots) from which off-take was measured by comparison with a matched caged quadrat. Sites (white outline) comprised mainly of Nature Reserve (green shading). a, Dunnarts Flat kangaroo exclosure within Goorooyarroo Nature Reserve; b, Mulanggari Nature Reserve (and adjoining habitat); c, Gungaderra Nature Reserve (and adjoining habitat); d, Farrer Ridge Nature Reserve; e, Jerrabomberra East Grasslands (and adjoining conservation land); and f, Googong Foreshores Nature Reserve. Thick black line in e indicates the ACT border; blue indicates water bodies.

Table 1 A summary of grass associations in terms of species composition and pasture structure. A full classification for grass species observed in terms of grass association categories can be found in Appendix 2.

| Grass Association | Typical species or genera* | Description of ecology and structure |
|---|---|---|
| Annuals | *Avena fatua, Aira spp., Briza spp., Bromus spp., Vulpia spp.* | Generally occur in more open and degraded areas with reasonable fertility. Variable structure from wispy, low herbage mass pasture (*Briza, Vulpia*) to more dense swards for *Avena.* Dominant in terms of herbage mass only during the warmer months. Generally absent altogether in cooler months. |
| Exotic Perennials | *Phalaris aquatica, Holcus lanatus, Paspalym dilatum, Nasella spp.* | Common in degraded areas with reasonable (often historically improved) soil fertility and moderate to high soil moisture. Often forms tall (> 40 cm), high to very high herbage mass swards with little inter-tussock space. Significant accumulation of thatch under high herbage mass conditions. |
| Small Tussock | *Rytidosperma spp.* (excluding *R. pallidum*), *Aristida ramosa* | Often occurs on shallow, nutrient poor soils and thus has lower productivity (growth rate) and a sparse, open structure with distinct inter-tussock spaces and higher levels of bare ground. |
| Medium Tussock | *Austrostipa spp., Dichelachne spp.* | Common and widespread within Canberra Nature Park. Tussock forming grasses although structure varies from dense, continuous sward to more sparsely distributed tussocks with defined inter-tussock space. Commonly occurs interspersed with *Rytidosperma* spp. |
| Large Tussock | *Rytidosperma pallidum, Poa spp.* | Uncommon in grassy ecosystems of Canberra Nature Park although *R. pallidum* is common in more heavily wooded areas. Forms tussocks with large over-hanging canopies. Generally not a preferred food source for native herbivores. |
| Native Tuft | *Themeda triandra, Bothriochloa macra, Microlaena stipoides, Eragrostis brownii, Anthosachne scaber, Panicum effusum* | Reasonably common grass association within Canberra Nature Park in areas with minimal historical disturbance. Can form tall (> 25 cm), dense swards under good conditions but often assumes a prostrate form under heavier grazing. Bare ground is less common than for tussock grasses. |

Models considered to describe the relationship between kangaroo density and off-take according to pasture growth, season and standing crop conditions were of the form:

$$Offtake = \int(pasture\ growth\ \times season) + \int(kangaroo\ density) + \int(standing\ crop) + \ season + \ \mu$$

and

$$Offtake = \int(pasture\ growth) + \int(kangaroo\ density) + \int(standing\ crop) + \ season + \ \mu$$

where ∫ is the function predicted by the loess smoother and μ represents the random effects. The model fitted to plots dominated by annual grasses was:

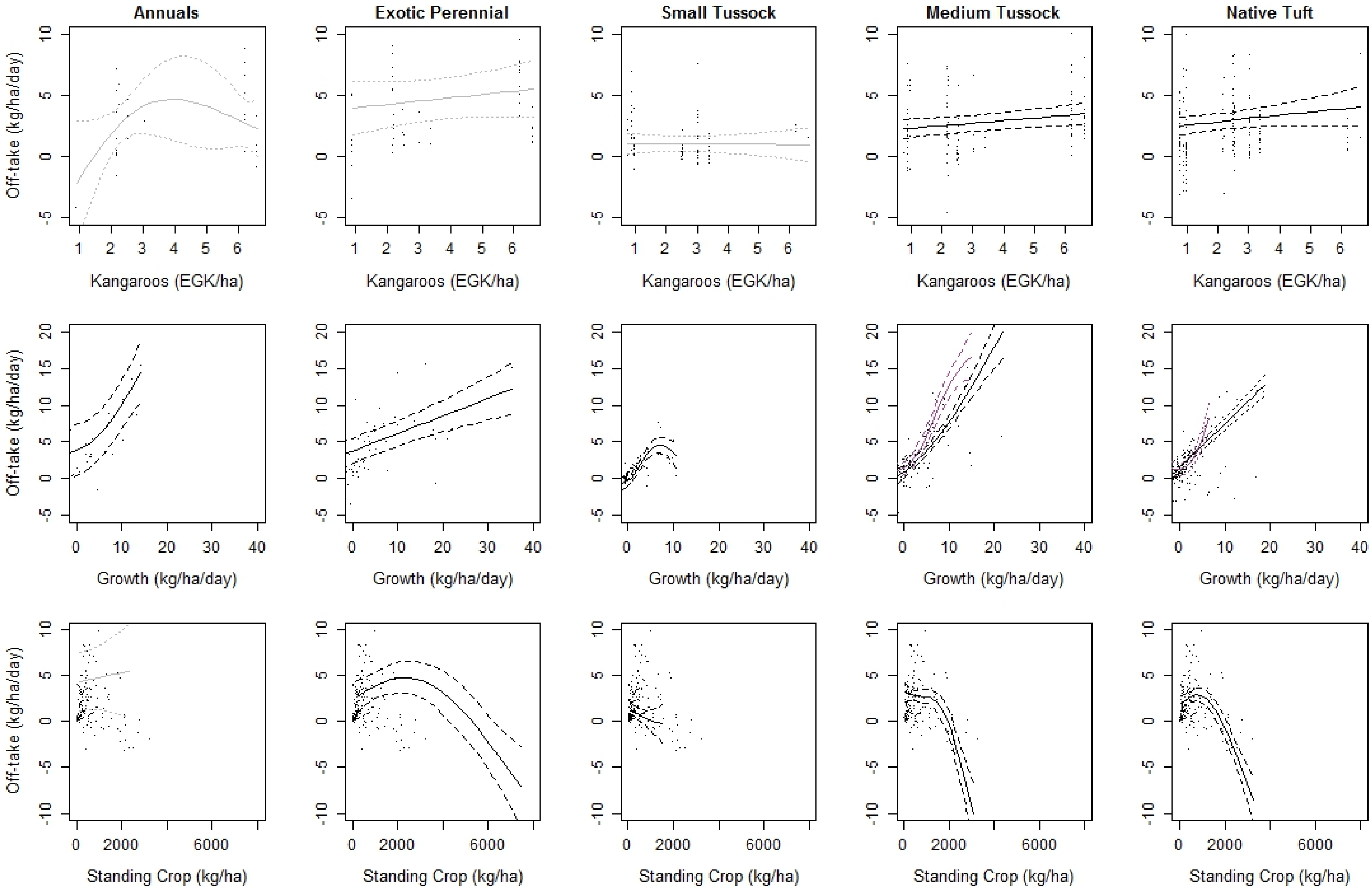
$$Offtake = \int(pasture\ growth) + \int(kangaroo\ density) + \int(standing\ crop) + \ \mu$$

# RESULTS

Kangaroo density had a significant positive effect on off-take for 'medium tussock' dominated grass associations (higher kangaroo density resulted in higher off-take; $p = 0.018$) and kangaroo density also showed a near-significant effect on 'native tuft' grasses ($p = 0.087$). There was no relationship between kangaroo density and off-take for 'annual', 'exotic perennial' or 'small tussock' dominated grass associations ($p > 0.15$). The positive effect of pasture growth on off-take was highly significant for all grass associations ($p < 0.001$), where higher pasture growth resulted in higher off-take. The significance of the effect of standing crop on off-take varied between grass associations. In exotic perennial, medium tussock and native tuft dominated grass associations, off-take showed a threshold effect where off-take initially increased with increasing standing crop, but where above some threshold additional increases in standing crop resulted in off-take being significantly reduced (all $p < 0.001$). In small tussock grasses, off-take decreased in a linear fashion as standing crop increased although this effect did not reach statistical significance ($p = 0.059$). There was no effect of standing crop on off-take of annuals ($p > 0.5$).

For medium tussock and native tuft dominated pastures, the model which included a smoother for the pasture growth by season interaction showed a better fit to the data than a model which fitted the same slope for each season, because the seasons differed in their rate of off-take per unit of pasture growth (a greater proportion of growth was consumed in autumn compared to spring, both $p < 0.001$). The relationship between off-take and pasture growth did not vary with season for exotic perennial and small tussock grasses ($p > 0.15$). The effect of season was not considered for annuals. The graphical output from these models is shown in Figure 10. The printed model output is in Appendix 3.

Figure 10 (following page). The relationships between off-take and kangaroo density, grass growth and standing crop are shown for each of five grass associations. Where a growth by season interaction was observed, spring and autumn data are represented by black and pink lines respectively. Relationships are displayed in bold if $p < 0.1$ (i.e. significant and near-significant effects; see text for details). Grey lines indicate relationships where $p > 0.1$. Confidence intervals are at 95%.



Annuals
Exotic Perennial
Small Tussock
Medium Tussock
Native Tuft
Off-take (kg/ha/day)
Kangaroos (EGK/ha)
Growth (kg/ha/day)
Standing Crop (kg/ha)

# DISCUSSION

This study has demonstrated that kangaroo density, pasture growth, standing crop and season all contribute significantly to determining off-take in grassy ecosystems. Different off-take relationships with kangaroo density, pasture growth and standing crop have also been demonstrated based on grass association.

The strong effect of pasture growth on off-take across all grass associations supports previous work indicating that kangaroos show a strong preference for the 'green pick' component of pasture (Billing, 2007; Meers and Adams, 2003). This reflects the greater nutritional content of actively growing pasture (Lodge and Whalley, 1983) and is in keeping with the ability of short 'marsupial lawns' to maintain high kangaroo densities at sites within the ACT (Figure 11, Fletcher, 2006; Neave and Tanton, 1989). Green pick is less accessible in pastures with high standing crop due both to a dilution effect, where small amounts of new growth are shielded by large amounts of less palatable grass (Tothill, 1971); and because 'rank' pastures are less productive generally (Brougham, 1956). As such, the observation of a threshold or negative effect of standing crop on off-take in these models can also be explained based on the preference of kangaroos for new growth. The different relationships observed between grass associations likely reflects the influence of different grass structures on the relative 'availability' and 'accessibility' of green pick (Ungar and Noy-Meir, 1988). A negative effect of high standing crop on off-take has not previously been described in pasture functional response models for kangaroos, as the parameter *V*, which represents vegetation biomass (i.e. food), has previously considered either total herbage mass (Short, 1986; albeit recognising an 'ungrazable residual biomass') or just the living component of the pasture (Fletcher, 2006). Separate parameters estimating the 'palatable' and 'unpalatable' components of standing crop as well as the availability of new pasture growth will inform a predictive functional response model to be developed from this work. This model, once developed, will be reported on separately and would aim to form the basis of kangaroo management in the ACT into the future.

The positive relationship between off-take and kangaroo density in medium tussock and native tuft dominated grass associations was an expected outcome of this study, although the relationship for native tuft grasses did not reach statistical significance. A comparable result was also expected (but not observed) for small tussock, exotic perennial and annual dominated pastures. It is possible that the difference in relative palatability between grass associations is responsible for this observation, where the effect of kangaroo preference overshadows the predicted density dependent relationships. Importantly, these are not food limited populations. For example, exotic perennial grasses such as *Phalaris aquatica* can be highly nutritious for Eastern Grey Kangaroos at low standing crop values (Fletcher, 2006) but cause toxicity when rank (Bacci et al., 2014). Off-take in this grass association would as such be expected to reflect the pasture condition (in terms of standing crop) rather than a direct relationship with kangaroo density, and may explain why no effect of reduced kangaroo density was observed on exotic perennial herbage mass in a previous local study (McIntyre et al., 2014, but see study by Fletcher, 2006 under low herbage mass conditions). Conversely, annual grasses are likely to be a preferred food, where maximum off-take is capped (regardless of kangaroo density) by their limited and seasonal availability. The comparatively low availability of new growth in small tussock associations may make foraging in these communities inefficient relative to in other associations. These hypotheses are supported by our observations of relationships between off-take and pasture growth and between off-take and standing crop for exotic, annual and small tussock associations.

This first component of this study has confirmed the strong effect of pasture growth (and hence weather conditions; Caughley, 1987; Clark et al., 2000; Cullen et al., 2008) on off-take dynamics. It has also highlighted the strong role of grass association and pasture condition (standing crop) in predicting ecological relationships within grassy ecosystems. Future work should re-assess these relationships under different climatic conditions, to enable climate- and current pasture sensitive kangaroo management to be undertaken within the ACT (Morellet et al., 2007). It should be noted that the relationships observed in the current study are unlikely to be maintained under exceptionally high or low pasture growth conditions.

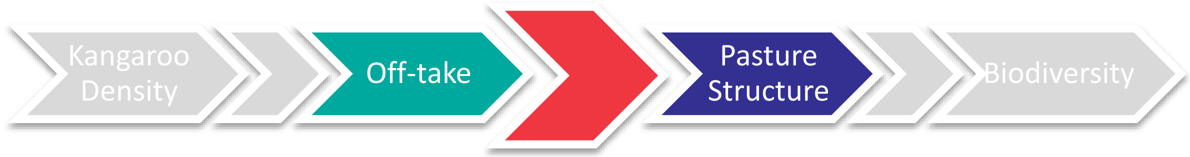
Figure 11 Pastures with low herbage mass can support surprisingly large densities of kangaroos under favourable climatic conditions, as short grass can grow exponentially and provide kangaroos with unimpeded access to preferred forage. When pasture growth slows or ceases completely in less favourable periods (such as during the cold winter months), die-off events affecting predominantly sub-adult animals are commonly observed when standing crop is low.

# RELATIONSHIPS BETWEEN GRAZING PRESSURE AND PASTURE STRUCTURE

## INTRODUCTION

The capacity of a heterogeneous habitat structure to promote biodiversity in grassy ecosystems through the provision of a variety of habitat niches for both fauna and flora has been well established (Fischer et al., 2004 and references within). The ability of land managers to achieve a beneficial pasture structure however can be confounded by the vague definition what 'structure' is, and how to achieve it using practical management techniques. Studies investigating lowland grassy ecosystems often use composite indices of herbage mass, grass height and/or some measure of vegetative cover to describe pasture structure (e.g. Howland et al., 2014), which may also include factors such as the occurrence of woody debris, rocks, or even the occurrence of spiders (e.g. Fischer et al., 2004). Whilst such analyses are beneficial in understanding which of the many possible environmental conditions drive species occurrence, the combined suite of environmental conditions supported by such models may be difficult to readily identify in the field. The relationships derived from such studies have enabled this investigation to examine more closely some of the specific habitat elements identified as being important in the ecology of a range of grassy-layer dependent species, with the aim to improve the capacity of conservation land managers to recognise and/or work towards achieving a ground layer structure beneficial for a range of taxa.

In the first section of this report, the relationship between kangaroo density and off-take has been assessed in light of the additional influences of pasture growth, standing crop (i.e. average herbage mass) and season for a range of grass associations common within lowland grassy ecosystems of the ACT. The second component of this study, presented here, aimed to assess the relationships between off-take and the specific attributes of pasture structure we consider likely to be key determinants of habitat quality for a range of flora and fauna. Namely, we assessed the effect of off-take on average grass height (indicative of herbage mass or the 'amount' of grass), the relative grass height variability (a measure of the 'heterogeneity' of the grassy layer at the hectare scale), and the proportion of bare ground (a measure of the 'patchiness' of vegetation generally).




Maintaining separation between these individual structural elements enabled assessment of both the effects of kangaroo grazing and grass association on each structural attribute, and to go on to discover the specific aspects of grass structure which drive biodiversity of different taxonomic groups (e.g. plants and reptiles). Our focus on presenting structural variables on the 'raw' scale (e.g. grass height in cm, and grass height variability and bare ground as proportions) aimed to make the recognition and achievement of individual structural components straightforward in a field setting. In light of the results from the first section of this report, the intrinsic differences between grass associations have been considered as part of the analysis; as were the additional effects of canopy cover class.

# METHODS

The relationship between off-take and pasture structure was assessed at the plot (1 ha) scale to enable analysis of the localised effects of kangaroo grazing on pasture structure. Off-take was used as a measure of kangaroo impact, as direct measures of kangaroo density at this scale were not considered to be independent of other plots within the site (Viggers and Hearn, 2005). We also did not expect a given density of kangaroos to exhibit a consistent impact across all sites (Ungar and Noy-Meir, 1988). Plots were positioned within 26 sites across the ACT between 2012 and 2015. Attempts were made to achieve even sampling of canopy cover classes ('grassland' < 2% canopy cover, or 'open woodland' 2-20% canopy cover), grass association (six categories based on growth habit, growth season, palatability and grazing tolerance) and estimated site-scale kangaroo density (0 - 7 kangaroos/ha) strata. An earlier experimental design (2012 – mid 2014) made no attempt to balance sampling across these strata and so early data are biased toward common combinations (medium tussock dominated grass associations with low kangaroo density).

