Manaaki Whenua
Landcare Research

The effects of deer control on alpine plant browse in Fiordland National Park from 2006–2024

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The effects of deer control on alpine plant browse in Fiordland National Park from 2006–2024

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Summary

Project and client

- The Department of Conservation (DOC) requested an analysis of deer control and alpine vegetation monitoring data collected from 2006 – 2024 within Fiordland National Park. Deer are controlled in Fiordland National Park under three differing regimes: DOC-led suppression in the Murchison Mountains for the conservation of takahē (*Porphyrio hochstetteri*); maintenance of the wapiti herd quality in the Wapiti Area managed by the Fiordland Wapiti Foundation (FWF); and commercial removal of red deer for the venison market by wild animal recovery operators (WARO) across the remainder of Fiordland National Park.
- This work will help stakeholders to better understand the effectiveness of the three deer control regimes for reducing deer impacts on browse-sensitive alpine plant species and inform whether the trajectory of these regimes is meeting the Fiordland National Park Management Plan goal of promoting the regeneration of browsed indigenous flora.

Objectives

- The overall objective of this report is to determine the relationships between deer browse on monitored alpine plant species, deer activity, and the number and timing of deer harvested within and between the three management areas, over time. Specifically, we used long-term data to quantitatively assess the following five questions.

1 How does hunting effort and harvest rate vary in space and time?

2 Is deer activity related to hunting effort or harvest rate?

3 How does alpine plant browse vary with respect to deer activity, harvest rate and hunting effort?

4 What is the relationship between plant abundance and deer browse?

5 Does the size class structure of *Ranunculus lyallii* (Mount Cook buttercup) change over time, and is this related to deer browse, deer activity and harvest rate?

Methods

- All data were supplied by DOC. Transects to monitor browse on alpine vegetation were established at 54 sites across the three management areas in Fiordland National Park and have been remeasured 2 – 5 times since 2006. At each site, the number of browsed and unbrowsed plants of three palatable species (*Celmisia verbascifolia* subsp. *verbascifolia* – purple-stalked mountain daisy, *Dolichoglottis scorzoneroides* – snow groundsel, and *Ranunculus lyallii*) were recorded. The relative level of deer activity at each site was estimated using the number of pellet groups present.
- The location of all deer shot by helicopter operators within the three management areas was recorded by GPS, with these data used to estimate metrics of annual hunting effort and harvest rate. We also calculated proximity metrics of harvest rate by identifying the number of deer removed within all combinations of three spatial

buffers (1 km, 5 km, 10 km) of each vegetation transect within the preceding 180, 365 and 730 days.

- We assessed the following relationships using generalised linear mixed effects models, focusing on potential differences between the three management areas.
  - Changes in hunting effort, harvest rate, alpine plant abundance and browse over time.
  - Relationships between hunting effort, harvest rate and deer activity (measured as pellet group counts).
  - The relationship between alpine plant browse (each indicator plant species and all species combined) and harvest rates or deer activity.
  - The relationship between alpine plant abundance and proportion of browse for each indicator species and all species combined.
  - Changes in size class of *Ranunculus lyallii* over time and in relation to harvest rate, deer activity or the proportion of browsed *Ranunculus lyallii*

Results and discussion

- Both hunting effort and deer harvest rate were highly variable over time, particularly with respect to management area. Overall, harvest rates have increased in the Murchison Mountains, decreased in the WARO Area and remained stable in the Wapiti Area since 2006.
- Deer activity significantly declined in the WARO Area as harvest rate increased but there was no significant relationship in the Murchison Mountains or Wapiti Area. These results suggest that the fixed targets for management have not been sufficient to reduce deer activity, while the commercial recovery model was associated with lower deer activity only under favourable economic conditions.
- Browse observed on selected alpine plant species was related to deer activity, harvest rate and management area in complex ways. However, browse significantly increased with increasing deer activity for most species in most areas.
- The relationship between plant abundance and browse was highly variable among species, sites and management areas. However, despite high variation in deer activity, harvest rate and browse damage, we did not detect any significant changes in overall plant abundance (total number of plants observed within sites) over time across the three indicator species monitored.
- The proportion of large *Ranunculus lyallii* in populations within a site decreased with increasing deer activity across all management areas. *Ranunculus lyallii* is considered highly sensitive to deer browse and our finding suggest that increasing deer activity, even at the very low deer densities in the Murchison Mountains, is associated with a decline in larger *Ranunculus lyallii* in the most recent survey.

Recommendations

- Collect more detailed information about management activities, particularly helicopter flight logs, to enable better estimation of management effort and the frequency of disturbance to deer.
- Consider using browse metrics to update management targets in the Murchison Mountains and Wapiti Area rather than a fixed harvest target.
- Use harvested deer or deer pellets to determine the relative contribution of the monitored alpine species to deer diet using molecular techniques.
- Widen measurements of the indicator alpine plant species to include demographic measures of plant mortality and reproduction to evaluate long-term population viability.
- Consider including measurement of dominant plant species on monitoring transects to determine whether browse is driven by the palatability of other plant species that co-occur within sites and enable assessment of other drivers of long-term change in alpine communities.

1 Introduction

Non-native (introduced) wild animals, such as deer, can damage vulnerable ecosystems and vegetation. Most management of deer seeks to prevent or reverse these impacts by reducing population size within management areas (e.g. Coomes et al. 2003). Much of the research to date has focused on the effects of deer within indigenous forests on plant biodiversity, or potential carbon sequestration (see reviews of Carswell et al. 2015; Allen et al. 2023; Peltzer & Nugent 2023). Across most studies, the effects of deer are highly variable among sites and rarely linked quantitatively to management efforts (Husheer & Tanentzap 2023; Peltzer et al. 2024). Despite the long-term interest in deer management, relatively little effort has gone into monitoring and understanding their effects in non-forest vegetation including alpine communities.

In the early 20th century, red deer (*Cervus elaphus*) and wapiti (*Cervus canadensis*) were introduced into Fiordland National Park (FNP)[1]. Being adaptable generalist browsers, the deer found the environment highly suitable, leading to a steady increase in their population. By the 1960s, deer numbers had reached peak levels across the park, resulting in significant browsing pressure on both forest and alpine ecosystems (Rose & Platt 1987; Stewart et al. 1987; Mark 1989). However, the establishment of a feral venison industry in the 1960s led to a sharp decline in deer populations (Nugent et al. 1987; Nugent & Sweetapple 1989). Between 1969 and 1984, alpine deer numbers in northern Fiordland dropped by approximately 81% (Nugent et al. 1987), with an overall population reduction of c. 90% from peak levels, and this reduction was sustained for three decades (Challies 1991). Research showed that decreased deer browsing, especially in alpine regions, facilitated partial vegetation recovery in many areas (Rose & Platt 1987; Stewart et al. 1987).

Deer are managed by the Department of Conservation (DOC) in Fiordland under the Fiordland National Park Management Plan (FNPMP) to reduce the impacts of herbivory on sensitive vegetation. This management uses three primary mechanisms (Department of Conservation 2007).

1 Suppression in the Murchison Mountains managed by DOC for the conservation of takahē (*Porphyrio hochstetteri*).
2 Maintenance of the wapiti herd quality (within acceptable environmental limits) managed by the Fiordland Wapiti Foundation (FWF) through the use of wild animal recovery operators and recreational hunting within the Wapiti Area.
3 Commercial removal of red deer for the venison market by wild animal recovery operators (WARO) across the remainder of Fiordland National Park.

As a consequence, the control of deer in these three areas of Fiordland National Park is driven by different management objectives.

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[1] A glossary of terms and abbreviations is provided in Section 8 at the end of this report.

In some areas, conservation and threatened species management is prioritised, and largely driven by long-term takahē recovery. Red deer have been managed by the New Zealand Government in the Murchison Mountains since 1948 to protect takahē habitat, with a range of control strategies employed over that time. Early control efforts were based on ground control by government cullers, with commercial hunting (both ground and aerial control) becoming more prevalent from the late 1970s. As a result of these management efforts, significant declines in deer numbers were recorded from the 1960s to 1980s. From 2006–2013, deer control in the Murchison Mountains was a mix of ground and aerial control, with a target of 120 animals per year. The management strategy changed to a wild animal recovery model from 2014–2018, with commercial operators removing 120 animals per year over approximately six flights. From 2019– 021, DOC moved to a 'search and destroy' model, where commercial operators removed the target 120 animals per year on a fixed price contract. Finally, DOC led a series of control flights from 2022–2024 to achieve, and in one year significantly exceed, the target level of control with an increased number of flights.

The FWF undertake wapiti management, alongside other conservation activities, in the core area of the wapiti distribution through a community agreement established with DOC (Fiordland Wapiti Foundation 2024). This core area, known as the Wapiti Area, covers 175,000 ha of FNP. The community agreement requires the development of annual Animal Control Plans to achieve the relevant biodiversity objectives in the FNPMP, particularly around the maintenance of browse-sensitive indigenous flora species. The management is funded by the FWF and has required the removal of at least 900 deer each year, intended to benefit both the quality of the herd for recreational hunting and conservation values within the area. Targets are guided by vegetation monitoring results as part of an adaptive management framework established to meet the goals of the community agreement. Herd management has focused on three key aspects: genetics, age, and food availability – with some changes in strategy since the agreement was signed. Early management efforts were largely based on phenotype, with any deer that looked like a red deer removed from the population. Since 2015, female deer have been controlled by phenotype, while most males have been left until they are four years old and then managed for antler quality.

Finally, over extensive areas of Fiordland, deer numbers have been primarily regulated by broad-scale commercial aerial recovery. WARO management is driven by economic factors such as venison prices, processor demand and operational costs. As a consequence, the number of deer harvested by commercial operators has varied dramatically over the decades since the inception of the industry in the late 1960s, with a general decline over the past decade. When commercial returns are low, the number of operators reduces along with the number of deer harvested and the geographic extent they are harvested from (e.g. deer in remoter areas are overlooked in favour of deer closer to collection points that are cheaper to recover). Higher commercial returns result in more deer being removed from the National Park over a wide geographical area.

Each of these control regimes has spanned several decades, and they provide crucial long-term information about changes in both deer activity and conservation outcomes (e.g. Tanentzap et al. 2009). Since 2006, DOC has been monitoring sites established in alpine areas across FNP that are under the three different deer control regimes (Figure 1). The three regimes include areas where deer are controlled by DOC (Murchison Mountains), WARO (Wild Animal Recovery Operators, wider FNP) and FWF (Fiordland Wapiti Foundation, Wapiti Area). Outside the Murchison Mountains and the Wapiti Area, the general approach to deer control across FNP is to encourage commercial recovery operations (WARO), with operators authorised through a concession.

The original purpose of this monitoring program was to evaluate the link between WARO, deer activity, and deer browse patterns across the whole of FNP through time. The subsequent changes in WARO activity and effects on browse, and the inception of the community agreement with the Fiordland Wapiti foundation that established deer harvest targets, occurred after the monitoring programme was established. The monitoring program has since been expanded to enable comparisons of browse and deer activity between different control areas.

The Department of Conservation requested an analysis of deer management and alpine vegetation monitoring data collected from 2006–2024 within FNP. The results and interpretation of key findings from these analyses are to be shared with stakeholders, with a goal of their better understanding the effectiveness of the three deer management regimes (i.e. DOC-led, FWF-led, WARO-led) for reducing deer impacts on selected alpine plant species. This information is also intended to support managers and stakeholders to understand if the trajectory of these management programs is meeting the FNPMP goal of promoting the regeneration of browsed indigenous flora (Department of Conservation 2007).

The purpose of this report is to quantify, in a robust manner, the effectiveness of these three deer management regimes in limiting or reversing deer impacts on selected indigenous alpine plant species.

2 Objectives

The overall objective of this work is to determine the relationships among deer browse on monitored alpine plant species, deer activity, and the number and timing of animals harvested within and between the three management areas over time. Specifically, we used long-term data to quantitatively assess five questions:

1. How does hunting effort and harvest rate vary in space and time?
2. Is deer activity related to hunting effort or harvest rate?
3. How does alpine plant browse vary with respect to deer activity, harvest rate and hunting effort?
4. What is the relationship between plant abundance and browse?
5. Does the size class structure of *Ranunculus lyallii* (Mount Cook buttercup) change over time, and is this related to deer browse, deer activity and harvest rate?

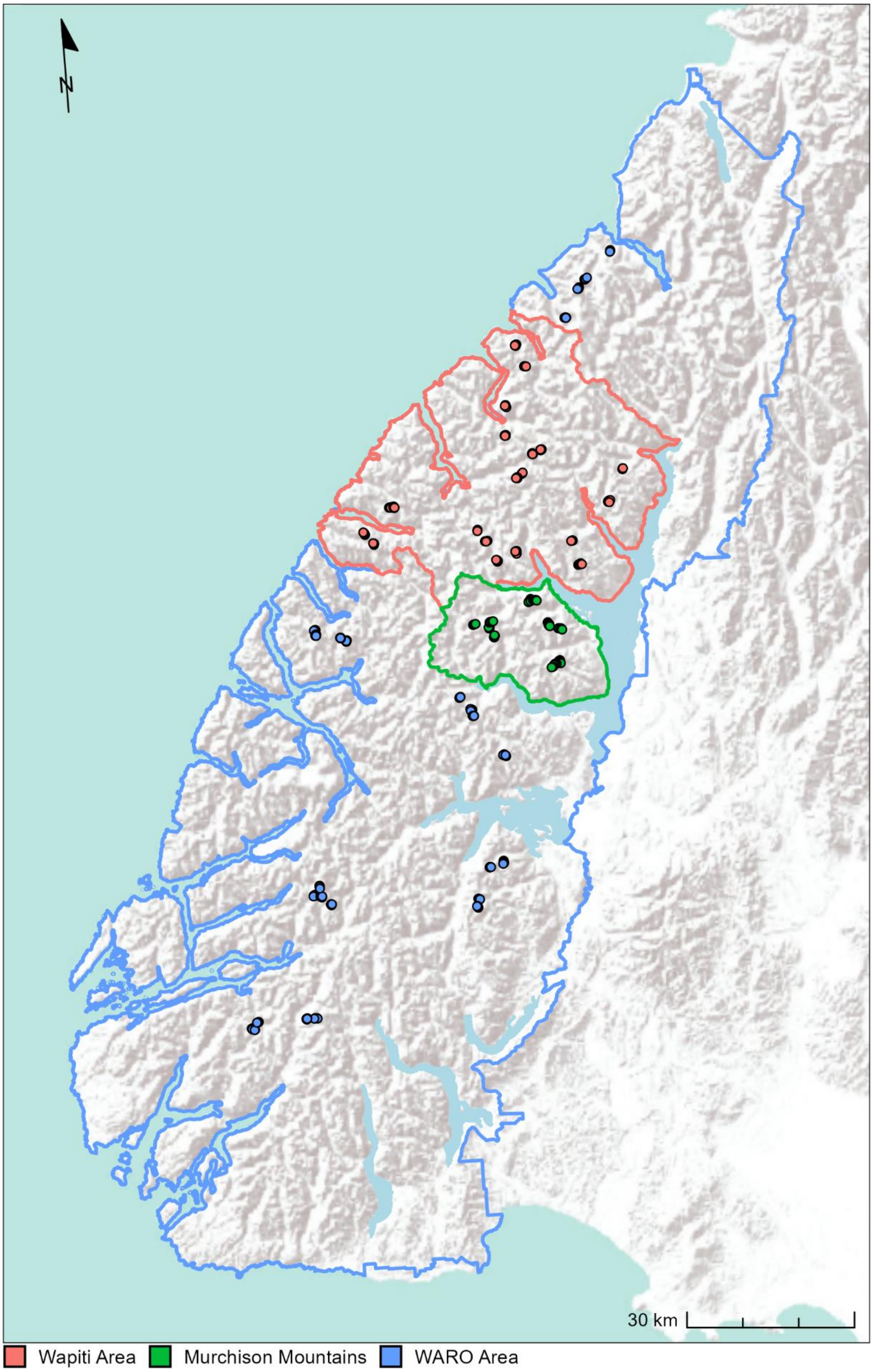

Figure 1. Map of the three management areas (coloured lines) and location of the alpine vegetation monitoring sites (coloured dots). Basemap © Esri — Source: USGS, Esri, TANA, DeLorme, and NPS.

3 Methods

3.1 Study area

We evaluated long-term alpine plant monitoring and operational data from throughout FNP to resolve the five questions posed above. This report focuses on three large management areas in FNP under different deer management regimes (Figure 1): the Murchison Mountains (DOC-led), WARO Area (WARO-led) and Wapiti Area (FWF-led).

Alpine grasslands in Fiordland are generally dominated by snow tussocks (*Chionochloa* spp.). Snow tussocks, along with large herbs and some woody species, are all major components of deer diet in alpine grasslands (Lavers et al. 1983). In Fiordland, deer show a strong preference for grasslands characterised by *Chionochloa pallens* and large-leaved herbs (Rose & Platt 1987).

Several herbaceous species above the treeline that appear to be particularly vulnerable to deer include *Anisotome haastii, Celmisia verbascifolia, Celmisia holosericea, Dolichoglottis scorzoneroides, D. lyallii, Ranunculus lyallii, Ourisia macrophylla, O. macrocarpa* and *Gentiana* spp. (Rose & Platt 1987; Mark 1989; Lee 1990; Lee et al. 2003). Three of these herbaceous species (*Celmisia verbascifolia* subsp. *verbascifolia* [hereafter referred to as *Celmisia verbascifolia*] -– purple-stalked mountain daisy, *Dolichoglottis scorzoneroides* – snow groundsel, and *Ranunculus lyallii* – Mount Cook buttercup) were selected as indicator species due to their widespread abundance across FNP and the ease with which they could be assessed for browse. *Celmisia holosericea* was also recorded at some sites but not consistently across the monitoring period and was, therefore, not considered further in this report.

3.2 Data collection

All data for this report were provided by DOC. We provide a brief description of the data collection methods below.

3.2.1 Alpine vegetation and deer pellet data

Across the three management areas in FNP, twelve subregions were selected in 2005 to represent a range of geographical locations, deer numbers and control histories (Figure 1, Table 1). Within these subregions, 44 sites were initially established in 2006 in habitats representing alpine head basins, terraces or faces based on accessibility and the presence of at least one of the three indicator species. An additional 8 sites were established in the Wapiti Area in 2015 and 2016 to enable more robust long-term comparisons with the other management areas (Ledgard 2018), and an additional 6 sites were established in the Murchison Mountains in 2019. Within each site, 5 browse transects were established and remeasured by DOC. Transects were relocated using GPS coordinates and detailed photographs taken during the first survey. Each transect was measured 2–6 times between 2006 and 2024 (Figure 2). Given that both management operations and alpine surveys were carried out over the austral summer, we use financial year (i.e. July-June) for analyses and when describing results.