## OFF-TAKE MEASUREMENTS

Off-take was measured biannually (in February and August) by comparing the dry herbage mass at an uncaged quadrat (0.25 $m^2$) with a matched quadrat which had been protected from grazing using a mobile herbivore exclusion cage made of 50 mm wire mesh (Cayley and Bird, 1996; Robertson, 1987a, b, 1988; t'Mannetje and Jones, 2000). The use of an additional set of hinge-joint cages (allowing herbivory by rabbits) was discontinued after lagomorph impact on off-take was undetectable (data not shown). Uncaged quadrats marked on the ground with an aluminium tag and peg were positioned at predetermined intervals along north-south running transects positioned 10 m from the east and west boundaries of the plot. The caged quadrat was positioned nearby such that the caged and uncaged quadrats were initially comparable in terms of estimated herbage mass (from average grass height), species composition and structural attributes (e.g. large *vs.* small tussocks, proportion of bare ground and presence of non-grass vegetation). When revisited after approximately 6 months, measurements within each quadrat were repeated and grass was clipped to within 1 cm of the ground, oven dried (70$^{o}$C over 24-48 hrs) and weighed on electric scales to accurately determine dry herbage mass. The difference in dry herbage mass between caged and uncaged quadrats (divided by the number of days elapsed since set up) was calculated to give off-take (kg/ha/day). When sampling was complete, the uncaged quadrat was moved 6 m south along the transect line and a new matched caged quadrat was positioned to begin the next survey period. Measurements made in February were considered to represent 'spring' whilst measurements made in August represent 'autumn'. Detailed field methods used during the survey can be found in Appendix 1.

## PASTURE STRUCTURE MEASUREMENTS

Pasture structure was measured annually in spring (September – November) from 15 x 1 $m^2$ quadrats within each 1 ha plot. Quadrats were arranged in a 5 x 3 grid, 25 m and 40 m apart north-south and west-east respectively. Surveys included assessment of average grass height (average of 4 measurements made with a ruler within each quadrat), the proportion of bare ground (estimated visually) and the dominant grass species or genus (based on estimated dry weight). Survey was preceded each year by an initial 'calibration' session where all field staff worked together to achieve consistent estimations of grass height and bare ground. Details of collection methods for these and other structural attributes measured but not reported on here can be found in Appendix 4.

Plot level structural attributes were calculated based on measurements at the 15 quadrats. Grass association for the plot reflected the most common grass association within quadrats (i.e. plots with mostly 'medium tussock' dominated quadrats were classified as 'medium tussock' plots). Canopy cover class was based on vegetation mapping (Wimpenny et al., 2015). Average grass height for the plot was the mean of grass height measurements across all 15 quadrats. Grass height variability was the coefficient of variation across the plot (expressed as a proportion) based on the mean grass height within each quadrat. The proportion of bare ground for the plot was the average for all 15 quadrats.

## STATISTICAL ANALYSIS

Data were inspected for outliers, collinearity, and influential observations and covariates according to the methods described in Zuur (2009; 2014) prior to analysis using R version 3.3.1 (R Core Team, 2013). The relationships between spring off-take (August – February) and grass structural variables (average grass height, grass height variability and proportion of bare ground), also measured in spring, were assessed at the plot scale using linear mixed models (LMM; Bates et al., 2015) following an initial assessment for non-linear patterns using generalised additive mixed models (GAMM; Wood and Scheipl, 2014). Data for autumn off-take (February – August) were insufficient to be included in the analysis, nor were sufficient data available to model the relationships between off-take and grass structural attributes separately for each grass association.

The model examining the effect of spring off-take on average grass height considered grass association and canopy cover class as categorical fixed terms. An interaction between off-take and grass association was also examined to allow for different relationships between off-take and average grass height in different pasture types. Models for grass height variability and the proportion of bare ground considered average grass height as a continuous covariate in addition to fixed effects of grass association, canopy cover class and an off-take by grass association interaction. All models included a random intercept for site, whilst year was considered as a further fixed effect due to insufficient levels being sampled for its inclusion as a nested random term (*n*=1-3 per site). Backward selection was applied to each full model using both AIC and inspection of residuals to achieve the simplest model for each grass structural variable without violating model assumptions (Anderson, 2008). Where nonlinear effects were observed within additive models, linear models were re-specified using an appropriate non-additive term to allow for more straightforward interpretation. Although pasture growth was considered likely to influence grass structural attributes in these ecosystems, it was not considered in these models due to collinearity with off-take ($r^2 = 0.6$).

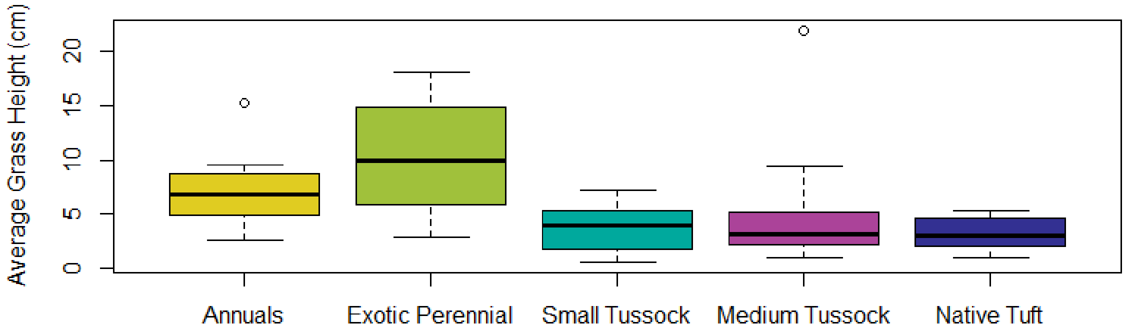
# RESULTS

Average grass height differed significantly between grass associations (Figure 12) being higher in exotic perennial and annual grass associations than native pastures. Average grass height was not significantly related to off-take however the term for off-take was retained in the model for interest as it had little effect on AICc ($\Delta$ AIC < 2). Terms for canopy cover class and the off-take by grass association interaction were dropped from the model. A significant effect of year was observed, although its effect was not of primary interest. The final model took the form:

$$Grass\ Height = \alpha + \beta_1 Offtake + \beta_2 Grass\ Association + Year + \mu$$

where $\alpha$, $\beta_1$ and $\beta_2$ were parameters estimated by the model and *Year* is the average parameter for year across the survey period (Appendix 5). The random effect of site is represented by $\mu$.

Figure 12 The effect of grass association on average grass height.

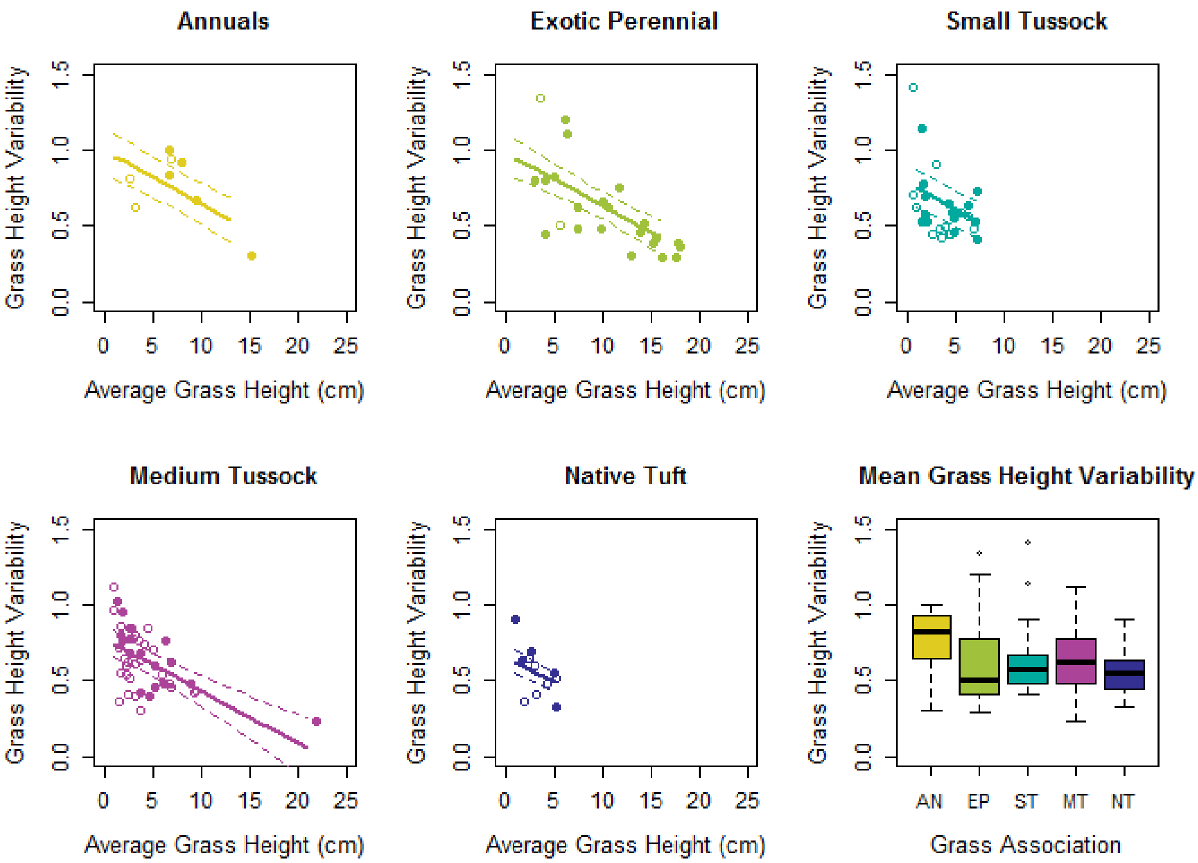



Grass height variability was negatively related to average grass height, i.e. shorter pastures had greater grass height variability compared to taller pastures (Figure 13). Grass association was also a significant predictor of grass height variability, with annuals being most variable followed by medium tussock dominated grass associations. There was no effect of spring off-take on grass height variability, and this term was dropped during the model selection process along with terms for canopy cover class and an off-take by grass association interaction. The final model took the form:

$$Grass\ Height\ Variability\ =\ \alpha\ + \beta_1 Average\ Grass\ Height\ +\ \beta_2\ Grass\ Association\ +\ \mu$$

where $\alpha$, $\beta_1$ and $\beta_2$ are parameters estimated by the model (Appendix 6) and µ represents the random effect of site.

Figure 13 Relationship between average grass height and grass height variability and the difference between mean grass height variability for each grass association (● AN, annuals; ● EP, exotic perennial; ● ST, small tussock; ● MT, medium tussock; ● NT, native tuft). A term for canopy cover class (● grassland; ○ open woodland) was not supported in this model.



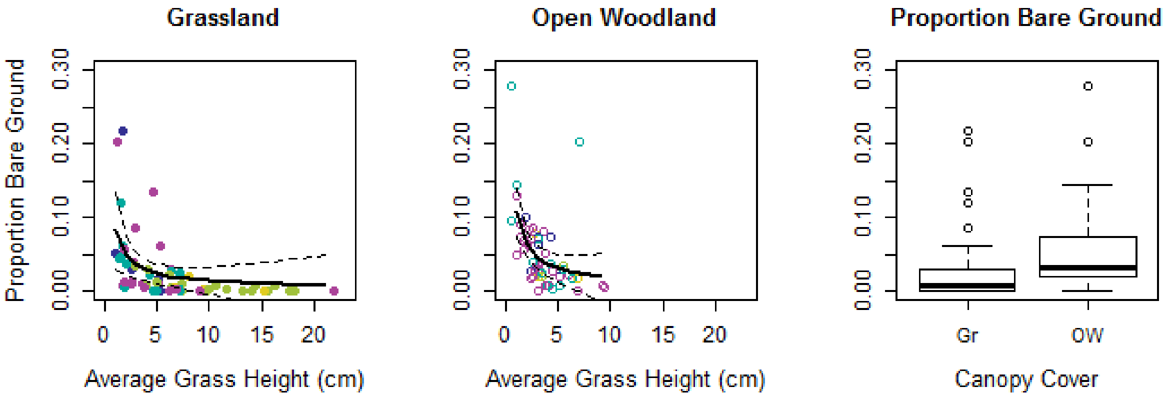
Proportion of bare ground estimates were logit transformed (+ 0.01) to achieve normally distributed errors from proportional data. Generalised additive mixed modelling indicated a nonlinear relationship between average grass height and logit of the proportion of bare ground (results not shown) and so a negative exponential term for average grass height was instead assessed in a Gaussian linear mixed model. The proportion of bare ground was found to be negatively related to average grass height and was higher in open woodland compared to grassland plots (Figure 14).

Terms for off-take, grass association, an off-take by grass association interaction and year were not supported in the model explaining the proportion of bare ground. The final model was of the form:

$$Logit(Bare\ Ground + 0.01) = a + \log(\beta_1 Average\ Grass\ Height) + \beta_2 Canopy + \mu$$

where $\alpha$, $\beta_1$ and $\beta_2$ are parameters estimated by the model (Appendix 7), and µ represents the random effect of site.

Figure 14 The relationship between average grass height and the proportion of bare ground for grassland (Gr, ●) and open woodland (OW, O) plots. Fitted models included a random term for site. The difference between the mean proportion of bare ground is also shown for each canopy class. An effect of grass association (● annuals; ● exotic perennial; ● small tussock, ● medium tussock; ● native tuft) was not supported in this model.




# DISCUSSION

Off-take by kangaroos was not found to be a significant predictor of average grass height, grass height variability or the proportion of bare ground at the 1 ha level based on the two years of spring measurements represented in this analysis. Rather, grass association, canopy cover and average grass height were the key predictors of spring pasture structure in lowland grassy ecosystems. Previous studies have demonstrated a significant relationship between kangaroo density and measures of pasture structure over the longer term (Howland et al., 2014; McIntyre et al., 2014; Neave and Tanton, 1989, and preliminary results of the current data). As such, the relationship between off-take (the presumed mechanism by which kangaroos impact pasture) and pasture structure deserves further investigation at different spatial (e.g. 1 $m^2$ *vs.* 1 ha) and/or temporal (e.g. spring *vs.* autumn, or dry *vs.* wet years) scales. Given the strong effects of grass association on pasture structure variables, future analysis of the relationship between off-take and pasture structure should be undertaken within grass association classes where permitted by a larger dataset.

The previous section of this report demonstrated that standing crop (i.e. an estimate of the average herbage mass across the six month sampling periods) played a significant role in determining off-take by kangaroos. From the previous section (and the hypothetical model shown in Figure 5), it is apparent that

off-take may be low under low standing crop conditions (as a result of low pasture availability), and off-take may also be low when standing crop is high (as a result of decreased palatability and accessibility of green pick). This aspect of the functional response indicates possible circularity in the relationship between off-take and pasture structure, as off-take can simultaneously influence, and be influenced by, pasture structure. Such a dome shaped ('Type 4') functional response (Caughley, 1987; Fletcher, 2006; Holling, 1965) is rarely observed within the relatively artificial conditions under which such relationships are usually tested (i.e. where pasture is homogeneously edible and no 'rank' patches occur; Fletcher, 2006). As such this study may have described the rarely recorded Type 4 functional response, indicating that it may be more common in the real world than previously expected.

Where kangaroos select fresh green pick, the effect of their grazing on pasture structure will depend on the rate of off-take *versus* the rate at which new growth is available. This effect of the short term influences of kangaroos on the longer term condition of their environment is represented as a pasture budget by Robertson (1987b). Whilst grass is actively growing, pasture will either be maintained in its current state (where off-take = pasture growth) or will increase in herbage mass (where off-take < pasture growth). In the latter scenario, excessive pasture growth may result in pastures becoming unpalatable (rank) and hence off-take will subsequently decline. In a less productive climate, e.g. when pasture growth slows in winter or during drought (Clark et al., 2000; Cullen et al., 2008), the reduced availability of high quality forage is likely to result in off-take showing a measurable impact on pasture structure as a higher proportion of 'standing crop' is consumed (where off-take > pasture growth). How such effects might influence measures of biodiversity may be difficult to ascertain however as the effect of winter pasture structure on predominantly spring or summer active species is rarely examined (but see Dennis et al., 1994 for beetles) and the environmental stressors experienced under drought conditions may confound measures of habitat suitability (Dimond et al., 2012).

Given that the level of selectivity demonstrated by foraging kangaroos (Billing, 2007; Davis et al., 2016; Jarman and Phillips, 1989) implies that the impacts of grazing might act at a very fine scale (i.e. down to the individual plant), it is possible that the scale or sampling effort used for measuring off-take within 1 ha plots in this study (two pairs of 0.25 m$^2$ quadrats) was inappropriate for assessing relationships between off-take and pasture structure. This hypothesis, and the relationships between off-take and pasture structure at a small ($< 1$ m$^2$) scale, could instead be assessed using data collected for the previous section of this report (i.e. off-take, average grass height and the proportion of bare ground from 30 pairs of off-take cages across each site, stratified by grass association). The collection of these data from both spring and autumn over multiple years would likely allow relationships to be examined both within grass association classes and under different pasture growth scenarios; and thus further analysis of these data – whilst outside the scope of the current report – should be considered.

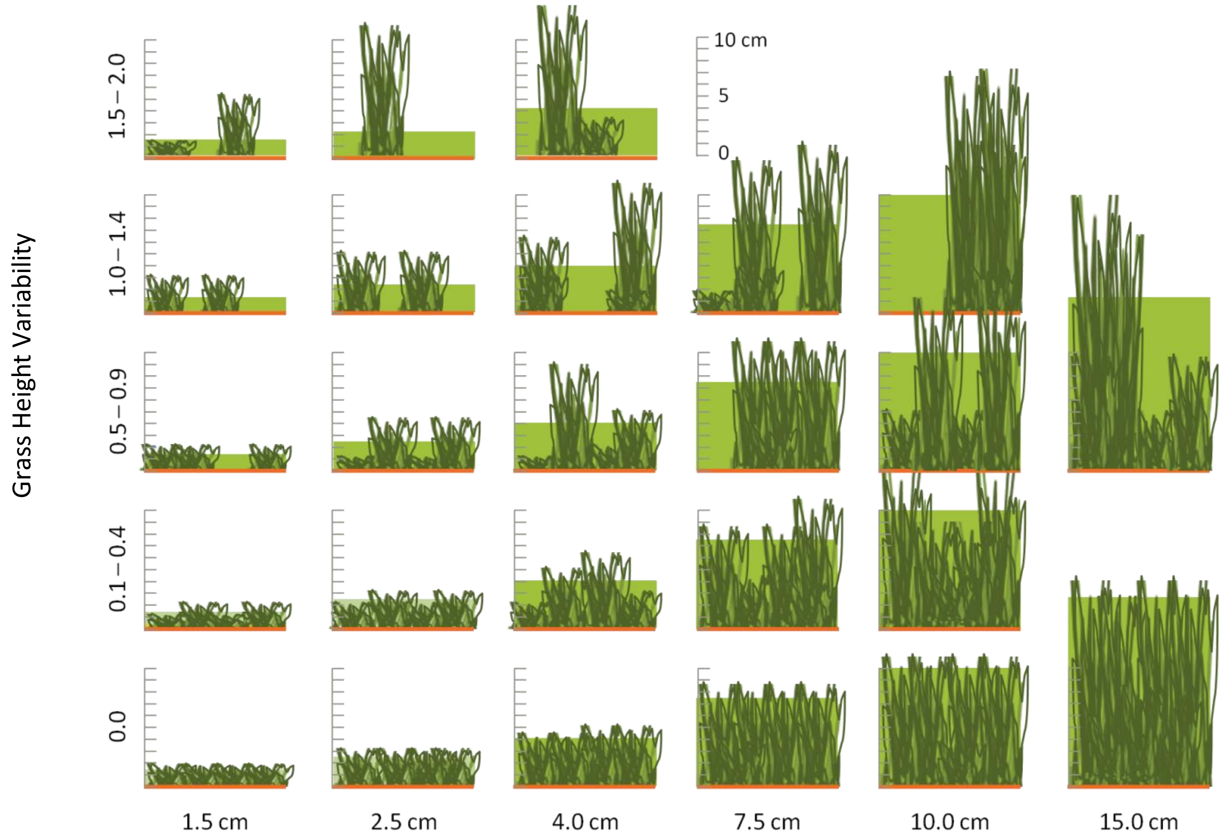
Irrespective of off-take, average grass height and the dominant grass association within the plot were both found to have a strong influence on grass height variability in this study. As high scores of grass height variability (calculated as the standard deviation of average grass height divided by the mean) are most readily achieved through short grassy patches coupled with bare ground within the sampling unit (i.e. high standard deviation and low mean height; Figure 15), such an outcome was expected. The particularly high grass height variability score for annuals likely reflects their tendency to invade areas of degraded bare ground (Lenz and Facelli, 2005) increase quickly in herbage mass and height, and leave behind little residual herbage mass from year to year. Comparable results for each of the native perennial dominated associations reflect a tendency for these plants to be interspersed with either forbs or bare ground (McIntyre et al., 2010) although *Themeda triandra* in the native tuft association may form a more continuous sward under favourable conditions (Lunt, 1995). Except under heavy grazing conditions,

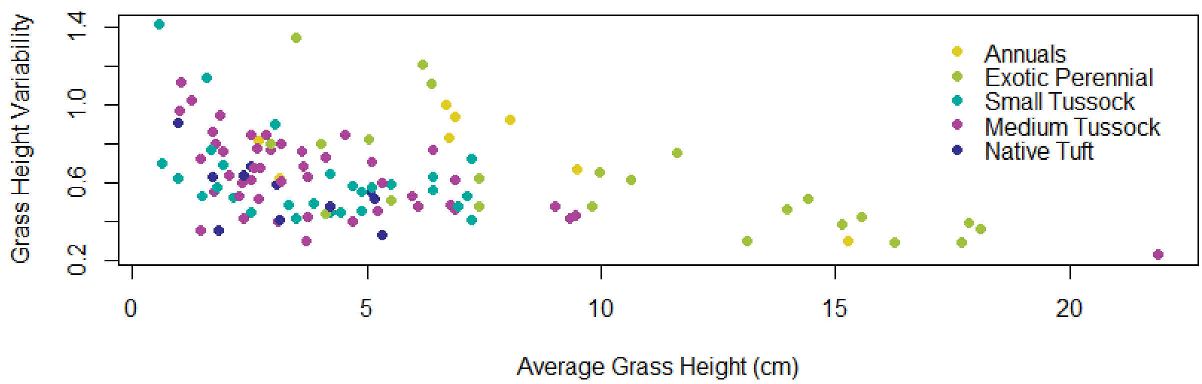
exotic perennial grasses form tall (> 15 cm), dense swards with a mulch of dead grass between clumps (Tothill, 1971) and hence generally have low variability. The significant effect of grass association on grass height variability in this study supports our inclusion of this factor in our research, and will assist land managers to predict the likely structural variability of different grass communities in the field – regardless of grazing intensity – from estimates of average grass height.

Canopy cover class will also assist in predicting structural variability in grassy ecosystems as open woodland plots were found to be more likely to contain a higher proportion of bare ground which we consider to represent 'patchiness' of vegetative cover. This result supports a number of previous studies which have associated a more variable ground layer structure with the higher number of microclimates available within wooded areas (e.g. Dorrough et al., 2012). As our assessment of average grass height included patches of bare ground as having a 'height' of zero, the negative exponential relationship between average grass height and the proportion of bare ground was also expected. Such a relationship is an important consideration from a management perspective as it indicates a rapid decline in the likelihood of bare ground with small increases in grass height. Indeed, bare ground did not exceed 5% in either grassland or open woodland plots when average grass height was greater than 5 cm.

Whilst it is very possible that the intrinsic effects of grass association, canopy cover class and average grass height overshadow any short term effects of kangaroo grazing on pasture structure – especially during years of high pasture growth – further investigation into this relationship is warranted given the negative effect of kangaroo density on pasture structure described previously at the site scale (e.g. Howland et al., 2014, and preliminary results from this study). Regardless of the effects of off-take however, it is clear that recognition of the likely grass structural attributes achievable within a pasture – being dependent on grass association and canopy cover class – will be an important consideration in managing grass height and prioritising areas for the conservation of particular species or habitat elements.

Figure 15 Schematic (top) demonstrating the range of grass height variability scores obtained across different average grass height measurements and (bottom) the actual range of data collected. In the schematic above, light green shading indicates the average grass height in each case. Grass height variability was calculated as the standard deviation in grass height divided by the mean (i.e. the coefficient of variation). Scores above one were achieved where average grass height is low and standard deviation is high; which generally involves the presence of at least some bare ground (grass height of zero in part of the survey quadrat). Few scores above one were observed in the field.



# RELATIONSHIPS BETWEEN PASTURE STRUCTURE AND BIODIVERSITY

## INTRODUCTION

The interactions between herbivores and grass structure play a pivotal role in determining habitat suitability for the majority of species which inhabit grassy ecosystems (Dorrough et al., 2012). For ground dwelling species, the amount and distribution of grass can determine the availability of shelter, the abundance of and access to food resources and, for fauna, the ease with which a species can navigate through its home range (Stevens et al., 2010). For woodland birds – for which habitat is primarily driven by resources relating to trees – pasture structure can also be an important consideration in regards to the availability and accessibility of food (e.g. seeds or insects; Buckingham et al., 2006; Howland et al., 2016b). Previous studies have shown pasture structure to be an important driver in the diversity of both reptiles (Brown et al., 2011; Howland et al., 2014; Manning et al., 2013) and plants (Dorrough et al., 2011; Tremont and McIntyre, 1994). These two groups are commonly considered as indicator taxa for grassy ecosystem health as their distribution reflects habitat suitability on a small scale (i.e. < 5 ha). In the case of reptiles, the role of pasture structure as habitat in previous studies has been represented by a composite measure of herbage mass, grass height, grass cover and/or the occurrence of non-grass structures (Fischer et al., 2004; Howland et al., 2014) and thus the relative importance of each individual structural component is unclear. Given the focus of this research on kangaroo grazing impacts, continuing to consider the preferences of different taxa in terms of average grass height (amount of herbage mass), grass height variability (heterogeneity of herbage mass) and the proportion of bare ground (distribution of herbage mass) is warranted (Howland et al., 2014; Neave and Tanton, 1989; Tremont and McIntyre, 1994).


In this section, the effects of pasture structure on floristic richness, floristic value score and both reptile abundance and reptile diversity are considered. As with previous analyses, the influences of grass association and canopy cover class are also considered in recognition of the overarching effects of these habitat characteristics on both pasture structure and biodiversity itself (Lunt, 1995; Michael et al., 2014; Tremont and McIntyre, 1994). It is recognised that whilst not impacted directly by kangaroo grazing, non-grass structural elements such as the occurrence of litter, logs, shrubs and rocks are also likely to drive microhabitat suitability for a number of taxa (Barton et al., 2011; Fischer et al., 2004; Manning et al., 2013; McDougall et al., 2016; McIntyre et al., 2014); and thus the interactive effects of these additional elements with pasture structure are also assessed.

## METHODS

### PASTURE STRUCTURE MEASUREMENTS

The pasture structure measurements used here are identical to those in the previous section, thus the methods used to determine average grass height, grass height variability and the proportion of bare ground can be found earlier in this document. Briefly, pasture structure (average grass height, grass height variability and the proportion of bare ground) was based on data collected from fifteen

1 $m^2$ quadrats per plot between September and November each year. In addition to these measures of pasture structure, the proportion of the 15 surveyed quadrats which were within 2 m of a rock, shrub or log was recorded, as was the average percent cover of leaf litter (based on visual estimation) within each quadrat across the plot. Data on the presence of rocks were collected in 2014 and 2015 only. The grass association for the 1 ha plot was assigned based on the grass association most frequently recorded at the quadrat scale, and the assigned canopy cover class was based on vegetation mapping (Wimpenny et al., 2015).

## REPTILE DIVERSITY AND ABUNDANCE

A 5 x 6 grid of corrugated concrete roof tiles (40 x 32 cm) were used to survey reptiles across each 1 ha plot. Distances between tiles were 20 m (east – west) or 25 m (north – south) and tiles were assumed to be independent sampling units for the small species most commonly observed. Tiles were positioned ~10 weeks prior to the onset of sampling to allow reptiles to become accustomed to utilising the artificial shelters and to allow some degree of curing of the vegetation beneath tiles. To prevent a change in reptile abundance and reptile diversity as a result of the addition of these artificial shelters, tiles were removed at the end of each survey period and repositioned in a similar location the following year.

Reptile surveys took place during spring and early summer (October-December) between 2012 and 2015. Tiles were checked (i.e. the area underneath was inspected before the tile was carefully replaced) in the morning on fine days when ground temperature in the shade was between 5 – 20ºC. Surveys undertaken when temperatures exceeded this maximum tended to result in few reptiles seen or high numbers of unidentified reptiles due to quick escape from beneath upturned tiles. Data collected during reptile surveys included the species and number observed for each tile at each of seven checks performed throughout the survey period, approximately 1-2 weeks apart. Any additional notes (e.g. lost tail, juvenile, etc.) were also recorded, as were incidental observations of reptiles not associated with a tile. Reptiles were captured only when required for identification or training purposes, in which case they were released carefully next to the tile to allow quick escape from predation but to avoid potential injury caused by placing a tile on top of an animal. Reptile surveys were approved under animal ethics permit CEAE 12-08.

Reptile diversity was calculated using Shannon's diversity index, based on the number of species observed at each plot. Reptile abundance estimates were also made assuming repeat captures of the same species under one tile represented the same individual. As such, reptile abundance estimates were the sum of the maximum number of each species observed under each tile during a single visit. For example, if two reptiles of the same species were observed simultaneously under a tile on one occasion, and only one animal of that species was observed under that tile on three other occasions, the total abundance of that species for that tile would be two. Incidental observations (not associated with a tile) contributed to the reptile diversity and reptile abundance of the plot only if that species was not observed in association with a tile. These procedures gave a conservative estimate for total reptile abundance.

## FLORISTIC RICHNESS

Floristic composition was recorded within 1 ha research plots during spring (October - November) in 2014 and 2015. A general survey of vascular plant floristic richness was made (total species richness, native species richness and exotic species richness) at each plot. A floristic value score was also calculated for the plot according to the method described by Rehwinkel (2014) for Natural Temperate Grasslands and

associated grassy ecosystems, which is based on a combination of native species richness and abundance with an additional weighting given for 'rare' native species.

### STATISTICAL ANALYSIS

Data were inspected for outliers, collinearity, and influential observations and covariates according to the methods described in Zuur (2009, 2014) prior to analysis using R version 3.3.1 (R development core team, 2008).

The effect of various pasture structure measures on reptile abundance, Shannon's diversity of reptiles, total, native and exotic floristic richness and floristic value score were assessed using linear models after first checking for non-linear relationships using GAMMs. The full model tested initially for each response included average grass height, grass height variability and the proportion of bare ground as continuous covariates and grass association and canopy cover class as factor variables. An interaction between average grass height and grass height variability was also included in the full model to allow detection of a specific preference for variability in short or long grass conditions. Site was fitted as a random term however year (as a factor) was included as a further fixed effect due to insufficient levels having been surveyed to include it as a random term. Backward selection was applied to each full model using both AICc and inspection of residuals to achieve the simplest valid model for each grass structural variable (Anderson, 2008). Additional interactions between significant terms were considered as a final step and retained where their effects improved model fit. Models for Shannon's diversity of reptiles and floristic value score were fitted assuming a Gaussian distribution, whilst a Poisson distribution and a log link function were used for reptile abundance and floristic richness measures. Tests for overdispersion were also performed for Poisson models and a negative binomial model was fitted as an alternative where overdispersion was detected.

The interactions between average grass height and the occurrence of logs, litter, rocks and shrubs, were assessed separately for each response variable with site and grass association as random terms. Due to the paucity of litter, shrubs and logs in grassland plots, only data from open woodland plots were considered for these analyses. Data on the presence of rocks were collected in 2014 and 2015.

## RESULTS

### RELATIONSHIPS BETWEEN PASTURE STRUCTURE AND REPTILES

A total of 1432 reptiles were observed during this four year study, spanning 18 different species.

### REPTILE ABUNDANCE

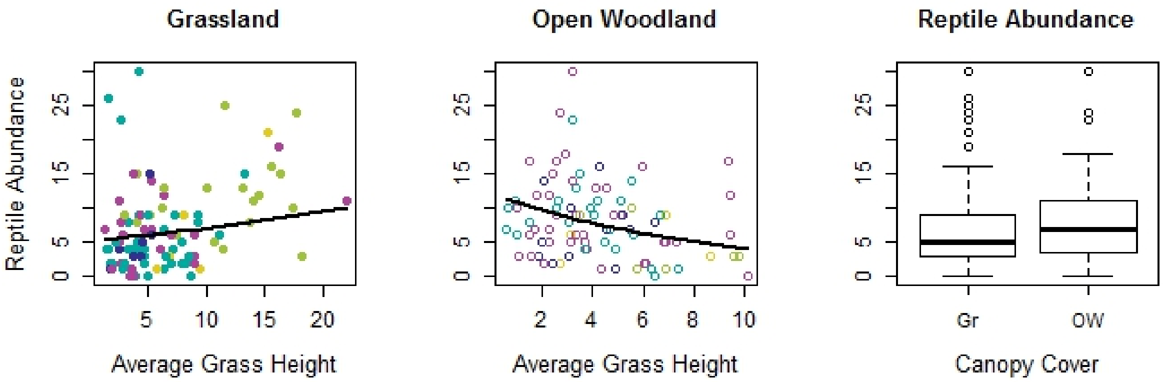
Reptile abundance ranged from 0 to 30 individuals at the plot level with a mean of 7.6 individuals detected per plot. There was a highly significant effect of both average grass height ($p < 0.001$) and canopy cover class ($p < 0.0001$) on reptile abundance. Overall reptile abundance increased with average grass height, and reptile abundance was higher in open woodland than grassland communities. A significant interaction between these two terms ($p < 0.0001$) indicated that the increased reptile abundance with increasing average grass height was a grassland-specific effect. A slight negative effect of average grass height on reptile abundance was observed in open woodland plots (Figure 16). Inclusion of terms for grass association, grass height variability and the proportion of bare ground were not supported in the model for reptile abundance, nor was the average grass height x grass height variability interaction.