On each 50 × 2 m belt transect, the number of browsed and unbrowsed individual rosettes (plants) of each indicator species rooted within the transect area was recorded for rosettes having leaves at least 8 cm long (*Celmisia verbascifolia, Dolichoglottis scorzoneroides*;

Table 2). These size thresholds were selected to balance the ability to detect browse on individual plants likely to be impacted by deer and monitoring efficiency (Lake & Ewans 2005). *Ranunculus lyallii* plants are highly palatable to deer but the seedlings are very low to the ground and difficult for deer to access. This means that monitoring in areas with high deer activity may not portray the impacts of deer accurately as the proportion of browsed plants is often low. Therefore, browsed and unbrowsed *Ranunculus lyallii* plants were counted for individuals in two size classes based on maximum leaf width: 3–8cm and > 8cm. Changes in browse and abundance of plants in each size range over time should reflect the condition of this species in each area more accurately (Lake & Ewans 2007).

Most sites are located away from the main chamois (*Rupicapra rupicapra*) populations identified in FNP. However, on the seven occasions (0.57% of observations) where both deer and chamois pellets were observed at a site, all ungulate browse on indicator species was recorded as deer browse. Insect browse was easily distinguished from deer browse by experienced observers and, where plant damage could not be confidently attributed to ungulates, no browse was recorded.

Table 1. Summary of sample design (number of subregions, sites and transects) and mean number of surveys for each management area. Mean deer pellet groups, proportion of browsed and mean total number of plants (browsed and unbrowsed) for each indicator species (Celver: *Celmisia verbascifolia*, Dolsco: *Dolichoglottis scorzoneroides*, Ranlya: *Ranunculus lyallii*)[2], mean proportion of browsed Ranlya by structural class and mean proportion of large Ranlya (>8cm) with standard deviation (± SD) are calculated by transect across all surveys based on raw data.

Metric	Murchison Mountains	Wapiti Area	WARO Area
Number of subregions	1	5	6
Number of sites	10	20	24
Number of transects	50	100	120
Mean (± SD) number of surveys	2.44 ± 1.37	3.13 ± 1.7	2.99 ± 1.41
Mean deer pellet groups	0.26 ± 0.75	1.07 ± 2.23	0.85 ± 1.77
Mean proportion of browsed Celver	0.08 ± 0.14	0.11 ± 0.16	0.09 ± 0.18
Mean proportion of browsed Ranlya	0.08 ± 0.18	0.08 ± 0.15	0.07 ± 0.12
Mean proportion of browsed Dolsco	0.12 ± 0.22	0.25 ± 0.27	0.20 ± 0.25
Mean number of Celver	210.48 ± 176.10	184.21 ± 179.5	97.25 ± 125.09
Mean number of Ranlya	81.46 ± 95.26	36.28 ± 51.91	46.57 ± 62.08
Mean number of Dolsco	135.22 ± 159.29	69.56 ± 87.85	79.07 ± 114.94
Mean proportion of browsed Ranlya 3 to 8cm	0.04 ± 0.13	0.07 ± 0.15	0.04 ± 0.09
Mean proportion of browsed Ranlya >8cm	0.1 ± 0.19	0.12 ± 0.25	0.1 ± 0.22
Mean proportion of Ranlya >8cm	0.66 ± 0.29	0.20 ± 0.26	0.34 ± 0.32

Table 2. Criteria defining the three indicator plant species monitored for alpine deer browse. Individual plants were only recorded if the leaf size was greater than or equal to the specified metric size threshold.

Indicator species	Metric	Size threshold (cm)
Celmisia verbascifolia	Leaf length	8
Dolichoglottis scorzoneroides	Leaf length	8
Ranunculus lyallii	Leaf width	3 – 8 & >8

[2] See also glossary of terms and abbreviations provided in Section 8 at the end of this report.

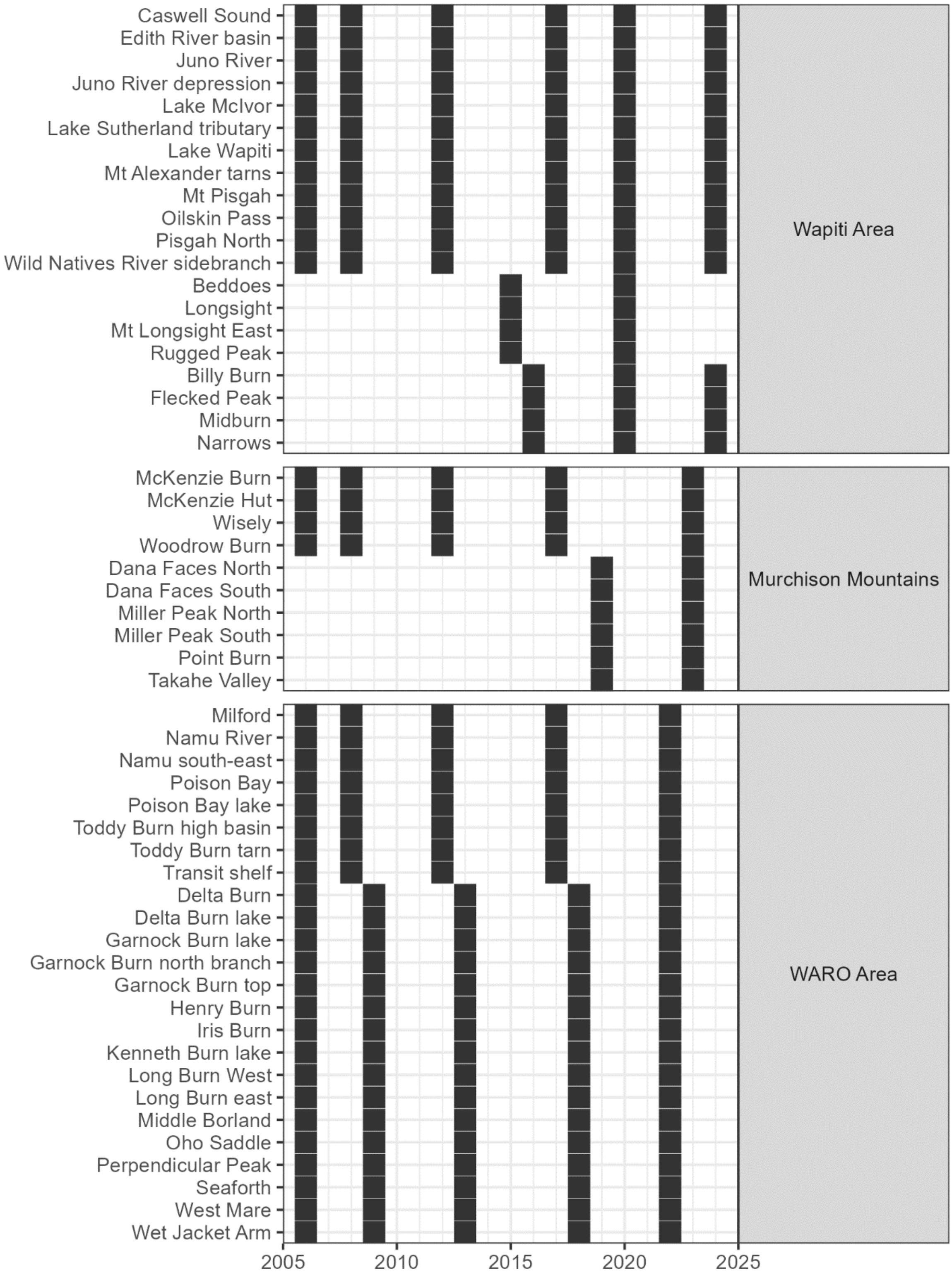

Figure 2. The timing of browse surveys (*x*-axis, black cells) within sites (*y*-axis) grouped by management area (grey cells). Five alpine transects were monitored within each site on each sampling date. Data were grouped into distinct survey periods for each management area when the monitoring occurred over consecutive years (e.g. sites measured in the WARO Area in 2008 and 2009 were grouped into one survey period).

The number of deer pellet groups per transect was also recorded. A pellet group has been previously defined as 'intact pellets voided in the same defecation' (see section 3.3.3 in Forsyth 2005). Here, all deer pellet groups were counted regardless of whether pellets were intact or not. This metric provides a relative index of deer activity in the absence of counts of individual animals (Forsyth et al. 2011; Moloney et al. 2021).

For each indicator plant species, and for all species combined, we calculated the total number of plants by summing the number of browsed and unbrowsed plants; and we calculated the proportion of browsed plants by dividing the number of browsed plants by the total number of plants. We used a similar method to calculate the proportion of large *Ranunculus lyallii* (leaf width >8 cm; hereafter referred as 'large Ranlya') by first calculating the total number of *Ranunculus lyallii* by size class (large Ranlya: > 8cm leaf width, and small Ranlya: 3–8 cm leaf width), combining browsed and unbrowsed plants; and then dividing the number of large Ranlya by the total number of Ranlya.

Because not all sites within a management area were always measured in the same year (Figure 2), we pooled data in consecutive years into discrete survey periods to better reflect the overall values of the deer pellet groups, alpine plant abundance and browse within each management area. These survey periods were included in some of the statistical analyses described in Section 3.3 below.

3.2.2 Hunting effort and harvest rate

The date and location of each deer harvested during aerial hunting operations within each management area was collected by helicopter operators between 2006–2024 and provided to DOC. However, the GPS tracks of each helicopter flight were not available. Additional information on the total number of deer harvested and the number of operational flights within the Murchison Mountains in each financial year (July–June) between 2002 and 2005 was collated by DOC from annual reports. A small number of harvest records (1,110 or 1.7% of all records) were missing dates, although the financial year in which they occurred was known. Missing dates were imputed by randomly selecting a day of the year from the known distribution for each management area, whereby days (1–365) that were more commonly hunted were more likely to be selected. An additional 189 records for the 2022/2023 financial year were known to be missing from the Wapiti Area (G. Ledgard, DOC, pers. comm., 13 August 2024). These records were included in the total number of deer removed and were assigned an imputed date. However, they were not included in any calculations that required their spatial location to be known. A further 221 records (0.3%) were also excluded from the proximity metrics due to missing location data.

The harvest data were summarised to generate annual metrics of hunting effort (operator days per year) and harvest rate (deer removed per year) within each management area from July–June. In addition, we generated area-scaled versions of these metrics by dividing by the total huntable region within each management area (operator days per year per km^2, deer removed per year per km^2), where the huntable region for helicopters was considered to be any habitat within the following vegetation classes in the Land Cover Database (Manaaki Whenua – Landcare Research 2020, Version 5): alpine grass/herbfield, gravel or rock, landslide, sub alpine shrubland, or tall tussock grassland.

Because the proximity of harvest in both space and time to the vegetation browse monitoring sites could influence the likelihood of browse (i.e. by creating a 'landscape of fear' to aerial operations; Latham et al. 2018), we also generated a range of harvest rate proximity metrics that calculated the number of deer removed within a specified number of days preceding the vegetation monitoring and within a specified spatial buffer of the site location. We considered time windows of 180, 365 and 730 days before the vegetation monitoring and spatial buffers of 1 km, 5 km and 10 km, calculating harvest rates (deer removed per km^2) for all combinations (e.g. the number of deer removed within 1 km of a site in the 180 days before the vegetation monitoring). However, we were unable to calculate these metrics for years where we were missing data for a period within the time window (e.g. harvest records prior to 2006). We also calculated hunting effort (operator days per km^2) within the same time windows for each management area. However, because we did not have the GPS tracks for the operational helicopter flights, we were unable to calculate effort within the spatial buffers. These metrics are subsequently referred to as 'proximity metrics' (see Glossary)

3.3 Statistical analyses

All statistical analyses were conducted in R (R Core Team 2024, Version 4.4.0). A brief description of the general modelling approach used to develop and assess the statistical models generated for this report is described below, with specific model details described under each section.

For each response variable (described in more detail below), we first used the *fitdistrplus* package (Delignette-Muller 2015) to identify the most appropriate distribution to use for subsequent modelling. We then developed a candidate set of models that included all sensible combinations of the available predictor variables required to answer the specific question. Individual models were developed using the *glmmTMB* package (Brooks et al. 2017) and the best model within the candidate set was identified as the model with the lowest corrected Akaike's Information Criterion (AICc) value using the *MuMIn* package (Bartoń 2024). The best model for each response was assessed to ensure that it met assumptions of homoscedasticity, overdispersion and zero-inflation using the *DHARMa* package (Hartig 2022). We identified significant covariates using a Wald chi-square test with the *Anova* function from the *car* package (Fox & Weisberg 2019). Model predictions for the significant fixed effects were generated using the *ggeffects* package (Lüdecke 2018) and plotted against the raw data to visualise the relationships. Post-hoc analyses were conducted using the *emmeans* package (Lenth 2024) to identify significant differences between groups (e.g. pairwise comparisons between survey periods or management areas).

All work was conducted within a version-controlled git repository and this repository was made available to DOC at the completion of the contract. This approach was adopted to ensure the entire workflow from raw data through to the production and presentation of results in this report is transparent and reproducible. All data and code are available upon request.

3.3.1 How does hunting effort and harvest rate vary in space and time?

To understand how hunting effort and harvest rate changed over time and space within FNP, we developed a series of generalised linear models (GLM) that included management area and year (as a continuous variable) as fixed effects. We developed an initial candidate set of models that used a negative binomial distribution to assess two response variables: total annual hunting effort (operator days) and total annual harvest rate (animals removed).

We then fitted a second candidate set of models with a Gaussian distribution where the response variables were the annual hunting effort and harvest rate scaled by the huntable region within each management area (operator days per km^2 and deer removed per km^2, respectively).

Finally, we assessed the relationship between annual harvest rate and hunting effort to determine if there were differences in the apparent efficiency of hunting among the management areas. We developed a candidate set of models using generalised linear mixed-effects models (GLMM) for the total annual and area-scaled metrics, with negative binomial and Gaussian distributions, respectively. Annual hunting effort and management area were included as fixed effects, while year (as a continuous variable) was included as a random effect.

3.3.2 Is deer activity related to hunting effort or harvest rate?

The number of faecal pellet groups is often used as an indicator of the likely browsing pressure of ungulates at a site, with higher values typically associated with higher deer activity and densities of animals. Therefore, it is often assumed that higher rates of hunting effort or harvest will reduce the number of pellet groups at a site.

We assessed the relationship between deer activity (measured as the number of pellet groups) and harvest rate by developing a candidate set of GLMMs that included management area and each of the harvest proximity metrics. All models were fitted with a negative binomial distribution, with line nested within site included as a random effect.

3.3.3 How does alpine plant browse vary with respect to deer activity, harvest rate and hunting effort?

For each indicator plant species and all species combined, we investigated the relationship between the proportion of browsed plants and deer activity (measured as the number of pellet groups), harvest rate or hunting effort. We ran zero-inflated and non-zero-inflated GLMMs with a binomial error distribution. To account for the survey design (Table 1), site nested within subregion, line or site by itself, and survey period were included in the models as random factors. Due to high correlation between some variables of interest, we ran multiple models across and within management areas including only one variable of interest – and then retained the best-fitting model per category (e.g. pellet groups, harvest rate and hunting effort) based on AICc values and model diagnostics.

As we were not able to calculate variables corresponding to harvest rates within a buffer for the first two surveys in the Murchison Mountains, we excluded the 2006 and 2008 surveys for all management areas *only* when comparing the relevance of the different variables of interest for predicting alpine plant browse. We were unable to investigate the role of hunting effort as most models failed to converge for some combinations of management area and alpine plant species.

3.3.4 What is the relationship between plant abundance and browse?

For each indicator plant species and all species combined, we investigated the relationship between plant abundance and the proportion of browsed plants within and across management area (modelled with or without an interaction term). We ran zero-inflated and non-zero-inflated GLMM with either Poisson or negative-binomial error distribution. Line nested within site, line or site by itself, and survey period were included in the models as random factors. Due to the poor fit of the models predicting the abundance of alpine plants, the total number of alpine plants per transect was log-transformed (i.e. $\log(x + 1)$) before being used as a response variable in a GLMM with a Gaussian error distribution. Multiple models were run with a combination of predictor variables including management area modelled with or without an interaction term with the proportion of browsed plants. The best-fitting model was selected based on AICc values and model diagnostics.

3.3.5 How does alpine plant browse and plant abundance change over time?

To investigate changes in alpine plant browse and abundance between survey periods, we ran a GLMM for each indicator species and management area separately with site, line nested within site, or line included as a random factors; and with survey period included as an explanatory variable. For models predicting plant browse, both the zero-inflated and non zero-inflated models were fitted with a binomial error distribution. For models predicting plant abundance, the models were fit with either a negative-binomial or zero-inflated negative binomial error distribution. The best-fitting model was selected based on AICc values and model diagnostics.

3.3.6 Does the size class structure of *Ranunculus lyallii* change over time, and is this related to browse, deer activity and harvest?

We assessed the relationship between the size class structure of *Ranunculus lyallii* and deer activity and harvest by focusing on the proportion of large *Ranunculus lyallii* (leaf width > 8cm) within the total observed plants in each transect. We ran a GLMM with a binomial or zero-inflated binomial distribution and line nested within site or line by itself and survey period included as random factors. The proportion of large *Ranunculus lyallii* was predicted from the proportion of browsed *Ranunculus lyallii*, pellet groups, or harvest rate with or without an interaction term with management area.

We investigated whether the size class structure of *Ranunculus lyallii* changed over time by running a GLMM with a binomial distribution with line nested within site included as a random factor. The survey period was included as a discrete explanatory variable. The survey period including the calendar year 2006 was not included in this analysis as the size class structure of *Ranunculus lyallii* was not recorded at that time. Model diagnostics confirmed that zero-inflated binomial models were not required.

4 Results

4.1 How does hunting effort and harvest rate vary in space and time?

Approximately 65,200 deer were removed from FNP for management purposes between July 2006 and June 2024. Annual hunting effort varied across the three management areas, with the highest average total values observed in the WARO Area (Table 3). However, the average area-scaled hunting effort was similar across the management areas, ranging from 0.05–0.07 operator days per km^2 of alpine habitat. The highest annual harvest rates were observed in the WARO Area, with 2,623 deer removed on average per year. In comparison, an average of 110 and 903 deer were removed from the Murchison Mountains and Wapiti Area, respectively. The highest area-scaled harvest rate was observed within the Wapiti Area, with an average of 1.59 deer removed per km^2 of alpine habitat.

Table 3. Mean (± SD) annual hunting effort (operator days) and harvest rate (deer removed) within the three management areas.

Management area	Annual hunting effort		Annual harvest rate	
	Total	Per km^2	Total	Per km^2
Wapiti Area	48.06 ± 13.57	0.08 ± 0.02	903.11 ± 200.15	1.59 ± 0.35
Murchison Mountains	10.47 ± 8.85	0.05 ± 0.04	102.18 ± 59.31	0.49 ± 0.28
WARO Area	199.89 ± 147.63	0.07 ± 0.05	2623.56 ± 1320.68	0.93 ± 0.47

Hunting effort and annual harvest rates (Figure 3) also varied over time and space, with the best models describing temporal trends including a significant interaction between year and management area (Table in Appendix 1).[3] For example, temporal trends in hunting effort varied between management areas (Figure 4a, Table 4), with significant declines over time in both total annual hunting effort and area-scaled effort in the Murchison Mountains and WARO Area. However, no significant change was observed in the Wapiti Area for either metric of annual hunting effort.