The final model best predicting reptile abundance assumed Poisson errors and took the form:

$$Log(Reptile\ Abundance) = \alpha + \beta_1 Average\ Grass\ Height + \beta_2 Canopy + \beta_3 (Average\ Grass\ Height * Canopy) + Year + \mu$$

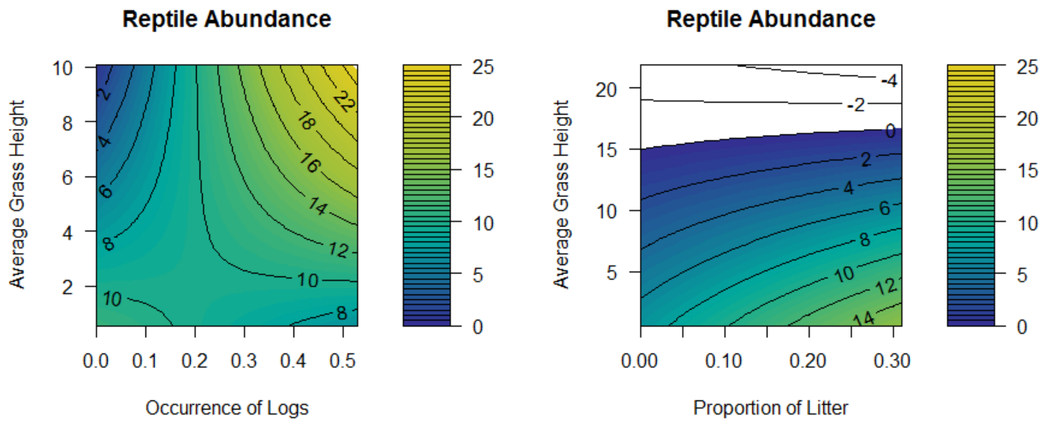
$\alpha$, $\beta_1$, $\beta_2$ and $\beta_3$ are terms estimated by the model and a significant effect of Year is averaged across the study period to give *c* (Appendix 8). The random effect of site is represented by µ.

Figure 16 The relationship between average grass height and reptile abundance for grassland (Gr, ●) and open woodland (OW, ○) plots, and the difference between the means for the two canopy cover classes. For simplicity, the fitted model shown does not take into account the effect of year but does include the random effects of site. Estimation of the variance around the fixed effects for the true Poisson mixed model is shown in Appendix 8. An effect of grass association (● annuals; ● exotic perennial; ● small tussock, ● medium tussock; ● native tuft) was not supported in this model.




The occurrence of logs was found to increase reptile abundance in open woodland plots, especially where average grass height was high (interaction: $p = 0.047$). Litter was also found to increase reptile abundance in open woodland ($p = 0.028$; Figure 17) although the interaction with average grass height was not significant ($p > 0.5$). There was no effect of shrubs on reptile abundance in open woodland plots, nor of rocks in either grassland or open woodland communities (data not shown).

Figure 17 Significant interactions between average grass height and logs, and average grass height and litter on reptile abundance in open woodland plots. Areas shown in white represent predictions outside the range of the data.



## REPTILE DIVERSITY

The number of reptile species observed varied between 0 and 7 (mean 2.7) within individual plots, giving a range in Shannon's diversity index of 0 to 1.84 (mean 0.75). Reptile diversity was found to be positively related to the proportion of bare ground (*p* = 0.042) and was higher in open woodland compared to grassland plots (*p* = 0.0001; Figure 18). There was no support for an interaction between canopy cover class and the proportion of bare ground. Average grass height was not supported as a term in the final model for reptile diversity, nor was grass height variability or an interaction between these two terms. Grass association was also not found to influence reptile diversity at the plot level. The final model for estimating reptile diversity assumed Gaussian errors and took the form:

$$Reptile\ Diversity\ =\ a\ +\ \beta_1 Bare\ Ground + \beta_2 Canopy + Year +\ \mu$$

where $\alpha$, $\beta_1$ and $\beta_2$ are parameters estimated by the model (Appendix 9). The random effect of site is represented by μ.

In open woodland plots, the combined effects of high log occurrence and greater average grass height was related to higher reptile diversity (*p* = 0.089). Neither the occurrence of shrubs nor litter showed significant effects on reptile diversity either independently or in association with average grass height (*p* > 0.2). In grasslands, rocks increased reptile diversity regardless of average grass height (rocks: *p* = 0.023; interaction with grass: *p* > 0.1; Figure 19) but no effect of rocks was observed in open woodland habitat.

Figure 18 The relationship between the proportion of bare ground and Shannon's diversity index for reptile diversity in grassland (Gr, ●) and open woodland (OW, ○) plots, and the difference in the means between these two canopy cover classes. For simplicity, the fitted model shown does not consider the effect of year. Fitted models do consider a random term for site. Confidence intervals for these models can be found in Appendix 9. An effect of grass association (● annuals; ● exotic perennial; ● small tussock, ● medium tussock; ● native tuft) was not supported in this model.

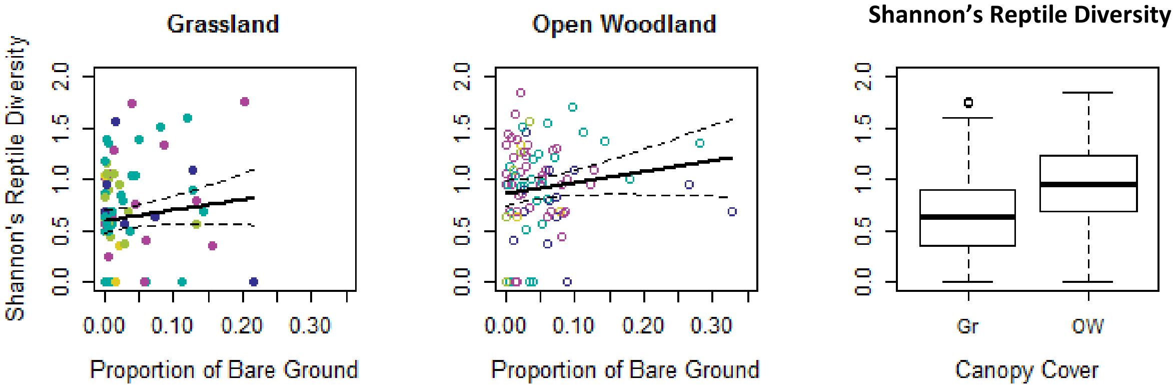
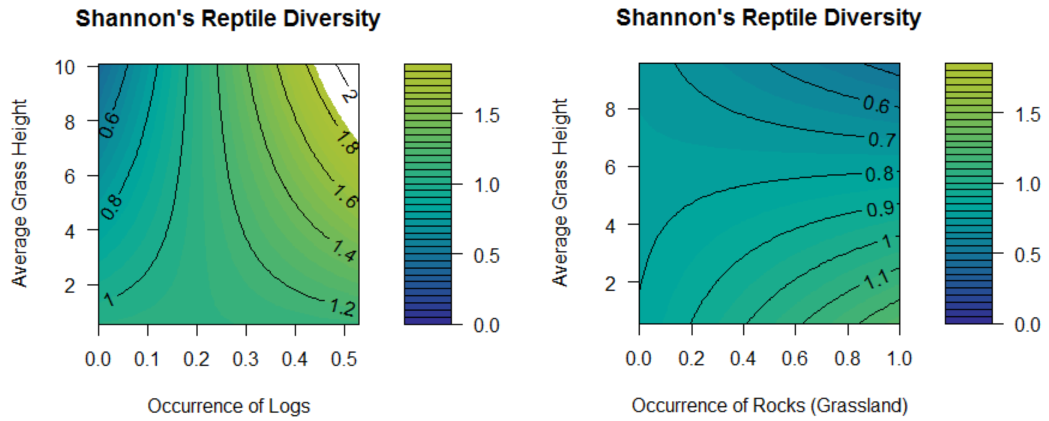


Figure 19 Significant interactions between the effects of average grass height and logs (open woodland) and average grass height and rocks (grassland) on reptile diversity. Areas shown in white represent predictions outside the range of the data.




## RELATIONSHIPS BETWEEN FLORISTIC RICHNESS AND PASTURE STRUCTURE

Total floristic richness ranged from 19 to 198 within 1 ha plots, with an average of 56 native and 42 exotic species being detected per plot. Floristic value scores ranged from 0 to 71. Grass height variability was a key variable in estimating total, native and exotic species richness; and both canopy cover class and grass association were also included in the final model for most floristic response variables.

## TOTAL FLORISTIC RICHNESS

Total floristic richness (on a log scale) was found to increase with increasing grass height variability ($p$ = 0.005) and was higher in open woodland plots compared to grasslands ($p$ = 0.029). Although not significant at the 0.05 level, total floristic richness also differed between plots dominated by different grass associations, with medium tussock, native tuft and annual dominated pastures having a greater total floristic diversity compared to exotic perennial and small tussock dominated grass associations. A non-significant term for grass association was thus included in the model to improve residual homogeneity however relationships for individual grass associations are not presented (Figure 20). Average grass height, the proportion of bare ground and the interaction between average grass height and grass height variability were not supported as terms in the final model, which assumed negative binomial errors and took the form:

$$Log(Total\ Floristic\ Richness) = a + \beta_1 Grass\ Height\ Variability + \beta_2 Canopy + \beta_3 Grass\ Associaiton + \mu$$

$\alpha$, $\beta_1$, $\beta_2$ and $\beta_3$ were parameters estimated by the model (Appendix 10) and the random effect of site is represented by µ.

In regards to additional habitat elements, total floristic richness was higher in plots which had high average grass height and few logs or shrubs, or low average grass height and a high occurrence of logs or shrubs (interactions both: $p$ < 0.001). Litter also had a positive effect on total floristic richness when average grass height was high (interaction: $p$ = 0.006; Figure 21).

Figure 20 The relationship between grass height variability and total floristic richness for grassland (Gr, ●) and open woodland (OW, ○) plots, and the difference in means between the two canopy cover classes. The fitted model shown here includes a random term for site but does not consider the non-significant effect of grass association (● annuals; ● exotic perennial; ● small tussock, ● medium tussock; ● native tuft) fitted in the true model to improve model assumptions. Confidence intervals for the true models can be found in Appendix 10.

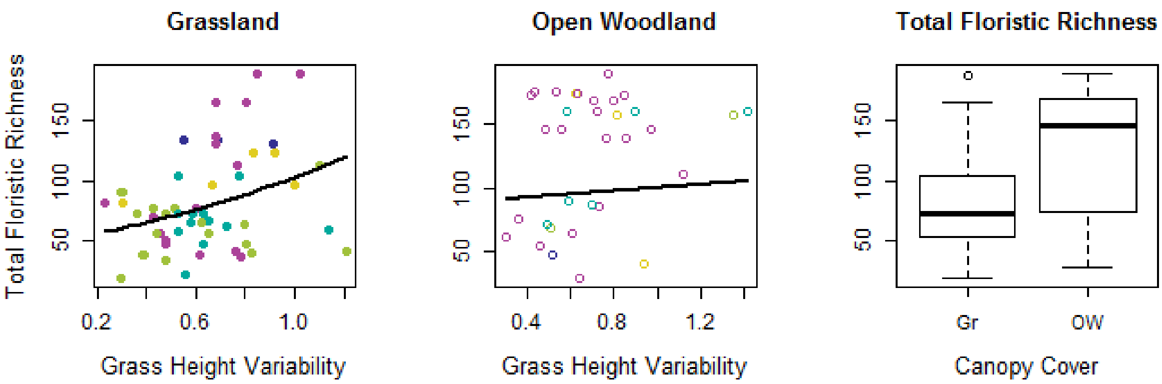
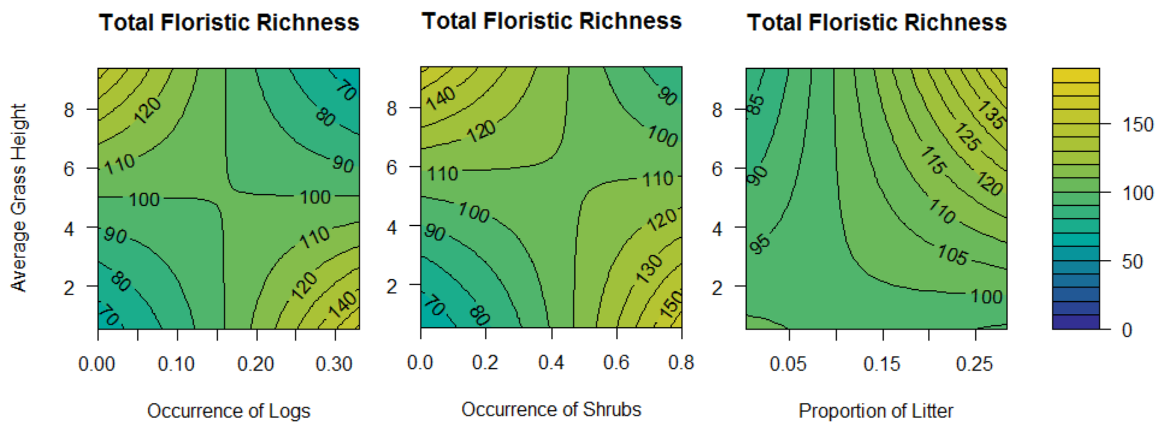



Figure 21 Interactions between average grass height and the occurrence of and logs, shrubs and litter on total floristic richness. All relationships reflect data from open woodland plots only.




## NATIVE FLORISTIC RICHNESS

Native floristic richness increased in response to increasing grass height variability especially in grassland plots (grass height variability: $p < 0.001$; interaction: $p = 0.048$) although native floristic richness was higher in open woodland over all ($p = 0.006$; Figure 22). Grass association was also a significant term in the model predicting native floristic richness ($p = 0.002$), with medium tussock and native tuft dominated grass associations containing the highest numbers of native plant species and very few native species being detected in plots dominated by exotic perennial grasses. Inclusion of terms representing average grass height, the proportion of bare ground or the interaction between average grass height and grass height variability were not supported in the final model for native floristic richness, which was fitted assuming a negative binomial distribution due to overdispersion and was of the form:

$$Log(Native\ Floristic\ Richness) = \alpha + \beta_1 Grass\ Height\ Variability + \beta_2 Canopy + \beta_3(Grass\ Height\ Variability * Canopy) + \beta_4 Grass\ Association + \mu$$

where $\alpha$, $\beta_1$, $\beta_2$, $\beta_3$ and $\beta_4$ were parameters estimated by the model (Appendix 11) and the random effect of site is represented by μ.

Native floristic richness was higher in plots with higher average grass height and a low occurrence of logs and shrubs, or low average grass height and high occurrence of logs and shrubs (interaction with logs: $p$ = 0.003; interaction with shrubs: $p$ = 0.019; Figure 23). Rocks had a positive effect on native floristic richness in grasslands ($p < 0.001$) but there was no significant interaction between this effect and average grass height ($p > 0.8$). There was no significant effect of litter on native floristic richness.

Figure 22 The relationships between grass height variability and native floristic richness for each grass association (● annuals; ● exotic perennial; ● small tussock, ● medium tussock; ● native tuft) within grassland (Gr, ●) and open woodland (OW, O) plots. The difference in means between the two canopy cover classes is also shown. Fitted models include a random term for site. Confidence intervals for these models can be found in Appendix 11.

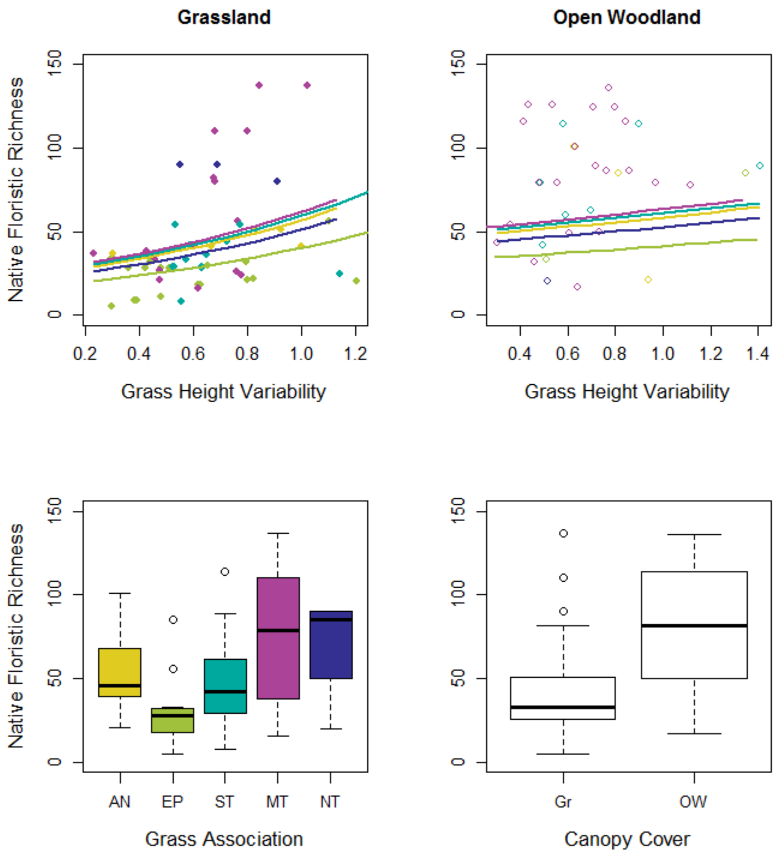
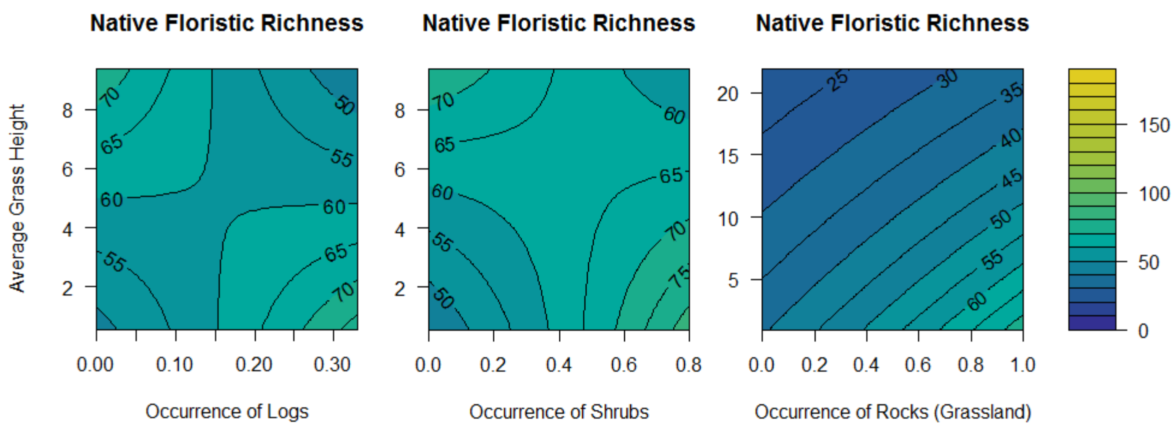



Figure 23 The interactive effects between average grass height and logs, shrubs and rocks on native floristic richness within open woodland (logs, shrubs) and grassland (rock) plots.



## EXOTIC SPECIES RICHNESS

For exotic species richness, a positive effect of grass height variability was observed alongside a significant effect of grass association (Figure 24). Terms for canopy cover class, average grass height, the proportion of bare ground and an interaction between average grass height and grass height variability were not retained in the final model. The final model fitted assuming negative binomial error structure was of the form:

$$Log(Exotic\ Floristic\ Richness) = a + \beta_1 Grass\ Height\ Variability + \beta_2 Grass\ Association + \mu$$

where $a$, $\beta_1$ and $\beta_2$, were parameters estimated by the model (Appendix 12) and µ represents the random effect of site.

Logs and shrubs had a positive influence on exotic floristic richness when average grass height was low, and a negative effect when average grass height was high (both interactions: $p < 0.0001$; Figure 25). Litter had a positive effect on exotic floristic richness in open woodlands when average grass height was high ($p = 0.006$) whilst in grasslands, the combined effects of increased rock occurrence and high average grass height had non-significant a negative influence ($p = 0.089$). There was no effect of rocks on exotic floristic richness in open woodland plots.

## FLORISTIC VALUE SCORE

Maximum floristic value score (FVS) decreased at higher average grass heights ($p = 0.033$). Grass association was also a key driver of FVS ($p < 0.001$), with the native perennial grass associations (especially medium tussock) having greater FVS compared to annual and exotic perennial dominated grass associations (Figure 26). The model was not improved by considering an average grass height by grass association interaction. Grass height variability, the proportion of bare ground, canopy cover class and an interaction between average grass height and grass height variability were not supported in the final model, which assumed Gaussian errors and took the form:

$$Floristic\ Value\ Score = a + \beta_1 Grass\ Height + \beta_2 Grass\ Association + \mu$$

where $a$, $\beta_1$ and $\beta_2$ were parameters estimated by the model (Appendix 13) and µ represents the random effect of site.

Floristic value score was highest in plots which had either low average grass height in association with few logs or shrubs; or high average grass height in association with a high occurrence of logs and shrubs (interaction for logs: $p = 0.008$; interaction for shrubs: $p = 0.011$; Figure 27). The combination of low litter cover and low average grass height also benefited floristic value score (interaction: $p = 0.035$). Rocks had a positive effect on floristic value score in grasslands ($p = 0.014$) and a near-significant negative effect in open woodlands ($p = 0.066$). Both of these effects were more prominent under high average grass height conditions but the interactions were not statistically significant.

Figure 24 The relationship between grass height variability and exotic floristic richness for each grass association (● AN, annuals; ● EP, exotic perennials; ● ST, small tussock; ● MT, medium tussock; ● NT, native tuft). The difference in means between each grass association is also shown. Fitted models include a random term for site. Confidence intervals for these models can be found in Appendix 2. A term for canopy cover (● grassland; ○ open woodland) was not supported in this model.

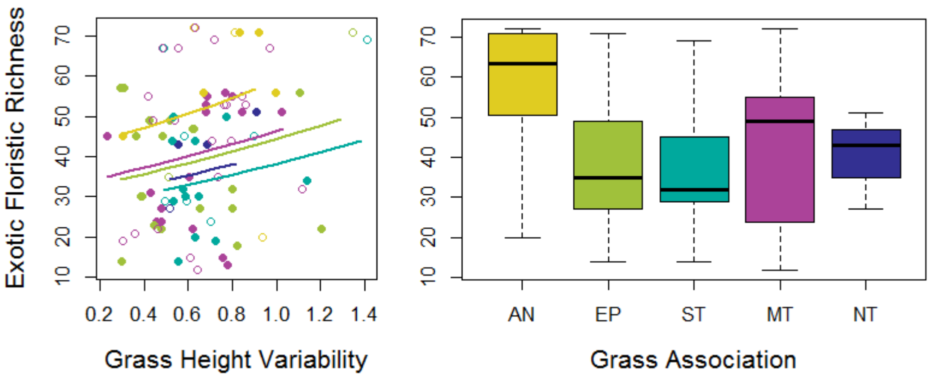



Figure 25 The significant interactive effects between average grass height and logs, shrubs and the proportion of litter on exotic floristic richness within open woodland plots, and between average grass height and rocks in grasslands.

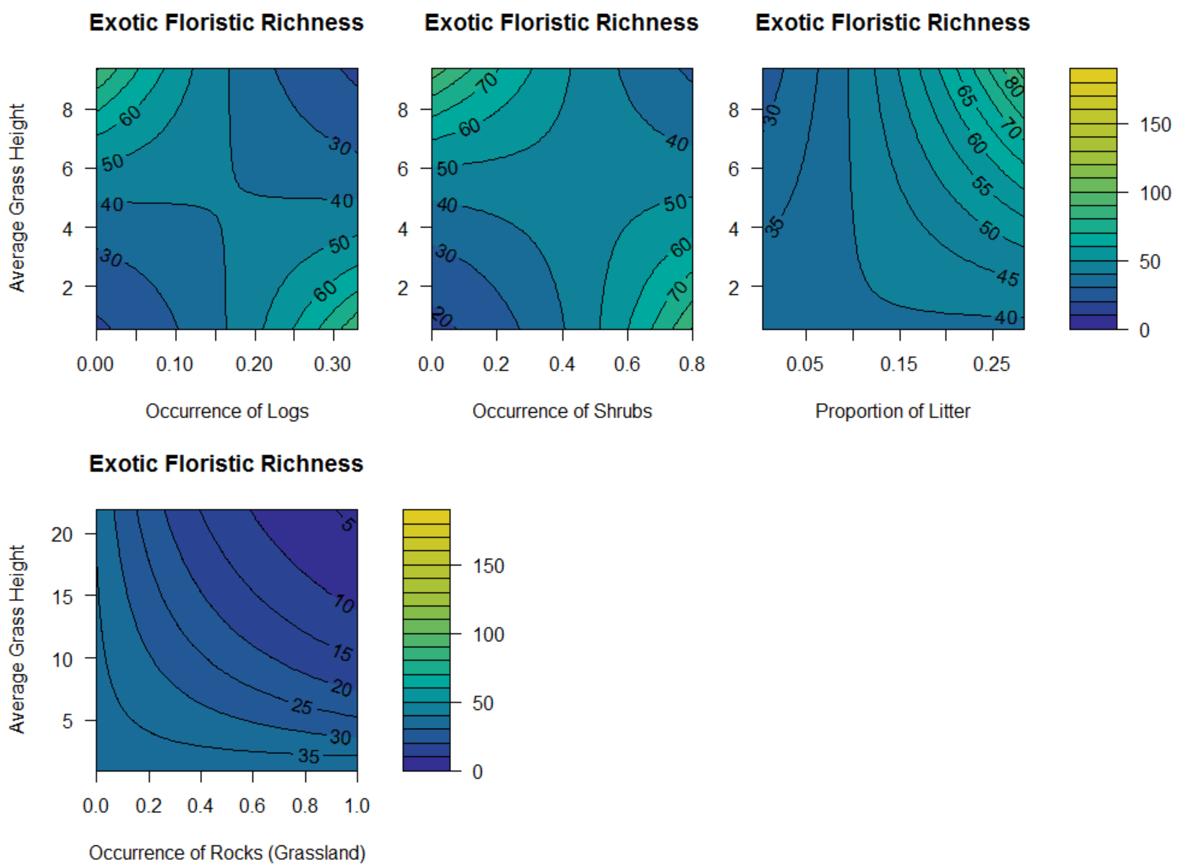


Figure 26 The relationship between grass height variability and exotic floristic richness for each grass association (● AN, annuals; ● EP, exotic perennials; ● ST, small tussock; ● MT, medium tussock; ● NT, native tuft). The difference in means between each grass association is also shown. Fitted models include a random term for site. Confidence intervals for these models can be found in Appendix 13. A term for canopy cover (● grassland; ○ open woodland) was not supported in this model.

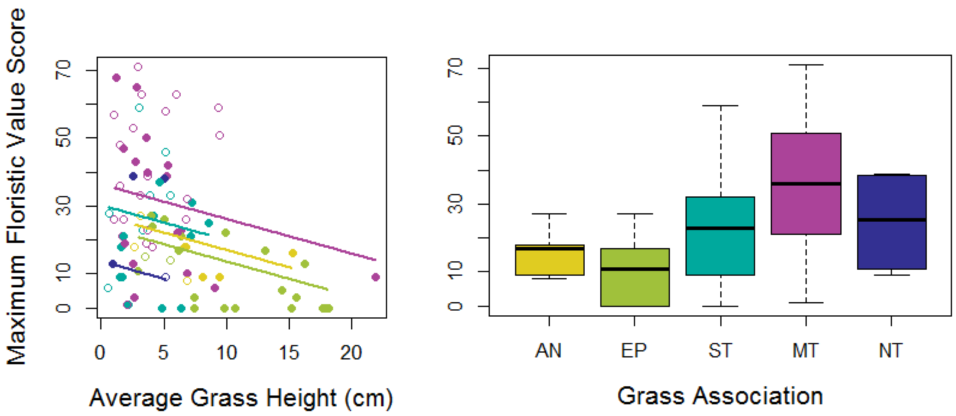
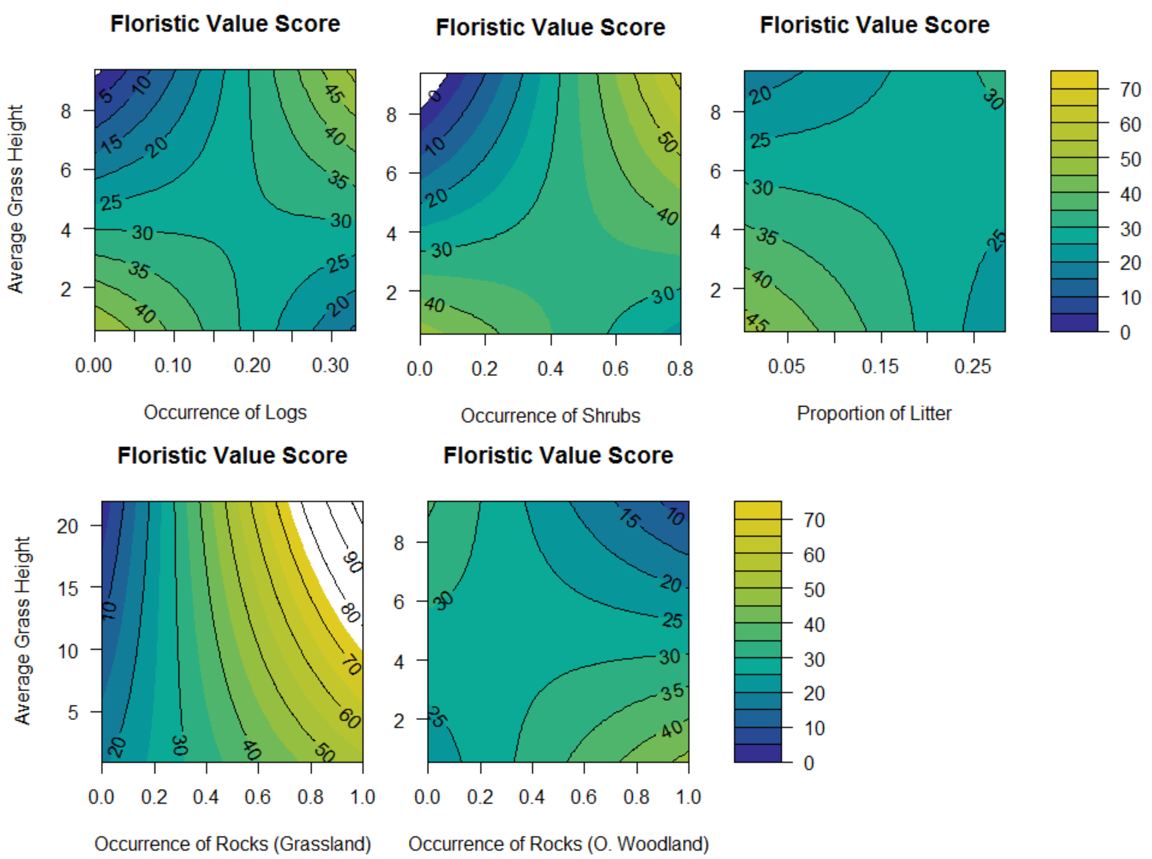



Figure 27 Significant interactions between average grass height and logs, shrubs, rocks and the proportion of litter on exotic floristic richness within open woodland plots, and between average grass height and rocks in grasslands. White areas represent predictions outside the range of the data.



# DISCUSSION

The response variables chosen to represent grassy ecosystem biodiversity in this study (reptile abundance and reptile diversity, floristic richness and floristic value score) each differed in their responses to specific elements of grass structure. Reptile abundance, for example, was positively influenced by average grass height whilst reptile diversity was influenced by the proportion of bare ground. Measures of floristic richness responded positively to increased grass height variability and floristic value score decreased within increasing average grass height. All three of the individual measures we chose to describe the amount, variability and distribution of grass within grassy ecosystems were useful in predicting the biodiversity conservation value of pasture for different taxa. The five categories of grass association and two levels of canopy cover class were also commonly found to significantly influence biodiversity measures, indicating that intrinsic differences in structure and biodiversity between these ecosystem types are also important considerations for management.

The strong positive effect of increasing average grass height on reptile abundance in grasslands is likely driven by the preference of a few grassland specialist species for habitat conditions associated with high herbage mass. Although the responses of individual species have not been examined in this report, the grassland-adapted Striped Legless Lizard *Delma impar* and Three-toed Earless Skink *Hemiergis talbingoensis* were both commonly observed species in this study and each has previously been observed to respond positively to the increased shelter and availability of insect prey associated with intermediate to long grass conditions (Howland et al., 2014). Given that *D. impar* is threatened across its former range in south eastern Australia, further analysis is warranted to test the specific preference for long grass in this species (Dorrough and Ash, 1999; Howland et al., 2016a).

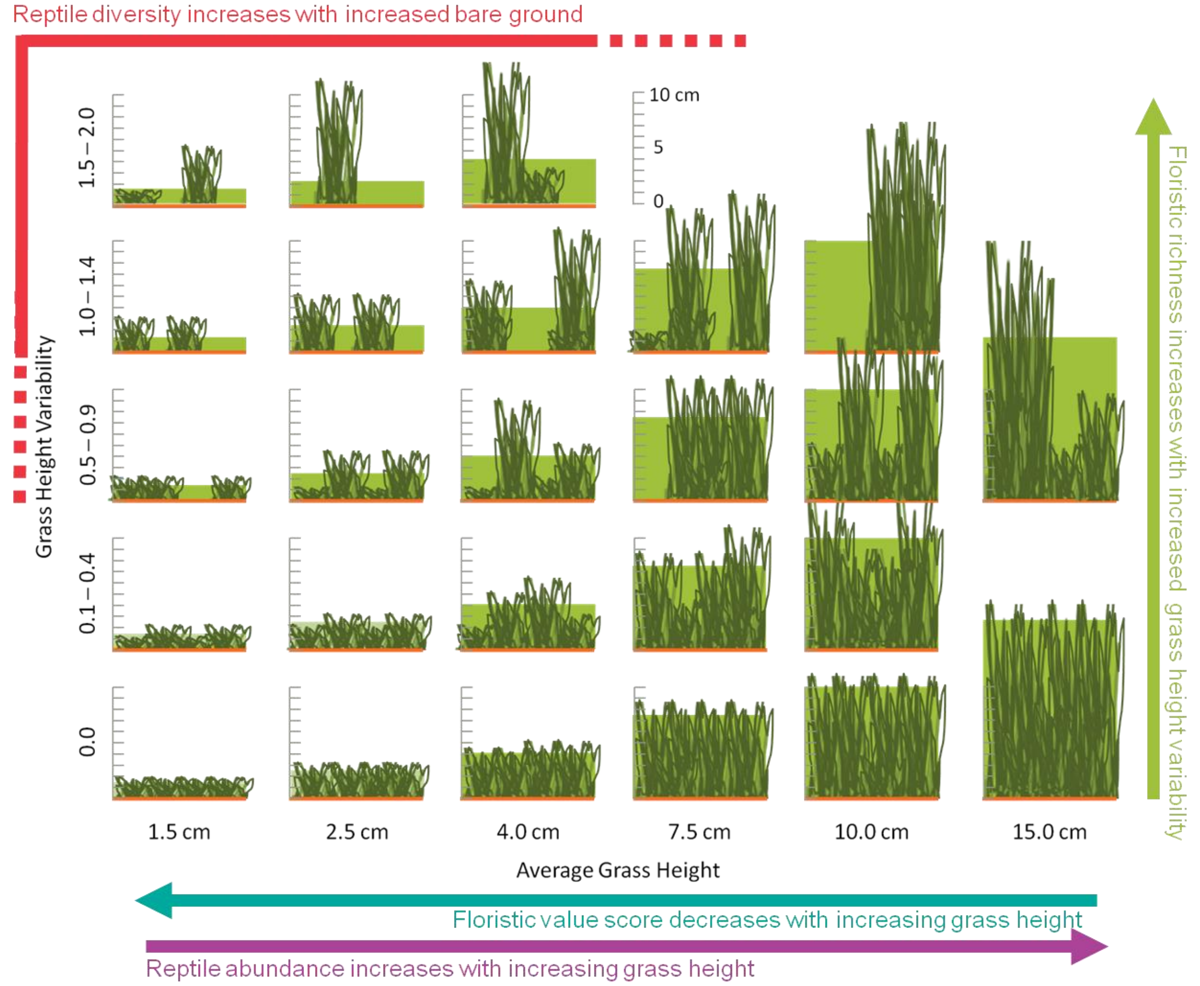
A higher reptile abundance in open woodland plots and reduced dependency on grass height by reptiles in this habitat suggests that the mix of grass and non-grass structures (e.g. logs, shrubs) available in open woodland drives abundance for the remainder of the common reptile species observed (Dorrough et al., 2012; Fischer et al., 2004; Michael et al., 2014). The positive effect of litter on reptile abundance, as well as that of logs in high grass conditions, likely indicates the role of woody debris in providing food, shelter and open (i.e. grassless) basking sites for woodland or generalist species in otherwise homogenous grassy ecosystems (Manning et al., 2013; Michael et al., 2014). Similar factors drove reptile diversity, where the availability of a range of habitat niches brought about by bare ground (i.e. patchily distributed grass) and the addition of non-grass elements (logs in open woodland and rocks in grassland) again represented a benefit to reptile diversity in this and previous studies (Michael et al., 2004). It should be noted that the maximum proportion of bare ground sampled in our study was less than 0.35 (35%), and that higher proportions of bare ground may not continue to show a positive effect on reptile diversity.