Harvest rate also varied between management areas over time (Figure 4b, Table 4), with both total annual harvests and area-scaled harvests increasing significantly over time in the Murchison Mountains and significantly decreasing in the WARO Area. No significant change was observed in the Wapiti Area for either metric of annual harvest rate.

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[3] Tables and figures in appendices are prefixed by the letter A and the relevant appendix number, and numbered within each appendix (e.g. Table A1.1 is the first table in Appendix 1, Tables A2.1–A2.x are the first to xth tables in Appendix 2.

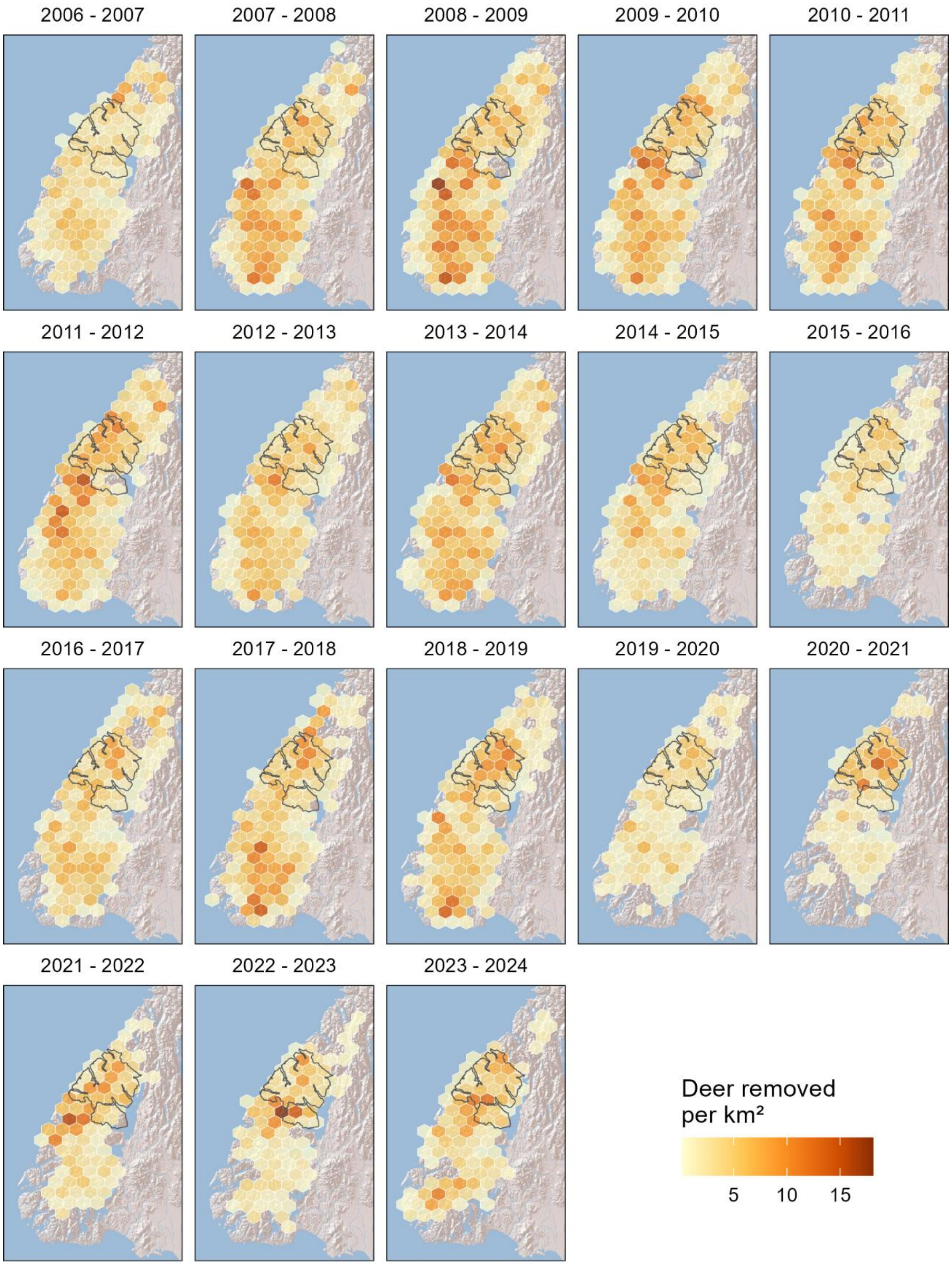

Figure 3. The harvest rate (deer removed per km^2) across Fiordland National Park from 2006–2024, where each panel represents one financial year (1 July to 30 June). Each hexagon covers an area of 10 km^2, and missing hexagons indicate zero recorded kills in that location. The boundaries for the Murchison Mountains and Wapiti Area are shown (see Figure 1 for more details). Tiles © Esri — Source: Esri.

Table 4. Relationship between management area and year for four response variables relating to annual hunting effort and harvest rate. Shading indicates management areas with significant positive (orange) or negative (blue) relationships. Estimate (± SEM) values for year represent the direction and magnitude of the slope (Figure 4), with the estimates for total annual effort and harvest rate presented on the log scale. The error distribution used is shown under each model, with the full candidate model sets provided in Table in Appendix 1.

Response	Model	Management area	Estimate ± SEM	Statistic	p value
Annual effort	year (Negative binomial)	Wapiti Area	-0.026 ± 0.018	-1.467	0.142
		Murchison Mountains	-0.090 ± 0.023	-3.964	<0.001
		WARO Area	-0.154 ± 0.018	-8.690	<0.001
Annual effort per km^2	year (Gaussian)	Wapiti Area	-0.002 ± 0.001	-1.614	0.113
		Murchison Mountains	-0.005 ± 0.001	-3.497	0.001
		WARO Area	-0.008 ± 0.001	-6.638	<0.001
Annual harvest	year (Negative binomial)	Wapiti Area	0.015 ± 0.022	0.690	0.490
		Murchison Mountains	0.058 ± 0.022	2.668	0.008
		WARO Area	-0.076 ± 0.022	-3.459	0.001
Annual harvest per km^2	year (Gaussian)	Wapiti Area	0.023 ± 0.013	1.720	0.092
		Murchison Mountains	0.030 ± 0.014	2.156	0.036
		WARO Area	-0.063 ± 0.013	-4.737	<0.001

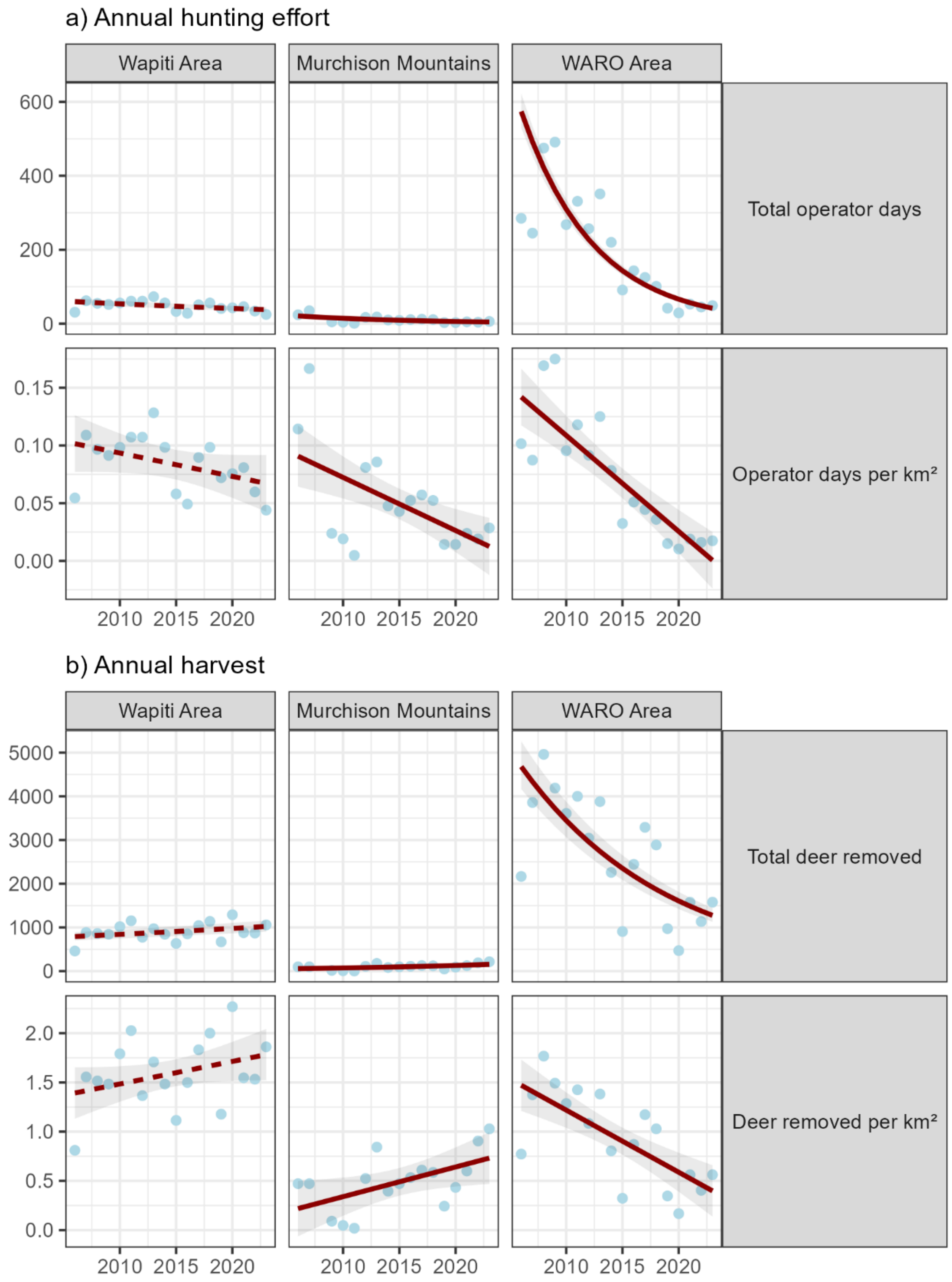

Figure 4. Annual data within the three management areas: a) hunting effort; b) deer harvest. Blue points show the annual data, while red lines represent the regression line (± 95% confidence intervals, shown by grey shading) derived from a GLM, where a separate model was fitted for each response variable (Table 4). Solid lines indicate a significant slope, while dashed lines indicate a non-significant slope at α = 0.05.

The best model predicting the relationship between area-scaled harvest rate and area-scaled hunting effort included management area, with year as a random effect (see Table A1.2). There was a significant interaction between hunting effort and management area, with a significant increase in harvest rate observed with increasing effort in the WARO Area (Figure 5, Table 5). However, there no significant relationships were observed in the Murchison Mountains or Wapiti Area.

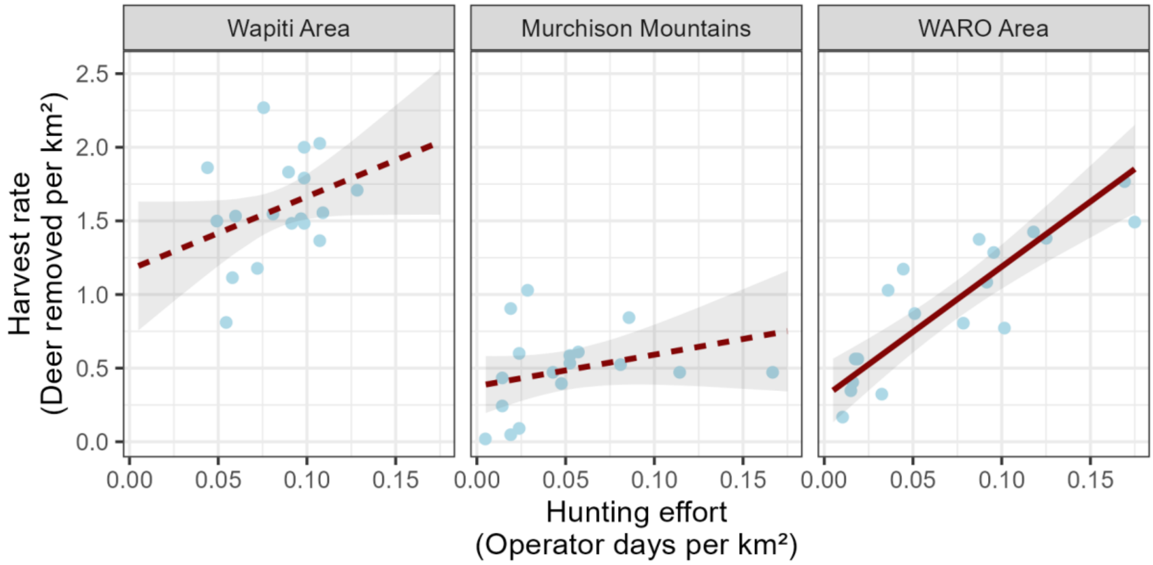

Figure 5. The relationship between area-scaled annual harvest rate and hunting effort. Blue points show the annual data, while the lines represent the regression line (± 95% confidence intervals, shown by grey shading) derived from a GLM (Table 5).

Table 5. Relationship between management area and hunting effort with respect to annual harvest rate. Shading indicates management areas with significant positive (orange) relationships. Estimate (± SEM) values represent the direction and magnitude of the slope (Figure 5). The model used a Gaussian error distribution, with the full candidate model set provided in Table (in Appendix 1).

Model	Management area	Estimate ± SEM	Statistic	p value
annual effort per km^2 * management area +(1 | year) (Gaussian)	Wapiti Area	4.957 ± 2.685	1.846	0.071
	Murchison Mountains	2.134 ± 1.583	1.348	0.184
	WARO Area	8.846 ± 1.330	6.653	<0.001

4.2 Is deer activity related to hunting effort or harvest rate?

The number of pellet groups are typically associated with the density or activity levels of ungulates, so it would be expected that high hunting effort or harvest rate should result in lower numbers of pellet groups. The best predictor of deer pellet groups was the harvest rate within a 5 km buffer of each site in the preceding two years (Table A2.1 in Appendix 2). Overall, there was a significant interaction between management area and the harvest metric, with deer pellets significantly decreasing in the WARO Area as the harvest rate increased (Figure 6, Table 6). However, no significant relationships were observed in the Murchison Mountains or Wapiti Area.

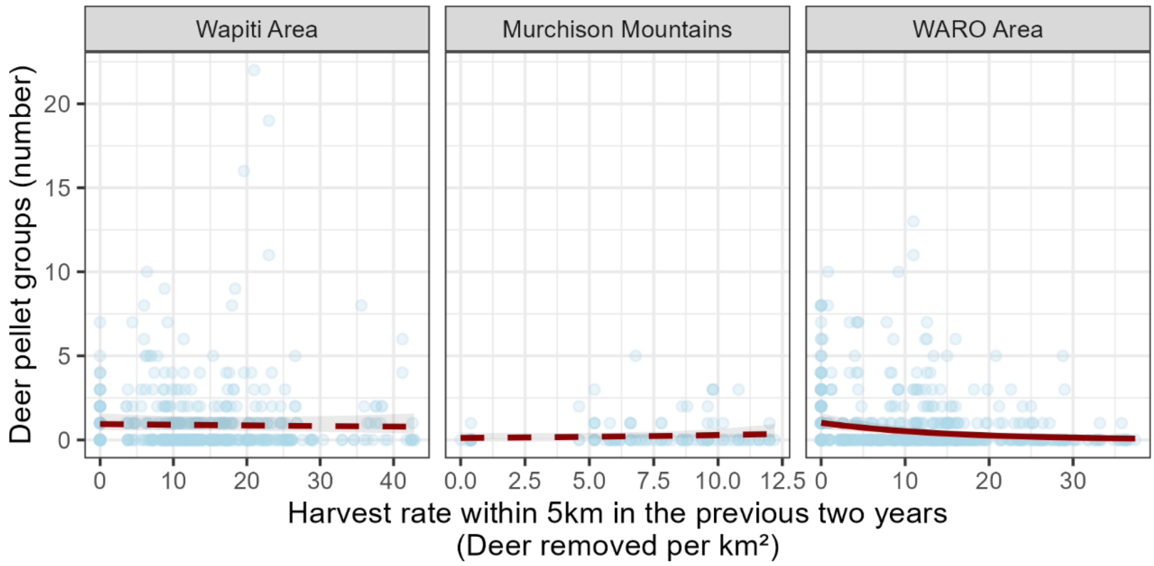

Figure 6. Relationship between the deer pellet groups (number per transect) and harvest rate within a 5 km buffer in the previous two years (deer removed per km^2). Note that the *x*-axis range differs across panels. Blue points show the annual data, while red lines represent the regression line (± 95% confidence intervals, shown by grey shading) derived from a GLMM (Table 6). Solid lines indicate a significant slope, while dashed lines indicate a non-significant slope at α = 0.05.

Table 6. Relationship between the number of deer pellet groups observed on transects and harvest rate within a 5 km buffer in the previous two years. Shading indicates management areas with significant negative (blue) relationships. Estimate (± SEM) values for harvest rate show the direction and magnitude of the slope presented on the log scale (Figure 6). The full candidate model set provided in Table A2.1 (Appendix 2).

Model	Management area	Estimate ± SEM	Statistic	p value
harvest_km_5000_730 + (1|site/line) + (1|year) (Negative binomial)	Wapiti Area	-0.004 ± 0.009	-0.456	0.648
	Murchison Mountains	0.089 ± 0.071	1.252	0.211
	WARO Area	-0.067 ± 0.010	-6.774	<0.001

4.3 How does alpine plant browse vary with respect to deer activity, harvest rate and hunting effort?

To identify the measure of the deer population that best explained the variation in alpine plant browse, the surveys done in and before 2008 were excluded from the analysis, as spatial data on the harvest rate in the preceding two years was not available. Across all plant species, deer pellet groups better predicted the variation in alpine plant browse compared to models including harvest rate (either within a 5 or 10 km buffer) or hunting effort (Table A3.1 in Appendix 3). When focusing on harvest rate, models with harvest rate within 10 km showed a better fit for *Celmisia verbascifolia* and *Ranunculus lyallii*, whereas models that included harvest rate within 5 km were better for all species combined and *Dolichoglottis scorzoneroides*.

Although the magnitude of the slope of the relationship between alpine plant browse and deer pellet activity varied by plant species and management area, there was a consistent positive relationship (i.e. browse increased with increasing pellet groups) for almost all species and areas; the two exceptions were non-significant relationships for *Dolichoglottis scorzoneroides* and *Ranunculus lyallii* in the Murchison Mountains (Figure 7, Table A3.2, Table A3.4).