Grass height variability at the 1 ha scale had a positive effect on total, native and exotic floristic richness in this study. Interestingly, there was no support for the interaction term between average grass height and grass height variability for any plant response variable, suggesting that highly variable short grass was just as beneficial to plant species richness as comparatively variable grass under higher herbage mass conditions. In practice however use of the coefficient of variation as the relative grass height variability score (i.e. the standard deviation in height measures divided by the mean) resulted in an absence of grass height variability scores greater than 0.8 (80%) above an average grass height of around 10 cm. As such, the benefits of high grass height variability on floristic richness also indicate that floristic richness, as well as floristic value score, would likely be higher under shorter grass conditions as has been described previously (Lunt, 1991; Lunt et al., 2012; Morgan, 1998; Tremont and McIntyre, 1994). An assessment of relationships between structural variables and floristic diversity at a finer scale (e.g. 0.5 – 1 $m^2$) may also better reflect the responses of individuals species to their immediate habitat (Jalonen et al., 1998).

Native floristic richness was higher in open woodlands compared to grasslands but all floristic richness measures in this canopy cover class were benefited by a ground layer dominated either by high average grass height or by logs and shrubs. This likely reflects two suites of species; namely those adapted to grassland and open woodland conditions respectively (Vivian and Baines, 2014). The opposite effect was true for floristic value score which was highest where high average grass height and logs or shrubs occurred together, or where low average grass height was found in the absence of non-grass structures. The reason for this contrasting result is not immediately clear but may reflect the relative weighting given to particular species in calculation of floristic value score (Rehwinkel, 2014). Exotic species richness increased where litter cover was high in association with high average grass height, which may either represent invasion by a diversity of exotic plants into open ground in habitats already dominated by tall exotic grasses, or a response of exotic plants to the increased soil nutrient levels associated with the decomposition of organic matter (Dorrough et al., 2006; McIntyre et al., 2014). Where the average grass height was low, as was more common in open woodland pastures dominated by native grasses, an increase in litter cover – again indicative of an open structure – was associated with increased floristic value score. Rocks were the only non-grass structural element commonly found within grasslands and these were also associated with increased native species richness and floristic value score. Again, such non-grass structural attributes may decrease herbage mass in grasslands allowing opportunity for inter-tussock forb germination (McDougall et al., 2016).

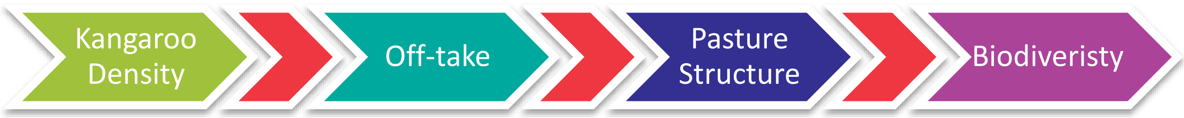
Overall, measures of biodiversity across the two taxa examined here (plants and reptiles) are supported by a variable grassy layer. Different conservation outcomes can be expected for different taxa however depending on whether pasture structural heterogeneity is achieved through grass which is variable in its height, its distribution, or it's co-occurrence with non-grass structural elements such as logs, shrubs, litter or rocks (Figure 28). The influence of grass association on the diversity of different taxa supports the need to conserve and map these different associations.

Figure 28 Specific attributes of pasture structure, namely average grass height, grass height variability and the proportion of bare ground, vary in their effects on individual taxa. This schematic summarises the different pasture structure attributes and their predicted effects on reptile abundance and diversity, and on floristic richness. The additional significant influences of canopy cover (grassland or open woodland), grass association (annuals, exotic perennial, small tussock, medium tussock and native tuft; Table 1) and non-grass habitat elements such as rocks, logs, shrubs and litter on these relationships should also be considered when interpreting this diagram.



# SUMMARY AND MANAGEMENT IMPLICATIONS

This study has developed quantitative models describing relationships between kangaroo density and off-take, off-take and pasture structure, and pasture structure and biodiversity.




From this work, we have determined that under the broadly 'average' climatic conditions experienced in the ACT between 2012 and 2015, kangaroo off-take is likely driven by the availability of 'green pick', that a relationship between rates of off-take and pasture structure is not detectable above intrinsic influences of grass association and canopy cover class at the 1 ha scale in spring, and that a variable pasture structure including both grass and non-grass elements is beneficial for biodiversity conservation.

A number of local studies have previously examined similar ecological relationships in the ACT, including an assessment of kangaroo diet (Billing, 2007), the effect of weather on vegetation (Fletcher, 2006), the effect of vegetation on kangaroo population growth rate (Fletcher, 2006), how kangaroo density effects ground layer vegetation (Godfree, 2014; Howland et al., 2014; McIntyre et al., 2014; Neave and Tanton, 1989), and the relationships between pasture structure and biodiversity (Barton et al., 2011; Howland et al., 2014; Manning et al., 2011; McIntyre et al., 2010; Neave and Tanton, 1989). Whilst our results fit within the broad principles explored within these earlier studies, our research also extends the capacity of land managers to understand and respond to the ecological processes at a sub-landscape scale (1 – 100's ha) such that conservation gains can be maximised according to specific environmental and climatic conditions.

The strong influence of available herbage mass ('standing crop') on off-take by kangaroos is an important unexpected result from this study. In practice, this result indicates that where pasture growth exceeds off-take, the resulting 'long' grass ceases to be a preferred food source for kangaroos. The pasture structure is thus unlikely to be influenced by grazing. The point at which grass becomes 'long' enough to observe this effect differs according to grass association. Even if long grass is still actively growing (Brougham, 1956), the decline in foraging efficiency associated with long grass may – paradoxically – result in animals becoming nutritionally stressed (Curran et al., 2010). Based on the known relationship between pasture growth and climate (Clark et al., 2000; Cullen et al., 2008; Fletcher, 2006), this result highlights the likely benefit of models allowing environment- and climate-specific predictions of target kangaroo densities for individual management units. In face of the uncertainty inherent in forecasting weather, and further still in predicting pasture growth rates, these results also emphasise the importance of having alternative herbage mass management tools, such as slashing, cattle grazing and fire, available in the management 'toolbox' such that pasture can maintained within palatable thresholds (despite a varying climate) from season to season. Such management would aim to maintain both pasture productivity and structural variability – and to facilitate the natural role of kangaroos in these processes – whilst avoiding large expanses of the conservation estate becoming over-grown or over-grazed and hence structurally more homogenous and species poor. Kangaroos alone will not be sufficient to maintain conservation appropriate pasture structure in the fragmented Canberra Nature Park environment as would occur within less modified landscapes however, as whilst kangaroo density can be

reduced to target levels with around 6-12 months lead time (ACT Government, 2016), a range of factors preclude population supplementation as an option where pasture growth is rapid (ACT Government, 2017b).

The effect of grass association on ecological processes at all levels was another major finding of this research. Consideration of the palatability and structural differences between different grass associations demonstrated the relative contributions different pasture types can make to grassy layer heterogeneity at the site or landscape scale (Lunt, 1995). For example, exotic perennial grasses tended to form tall, dense grass swards under most levels of kangaroo grazing although shorter areas were often kept short by grazing due to the high nutritional content of the fresh growth. Small tussock dominated grass associations often occurred on shallow, rocky soil and so along with medium tussock grasses and to some extent native tuft associations, tended to maintain an open structure with high relative variability and a reasonable proportion of bare ground which promoted floristic and reptile diversity. In regards to canopy cover, grass was patchier and non-grass structural elements more common in open woodland ecosystems whilst rocks played a pivotal role in providing abiotic structure in grasslands. This quantitative insight into the structural attributes of different grass associations and canopy states common across the lowland grassy ecosystem of the ACT will allow managers to match conservation effort to areas most likely to favour particular species or suites of species of concern, based on an understanding of their specific habitat requirements. Similarly, the ability to recognise the different structural elements referred to in this study within the broader landscape (e.g. grass height of 7 cm, or 10% bare ground), and to make adjustments to structural elements where preferred combinations are missing, will enable managers to more easily maintain a strong and biodiverse ecosystem.

The habitat responses of individual species have not been assessed in this report. Thus the flow on effects of kangaroo grazing, pasture structure and the relative influences of grass association and canopy cover has not been determined for threatened or endangered lowland species. The results presented here do however provide a framework for such analyses to be undertaken and understood in terms of the broader ecosystem function. The dataset used in this study contains data on the fine scale microhabitat (1 $m^2$) preferences of the threatened Striped Legless Lizard (*Delma impar*) as well as the plot level habitat conditions observed in association with a number of rare plants. Targeted surveys using appropriate capture techniques for species such as Pink-tailed Worm-lizard, Grassland Earless Dragon and Golden Sun Moth (ACT Government, 2017a) could be undertaken using a similar experimental design. Similarly the influences of alternative herbage mass removal techniques such as slashing and fire could be substituted for off-take in this framework and the biodiversity impacts inferred without need for further survey of all biodiversity variables.

One of the main drivers of ecosystem function and the interaction of kangaroos with their environment has been shown in previous studies to be weather (Caughley et al., 1984; Clark et al., 2000; Fletcher, 2006). Specifically, the interaction between rainfall and temperature during the key growth times for different grasses can have a tremendous influence on pasture and subsequently kangaroo productivity. As such, it is important to view the relationships presented here as being informative only under similar climatic conditions. After consecutive years of particularly high or low rainfall, or where temperatures are observed in either extreme during key pasture growth periods, the kangaroo-pasture dynamics in this environment are likely to change. Thus additional sampling would be recommended under such conditions in order to continue to inform kangaroo management and promote the conservation of biodiversity under the range of climatic and environmental conditions likely to be observed in these endangered communities in the future.

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# APPENDIX 1

## METHODS FOR MEASURING KANGAROO OFF-TAKE

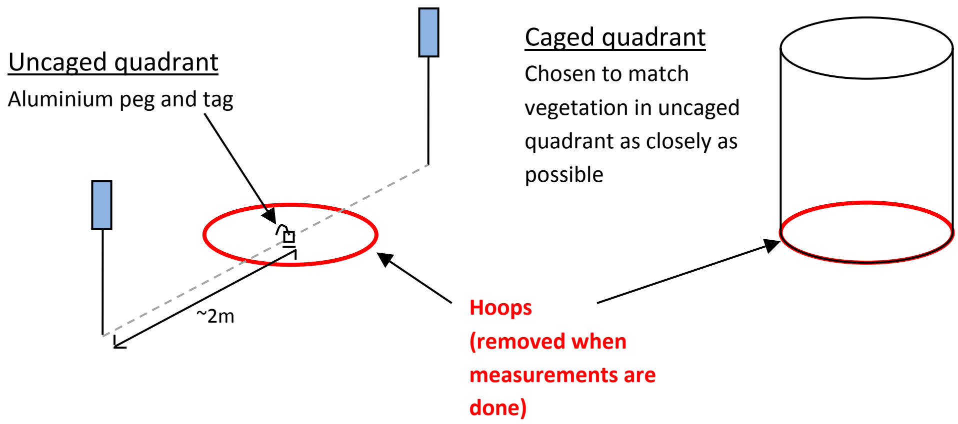
Kangaroo off-take will be measured at two scales. At the reserve (site) scale, 30 pairs of off-take cages will be set up according to a randomised grid design and monitored at 6 monthly intervals (Reserve Level Off-take). At the plot scale, two pairs of off-take cages will also be set up at predetermined intervals along north-south running transects (Plot Level Off-take) to be monitored at the same time interval. The measurements made for all cages (regardless of the scale which they represent) are the same. Each pair of cages consists of one uncaged quadrat (a peg in the ground) and one caged quadrat (surrounded by 50mm mesh).

### RESERVE LEVEL OFF-TAKE

The GPS coordinates of the 30 sampling sites will have been loaded into your GPS. Each one of these points should be set up as the 'uncaged quadrat' of a pair. To do this, hammer an aluminium tent peg and metal tag into the ground, and place two pin markers approx. 2 m either side (such that the peg is on the imaginary line between them) to enable easier detection of the uncaged quadrat in future. Next place a hoop (55 cm diameter) around the peg to demarcate the uncaged quadrat and measure the vegetation as described below. Once measured, find a nearby area of vegetation comparable to the uncaged quadrat (in terms of vegetative composition, structure and herbage mass). Measure the vegetation as for the 'uncaged quadrat' before surrounding it with a 50 mm mesh cage (~ 85 cm diameter) with white trim (plastic mesh or rope) to increase its visibility to management/research vehicles. Secure the cage to the ground with at least 6 medium or 8 small tent pegs. Where the ground is soft, more tent-pegs should be used and 'crossed over' where necessary.

## PLOT LEVEL OFF-TAKE

The north-western corner of the research plots will also be in your GPS. The transects on which the uncaged quadrat should be positioned run south from 10 m and 90 m along the (magnetic) northern boundary of the plot. The first cage should be placed 15 m south of the northern edge of the plot and subsequent sampling should be done at 6 m intervals along the transect (to avoid pellet count quadrats). It is not necessary to mark the uncaged quadrats with pin markers as they should be easier to find using a compass and metal detector. The position of the caged quadrats should be determined as described for the Reserve Level Off-take cages.




## MEASURING THE VEGETATION

***Reserve*** **and** ***Plot***

The reserve and plot ID should be chosen from the drop down lists provided in the spreadsheet.

***Surveyor***

Just the person who is doing the measurements initials should be recorded here.

***Date***

In dd/mm/yy format please.

***Plate meter:***

There are three types of falling plate meter, the round one, the square one and the Jenquip ones. They each give a different value depending on the height of the grass and so it is important to specify in the data sheet which one is being used. As we have a number of comparable Jenquip devices it would be best to use these consistently.

***Transect:***

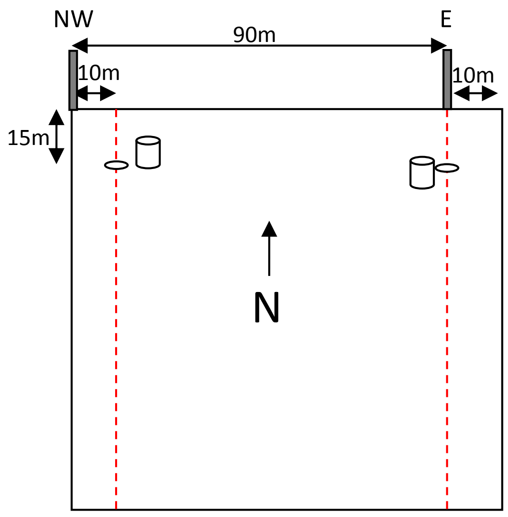
This refers to you either being on the east or west transect of the plot. Please choose from the drop down list.

***Timing:***

If the quadrat is being measured for the first time, select 'New'. If you are measuring a quadrant after it's been in place for 6 months already select 'Revisited'. In general you will do both in a single visit.

***Uncaged plot placement:***

Please specify how many meters south of the northern edge of the plot the uncaged quadrat was placed. Initially this will be 15 m but if there is a blackberry bush or some other awkward feature in the way it can be placed elsewhere (9 m or 21 m – remember this line is also used for pellet counts and you don't want the uncaged quadrant to be near a multiple of 6 m).




***Grass No. 1-3:***

For each quadrat, identify the dominant three **grasses** based on their contribution to the dry weight of the herbage mass. Look at the reference photos for a guide to help you know how much different grasses weigh when dried. Please choose the grass species from the list provided. If it's not on the list then make a note in the notes section of what it was and I'll add it to the list for future. Note that it is not necessary to ID *Rytidosperma spp.* to species level.

***Percent grass cover:***

This is the percentage of the quadrat which is covered by grass (tussock base or overhanging foliage).

***Percent bare:***

This is the percentage of the ground within the quadrat which is bare dirt. A cover of rock, lichen or any other crust does not count as bare. This measure is to do with erosion potential.

***Percent green:***

This is the percentage of the attached grass (i.e. not unattached thatch, see Glossary) which is green. Note that it is often much lower than you'd think – it often helps to grab a handful and then look closely at how many blades are green vs. dried.

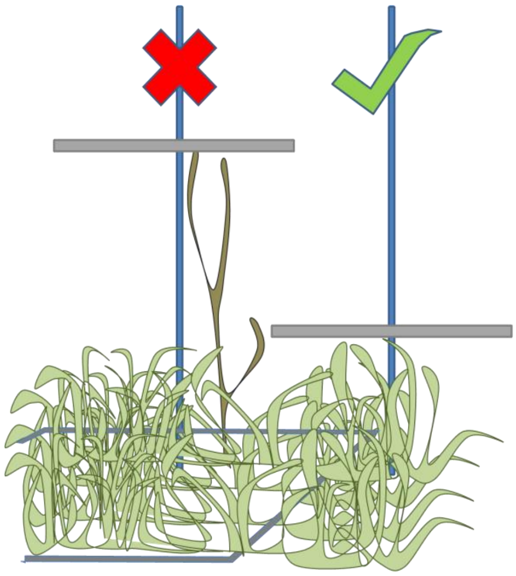
***Average grass height:***

The average height of the grass over the plot should reflect just the grass blades, not the flowering stems or any thatch. This is true even of *Aristida* sp. (which is pretty much only stem at some times of year). Where there are patches without any grass, these should be considered as having a grass height of zero. As such, a quadrat with 50% cover of 10 cm grass and 50% cover of no grass would have an average height of 5 cm. To estimate this measure, place the ruler in a couple of different spots within the quadrat

and average each reading to give the overall average to be recorded. With time you'll be able to do this by eye whilst holding the ruler in the centre of the plot.

***Falling plate meter:***

The falling plate meter is designed to give an approximation of the herbage mass of the grass (**excluding flowering stems**), with both grass height and density contributing to where it falls. The plate meter should be positioned such that the rod is touching the ground (i.e. penetrates any thatch or litter) and so that there are no obstacles (such as sticks, woody stems or rocks etc.) influencing the reading. If there are obstacles in the quadrat they should be removed where possible. Where removing them is not possible try and measure a comparable amount of grass of the same species nearby where no obstacles are present. If the ground is steeply sloped, the plate meter should be used perpendicular to the ground so that the plate does not get caught on the ground.



***Percent contribution of non-grass***

This measure should also be based on an estimate of dry weight contributions. If the plot has a short covering of grass and lots of woody weeds, then you might enter 90% for woody weeds (hence assuming grass makes up only 10% of the total dry weight). If there are equal amounts of grass and weeds it would be 50% non-grass. Note that this could be anything from woody weeds, to native forbs, to sedges and rushes. Only ground layer plants count so shrubs and trees above about 30 cm are excluded. Small saplings contributing to the ground layer are included.

***Cutting a plot***

When cages are revisited, the grass should be clipped for drying and weighing. As much as is possible, non-grass vegetation, litter, dirt and anything else that isn't grass should be excluded either before the quadrat is clipped or from the clipped material. Note that flowering grass stems and thatch should also be removed prior to the quadrat being clipped. Clipping the plots is the most accurate way of knowing herbage mass (and the most consistent between people), and we will also use this data to calibrate the indirect (height and plate meter) measures. Grass should be clipped as low as a kangaroo can graze, which is about 1 cm from the ground and as close as you can really get without losing bits of grass or a finger. **Be really careful with the clippers and wear gloves.** Really short bits of fine grass (such as heavily grazed *Rytidosperma*) can be harvested with scissors instead if more practical. For large tussocks, such as *Phalaris*, you will get to a really dense, unclippable tussock base which you can just leave as is.

## GLOSSARY

**Grass** – the alive and dead portions of tussocky or spreading monocot species, not including sedges, rushes or lomandra, are classified as grass. Dead portions which are still attached (or intricately associated, i.e. woven in with the rest of a tussock) with the rest of the plant are generally counted as 'grass' rather than 'thatch' and contribute to the measures of height, % green and the plate meter reading.

**Thatch** – the dead, unattached blades of grass which form a mat on the ground are thatch. Thatch does not count towards % green, height or, if you can avoid it, the plate meter measure.

**Flowering stem** – often stems with flowers on the end will also have a couple of leaves (although the might be different to the bulk). These leaves are fine to include but do not count the top of the flowering stem (usually where the flowers are) towards height measures and remove them where they influence the plate meter.

# APPENDIX 2

Grass association classification for each dominant grass species (or genus). Genus was recorded where grass species could not be readily identified in the field. Small, medium and large tussock and native tuft associations are broadly based on the '*Austrodanthonia*' (now *Rytidosperma*), '*Austrostipa*' and '*Poa labillardieri*' and combined 'Wet *Themeda*' and 'Dry *Themeda*' grasslands described in the ACT Lowland Native Grassland Conservation Strategy (ACT Government, 2005). Annual and exotic perennial grass associations were added to encompass the non-native pastures within Canberra Nature Park.

| Exotic Grass Species | Grass Association | Native Grass Species | Grass Association |
|---|---|---|---|
| *Aira spp.* | Annuals | *Agrostis avenacea* | Annuals |
| *Anthoxanthum odoratum* | Exotic | *Amphibromus neesii* | Native Tuft |
| *Avena fatua* | Annuals | *Annuals* | Annuals |
| *Briza spp.* | Annuals | *Aristida ramosa* | Small Tussock |
| *Bromus spp.* | Annuals | *Austrostipa bigeniculata* | Medium Tussock |
| *Critesion spp.* | Annuals | *Austrostipa densiflora* | Medium Tussock |
| *Cynodon dactylon* | Exotic | *Austrostipa scabra* | Medium Tussock |
| *Cynosurus echinatus* | Annuals | *Austrostipa spp.* | Medium Tussock |
| *Dactylis glomerata* | Exotic | *Bothriochloa macra* | Native Tuft |
| *Eleusine tristachya* | Exotic | *Chloris truncata* | Native Tuft |
| *Eragrostis curvula* | Exotic | *Dichelachne spp.* | Medium Tussock |
| *Festuca arundinacea* | Exotic | *Elymus scaber* | Native Tuft |
| *Festuca elatior* | Exotic | *Enneapogon nigricans* | Native Tuft |
| *Holcus lanatus* | Exotic | *Eragrostis brownii* | Native Tuft |
| *Hordeum leporinum* | Exotic | *Microlaena stipoides* | Native Tuft |
| *Hordeum spp.* | Exotic | *Panicum effusum* | Native Tuft |
| *Lolium perenne* | Exotic | *Poa labillardieri* | Large Tussock |
| *Nassella neesiana* | Exotic | *Poa sieberiana* | Large Tussock |
| *Nassella trichotoma* | Exotic | *Poa spp.* | Large Tussock |
| *Paspalum dilatum* | Exotic | *Rytidosperma pallidum* | Large Tussock |
| *Phalaris aquatica* | Exotic | *Rytidosperma spp.* | Small Tussock |
| *Poa annua* | Annuals | *Sorghum leiocladum* | Native Tuft |
| *Poa bulbosa* | Exotic | *Sporobolus creber* | Native Tuft |
| *Poa pratensis* | Exotic | *Themeda triander* | Native Tuft |
| *Setaria incrassata* | Exotic | *Tripogon loliiformis* | Annuals |
| *Setaria parviflora* | Exotic | | |
| *Vulpia spp.* | Annuals | | |

# APPENDIX 3

Model summary for the generalised additive mixed models examining the relationships between off-take and kangaroo density, pasture growth and standing crop. s() indicates that the term was fitted as a smoother and thus has no linear estimators; 'edf' is effective degrees of freedom where '1' is equivalent to a linear relationship; *t*- and *F*-values are presented for linear and smoothed estimators respectively.

| Model Terms | Estimate ± SE | edf | *t** or F value | *p*-value |
|---|---|---|---|---|
| **Annuals ($r^2$ = 0.65)** | | | | |
| Intercept | 3.64 ± 0.49 | - | 7.38* | <0.001 |
| s(Growth) | - | 2.32 | 16.78 | <0.001 |
| s(Kangaroo Density) | - | 2.03 | 1.96 | 0.162 |
| s(Standing Crop) | - | 1.00 | 0.31 | 0.584 |
| **Exotic Perennials ($r^2$ = 0.53)** | | | | |
| Intercept | 3.32 ± 0.65 | - | 5.10* | <0.001 |
| Season(Autumn) | 1.40 ± 1.18 | - | 1.18* | 0.243 |
| s(Growth) | - | 1.07 | 22.22 | <0.001 |
| s(Kangaroo Density) | - | 1.00 | 1.08 | 0.304 |
| s(Standing Crop) | - | 2.47 | 12.54 | <0.001 |
| **Small Tussock ($r^2$ = 0.55)** | | | | |
| Intercept | 1.03 ± 0.29 | - | 3.56* | <0.001 |
| Season(Autumn) | 0.76 ± 0.52 | - | 1.45* | 0.151 |
| s(Growth) | - | 2.89 | 33.85 | <0.001 |
| s(Kangaroo Density) | - | 1.00 | 0.015 | 0.904 |
| s(Standing Crop) | - | 1.51 | 2.40 | 0.059 |
| **Medium Tussock ($r^2$ = 0.77)** | | | | |
| Intercept | 2.77 ± 0.29 | - | 12.97* | <0.001 |
| Season(Autumn) | 1.64 ± 0.52 | - | 4.35* | <0.001 |
| s(Growth, Spring) | - | 2.33 | 86.98 | <0.001 |
| s(Growth, Autumn) | - | 2.68 | 72.26 | <0.001 |
| s(Kangaroo Density) | - | 1.00 | 5.75 | 0.018 |
| s(Standing Crop) | - | 2.77 | 24.83 | <0.001 |
| **Native Tuft ($r^2$ = 0.67)** | | | | |
| Intercept | 2.00 ± 0.29 | - | 6.97* | <0.001 |
| Season(Autumn) | 1.34 ± 0.88 | - | 1.52* | 0.130 |
| s(Growth, Spring) | - | 1.00 | 203.51 | <0.001 |
| s(Growth, Autumn) | - | 2.11 | 21.54 | <0.001 |
| s(Kangaroo Density) | - | 1.04 | 2.85 | 0.087 |
| s(Standing Crop) | - | 2.81 | 49.45 | <0.001 |

# APPENDIX 4

## Methods for measuring herbage mass and structure

Herbage mass and structure will be measured at each of our research plots. The purpose of these measurements is to be able to relate kangaroo off-take at the plot level to the resulting herbage mass and structure, which in turn will likely influence the ground layer floristic and reptile biodiversity. Within each plot, we will measure the vegetation in a 1 m x 1 m quadrat immediately surrounding all tiles in rows 2, 4 and 6 (Figure A1).

### AT EACH TILE

Check the plot ID on the NW or NE corner post to confirm your location. The following measurements should then be made around each tile:

- **Average grass height;** measured once on each side of the tile (i.e. four points within quadrat, Figure A2) to reflect the average height of the quarter being sampled
- **Plate meter reading;** measured once on each side of the tile (i.e. four points within quadrat, Figure A2)
- **Height of tallest tussock;** measured once on each side of the tile (i.e. four points within quadrat, Figure A2)
- **% Contribution to dry weight of top four plants;** grasses should be identified to species (where practical), any non-grass species in the top four can be grouped and classified as 'forbs', 'sedge/rush' or 'wood'.
- **% Cover of grass, non-grass vegetation, rock, log, thatch, bare ground and litter.** Combined total can exceed 100%.
- **% Grass which is green.**
- **Depth of thatch;** (cm). See definition of thatch.
- **Perennial grass reproductive status;** number of flowers/seed heads (None, 0-10, 11-50, >50).
- **If there is a log, shrub, rock or tree within 2m** of the tile.

### MEASURING THE VEGETATION

***Site*** and ***Plot ID***

The Site and Plot ID should be chosen from the drop down lists provided. Please ensure you use and carefully quote (including full stops) the plot name which will have the following structure:

XXX.YY.AAB e.g. 123.GU.GrT

**XXX** = three digit number, unique to that plot. First two numbers are specific to that reserve.

**YY** = two letter code for reserve.

**AA** = two letter code for vegetation type (grassland, Gr; or open woodland, OW)

**B** = one letter code for grass community type (P = *Phalaris*, S = *Austrostipa*, T = *Themeda*).

Figure A1. Research plot layout showing tiles which are measured during the initial herbage mass and structure surveys.

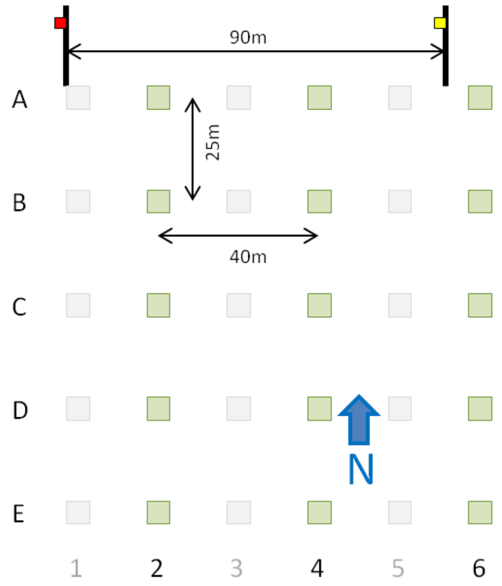
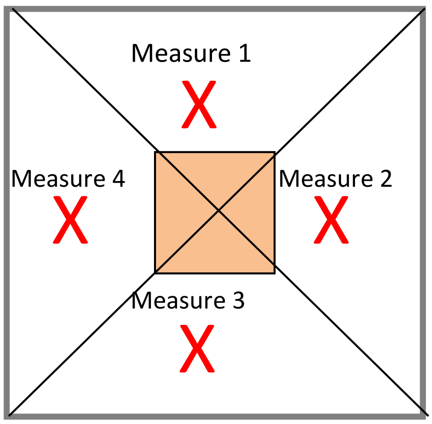



Figure A2. The approximate position at which height measures, falling plate readings and measures of the tallest tussock should be collected, relative to the tile in the centre.




***Surveyor***

Just the person who is doing the measurements initials should be recorded here.

***Date***

In dd/mm/yyyy format please.

***Average height***

Mentally divide the quadrat into 4 equal sections (Figure A2). Average height measurements should reflect the average height of the grass across the section of the quadrat being sampled. That is, it should take into consideration any areas where grass height equals zero (e.g. if there is only bare ground or litter). Grass height should not consider flowering stems. Four such measurements should be taken within each quadrat, once on each side of the tile.

***Plate meter***

The falling plate meter is designed to give an approximation of the herbage mass of the grass, with both grass height and density contributing to where it falls. The plate meter should be positioned such that the rod is touching the ground and so that there are no obstacles (such as sticks, woody stems or rocks, etc.) influencing the reading. If there are obstacles in the quadrat, try to measure a comparable amount of grass of the same species nearby where no obstacles are present. **DO NOT MOVE OBSTACLES OUT OF THE QUADRAT** as this will interfere with the microhabitat for reptiles also being surveyed here. If the ground is steeply sloped, the

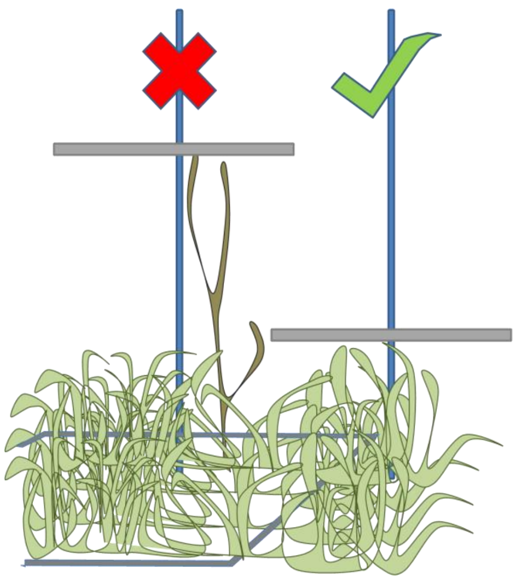
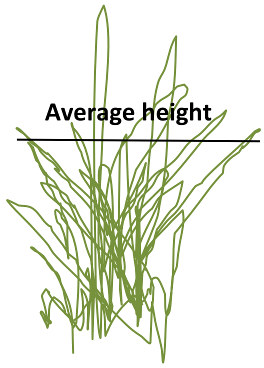


plate meter should be used perpendicular to the ground (i.e. sloped) so that the plate does not get caught on the ground.

There are three types of falling plate meter, the round one, the square one and the Jenquip ones. They each give a different value depending on the height of the grass and so it is important to specify in the data sheet which one is being used.

***Height of tallest tussock***




The height of the tallest tussock should be measured on each side of the tile (i.e. four measures per quadrat). Height measures still do not include flowering stems, but instead should reflect the average height of the non-flowering leaves of grass of that single tussock. This is not the highest point reached by any grass blade but rather where the bulk of the vegetation reaches to.