When considering all indicator species combined, the influence of harvest rate on alpine plant browse varied among management areas and species. To facilitate comparisons among areas over similar spatial scales, we present results from models that included harvest rate calculated within 10 km (Figure 8, Table A3.3, Table). Alpine plant browse significantly increased with increasing harvest rate in the Wapiti Area for all species combined, *Celmisia verbascifolia* and *Dolichoglottis scorzoneroides.* Similarly, alpine plant browse also significantly increased with increasing harvest rate in the Murchison Mountains for all species combined and *Dolichoglottis scorzoneroides* but declined for *Celmisia verbascifolia.* In the WARO Area, there was a significant increase in the proportion of *Dolichoglottis scorzoneroides* and *Ranunculus lyallii* plants browsed with increasing harvest rate, while browse on *Celmisia verbascifolia* significantly decreased.

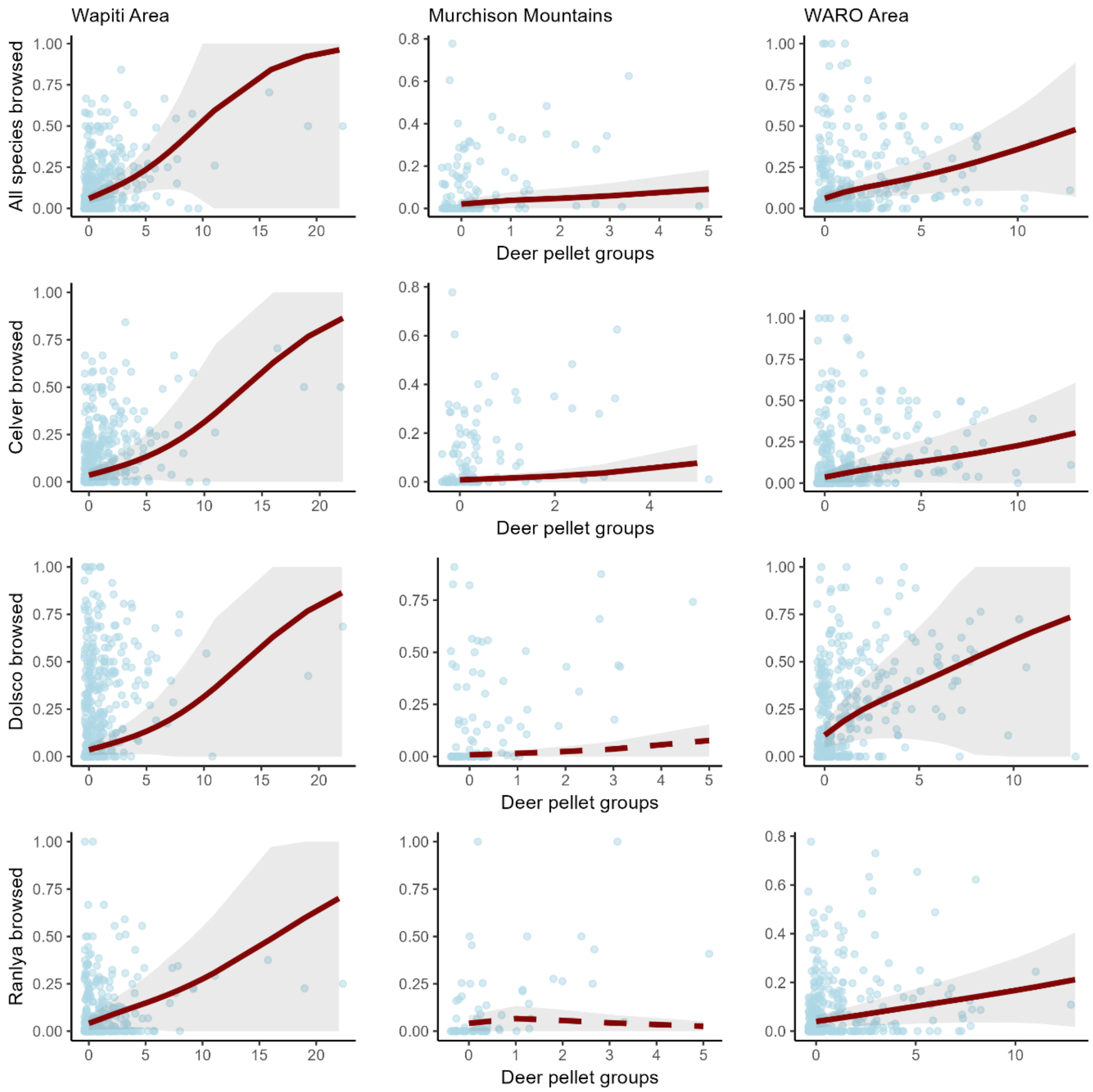

Figure 7. Mean (± 95% confidence intervals, shown by grey shading) relationship between the proportion of alpine plants browsed (all species combined, Celver: *Celmisia verbascifolia*, Dolsco: *Dolichoglottis scorzoneroides*, Ranlya: *Ranunculus lyallii*) and deer pellet groups (number per transect) for each management area (Wapiti Area, Murchison Mountains, WARO Area). Solid lines indicate a significant slope, while dashed lines indicate a non-significant slope at α = 0.05. The *y*-axes represent the proportion of each species browsed, with both the *x* and *y* axis values varying across the panels. See Table A3.2 and Table (both in Appendix 3) for detailed outputs.

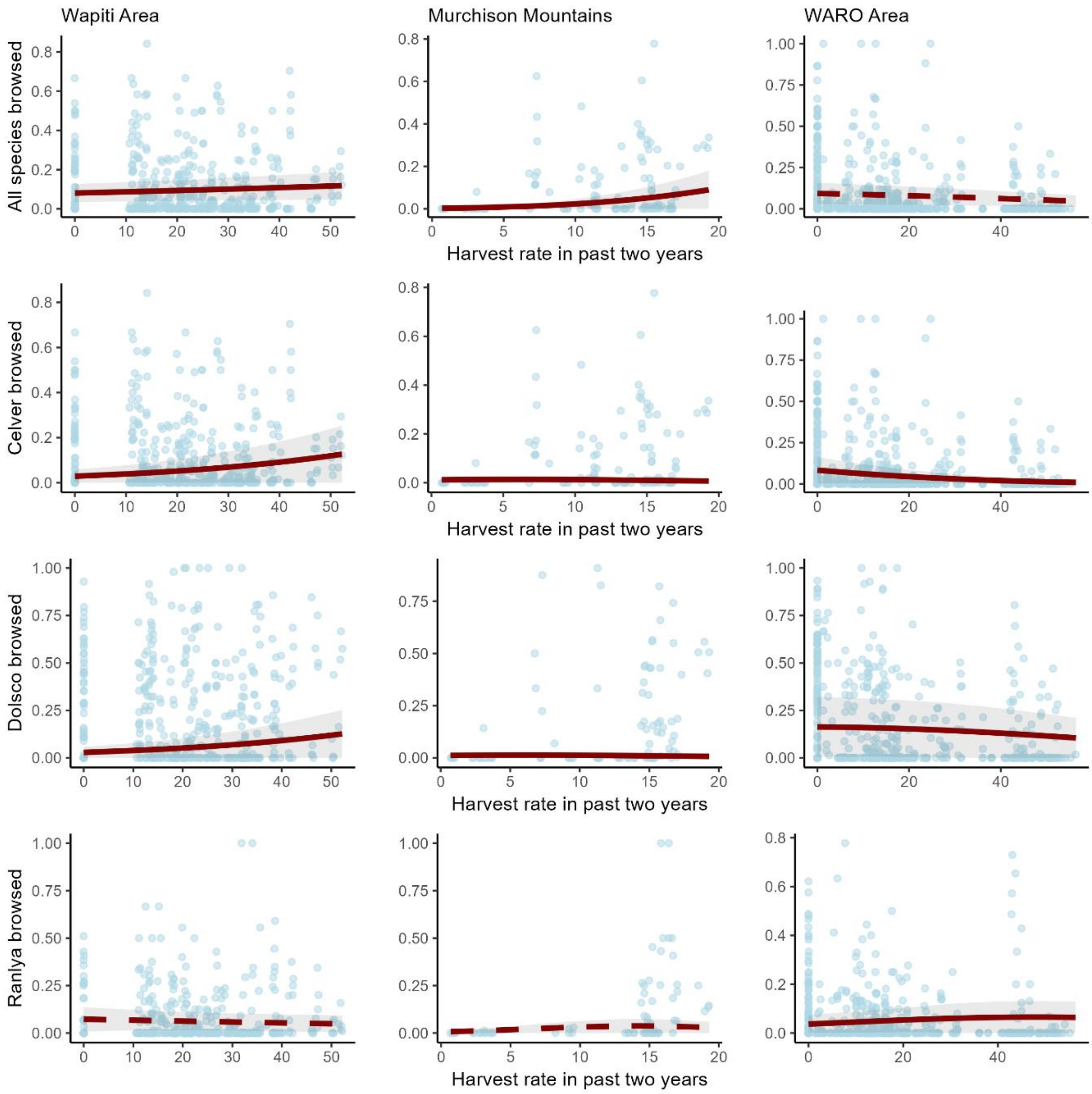

Figure 8. Mean (± 95% confidence intervals, shown by grey shading) relationship between the proportion of alpine plants browsed (all species combined, Celver: *Celmisia verbascifolia*, Dolsco: *Dolichoglottis scorzoneroides*, Ranlya: *Ranunculus lyallii*) and harvest rate within a 10 km buffer in the previous two years (deer removed per km^2) for each management area (Wapiti Area, Murchison Mountains, WARO Area). Solid lines indicate a significant slope, while dashed lines indicate a non-significant slope at α = 0.05. The *y*-axes represent the proportion of each species browsed, with both the *x* and *y* axis values varying across the panels. See Table A3.3 and Table A3.5 (both in Appendix 3) for detailed outputs.

4.4 What is the relationship between plant abundance and browse?

When assessing the influence of browse on alpine plant abundance, the most robust models fit to the data included log-transformed plant abundance with a Gaussian distribution (Table A4.2 in Appendix 4). We found no significant relationship between alpine plant abundance and the proportion of browse when considering all species combined and *Ranunculus lyallii* (Figure 9, Table A4.3). In contrast, the abundance of *Dolichoglottis scorzoneroides* increased in the WARO Area with increasing browse. *Celmisia verbascifolia* increased across all management areas. No significant relationships between browse and the abundance of *Dolichoglottis scorzoneroides* were observed in the Wapiti Area or Murchison Mountains.

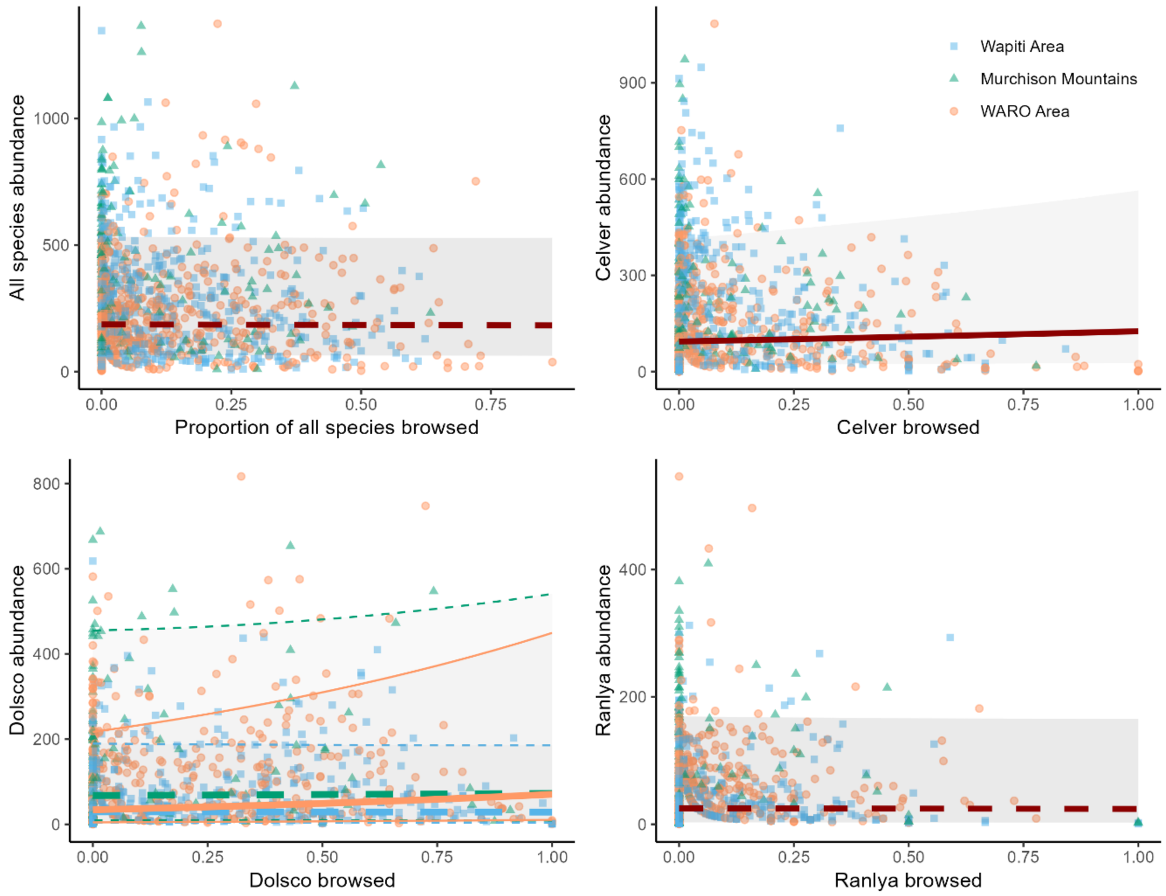

Figure 9. Mean (± 95% confidence intervals, shown by grey shading) relationship between alpine plant abundance (number of plants per transect) and the proportion of plants browsed (all species combined, Celver: *Celmisia verbascifolia*, Dolsco: *Dolichoglottis scorzoneroides*, Ranlya: *Ranunculus lyallii*). Solid lines indicate a significant slope, while dashed lines indicate a non-significant slope at α = 0.05. Thinner lines for Dolsco shows the limits of CI for each management area. Raw data from the three management areas are displayed with: Wapiti Area (blue square), Murchison Mountains (green triangle) and WARO Area (orange circle). Detailed model output is in Table A4.3 (in Appendix 4).

4.5 How does alpine plant abundance and browse change over time?

4.5.1 Alpine plant abundance

To investigate how alpine plant abundance changed over time, we ran multiple models including survey period as a predictor variable and site, line nested within site or line as random factors for each alpine plant species and management area. Depending on the combination of management area and plant species, zero-inflated models with a negative binomial error distribution provided a better fit (Table A4.1 in Appendix 4).

Overall, we found that alpine plant abundance varied across the survey periods, but this was dependent on the management area and plant species. For instance, we observed a slight decline in *Dolichoglottis scorzoneroides* and *Ranunculus lyallii* abundance in the Murchison Mountains when focusing on the last survey periods (Figure 10, Table A4.5). The abundance of *Celmisia verbascifolia* was higher in the surveys conducted after 2012 in the Wapiti Area, with an increase from 150 ± 148 plants (2011–2012) to 198 ± 189 plants (2014–2017) per monitoring line (Figure 10, Table A4.4). The change in alpine plant abundance between survey period in the WARO were less marked than in the other two management areas.

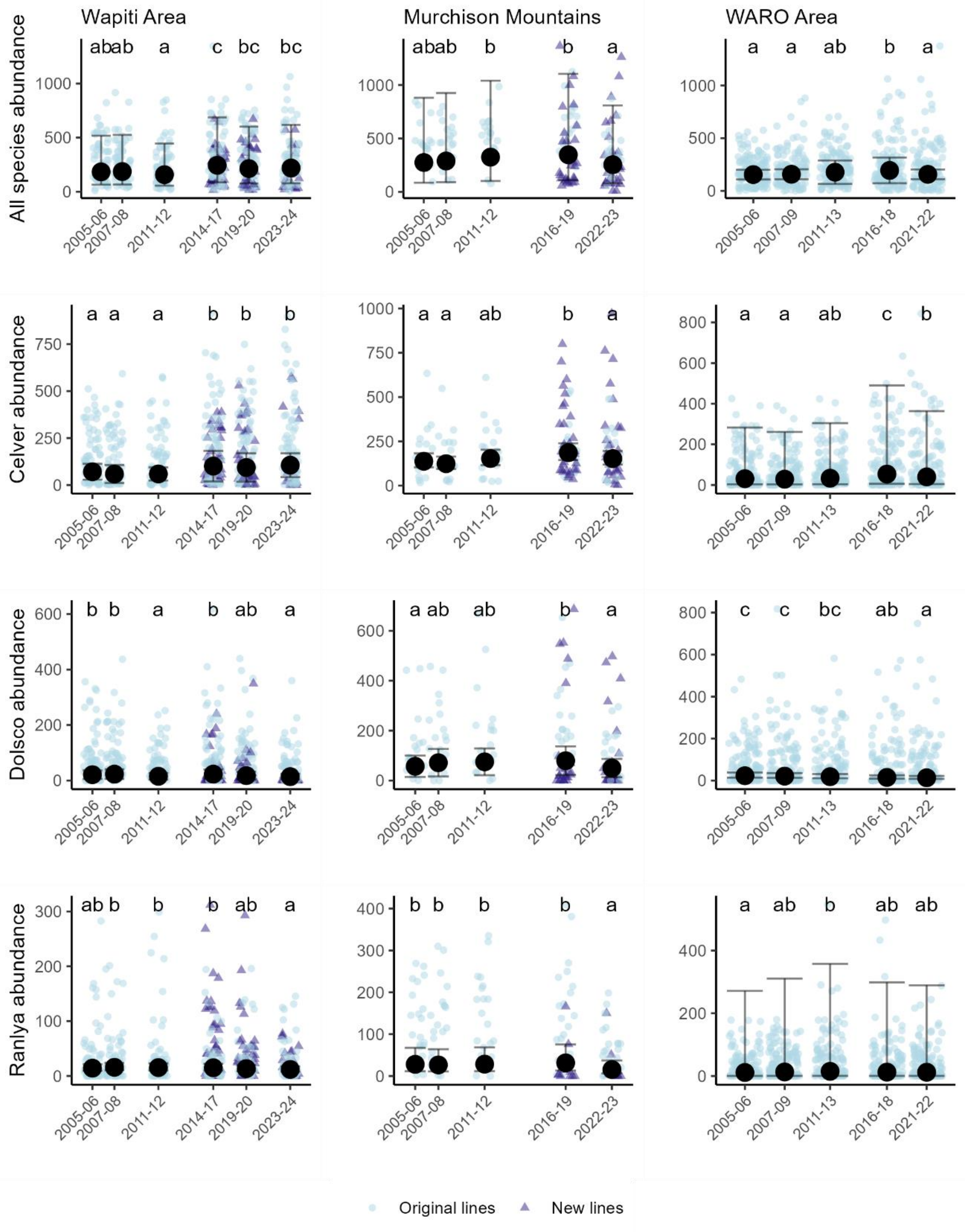

Figure 10. Mean (± 95% confidence intervals, shown as error bars) abundance of alpine plants (total number of plants per transect) per survey period for each indicator species (all species combined, Celver: *Celmisia verbascifolia*, Dolsco: *Dolichoglottis scorzoneroides*, Ranlya: *Ranunculus lyallii*). Points show the raw data differentiated by when the monitoring lines were established (original lines – blue circle; new lines – purple triangle). Letters highlight significant differences between survey periods (see Table 5 in Appendix 4 for detailed outputs). The *x*-axis represents the survey periods for each management area.

4.5.2 Alpine plant browse

Overall, how the proportion of alpine browse changed over time varied between management areas, with a gradual increase of alpine plant browse in the Murchison Mountains and a more heterogenous variation among years in the Wapiti and WARO Areas (Figure 11, Table A3.6).

Alpine browse in the Murchison Mountains was very low in the initial survey period (2005–2006), with the mean proportion of *Celmisia verbascifolia* plants browsed per monitoring line recorded at 0.02 ± 0.08 and effectively zero browse recorded for all species combined (0.00 ± 0.02), *Dolichoglottis scorzoneroides* (0.00 ± 0.01) and *Ranunculus lyallii* (0.00 ± 0.00). Rates of browse started to increase in the 2016–2019 survey period across all species combined and individually and reached 0.16–0.29 in the 2022–2023 survey period, depending on the species (Figure 11, Table A3.7, Table A3.8)

In the Wapiti Area, overall alpine plant browse across all species initially declined from 0.19 ± 0.18 of plants browsed (2005–2006) to 0.05 ± 0.08 (2011–2012), then increased to 0.17 ± 0.16 (2014–2017) before declining again to 0.08 ± 0.09 (2023–2024, Table A3.7, Table A3.8). Similar patterns were observed for the three species individually, with relatively low browse recorded in 2011–2012 and higher browse in the 2014-2017 or 2019–2020 survey periods, depending on the species. In addition, both *Dolichoglottis scorzoneroides* and *Ranunculus lyallii* had significantly lower browse recorded in the last survey period compared to the first survey period.

In the WARO Area, alpine plant browse varied among years and plant species. However, we can identify an overall decline from 2005–2006 to a low in 2012-2013 followed by a slow increase (Figure 11, Table A3.7, Table A3.8). The latest trend is more marked when focusing on *Dolichoglottis scorzoneroides*, with the mean proportion of browsed plants dropping from 0.35 ± 0.27 in 2005–2006 to a low of 0.05± 0.10 in 2011–2013 and then increasing back up to 0.27 ± 0.27 in the 2021–2022 survey period.

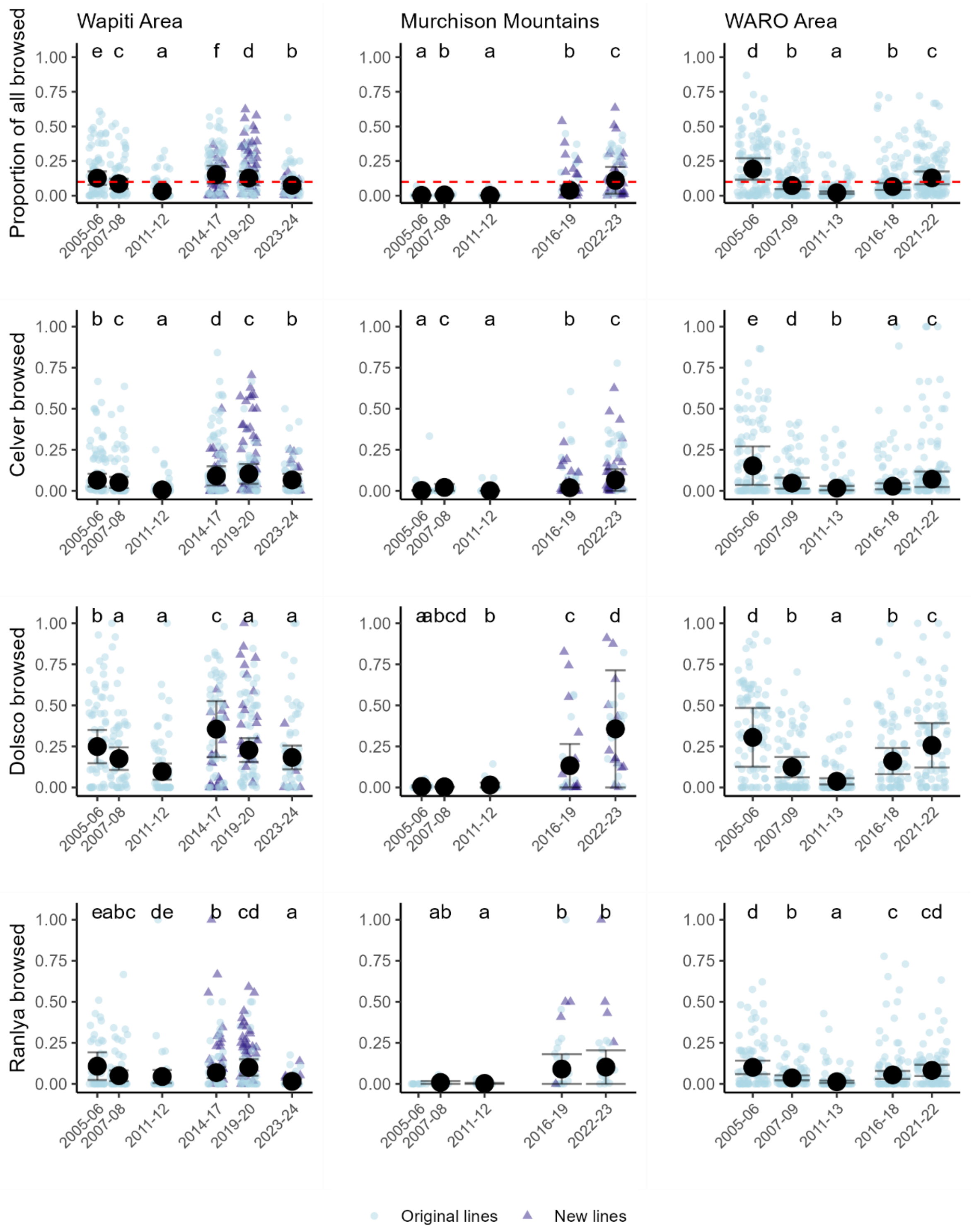

Figure 11. Mean (± 95% confidence intervals, shown by error bars) proportion of alpine plant browse per survey period for each indicator species (all species combined, Celver: *Celmisia verbascifolia*, Dolsco: *Dolichoglottis scorzoneroides*, Ranlya: *Ranunculus lyallii*). Points show the raw data differentiated by when the monitoring lines were established (original lines – blue circle; new lines – purple triangle). Letters highlight significant differences between survey periods (see Table A3.7 in Appendix 3 for detailed outputs). The *x*-axis represents the survey periods for each management area. The red dotted line in the top panel represents the 10% browse target across all monitored species that DOC has set as an interim target for the Wapiti Area.

4.6 Does the size class structure of *Ranunculus lyallii* change over time, and is this related to browse, deer activity and harvest?

4.6.1 Relationship between size class structure and browse, deer activity and harvest

Models including an interaction term between management area and harvest rate, deer pellet groups or the proportion of browsed alpine plants provided the best fit (Table A5.1). The proportion of large *Ranunculus lyallii* (leaf width >8cm) significantly decreased with increasing deer pellet groups across all management area (Figure 12, Table A5.2 in Appendix 5). When focusing on harvest rate, the proportion of large *Ranunculus lyallii* decreased with increasing harvest rate in the Wapiti Area, contrasting with the positive relationship observed in the Murchison Mountains and WARO Area (Figure 12, Table A5.2). The relationship between the proportion of large *Ranunculus lyallii* and the proportion of browsed *Ranunculus lyallii* (small and large plants combined) varied between management area, with a positive relationship observed in the Wapiti Area and a negative relationship found in the WARO Area (Figure 12, Table A5.2). No significant relationship was observed in the Murchison Mountains (Figure 12, Table A5.2).

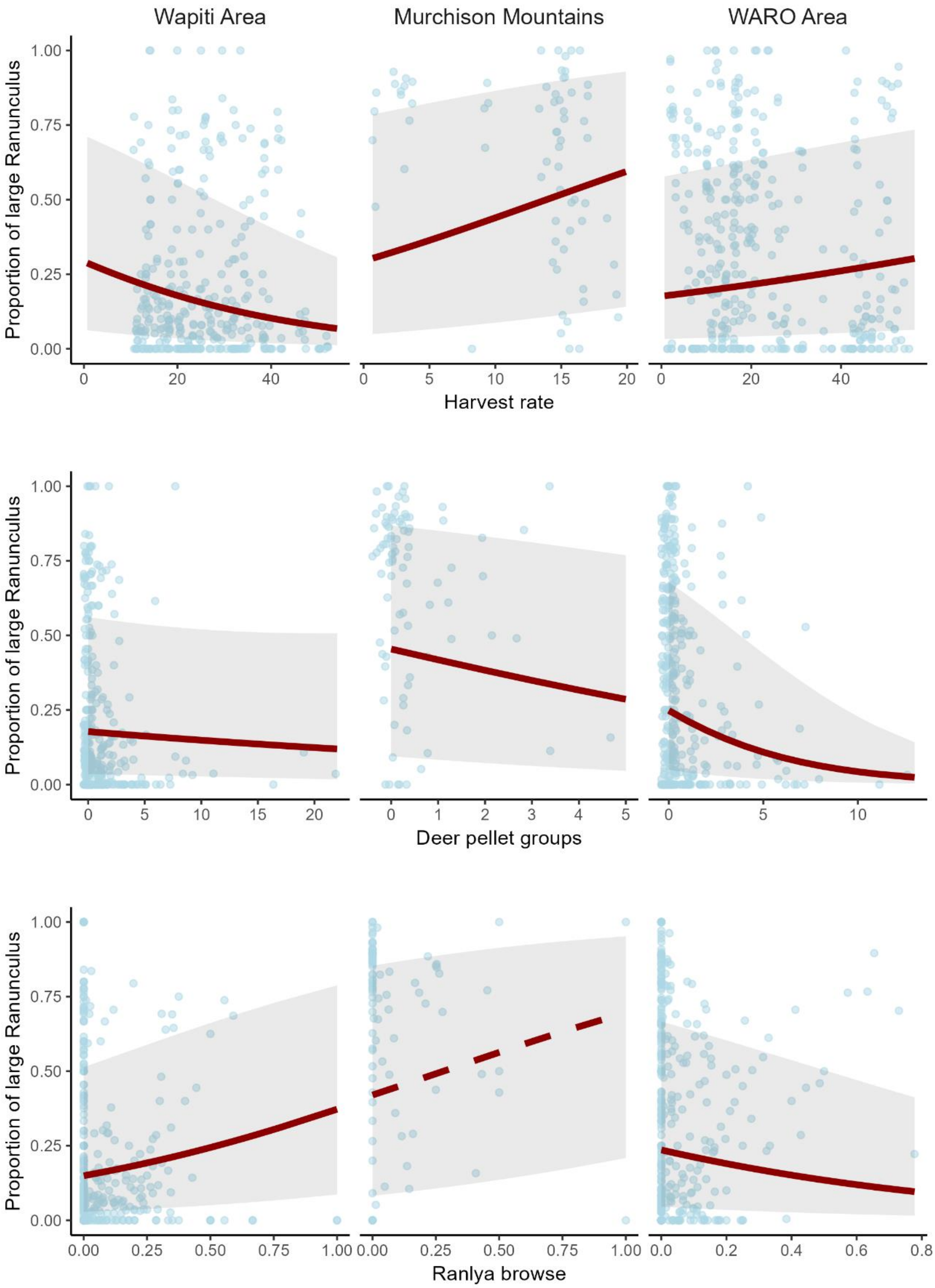

Figure 12. Mean (± 95% confidence intervals, shown by grey shading) relationship between the proportion of large *Ranunculus lyallii* (size class: >8cm) and harvest rate within a 10 km buffer in the previous two years (deer removed per km^2), deer pellet groups (number per transect) or the proportion of browsed *Ranunculus lyallii* by management area. Solid lines indicate a significant slope, while dashed lines indicate a non-significant slope at α = 0.05. The *y*-axes represent the proportion of each species browsed, with the *x*-axis values varying across the panels. Detailed model output in Table A5.2 (in Appendix 5).

4.6.2 Change of size class structure over time

The proportion of large *Ranunculus lyallii* changed over time with trends differing between management areas (Figure 13; and see Table A5.3, Table A5.4 in Appendix 5). In the Wapiti Area, the proportion of large *Ranunculus lyallii* per monitoring line gradually declined from 0.31 ± 0.32 (2011–2012) to 0.12 ± 0.18 (2023–2024). In the Murchison Mountains, a significant drop in the proportion of large *Ranunculus lyallii* was observed, with 0.76 ± 0.28 in 2011–2012 to 0.50 ± 0.31 in 2023–2024. When focusing on the WARO Area, we observed significant variation from one survey period to another but there was no clear overall trend.

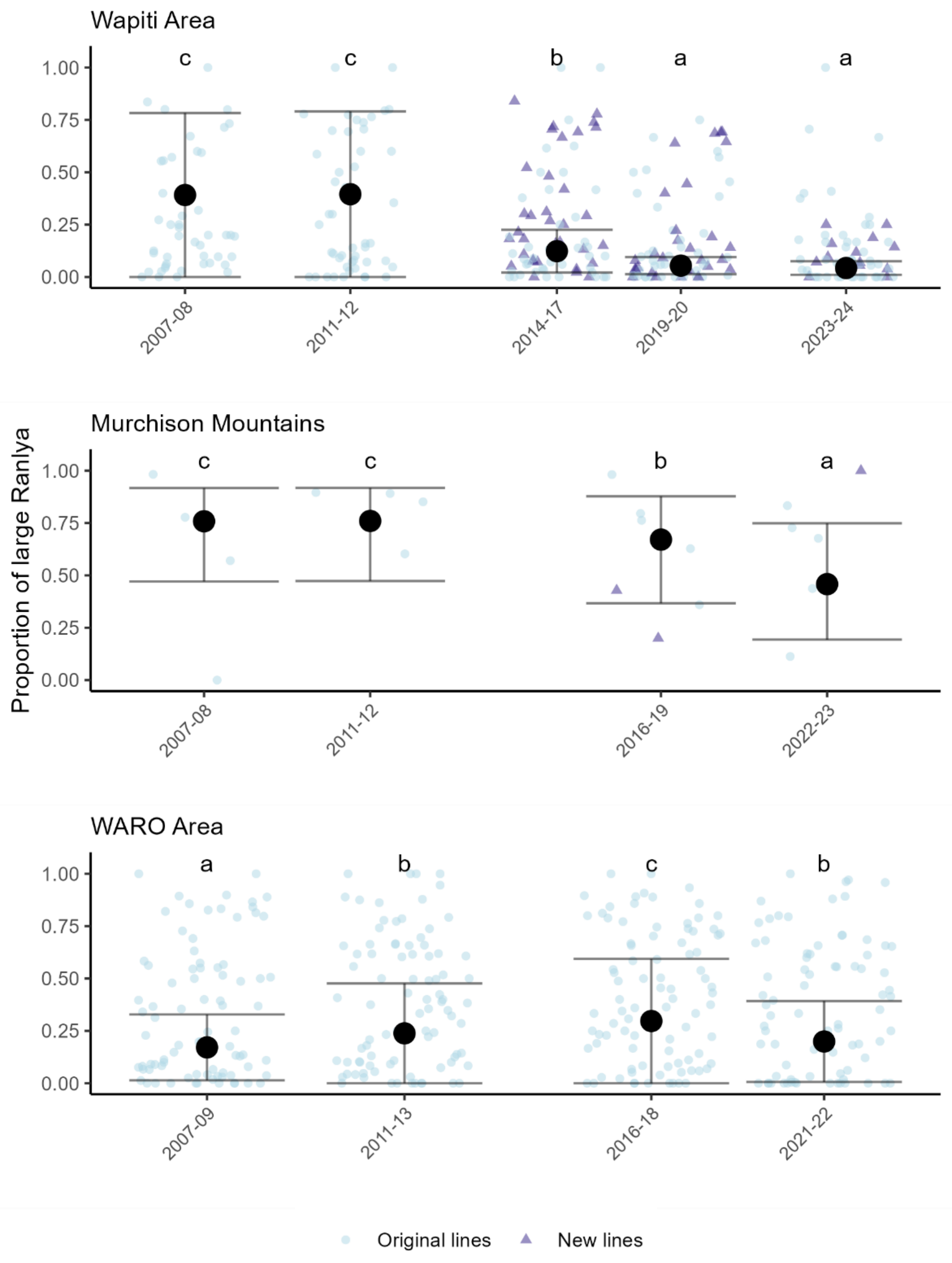

Figure 13. Mean (±95% confidence intervals, shown by error bars) proportion of large *Ranunculus lyallii* (Ranlya, size class: >8cm) per survey period across the three management areas. Points show the raw data differentiated by when the monitoring lines were established (original lines – blue circle; new lines – purple triangle). Letters indicate significant differences between survey periods, The x-axis represents the survey periods for each management area. See Table A5.3 (in Appendix 5) for detailed outputs.

5 Discussion

In this discussion we will comment on each of the five major questions posed in this work and provide more general interpretation of our findings.

5.1 Control effort has shifted over time

Both hunting effort and deer harvest rate was highly variable over time and across management areas (Question (Q)1). Overall, observed alpine plant browse and pellet group counts declined from 2006–2013 coinciding with the removal of c. 35,000 animals from FNP over this period. Change in hunting effort and harvest rate has been variable over time, particularly with respect to management area. Overall, harvest rates have increased in the Murchison Mountains, decreased in the WARO Area and remained stable in the Wapiti Area since 2006.

In the Wapiti Area, FWF-led management has been relatively stable over the nearly 20 years considered in this report, reflecting a target of ≥900 deer harvested per year as an agreed goal. Minor shifts from harvest based on phenotype that removed red deer in preference to wapiti occurred from 2006–2014. From 2015, females continued to be harvested based on phenotype, but males were selectively harvested at maturity (about 4 years old) based on antler quality. Despite high consistency in management effort and harvest over the entire period considered, there was a significant decrease in browse around 2012 for unknown reasons.