***Species composition***

For each quadrat, identify the dominant four plants based on their contribution to the dry weight of the herbage mass. Each of the four positions should be either filled with a specific grass species, or grouped 'forbs', 'sedge/rushes' or 'wood'. For example, you might record that 50% of the total dry weight is *Austrostipa scabra*, 30% is 'forbs' (various native and introduced species combined), 15% is *Themeda triandra* and 5% is a small sapling ('wood'). Look at the reference photos for a guide to help you know how much different grasses weigh when dried. Use the drop down lists to choose grass species and add extra species if necessary by inserting a cell in the middle of the list (unless you know how named ranges work). Note that it is not necessary to ID *Rytidosperma spp.* to species.

***Percent cover of grass, non-grass vegetation, litter, rock, log and bare ground***

Record the percentage of the quadrat which is covered by each category. 'Rock' should be of a size that couldn't be dislodged by animal movement. 'Logs' should be > 5 cm diameter otherwise recorded as litter. Lichen and moss count as 'non-grass vegetation'. 'Bare ground' must be bare dirt. The totals for the quadrat can exceed 100%.

***Percent green***

This is the percentage of the attached grass (i.e. not unattached thatch, see Glossary) which is green. Note that it is often much lower than you'd think – it often helps to grab a handful that is typical of the dead and live 'grass' mass and then look closely at how many blades are green vs. dried.

***Depth of thatch***

See Glossary for a definition of thatch. The depth of thatch should be measured using a metal ruler. Thatch shouldn't (in theory) also contribute towards grass height or the falling plate meter reading. It should not be considered as part of the % green measure.

***Grass reproductive status***

An estimate of the number of flowering stems (perennial grasses only) within the quadrat should be made. Estimates should be categorised as either 'None', '0-10', '11-50' or '> 50'. Note this is a measure for the whole quadrat, not for each species. Flowers or seed heads from annual grasses should not be included.

***Presence of log, rock, shrub or tree***

If there is a log (> 5 cm diameter), rock (not displaceable by animal movement), shrub (or shrub-like structure) or tree visible within 2 m of the tile it should be recorded here.

## Glossary

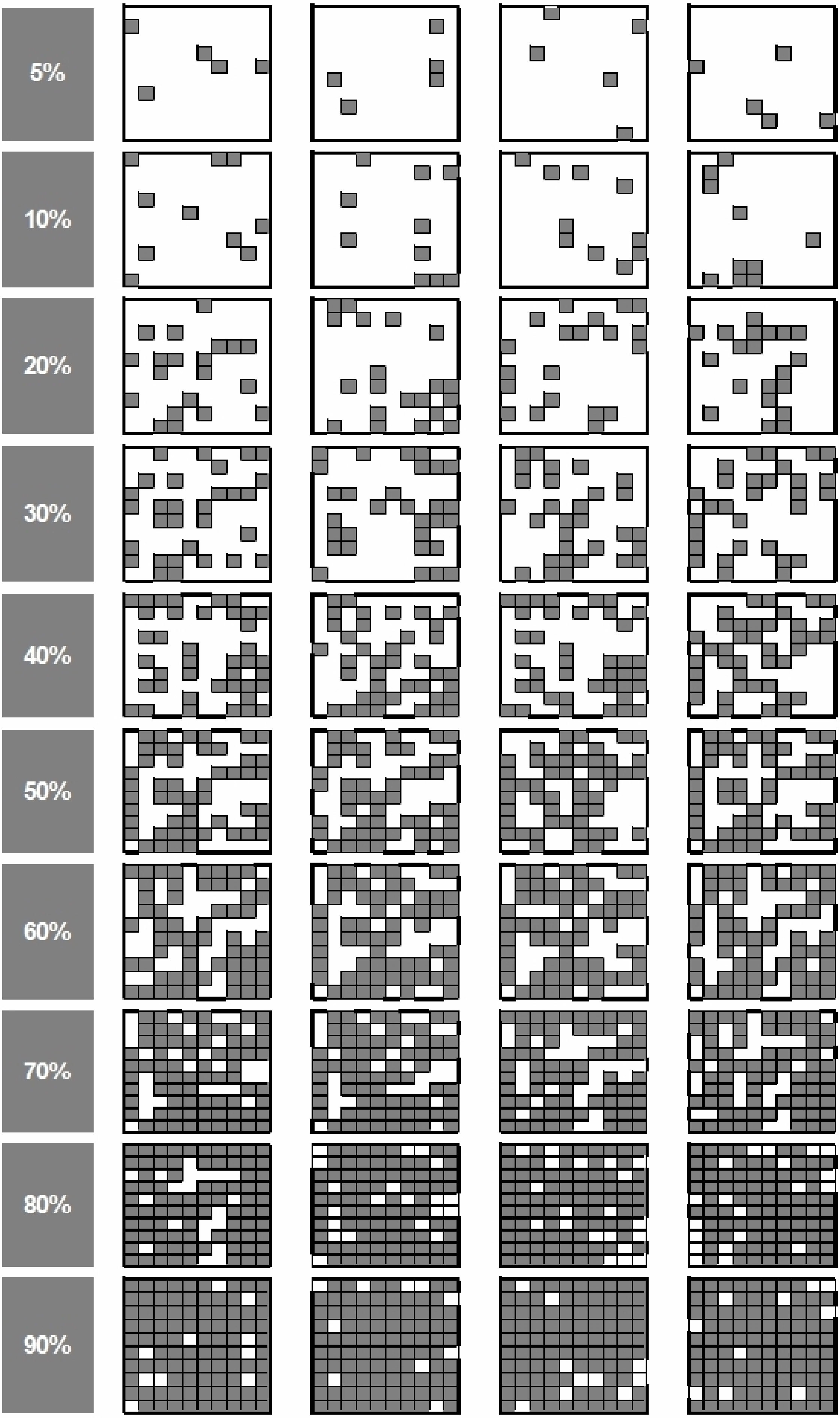
**Grass** – the alive and dead portions of tussocky or spreading monocot species, not including sedges, rushes or *Lomandra*, are classified as grass. Dead portions which are still attached (or intricately associated, i.e. woven in with the rest of a tussock) with the rest of the plant are generally counted as 'grass' rather than 'thatch' and contribute to the measures of height, % green and the plate meter reading.

**Thatch** – the dead, unattached blades of grass which form a mat on the ground are thatch. Thatch does not count towards % green, height or, if you can avoid it, the plate meter measure.

**Flowering stem** – often stems with flowers on the end will also have a couple of leaves (although the might be different to the bulk). These leaves are fine to include but do not count the top of the flowering stem (usually where the flowers are) towards height measures (including tallest tussock height) and avoid their influence on the plate meter where possible.

**Shrub** – a shrub can be a legitimate bush/shrub or something that has comparable 'bushy' structure such as a low/dense sapling or a large fern.

**Tree** – a tree is any upright woody structure that doesn't have much of a base to hide in (i.e. saplings or epicormic growth that provides ground cover should be classified as 'shrub' rather than 'tree').


5%
10%
20%
30%
40%
50%
60%
70%
80%
90%

# APPENDIX 5

Parameter estimates for predicting average grass height and their confidence intervals.

| Variable (level) | Coefficient | Estimate ± SE | 95% CI | *t*-value | *p*-value |
|---|---|---|---|---|---|
| **Intercept** | $\alpha$ | 6.57 ± 1.03 | 4.51 – 8.63 | 6.35 | <0.0001 |
| **Off-take** | $\beta_1$ | -0.07 ± 0.09 | -0.5 – 0.11 | -0.81 | 0.4195 |
| **Annuals*** | $\beta_2$ | 0.00 | - | - | - |
| **Exotic** | | 1.39 ± 0.28 | 0.83 – 1.95 | 1.08 | 0.2842 |
| **Small Tussock** | | -2.32 ± 0.88 | -4.08 – -0.56 | -2.63 | 0.0105 |
| **Medium Tussock** | | -2.39 ± 0.85 | -4.09 – -0.69 | -2.80 | 0.0066 |
| **Native Tuft** | | -2.76 ± 1.10 | -4.96 – -0.56 | -2.52 | 0.0142 |
| **Year** | $c$ | 0.07 | - | - | - |

*** reference level for the factor. Note individual effects of Year have been averaged (*c*) for simplicity.**

# APPENDIX 6

Parameter estimates for predicting grass height variability and their confidence intervals.

| Variable (level) | Coefficient | Estimate ± SE | 95% CI | *t*-value | *p*-value |
|---|---|---|---|---|---|
| **Intercept** | $\alpha$ | 1.02 ± 0.09 | 0.84 – 1.2 | 10.96 | <0.0001 |
| **Height** | $\beta_1$ | -0.04 ± 0.01 | -0.06 – -0.02 | -4.02 | 0.0001 |
| **Annuals*** | $\beta_2$ | 0.00 | 0.00 | - | - |
| **Exotic** | | 0.00 ± 0.09 | -0.18 – 0.18 | 0.01 | 0.9958 |
| **Small Tussock** | | -0.23 ± 0.09 | -0.41 – -0.05 | -2.73 | 0.0079 |
| **Medium Tussock** | | -0.24 ± 0.08 | -0.40 – -0.08 | -2.82 | 0.0063 |
| **Native Tuft** | | -0.35 ± 0.10 | -0.55 – -0.15 | -3.43 | 0.0010 |

*** reference level for the factor**

# APPENDIX 7

Parameter estimates for predicting the proportion of bare ground and their confidence intervals.

| Variable (level) | Coefficient | Estimate ± SE (Logit Scale) | Odds Ratio (95% CI) | *t*-value | *p*-value |
|---|---|---|---|---|---|
| **Intercept** | $\alpha$ | -2.40 ± 0.16 | 0.09 (0.07 – 0.12) | -14.81 | <0.0001 |
| **Log(Height)** | $\beta_1$ | -0.81 ± 0.08 | 0.44 (0.38 – 0.52) | -9.64 | <0.000 |
| **Grassland*** | $\beta_2$ | 0.00 | 1.00 | - | - |
| **Open Woodland** | | 0.28 ± 0.13 | 1.32 (1.02 – 1.72) | 2.22 | 0.0292 |

*** reference level for factor**

# APPENDIX 8

Parameter estimates for predicting reptile abundance and their confidence intervals.

| Variable (level) | Coefficient | Log(Estimate) ± SE | Multiplicative Factor (95% CI) | *z*-value | *p*-value |
|---|---|---|---|---|---|
| **Intercept** | $\alpha$ | 0.88 ± 0.17 | 2.41 (1.72 – 3.39) | 5.24 | <0.0001 |
| **Height** | $\beta_1$ | 0.04 ± 0.01 | 1.04 (0.14 – 7.69) | 3.56 | 0.0004 |
| **Grassland***<br>**Open Woodland** | $\beta_2$ | 0.00<br>0.65 ± 0.15 | 1.00<br>1.92 (1.42 – 2.59) | -<br>4.47 | -<br><0.0001 |
| **Grassland***<br>**Open Woodland** | $\beta_3$ | 0.00<br>-0.09 ± 0.02 | 1.00<br>0.91 (0.88 – 0.95) | -<br>-3.93 | <br><0.0001 |
| **Year** | $c$ | 0.59 | 1.80 | - | - |

*** reference level for the factor. Note individual effects of Year have been averaged (*c*) for simplicity.**

# APPENDIX 9

Parameter estimates for predicting reptile diversity and their confidence intervals.

| Variable (level) | Coefficient | Log(Estimate) ± SE | Multiplicative Factor (95% CI) | *z*-value | *p*-value |
|---|---|---|---|---|---|
| **Intercept** | $\alpha$ | 0.26 ± 0.09 | 1.30 (1.08 – 1.55) | 2.96 | 0.0035 |
| **Bare** | $\beta_1$ | 1.31 ± 0.64 | 3.71 (1.03 – 13.33) | 2.05 | 0.0424 |
| **Grassland***<br>**Open Woodland** | $\beta_2$ | 0.00<br>0.29 ± 0.07 | 1.00<br>1.33 (1.16 – 1.54) | -<br>4.09 | -<br>0.0001 |
| **Year** | $C$ | 0.29 | 1.33 | - | - |

*** reference level for the factor. Note individual effects of Year have been averaged (*c*) for simplicity.**

# APPENDIX 10

Parameter estimates for predicting total plant species richness and their confidence intervals.

| Variable (level) | Coefficient | Log(Estimate) ± SE | Multiplicative Factor (95% CI) | *z*-value | *p*-value |
|---|---|---|---|---|---|
| **Intercept** | $A$ | 4.22 ± 0.19 | 68.03 (46.52 – 99.48) | 22.47 | <0.0001 |
| **Variability** | $\beta_1$ | 0.46 ± 0.16 | 1.58 (1.15 – 2.18) | 2.80 | 0.0051 |
| **Grassland***<br>**Open Woodland** | $\beta_2$ | 0.00<br>0.20 ± 0.09 | 1.00<br>1.22 (1.02 – 1.46) | -<br>2.09 | -<br>0.0368 |
| **Annuals***<br>**Exotic Perennial**<br>**Small Tussock**<br>**Medium Tussock**<br>**Native Tuft** | $\beta_3$ | 0.00<br>-0.30 ± 0.14<br>-0.21 ± 0.13<br>-0.05 ± 0.13<br>-0.20 ± 0.20 | 1.00<br>0.74 (0.56 – 0.98)<br>0.81 (0.63 – 1.05)<br>0.95 (0.73 – 1.23)<br>0.82 (0.55 – 1.22) | -<br>-2.07<br>-1.56<br>-0.38<br>-0.96 | -<br>0.0386<br>0.0120<br>0.7075<br>0.3389 |

*** reference level for the factor**

# APPENDIX 11

Parameter estimates for predicting native species richness and their confidence intervals.

| Variable (level) | Coefficient | Log(Estimate) ± SE | Multiplicative Factor (95% CI) | *z*-value | *p*-value |
|---|---|---|---|---|---|
| **Intercept** | $A$ | 3.18 ± 0.24 | 24.05 (14.88 - 38.86) | 13.26 | <0.0001 |
| **Variability** | $\beta_1$ | 0.87 ± 0.24 | 2.39 (1.48 - 3.86) | 3.58 | 0.0004 |
| **Grassland*** | $\beta_2$ | 0.00 | 1.00 | - | - |
| **Open Woodland** | | 0.64 ± 0.23 | 1.90 (1.20 - 3.00) | 2.76 | 0.0058 |
| **Grassland*** | $\beta_3$ | 0.00 | 1.00 | - | - |
| **Open Woodland** | | -0.62 ± 0.31 | 0.54 (0.29 - 1.00) | -1.98 | 0.0477 |
| **Annuals*** | $\beta_4$ | 0.00 | 1.00 | - | - |
| **Exotic Perennial** | | -0.35 ± 0.14 | 0.70 (0.53 - 0.93) | -2.44 | 0.0145 |
| **Small Tussock** | | 0.04 ± 0.13 | 1.04 (0.80 - 1.35) | 0.31 | 0.7657 |
| **Medium Tussock** | | 0.08 ± 0.12 | 1.08 (0.85 - 1.38) | 0.65 | 0.5153 |
| **Native Tuft** | | -0.10 ± 0.20 | 0.90 (0.61 - 1.35) | -0.53 | 0.5970 |

*** reference level for factor**

# APPENDIX 12

Parameter estimates for predicting exotic plant species richness.

| Variable (level) | Coefficient | Log(Estimate) ± SE | Multiplicative Factor (95% CI) | *z*-value | *p*-value |
|---|---|---|---|---|---|
| **Intercept** | $\alpha$ | 3.71 ± 0.19 | 40.85 (27.94 – 59.74) | 19.63 | <0.0001 |
| **Variability** | $\beta_1$ | 0.37 ± 0.18 | 1.45 (1.01 – 2.08) | 2.05 | 0.0409 |
| **Annuals*** | $\beta_2$ | 0.00 | 1.00 | - | - |
| **Exotic Perennial** | | -0.28 ± 0.15 | 0.76 (0.56 – 1.02) | -1.81 | 0.0701 |
| **Small Tussock** | | -0.43 ± 0.15 | 0.65 (0.48 – 0.88) | -2.91 | 0.0036 |
| **Medium Tussock** | | -0.24 ± 0.14 | 0.79 (0.59 – 1.04) | -1.68 | 0.0929 |
| **Native Tuft** | | -0.36 ± 0.22 | 0.70 (0.45 – 1.08) | -1.64 | 0.1011 |

*** reference level for factor**

# APPENDIX 13

Parameter estimates for predicting maximum floristic value score and their confidence intervals.

| Variable (level) | Coefficient | Estimate ± SE | 95% CI | *t* - value | *p*-value |
|---|---|---|---|---|---|
| **Intercept** | $\alpha$ | 27.18 ± 5.96 | 15.26 – 39.1 | 4.56 | <0.0001 |
| **Grass Height** | $\beta_1$ | -1.02 ± 0.47 | -1.96 – -0.08 | -2.18 | 0.0330 |
| **Annuals *** | $\beta_2$ | 0.00 | - | - | - |
| **Exotic Perennial** | | -3.41 ± 5.69 | -14.79 – 7.97 | -0.60 | 0.5514 |
| **Small Tussock** | | 2.95 ± 5.39 | -7.83 – 13.73 | 0.55 | 0.5858 |
| **Medium Tussock** | | 9.15 ± 5.01 | -0.87 – 19.17 | 1.82 | 0.0728 |
| **Native Tuft** | | -13.60 ± 8.01 | -29.62 – 2.42 | -1.69 | 0.0946 |

*** reference level for factor**