The Murchison Mountains has had the longest running management of deer in New Zealand, primarily for habitat protection of threatened species. From 2009, there has been a harvest target of c. 120 deer each year, although the management methods have changed over time. From 2006–2013, a period of low estimated animal densities (<1 deer per km^2), management included both ground and aerial hunting. From 2014–2018, WARO was used to remove the same number of deer per year. WARO ceased in 2019–2021, with aerial 'search and destroy' (i.e. rather than commercial venison recovery) used instead. These strategies resulted in different frequencies of management: WARO required more flights to meet the target (about six or more flights per year) compared to search and destroy aerial control, which reached the target number of animals in far fewer flights per year. Less frequent management could create a reduced 'landscape of fear' (Latham et al. 2018), allowing deer to feed in alpine areas longer even with the same number of animals removed per year. This appears to be consistent with a shift toward greater deer activity (pellet counts) and browse despite more effective deer harvest rates from 2019 onwards (Figure 7, Figure 8). Most recently (2022–2023) DOC-led aerial management has increased with support from DOC's National Wild Animal Management (WAM) programme, resulting in increased effort particularly in the 2023 season. Given the lags between management effort and alpine plant responses (i.e. in most models the two-year previous effort was the best predictor of browse), we would expect to see responses in alpine browse from 2025 for the current increase in management effort.

The relatively large area of FNP under WARO management is not driven by consistent targets in deer harvest but rather by commercial recovery influenced by economic factors, including fuel and venison prices, and the ability to process recovered animals (Warburton et al. 2016). Management effort from WARO has declined strongly since 2006 (Figure 4). From 2006–2013 there were more commercial operators harvesting relatively high numbers of deer but, as venison export prices declined and fuel prices increased, many commercial operators stopped harvesting. From 2019, both low venison prices and limited demand further reduced the number of operators and the harvest rate.

Overall, both estimates of browse and deer activity (pellet counts) were extremely low in the Murchison Mountains (Ewans 2013), and higher, but also highly variable, among sites in the much larger Wapiti and WARO management areas. The number of deer removed increases with increasing area-scale hunting effort in the WARO Area, but not elsewhere, reflecting the different management objectives of the areas (i.e. set targets for the Murchison Mountains and Wapiti Area, but commercial viability in the WARO Area). It is difficult to determine whether greater increases in harvest efficiency in WARO are driven by increasing numbers of deer, or greater efficiency of operations; more information about true effort (e.g. GPS tracks and duration of effort) is required. However, management/hunting effort and harvest rate per se were both poor metrics for assessing browse impacts on vegetation compared to a direct measure of deer activity (pellet counts). Therefore, using a set number of animals to remove each year as a management strategy may not achieve the protection of vulnerable plant species (Whitmore 2023). Put another way, operational effort itself is not strongly linked to browse impacts; a more robust approach requires understanding thresholds of deer impacts and using this as evidence to determine the level of management effort that is required.

5.2 Deer activity and management effort

Pellet group counts were often related to hunting effort and deer harvest rate (Q2) but reflect different measures of potential deer activity or the likely effects on vegetation. For these relationships, harvest rate within a 5 km buffer over the previous 2 years was identified in statistical models as the best spatial predictor of pellet group counts (Table). Deer pellet group counts declined with increasing deer harvest only in the WARO Area; in contrast, pellet counts tended to increase with increasing harvest in both the Wapiti and Murchison Mountain areas (Figure 6). Pellet counts are an indirect proxy of deer population size and are better interpreted as a metric of deer activity within a site (Forsyth 2005; Forsyth et al. 2011).

While deer pellet counts are correlated with deer density (Forsyth et al. 2007), more robust measures of deer density and movement patterns across the landscape may prove to be more useful for guiding management decisions, particularly with respect to setting harvest targets that are responsive to both population size and vegetation browse (see also Forsyth et al. 2022). We recommend continuing to monitor deer pellet counts at the alpine browse sites but suggest that additional methods for estimating density be considered. For example, the addition of trail cameras as a monitoring tool at each site may enable both the estimation of deer density and provide information about other browsing species (e.g. chamois, hares) that might be influencing vegetation browse and recovery (Hickling et al. 2024). DOC has already been trialling new emerging monitoring techniques for estimating deer densities, including thermal imagery and genetic samples from deer pellets or culled animals, in the Snag Burn catchment of the Murchison Mountains (G. Ledgard, DOC, pers. comm., 13 August 2024) with reasonable success.

What the contrasting results among management areas suggest is that management effort and deer activity are positively related in the two areas where fixed targets for management occur, but that increased commercial recovery is associated with lower deer activity. Furthermore, the retrospective application of monitoring alpine areas does not generate the data or evidence needed for understanding the impacts that management effort or regime are having on deer populations overall or movement among habitats (e.g. more frequent helicopter disturbance creating a landscape of fear). The pellet count data reflects deer activity that occurs along the alpine plant monitoring transects but may not capture important effects of management on deer population changes or impacts over larger scales. Finally, given the high variability of pellet counts among sites, there is relatively low statistical power to detect threshold effects or to quantify relationships with operational effort (Mason et al. 2019). Without quantitative estimates of population abundance, or spatial information about the movement of deer among habitats under different management regimes, the actual effectiveness of management on deer populations themselves cannot be assessed.

5.3 Relationships between browse, deer activity and management

Browse observed on selected alpine plant species was related to deer activity, harvest rate and management area (Q3) in complex ways. The proportion of browsed plants increased with increasing deer activity (pellet groups) for all species, both separately and combined. In contrast, the relationship between plant browse and deer harvest rate was more complex, with differing patterns depending on the species and management area being considered. Overall, the positive relationships between proportion of plants browsed and pellet counts make intuitive sense because pellet counts should reflect deer activity within a site and in close proximity to monitored plant populations.

However, the more complex responses of browse to harvest rate are harder to interpret with the available data. One possibility is that the spatial buffers (5 or 10 km) and lags considered (previous 2 years of management) will include multiple drivers of variation in deer activity and consumption, including seasonal movement and diet effects, and behavioural changes in the use of habitats through management effort and frequency of disturbance (e.g. Latham et al. 2018). Other interactions among deer and vegetation are likely, but cannot be evaluated with the available data collected for few alpine species. For example, additional information about other plant species within sites is needed to understand if the browse damage of the indicator species reflects wider vegetation impacts. Similarly, previous studies have demonstrated that browse damage varies widely even within species because of environmental effects, such as soil fertility, or the palatability of neighbouring species (Coomes et al. 2003). Moreover, browsing animals can exert important indirect effects in ecosystems or communities through, for example, soil compaction, nutrient deposition or selective damage of some species (see review by Peltzer & Nugent 2023). What these and other studies demonstrate is that browsing impacts are complex, and driven only in part by interactions among browsing animals and management. Regardless of the mechanisms involved, management effort and harvest rates are far poorer predictors of browse damage than measurements of deer activity within a site.

5.4 Alpine plant abundance and browse

The relationship between plant abundance and browse (Q4) was highly variable among species, sites and management areas. Estimates of browse are important for monitoring damage to individual plants. However, understanding the cumulative effects of repeated damage to plants and whether these drive long-term changes in populations or communities is the ultimate goal. Moreover, changes in the distribution and abundance of native species, and the composition of communities, underly both biodiversity monitoring and additional considerations, such as ecological integrity (e.g. Lee et al. 2005; McGlone et al. 2020; Bellingham et al. 2021). Despite high variation in deer activity, management effectiveness and browse damage, we did not detect any significant changes in overall plant abundance over time (i.e. the total number of plants across all indicator species observed within sites). However, individual species responses differed among management areas. There was a slight decline in *Dolichoglottis scorzoneroides* and *Ranunculus lyallii* abundance in the Murchison Mountains in the last two survey periods (Figure 10). In contrast, *Celmisia verbascifolia* abundance was higher in the surveys conducted after 2012 in the Wapiti Area. What these findings suggest is that, for the period considered in this report, deer were not having a significant impact on these three plant species at the population level. Nevertheless, previous studies suggest that repeated browse damage can have threshold effects on plant populations, including perennial herbs, and especially when browsing lowers plant survival or reproductive output repeatedly (e.g. Knight et al. 2009). Additional information on population responses (i.e. recruitment, growth and mortality of species), and whether these are affected by other components of vegetation (e.g. suppression by increases in unpalatable plant species) is not available, but is needed to understand the long-term changes in alpine plant abundance (or any other species of interest).

Despite the more detailed understanding of population changes and demographic consequences of deer browse on the alpine species reported in this study, a crucial gap still remains in understanding both diet selection by deer of these species, and the responses or changes in other species even within monitored sites. Some of the interannual variation in abundance or browse is assumed to be related to preference and selective damage by deer, and this should be confirmed with independent analyses of deer diet within a site or the spatial buffers used in our analyses. Our results showing higher browse damage of *Ranunculus lyallii* associated with modest increases in deer activity in the Murchison Mountains, and longer term potential declines in *Dolichoglottis scorzoneroides* in the Wapiti and WARO areas are consistent with early selection of *Ranunculus lyallii* by deer, but perhaps diet switching or greater sensitivity of *Dolichoglottis scorzoneroides* to browse over the longer term. There are currently no data available to determine whether these changes are caused by deer selection and damage per se. These responses probably depend on multiple mechanisms such as lags in population responses, compensatory growth of co-occurring species, and the palatability of neighbouring plants (e.g. Coomes et al. 2003).

5.5 Size class responses of *Ranunculus lyallii*

We assessed whether the size class structure of *Ranunculus lyallii* has changed over time, and if so, whether this was related to browse, deer activity and harvest rate (Q5). The proportion of large *Ranunculus lyallii* in populations within a site increased with fewer deer pellet groups across all management areas. However, the pattern was not as straightforward when considering harvest rate or the proportion of browsed *Ranunculus lyallii* plants. The proportion of large *Ranunculus lyallii* decreased with increasing harvest rate in the Wapiti Area but the opposite pattern was observed in the Murchison Mountains and WARO Area. In addition, large *Ranunculus lyallii* were more prevalent in the population with increased levels of browse on *Ranunculus lyallii* plants in the Wapiti Area, while the WARO Area showed the opposite relationship. *Ranunculus lyallii* is considered highly sensitive to deer browse and our findings suggest that increasing deer activity, even at the very low deer densities that occur in the Murchison Mountains, is associated with a decline in larger *Ranunculus lyallii* in the most recent survey. Size class change is a first proxy of demographic changes in the population, but a more detailed understanding of population dynamics and the long-term viability of this species is needed to confidently set targets across all management areas.

5.6 Interpreting changes in management and vegetation responses

Despite different operational effort over time and large spatial scales among management areas (Figure 4), these differences were not strongly reflected in observed deer activity or browse damage at sites (Figure 6). Nevertheless, browse damage was most strongly associated with deer activity (pellet counts) within sites. What these findings demonstrate is that attributing broad-scale management approaches to responses of alpine plant populations requires additional knowledge of the biology and ecology of the alpine plants themselves, and of the responses of deer populations to management (e.g. density threshold impacts and altered movement and seasonal behaviours; see the general discussions of Côté et al. 2004; Tanentzap et al. 2012; Forsyth et al. 2022). One such unresolved issue is an understanding of to what level deer densities should be managed, and for what duration, to achieve one or more objectives. For example, management in the Murchison Mountains has maintained relatively low deer numbers over several decades but some ungulate impacts from historical population highs were detectable for decades (40+ years; Tanentzap et al. 2009). Moreover, even with sustained management to low densities using set harvest targets, very recent observed increases in deer activity have been associated with declines in large *Ranunculus lyallii* (but not in other species), suggesting that the previous management regime may not have been sufficient in preventing damage to the most highly selected or sensitive plant species. These observations are consistent with the much larger literature of deer impacts in forest vegetation that suggest highly palatable or selected plant species are affected at very low deer densities, and that if a management goal is to maintain biodiversity, sustain threatened populations, or ecological integrity, then adaptive management underpinned by evidence is required (Peltzer & Nugent 2023; Hawcroft et al. 2024).

The outcome monitoring in this project was initially designed to determine changes in the condition of three widespread indicator alpine plant species, and retrospectively used to relate alpine plant browse to management and deer activity to understand changes in deer impacts. The wider goal for this outcome monitoring was to provide the data to ensure that the FNPMP goal of 'promoting the regeneration of browsed indigenous flora' is met within the three management areas (Department of Conservation 2007).

While the monitoring and operational data allowed us to broadly address this goal, the monitoring design limits our ability to make some key inferences. For example, the browse monitoring focusses on three indicator species of alpine vegetation as a proxy for the overall impacts of deer. These species were selected because they are known to be susceptible to deer browse and are present at all monitored sites. While restricting monitoring to these species simplified the methodology, it did not allow us to investigate whether the level of browse was linked to the responses of other species within sites or whether shifts in vegetation composition towards non-palatable species in response to browse or other drivers is occurring.

Some additional information or data collection could improve our ability to understand changes in alpine communities, and attribute these changes to the effects of deer and their management. At a minimum, including cover estimates of common plant species within sites is needed to determine if browse is driven by the palatability of other plant species that co-occur within sites and enable assessment of additional drivers of long-term changes in alpine communities, such as compensatory growth of unpalatable species, or progressive changes or turnover in species composition (see also recommendations of Day et al. 2023 for understanding changes in tussock grasslands).

Such an approach could also be applied for monitoring the impacts of other wild animals on alpine vegetation such as tahr (*Hemitragus jemlahicus*) (Cruz et al. 2017). For the indicator species themselves, including demographic measures of plant mortality and reproduction is needed to evaluate long-term population viability within sites, regardless of whether these changes are caused by browse or other drivers.

It could also be valuable to consider including measurement of the dominant (> 5% cover) plant species along monitoring transects. This could be used to determine if browse is driven by the palatability of other plant species that co-occur within sites and enable assessment of additional drivers of long-term changes in alpine communities, such as compensatory growth of unpalatable species, or progressive changes or turnover in species composition.

6 Recommendations

Our analyses of monitoring data from 2006–2024 for selected alpine plant species, deer activity and management effort, and results for the questions posed relating management effort to browse impacts, demonstrate the crucial importance of long-term evidence for understanding the effectiveness of different deer management approaches. However, our findings also reveal several opportunities for supporting more robust data and evidence to better resolve issues around critical thresholds of deer abundance and impact, linking broad-scale deer management to their population control, and determining the long-term effects on species viability and vegetation. Our recommendations include:

- Capture flight information (e.g., helicopter track logs) for all aerial control activities. This is typically required for helicopter activity as part of operational work and would provide valuable additional information on the frequency of disturbance to deer, spatial distribution and coverage of operational effort, and return interval of management. In the absence of such information, the best metrics of harvest determined quantitatively here (e.g., deer harvested within a 10 km buffer in the previous two years) could be retained.
- Consider using browse metrics to actively update management targets for management of the Murchison Mountains and Wapiti Area. Our results demonstrate that harvest rate and management effort are poor predictors of browse compared to deer activity. Pellet counts could be used to update the following round of management with at least 1–2 years lead time for planning and resourcing of operations.
- Use harvested deer or deer pellets to determine the relative contribution of the monitored alpine species to deer diet using molecular techniques (de Sousa et al. 2019). This information is needed to determine if the three alpine plant species currently monitored reflect wider browse effects in alpine vegetation. In addition, a better understanding of the relative palatability or diet selection is needed to determine if threshold browse targets used to plan management interventions also benefit other alpine vegetation species.
- Widen measurements of the selected alpine plant species to include demographic measures of plant mortality and reproduction. Together with current monitoring data, this is needed to evaluate the long-term population viability within sites. Put another way, this information is needed to understand if repeated or long-term browsing increases plant mortality or reduces reproduction, both of which affect population growth.
- Consider including measurement of the dominant (>5% cover) plant species along monitoring transects with sites. This information could be used to determine if browse is driven by the palatability of other plant species that co-occur within sites and enable assessment of additional drivers of long-term changes in alpine communities, such as compensatory growth of unpalatable species, or progressive changes or turnover in species composition. This recommendation is consistent with Whitehead et al. (2024) for assessing the impacts of another wild animal species, tahr, on alpine vegetation.

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8 Glossary of abbreviations and terms

AICc	Corrected Akaike's Information Criterion
Celver	*Celmisia verbascifolia* subsp. *verbascifolia*
CI	Confidence interval
CL	Confidence limit
DOC	Department of Conservation
Dolsco	*Dolichoglottis scorzoneroides*
FNP	Fiordland National Park
FNPMP	Fiordland National Park Management Plan
FWF	Fiordland Wapiti Foundation
GLM	Generalised linear model – a regression model that does not include random effects
GLMM	Generalised linear mixed-effects model – a regression model that includes random effects
Murchison Mountains	The area of Fiordland National Park where deer are managed by DOC for the conservation of takahē (*Porphyrio hochstetteri*) (Figure 1)
MWLR	Manaaki Whenua – Landcare Research
Proximity metrics	Hunting effort (operator days per year) or harvest rate (deer removed per year) calculated within a specified spatial buffer (in m) of a vegetation monitoring transect within the specified preceding days
Ranlya	*Ranunculus lyallii*
SD	Standard deviation
SEM	Standard error of the mean
WAM	Wild Animal Management program run by the Department of Conservation
Wapiti Area	The area of Fiordland National Park that is managed by the Fiordland Wapiti Foundation (Figure 1)
WARO	Wild Animal Recovery Operators
WARO Area	The area of Fiordland National Park that is available for commercial wild animal recovery operators to recover deer outside the Wapiti Area and the Murchison Mountains (Figure 1)

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Appendix 1 – Model selection and analyses of hunting effort & harvest rate (Q1)

Table A1.1. Candidate model sets for a) total annual and b) area-scaled annual hunting effort and c) total annual and d) area-scaled annual harvest rate as evaluated by comparing corrected Akaike's Information Criterion (AICc). Models for the total annual metrics (a, c) used a negative binomial error distribution, while the models for the area-scale annual metrics (b, d) used a Gaussian error distribution. The log likelihood (logLik), differences in model AICc value from the best model (ΔAICc), degrees of freedom (df) and Akaike weights are shown for each model. The best model for each response variable (in bold) were identified using ΔAICc and model diagnostics.

	logLik	AICc	ΔAICc	df	weight
a) Annual hunting effort (operator days per year)					
year * management_area	**-227.52**	**471.54**	**0.00**	**7**	**0.999**
year + management_area	-237.29	485.85	14.31	5	0.001
management_area	-250.17	509.18	37.64	4	0.000
year	-281.24	568.98	97.44	3	0.000
1 (Intercept only)	-288.82	581.88	110.34	2	0.000
b) Annual harvest rate (deer removed per year)					
year * management_area	**-375.11**	**766.71**	**0.00**	**7**	**0.993**
management_area	-384.18	777.19	10.48	4	0.005
year + management_area	-384.11	779.50	12.78	5	0.002
year	-427.23	860.95	94.24	3	0.000
1 (Intercept only)	-428.52	861.28	94.57	2	0.000
c) Area-scaled annual hunting effort (operator days per year per km^2)					
year * management_area	**113.69**	**-210.89**	**0.00**	**7**	**0.946**
year + management_area	107.99	-204.70	6.19	5	0.043
year	104.30	-202.11	8.78	3	0.012
management_area	95.49	-182.14	28.75	4	0.000
1 (Intercept only)	92.83	-181.43	29.47	2	0.000
d) Area-scaled annual harvest rate (deer removed per year per km^2)					
year * management_area	**-13.67**	**43.82**	**0.00**	**7**	**1.000**
management_area	-25.49	59.81	15.99	4	0.000
year + management_area	-25.48	62.24	18.42	5	0.000
1 (Intercept only)	-46.87	97.97	54.15	2	0.000
year	-46.84	100.18	56.36	3	0.000

Table A1.2. Candidate model sets for area-scaled harvest rate (deer removed per year per km^2) as evaluated by comparing corrected Akaike's Information Criterion (AICc). All models used a Gaussian error distribution. The log likelihood (logLik), differences in model AICc value from the best model (ΔAICc), degrees of freedom (df) and Akaike weights are shown for each model. The best model (in bold) was identified using ΔAICc and model diagnostics.

Model	logLik	AICc	ΔAICc	df	weight
Area-scaled annual harvest rate (deer removed per year per km^2)					
annual_effort_km * management_area + (1 | year)	**-5.43**	**30.14**	**0.00**	**8**	**0.525**
annual_effort_km * management_area	-7.19	30.87	0.73	7	0.365
annual_effort_km + management_area	-11.39	34.06	3.92	5	0.074
annual_effort_km + management_area + (1 | year)	-10.86	35.54	5.40	6	0.035
management_area	-22.09	53.02	22.88	4	0.000
annual_effort_km	-34.93	76.34	46.20	3	0.000
1 (Intercept only)	-46.44	97.11	66.97	2	0.000

annual_effort_km = area-scaled hunting effort (operating days per year per km^2).

Appendix 2 – Model selection and analyses of deer pellet groups (Q2)

Table A2.1. Candidate model sets for the number of pellet groups as evaluated by comparing corrected Akaike's Information Criterion (AICc). All models used a negative binomial error distribution. The log likelihood (logLik), differences in model AICc value from the best model (ΔAICc), degrees of freedom (df) and Akaike weights are shown for each model. The best model (in bold) was identified using ΔAICc and model diagnostics.

Model	logLik	AICc	ΔAICc	df	weight
harvest_km_5000_730 * management_area + (1 | site/line)	**-1357.42**	**2732.99**	**0.000**	**9**	**0.924**
harvest_km_10000_730 * management_area + (1 | site/line)	-1359.92	2738.00	5.010	9	0.075
harvest_km_10000_730 + management_area + (1 | site/line)	-1368.36	2750.82	17.820	7	0.000
harvest_km_10000_365 * management_area + (1 | site/line)	-1366.81	2751.78	18.780	9	0.000
harvest_km_10000_365 + management_area + (1 | site/line)	-1369.25	2752.60	19.610	7	0.000
harvest_km_5000_730 + management_area + (1 | site/line)	-1369.53	2753.15	20.160	7	0.000
harvest_km_5000_365 * management_area + (1 | site/line)	-1367.58	2753.32	20.330	9	0.000
harvest_km_10000_180 + management_area + (1 | site/line)	-1370.98	2756.05	23.060	7	0.000
harvest_km_10000_180 * management_area + (1 | site/line)	-1369.20	2756.55	23.550	9	0.000
harvest_km_5000_365 + management_area + (1 | site/line)	-1372.28	2758.65	25.660	7	0.000
harvest_km_5000_180 * management_area + (1 | site/line)	-1372.56	2763.28	30.290	9	0.000
harvest_km_1000_730 + management_area + (1 | site/line)	-1375.41	2764.92	31.920	7	0.000
harvest_km_5000_180 + management_area + (1 | site/line)	-1376.29	2766.67	33.680	7	0.000
harvest_km_1000_730 * management_area + (1 | site/line)	-1374.76	2767.67	34.670	9	0.000
harvest_km_1000_365 + management_area + (1 | site/line)	-1378.29	2770.68	37.690	7	0.000
harvest_km_1000_365 * management_area + (1 | site/line)	-1378.14	2774.43	41.440	9	0.000
management_area + (1 | site/line)	-1381.92	2775.91	42.920	6	0.000
harvest_km_1000_180 + management_area + (1 | site/line)	-1380.96	2776.02	43.030	7	0.000
harvest_km_1000_180 * management_area + (1 | site/line)	-1379.54	2777.24	44.250	9	0.000
1 (Intercept only) + (1 | site/line)	-1386.70	2781.43	48.440	4	0.000

harvest_km_*buffer_days* = area-scaled harvest within a spatial *buffer* (in m) of a site within the preceding *days*.

Appendix 3 – Model selection and analyses of alpine plant browse (Q3)

Table A3.1. Identification of the best predictor of alpine browse between deer pellet groups, harvest rate within 10 or 5 km (harvest_km_10000_730 or harvest_km_5000_730) and hunting effort (effort_km_730) by comparing corrected Akaike's Information Criterion (AICc). The log likelihood (logLik), differences in model AICc value from the best model (ΔAICc), degrees of freedom (df) and Akaike weights are shown for each model. All models were zero-inflated mixed models with a binomial error distribution. The best model for each response variable (in bold) were identified using ΔAICc and model diagnostics.

Plant species	Formula	df	logLik	AICc	ΔAICc	weight
All	**deer_pellets + (1 | site/line) + (1 | financial_year_cont2)**	**7**	**-6996.2**	**14006.52**	**0**	**1**
	deer_pellets + (1 | line) + (1 | financial_year_cont2)	6	-7057.59	14127.28	120.76	0
	effort_km_site_730 + (1 | site/line) + (1 | financial_year_cont2)	7	-7120.33	14254.79	248.27	0
	harvest_km_5000_730 + (1 | site/line) + (1 | financial_year_cont2)	7	-7585.32	15184.76	1178.24	0
	harvest_km_10000_730 + (1 | site/line) + (1 | financial_year_cont2)	7	-7589.27	15192.67	1186.14	0
Celver	**deer_pellets + (1 | site/line) + (1 | financial_year_cont2)**	**7**	**-3266.04**	**6546.21**	**0**	**1**
	effort_km_site_730 + (1 | site/line) + (1 | financial_year_cont2)	7	-3311.43	6636.98	90.77	0
	deer_pellets + (1 | line) + (1 | financial_year_cont2)	6	-3346.26	6704.62	158.4	0
	harvest_km_10000_730 + (1 | site/line) + (1 | financial_year_cont2)	7	-3549.37	7112.86	566.64	0
	harvest_km_5000_730 + (1 | site/line) + (1 | financial_year_cont2)	7	-3550.9	7115.92	569.71	0
Dolsco	**deer_pellets + (1 | site) + (1 | financial_year_cont2)**	**6**	**-5562.49**	**11137.09**	**0**	**1**
	effort_km_site_730 + (1 | site) + (1 | financial_year_cont2)	6	-5671.56	11355.22	218.14	0
	harvest_km_5000_730 + (1 | site) + (1 | financial_year_cont2)	6	-5823.9	11659.9	522.82	0
	harvest_km_10000_730 + (1 | site) + (1 | financial_year_cont2)	6	-5834.85	11681.79	544.70	0
Ranlya	**deer_pellets + (1 | site/line) + (1 | financial_year_cont2)**	**7**	**-447.07**	**908.56**	**0**	**1**
	deer_pellets + (1 | line) + (1 | financial_year_cont2)	6	-454.46	921.24	12.68	0
	harvest_km_10000_730 + (1 | site) + (1 | financial_year_cont2)	6	-567.3	1146.91	238.36	0
	effort_km_site_730 + (1 | site) + (1 | financial_year_cont2)	6	-578.69	1169.68	261.13	0
	harvest_km_5000_730 + (1 | site) + (1 | financial_year_cont2)	6	-579.5	1171.32	262.77	0

Note: Celver: *Celmisia verbascifolia*, Dolsco: *Dolichoglottis scorzoneroides*, Ranlya: *Ranunculus lyallii* .

Table A3.2. Identification of the best combination of error distribution and random factors for models predicting the proportion of alpine browse of all species combined and each indicator species (Celver: *Celmisia verbascifolia*, Dolsco: *Dolichoglottis scorzoneroides*, Ranlya: *Ranunculus lyallii*) from deer pellet groups per management area by comparing corrected Akaike's Information Criterion (AICc). The log likelihood (logLik), differences in model AICc value from the best model (ΔAICc), degrees of freedom (df) and Akaike weights are shown for each model. The best model for each response variable (in bold) were identified using ΔAICc and model diagnostics.

Management area	Plant species	Distribution	Formula	df	logLik	AICc	ΔAICc	weight
Murchison Mountains	All species	**Zi-binomial**	**deer_pellets + (1 | site/line) + (1 | financial_year_cont2)**	**7**	**-944.89**	**1904.78**	**0.00**	**1**
		binomial	deer_pellets + (1 | site/line) + (1 | financial_year_cont2)	5	-1042.57	2095.68	190.90	0
		binomial	deer_pellets + (1 | line) + (1 | financial_year_cont2)	4	-1052.73	2113.82	209.04	0
		Zi-binomial	deer_pellets + (1 | site) + (1 | financial_year_cont2)	6	-1617.37	3247.49	1342.7	0
		binomial	deer_pellets + (1 | site) + (1 | financial_year_cont2)	4	-1826.19	3660.73	1755.95	0
	Celver	**Zi-binomial**	**deer_pellets + (1 | line) + (1 | financial_year_cont2)**	**6**	**-419.8**	**852.35**	**0.00**	**0.86**
		binomial	deer_pellets + (1 | site/line) + (1 | financial_year_cont2)	5	-422.76	856.05	3.71	0.14
		binomial	deer_pellets + (1 | line) + (1 | financial_year_cont2)	4	-443.66	895.66	43.31	0
		Zi-binomial	deer_pellets + (1 | site) + (1 | financial_year_cont2)	6	-503.38	1019.5	167.16	0
		binomial	deer_pellets + (1 | site) + (1 | financial_year_cont2)	4	-615.78	1239.91	387.56	0
	Dolsco	**Zi-binomial**	**deer_pellets + (1 | line) + (1 | financial_year_cont2)**	**6**	**-615.87**	**1244.56**	**0.00**	**1**
		binomial	deer_pellets + (1 | site/line) + (1 | financial_year_cont2)	5	-806.31	1623.21	378.65	0
		binomial	deer_pellets + (1 | line) + (1 | financial_year_cont2)	4	-809.54	1627.47	382.91	0
		Zi-binomial	deer_pellets + (1 | site) + (1 | financial_year_cont2)	6	-1051.29	2115.39	870.83	0
		binomial	deer_pellets + (1 | site) + (1 | financial_year_cont2)	4	-1299.87	2608.12	1363.56	0
	Ranlya	Zi-binomial	deer_pellets + (1 | site/line) + (1 | financial_year_cont2)	7	-177.12	369.79	0.00	0.74
		Zi-binomial	**deer_pellets + (1 | line) + (1 | financial_year_cont2)**	**6**	**-179.35**	**371.85**	**2.07**	**0.26**
		Zi-binomial	deer_pellets + (1 | site) + (1 | financial_year_cont2)	6	-253.42	519.98	150.20	0
		binomial	deer_pellets + (1 | site/line) + (1 | financial_year_cont2)	5	-304.86	620.52	250.73	0
		binomial	deer_pellets + (1 | line) + (1 | financial_year_cont2)	4	-311.25	631.04	261.25	0

Management area	Plant species	Distribution	Formula	df	logLik	AICc	ΔAICc	weight
		binomial	deer_pellets + (1 | site) + (1 | financial_year_cont2)	4	-366.21	740.95	371.16	0
Wapiti Area	All species	**Zi-binomial**	**deer_pellets + (1 | site/line) + (1 | financial_year_cont2)**	**7**	**-4645.93**	**9306.11**	**0.00**	**1**
		Zi-binomial	deer_pellets + (1 | line) + (1 | financial_year_cont2)	6	-4658.00	9328.18	22.07	0
		binomial	deer_pellets + (1 | site/line) + (1 | financial_year_cont2)	5	-5734.65	11479.44	2173.33	0
		binomial	deer_pellets + (1 | line) + (1 | financial_year_cont2)	4	-5747.33	11502.76	2196.65	0
		Zi-binomial	deer_pellets + (1 | site) + (1 | financial_year_cont2)	6	-6322.97	12658.13	3352.02	0
		binomial	deer_pellets + (1 | site) + (1 | financial_year_cont2)	4	-7681.04	15370.17	6064.07	0
	Celver	**Zi-binomial**	**deer_pellets + (1 | site/line) + (1 | financial_year_cont2)**	**7**	**-2550.62**	**5115.49**	**0.00**	**1**
		Zi-binomial	deer_pellets + (1 | line) + (1 | financial_year_cont2)	6	-2573.51	5159.2	43.71	0
		binomial	deer_pellets + (1 | site/line) + (1 | financial_year_cont2)	5	-2901.04	5812.21	696.72	0
		binomial	deer_pellets + (1 | line) + (1 | financial_year_cont2)	4	-2926.17	5860.43	744.94	0
		Zi-binomial	deer_pellets + (1 | site) + (1 | financial_year_cont2)	6	-3090.27	6192.72	1077.23	0
		binomial	deer_pellets + (1 | site) + (1 | financial_year_cont2)	4	-3469.95	6947.99	1832.5	0
	Dolsco	**Zi-binomial**	**deer_pellets + (1 | site/line) + (1 | financial_year_cont2)**	**7**	**-2729.61**	**5473.46**	**0.00**	**1**
		Zi-binomial	deer_pellets + (1 | site) + (1 | financial_year_cont2)	6	-3471.56	6955.31	1481.85	0
		binomial	deer_pellets + (1 | site/line) + (1 | financial_year_cont2)	5	-3921.31	7852.75	2379.29	0
		binomial	deer_pellets + (1 | line) + (1 | financial_year_cont2)	4	-3925.32	7858.73	2385.26	0
		binomial	deer_pellets + (1 | site) + (1 | financial_year_cont2)	4	-4707.65	9423.39	3949.93	0
	Ranlya	**Zi-binomial**	**deer_pellets + (1 | site/line) + (1 | financial_year_cont2)**	**7**	**-868.24**	**1750.72**	**0.00**	**1**
		Zi-binomial	deer_pellets + (1 | line) + (1 | financial_year_cont2)	6	-880.11	1772.4	21.68	0
		Zi-binomial	deer_pellets + (1 | site) + (1 | financial_year_cont2)	6	-925.79	1863.76	113.04	0
		binomial	deer_pellets + (1 | site/line) + (1 | financial_year_cont2)	5	-1088.86	2187.84	437.12	0
		binomial	deer_pellets + (1 | line) + (1 | financial_year_cont2)	4	-1099.46	2207.00	456.28	0

Management area	Plant species	Distribution	Formula	df	logLik	AICc	ΔAICc	weight
		binomial	deer_pellets + (1 | site) + (1 | financial_year_cont2)	4	-1194.16	2396.4	645.68	0
WARO Area	All species	Zi-binomial	deer_pellets + (1 | site/line) + (1 | financial_year_cont2)	7	-5126.99	10268.17	**0.00**	1
		Zi-binomial	**deer_pellets + (1 | line) + (1 | financial_year_cont2)**	**6**	**-5149.76**	**10311.65**	**43.49**	**0**
		Zi-binomial	deer_pellets + (1 | site) + (1 | financial_year_cont2)	6	-6071.83	12155.8	1887.63	0
		binomial	deer_pellets + (1 | site/line) + (1 | financial_year_cont2)	5	-6603.02	13216.13	2947.97	0
		binomial	deer_pellets + (1 | line) + (1 | financial_year_cont2)	4	-6630.95	13269.96	3001.79	0
		binomial	deer_pellets + (1 | site) + (1 | financial_year_cont2)	4	-7575.06	15158.18	4890.02	0
	Celver	**Zi-binomial**	**deer_pellets + (1 | site/line) + (1 | financial_year_cont2)**	**7**	**-1928.63**	**3871.46**	**0.00**	**1**
		Zi-binomial	deer_pellets + (1 | line) + (1 | financial_year_cont2)	6	-1958.92	3929.98	58.52	0
		Zi-binomial	deer_pellets + (1 | site) + (1 | financial_year_cont2)	6	-2137.78	4287.71	416.25	0
		binomial	deer_pellets + (1 | site/line) + (1 | financial_year_cont2)	5	-2432.48	4875.05	1003.59	0
		binomial	deer_pellets + (1 | line) + (1 | financial_year_cont2)	4	-2468.83	4945.72	1074.26	0
		binomial	deer_pellets + (1 | site) + (1 | financial_year_cont2)	4	-2694.97	5398.01	1526.55	0
	Dolsco	**Zi-binomial**	**deer_pellets + (1 | site/line) + (1 | financial_year_cont2)**	**7**	**-2852.1**	**5718.41**	**0.00**	**0.98**
		Zi-binomial	deer_pellets + (1 | line) + (1 | financial_year_cont2)	6	-2856.81	5725.77	7.36	0.02
		Zi-binomial	deer_pellets + (1 | site) + (1 | financial_year_cont2)	6	-3494.83	7001.82	1283.41	0
		binomial	deer_pellets + (1 | site/line) + (1 | financial_year_cont2)	5	-4074.20	8158.5	2440.09	0
		binomial	deer_pellets + (1 | line) + (1 | financial_year_cont2)	4	-4084.53	8177.12	2458.71	0
		binomial	deer_pellets + (1 | site) + (1 | financial_year_cont2)	4	-4689.39	9386.86	3668.45	0
	Ranlya	**Zi-binomial**	**deer_pellets + (1 | site/line) + (1 | financial_year_cont2)**	**7**	**-1178.65**	**2371.5**	**0.00**	**0.92**
		Zi-binomial	deer_pellets + (1 | line) + (1 | financial_year_cont2)	6	-1182.07	2376.29	4.79	0.08
		Zi-binomial	deer_pellets + (1 | site) + (1 | financial_year_cont2)	6	-1354.46	2721.07	349.57	0
		binomial	deer_pellets + (1 | site/line) + (1 | financial_year_cont2)	5	-1748.25	3506.61	1135.11	0

Management area	Plant species	Distribution	Formula	df	logLik	AICc	ΔAICc	weight
		binomial	deer_pellets + (1 | line) + (1 | financial_year_cont2)	4	-1751.88	3511.83	1140.33	0
		binomial	deer_pellets + (1 | site) + (1 | financial_year_cont2)	4	-1913.94	3835.96	1464.46	0

Table A3.3. Identification of the best combination of error distribution and random factors for models predicting the proportion of alpine browse of all species combined and each indicator species (Celver: *Celmisia verbascifolia*, Dolsco: *Dolichoglottis scorzoneroides*, Ranlya: *Ranunculus lyallii*) from harvest rate (harvest_km_10000_730) per management area by comparing corrected Akaike's Information Criterion (AICc). The log likelihood (logLik), differences in model AICc value from the best model (ΔAICc), degrees of freedom (df) and Akaike weights are shown for each model. The best model for each response variable (in bold) was identified using ΔAICc and model diagnostics.

Management area	Plant species	Distribution	Formula	df	logLik	AICc	ΔAICc	weight
Murchison Mountains	All species	**Zi-binomial**	**harvest_km_10000_730 + (1 | line) + (1 | financial_year_cont2)**	**6**	**-972.13**	**1957**	**0.00**	**1**
		binomial	harvest_km_10000_730 + (1 | site/line) + (1 | financial_year_cont2)	5	-1091.94	2194.42	237.41	0
		binomial	harvest_km_10000_730 + (1 | line) + (1 | financial_year_cont2)	4	-1102.80	2213.94	256.94	0
		Zi-binomial	harvest_km_10000_730 + (1 | site) + (1 | financial_year_cont2)	6	-1979.49	3971.73	2014.73	0
		binomial	harvest_km_10000_730 + (1 | site) + (1 | financial_year_cont2)	4	-2228.98	4466.32	2509.31	0
	Celver	**Zi-binomial**	**harvest_km_10000_730 + (1 | line) + (1 | financial_year_cont2)**	**6**	**-442.60**	**897.95**	**0.00**	**1**
		binomial	harvest_km_10000_730 + (1 | site/line) + (1 | financial_year_cont2)	5	-450.20	910.93	12.98	0
		binomial	harvest_km_10000_730 + (1 | line) + (1 | financial_year_cont2)	4	-470.48	949.31	51.36	0
		Zi-binomial	harvest_km_10000_730 + (1 | site) + (1 | financial_year_cont2)	6	-560.37	1133.49	235.54	0
		binomial	harvest_km_10000_730 + (1 | site) + (1 | financial_year_cont2)	4	-681.80	1371.96	474.01	0
	Dolsco	Zi-binomial	harvest_km_10000_730 + (1 | site/line) + (1 | financial_year_cont2)	7	-431.93	878.96	**0.00**	1
		Zi-binomial	harvest_km_10000_730 + (1 | line) + (1 | financial_year_cont2)	6	-444.85	902.52	23.55	0
		binomial	**harvest_km_10000_730 + (1 | site/line) + (1 | financial_year_cont2)**	**5**	**-611.04**	**1232.66**	**353.7**	**0**
		binomial	harvest_km_10000_730 + (1 | line) + (1 | financial_year_cont2)	4	-616.83	1242.04	363.07	0
		Zi-binomial	harvest_km_10000_730 + (1 | site) + (1 | financial_year_cont2)	6	-1153.54	2319.9	1440.94	0
		binomial	harvest_km_10000_730 + (1 | site) + (1 | financial_year_cont2)	4	-1424.54	2857.46	1978.50	0
	Ranlya	**Zi-binomial**	**harvest_km_10000_730 + (1 | site/line) + (1 | financial_year_cont2)**	**7**	**-160.83**	**337.22**	**0.00**	**0.73**
		Zi-binomial	harvest_km_10000_730 + (1 | line) + (1 | financial_year_cont2)	6	-163.04	339.22	2.00	0.27
		Zi-binomial	harvest_km_10000_730 + (1 | site) + (1 | financial_year_cont2)	6	-248.09	509.33	172.11	0

Management area	Plant species	Distribution	Formula	df	logLik	AICc	ΔAICc	weight
		binomial	harvest_km_10000_730 + (1 | site/line) + (1 | financial_year_cont2)	5	-323.68	658.18	320.95	0
		binomial	harvest_km_10000_730 + (1 | line) + (1 | financial_year_cont2)	4	-334.55	677.64	340.42	0
		binomial	harvest_km_10000_730 + (1 | site) + (1 | financial_year_cont2)	4	-394.51	797.56	460.33	0
Wapiti Area	All species	**Zi-binomial**	**harvest_km_10000_730 + (1 | site/line) + (1 | financial_year_cont2)**	**7**	**-5495.67**	**11005.59**	**0.00**	**1**
		Zi-binomial	harvest_km_10000_730 + (1 | line) + (1 | financial_year_cont2)	6	-5517.32	11046.82	41.23	0
		binomial	harvest_km_10000_730 + (1 | site/line) + (1 | financial_year_cont2)	5	-6887.11	13784.36	2778.77	0
		Zi-binomial	harvest_km_10000_730 + (1 | site) + (1 | financial_year_cont2)	6	-6908.05	13828.28	2822.69	0
		binomial	harvest_km_10000_730 + (1 | line) + (1 | financial_year_cont2)	4	-6912.10	13832.28	2826.69	0
		binomial	harvest_km_10000_730 + (1 | site) + (1 | financial_year_cont2)	4	-8387.62	16783.32	5777.73	0
	Celver	**Zi-binomial**	**harvest_km_10000_730 + (1 | site/line) + (1 | financial_year_cont2)**	**7**	**-2755.21**	**5524.66**	**0.00**	**1**
		binomial	harvest_km_10000_730 + (1 | site/line) + (1 | financial_year_cont2)	5	-3203.07	6416.27	891.61	0
		binomial	harvest_km_10000_730 + (1 | line) + (1 | financial_year_cont2)	4	-3238.88	6485.84	961.18	0
		Zi-binomial	harvest_km_10000_730 + (1 | site) + (1 | financial_year_cont2)	6	-3293.75	6599.69	1075.03	0
		binomial	harvest_km_10000_730 + (1 | site) + (1 | financial_year_cont2)	4	-3726.26	7460.61	1935.96	0
	Dolsco	**Zi-binomial**	**harvest_km_10000_730 + (1 | line) + (1 | financial_year_cont2)**	**6**	**-3078.63**	**6169.45**	**0.00**	**0.52**
		Zi-binomial	harvest_km_10000_730 + (1 | site/line) + (1 | financial_year_cont2)	7	-3077.67	6169.6	0.14	0.48
		Zi-binomial	harvest_km_10000_730 + (1 | site) + (1 | financial_year_cont2)	6	-3687.86	7387.9	1218.45	0
		binomial	harvest_km_10000_730 + (1 | site/line) + (1 | financial_year_cont2)	5	-4664.76	9339.66	3170.20	0
		binomial	harvest_km_10000_730 + (1 | line) + (1 | financial_year_cont2)	4	-4669.29	9346.67	3177.22	0
		binomial	harvest_km_10000_730 + (1 | site) + (1 | financial_year_cont2)	4	-5104.09	10216.27	4046.82	0
	Ranlya	**Zi-binomial**	**harvest_km_10000_730 + (1 | site/line) + (1 | financial_year_cont2)**	**7**	**-906.36**	**1826.97**	**0.00**	**1**
		Zi-binomial	harvest_km_10000_730 + (1 | line) + (1 | financial_year_cont2)	6	-918.48	1849.16	22.19	0
		Zi-binomial	harvest_km_10000_730 + (1 | site) + (1 | financial_year_cont2)	6	-953.68	1919.54	92.57	0

Management area	Plant species	Distribution	Formula	df	logLik	AICc	ΔAICc	weight
		binomial	harvest_km_10000_730 + (1 | site/line) + (1 | financial_year_cont2)	5	-1136.16	2282.45	455.48	0
		binomial	harvest_km_10000_730 + (1 | line) + (1 | financial_year_cont2)	4	-1147.54	2303.16	476.19	0
		binomial	harvest_km_10000_730 + (1 | site) + (1 | financial_year_cont2)	4	-1241.30	2490.68	663.71	0
WARO Area	All species	**Zi-binomial**	**harvest_km_10000_730 + (1 | site/line) + (1 | financial_year_cont2)**	**7**	**-5674.55**	**11363.29**	**0.00**	**1**
		Zi-binomial	harvest_km_10000_730 + (1 | line) + (1 | financial_year_cont2)	6	-5697.25	11406.65	43.35	0
		Zi-binomial	harvest_km_10000_730 + (1 | site) + (1 | financial_year_cont2)	6	-6985.57	13983.28	2619.99	0
		binomial	harvest_km_10000_730 + (1 | site/line) + (1 | financial_year_cont2)	5	-7286.86	14583.83	3220.53	0
		binomial	harvest_km_10000_730 + (1 | line) + (1 | financial_year_cont2)	4	-7318.15	14644.36	3281.07	0
		binomial	harvest_km_10000_730 + (1 | site) + (1 | financial_year_cont2)	4	-8509.60	17027.27	5663.98	0
	Celver	**Zi-binomial**	**harvest_km_10000_730 + (1 | site/line) + (1 | financial_year_cont2)**	**7**	**-2019.69**	**4053.57**	**0.00**	**1**
		Zi-binomial	harvest_km_10000_730 + (1 | site) + (1 | financial_year_cont2)	6	-2351.91	4715.97	662.40	0
		binomial	harvest_km_10000_730 + (1 | site/line) + (1 | financial_year_cont2)	5	-2567.36	5144.81	1091.25	0
		binomial	harvest_km_10000_730 + (1 | line) + (1 | financial_year_cont2)	4	-2605.60	5219.26	1165.70	0
		binomial	harvest_km_10000_730 + (1 | site) + (1 | financial_year_cont2)	4	-2955.45	5918.97	1865.41	0
	Dolsco	**Zi-binomial**	**harvest_km_10000_730 + (1 | site/line) + (1 | financial_year_cont2)**	**7**	**-3174.37**	**6362.95**	**0.00**	**1**
		Zi-binomial	harvest_km_10000_730 + (1 | site) + (1 | financial_year_cont2)	6	-3871.05	7754.26	1391.31	0
		binomial	harvest_km_10000_730 + (1 | site/line) + (1 | financial_year_cont2)	5	-4516.31	9042.73	2679.78	0
		binomial	harvest_km_10000_730 + (1 | line) + (1 | financial_year_cont2)	4	-4531.48	9071.02	2708.07	0
		binomial	harvest_km_10000_730 + (1 | site) + (1 | financial_year_cont2)	4	-5167.79	10343.65	3980.70	0
	Ranlya	**Zi-binomial**	**harvest_km_10000_730 + (1 | site/line) + (1 | financial_year_cont2)**	**7**	**-1174.45**	**2363.09**	**0.00**	**0.94**
		Zi-binomial	harvest_km_10000_730 + (1 | line) + (1 | financial_year_cont2)	6	-1178.26	2368.67	5.57	0.06
		Zi-binomial	harvest_km_10000_730 + (1 | site) + (1 | financial_year_cont2)	6	-1297.56	2607.27	244.18	0
		binomial	harvest_km_10000_730 + (1 | site/line) + (1 | financial_year_cont2)	5	-1835.00	3680.11	1317.02	0

Management area	Plant species	Distribution	Formula	df	logLik	AICc	ΔAICc	weight
		binomial	harvest_km_10000_730 + (1 | line) + (1 | financial_year_cont2)	4	-1843.28	3694.64	1331.55	0
		binomial	harvest_km_10000_730 + (1 | site) + (1 | financial_year_cont2)	4	-1947.09	3902.24	1539.15	0

Table A3.4. Best conditional models predicting the proportion of alpine plant browse from deer pellet groups for all species and each indicator species (Celver: *Celmisia verbascifolia*, Dolsco: *Dolichoglottis scorzoneroides*, Ranlya: *Ranunculus lyallii*) per management area. See Table A3.2 for detailed model selection.

Management area	Plant species	Variable	Estimates	Standard error	z value	*P*-value
Murchison Mountains	All species	(Intercept)	-3.445	0.880	-3.914	<0.001
		Deer pellets	0.228	0.027	8.347	<0.001
	Celver	(Intercept)	-4.483	1.186	-3.781	<0.001
		Deer pellets	0.399	0.055	7.292	<0.001
	Dolsco	(Intercept)	-1.549	0.533	-2.907	0.004
		Deer pellets	0.011	0.044	0.243	0.808
	Ranlya	(Intercept)	-2.265	0.796	-2.847	0.004
		Deer pellets	-0.273	0.124	-2.204	0.027
Wapiti Area	All species	(Intercept)	-2.476	0.215	-11.521	<0.001
		Deer pellets	0.259	0.007	39.797	<0.001
	Celver	(Intercept)	-2.958	0.361	-8.196	<0.001
		Deer pellets	0.218	0.010	22.18	<0.001
	Dolsco	(Intercept)	-1.352	0.231	-5.863	<0.001
		Deer pellets	0.255	0.01	24.615	<0.001
	Ranlya	(Intercept)	-2.483	0.356	-6.966	<0.001
		Deer pellets	0.152	0.022	6.763	<0.001
WARO Area	All species	(Intercept)	-2.231	0.217	-10.285	<0.001
		Deer pellets	0.165	0.005	32.249	<0.001
	Celver	(Intercept)	-2.544	0.377	-6.749	<0.001
		Deer pellets	0.132	0.01	13.408	<0.001
	Dolsco	(Intercept)	-1.388	0.246	-5.642	<0.001
		Deer pellets	0.185	0.008	24.455	<0.001
	Ranlya	(Intercept)	-2.501	0.272	-9.188	<0.001
		Deer pellets	0.092	0.017	5.323	<0.001

Table A3.5. Best conditional models predicting the proportion of alpine plant browse from harvest rate for all species and each indicator species (Celver: *Celmisia verbascifolia*, Dolsco: *Dolichoglottis scorzoneroides*, Ranlya: *Ranunculus lyallii*) per management area. See Table A3.3 for detailed model selection.

Management area	Plant species	Variable	Estimates	Standard error	z value	P-value
Murchison Mountains	All species	(Intercept)	-4.541	0.582	-7.809	<0.001
		Harvest rate	0.119	0.020	5.974	<0.001
	Celver	(Intercept)	-3.014	1.258	-2.396	0.017
		Harvest rate	-0.095	0.028	-3.452	0.001
	Dolsco	(Intercept)	-12.335	1.492	-8.267	<0.001
		Harvest rate	0.81	0.046	17.454	<0.001
	Ranlya	(Intercept)	-1.405	1.706	-0.824	0.410
		Harvest rate	-0.103	0.110	-0.931	0.352
Wapiti Area	All species	(Intercept)	-2.263	0.256	-8.823	<0.001
		Harvest rate	0.009	0.002	4.919	<0.001
	Celver	(Intercept)	-3.270	0.492	-6.640	<0.001
		Harvest rate	0.031	0.003	11.54	<0.001
	Dolsco	(Intercept)	-0.720	0.182	-3.964	<0.001
		Harvest rate	-0.008	0.003	-2.647	0.008
	Ranlya	(Intercept)	-1.957	0.355	-5.516	<0.001
		Harvest rate	-0.012	0.007	-1.901	0.057
WARO Area	All species	(Intercept)	-2.093	0.299	-7.005	<0.001
		Harvest rate	-0.001	0.002	-0.451	0.652
	Celver	(Intercept)	-2.118	0.399	-5.311	<0.001
		Harvest rate	-0.022	0.004	-6.140	<0.001
	Dolsco	(Intercept)	-1.384	0.351	-3.939	<0.001
		Harvest rate	0.006	0.002	2.691	0.007
	Ranlya	(Intercept)	-2.959	0.417	-7.090	<0.001
		Harvest rate	0.034	0.006	6.086	<0.001

Table A3.6. Candidate model sets to investigate alpine plant browse over time as evaluated by comparing corrected Akaike's Information Criterion (AICc). The family error distribution (binomial, zero-inflated binomial: zi-bino), log likelihood (logLik), differences in model AICc value from the best model (ΔAICc), degrees of freedom (df) and Akaike weights are shown for each model. The best model for each response variable (in bold) were identified using ΔAICc and model diagnostics.

Management area	Plant species	Distribution	Formula	df	logLik	AICc	ΔAICc	weight
Murchison Mountains	**All species**	**zi-bino**	**financial_year_fctv2 + (1 | site/line)**	**12**	**-1028.47**	**2083.08**	**0.00**	**1.00**
		binomial	financial_year_fctv2 + (1 | site/line)	7	-1272.02	2558.79	475.71	0.00
		binomial	financial_year_fctv2 + (1 | line)	6	-1281.34	2575.23	492.15	0.00
		binomial	financial_year_fctv2 + (1 | site)	6	-2410.12	4832.79	2749.71	0.00
	Celver	**zi-bino**	**financial_year_fctv2 + (1 | site/line)**	**12**	**-455.61**	**937.35**	**0.00**	**1.00**
		binomial	financial_year_fctv2 + (1 | site/line)	7	-561.35	1137.43	200.08	0.00
		binomial	financial_year_fctv2 + (1 | line)	6	-581.51	1175.57	238.22	0.00
		binomial	financial_year_fctv2 + (1 | site)	6	-789.85	1592.25	654.9	0.00
	Dolsco	**binomial**	**financial_year_fctv2 + (1 | site/line)**	**7**	**-851.61**	**1718.01**	**0.00**	**0.85**
	Dolsco	binomial	financial_year_fctv2 + (1 | line)	6	-854.41	1721.41	3.40	0.15
	Dolsco	zi-bino	financial_year_fctv2 + (1 | site)	11	-1327.92	2679.77	961.76	0.00
	Dolsco	binomial	financial_year_fctv2 + (1 | site)	6	-1630.3	3273.18	1555.17	0.00
	Ranlya	**binomial**	**financial_year_fctv2 + (1 | site/line)**	**7**	**-346.63**	**708.26**	**0.00**	**1.00**
		binomial	financial_year_fctv2 + (1 | line)	6	-354.70	722.14	13.88	0.00
		binomial	financial_year_fctv2 + (1 | site)	6	-408.27	829.29	121.03	0.00
Wapiti Area	**All species**	**zi-bino**	**financial_year_fctv2 + (1 | site/line)**	**14**	**-5461.76**	**10952.46**	**0.00**	**1.00**
		binomial	financial_year_fctv2 + (1 | site/line)	8	-6916.79	13849.9	2897.44	0.00
		binomial	financial_year_fctv2 + (1 | line)	7	-6942.11	13898.46	2945.99	0.00
		binomial	financial_year_fctv2 + (1 | site)	7	-8412.18	16838.61	5886.15	0.00
	Celver	**zi-bino**	**financial_year_fctv2 + (1 | site/line)**	**14**	**-2771.69**	**5572.33**	**0.00**	**1.00**

Management area	Plant species	Distribution	Formula	df	logLik	AICc	ΔAICc	weight
		binomial	financial_year_fctv2 + (1 | site/line)	8	-3258.67	6533.67	961.34	0.00
		binomial	financial_year_fctv2 + (1 | line)	7	-3293.14	6600.53	1028.20	0.00
		binomial	financial_year_fctv2 + (1 | site)	7	-3778.01	7570.27	1997.94	0.00
	Dolsco	**zi-bino**	**financial_year_fctv2 + (1 | site/line)**	**14**	**-3049.58**	**6128.11**	**0.00**	**1.00**
		binomial	financial_year_fctv2 + (1 | site/line)	8	-4651.66	9319.64	3191.53	0.00
		binomial	financial_year_fctv2 + (1 | line)	7	-4655.69	9325.63	3197.52	0.00
		binomial	financial_year_fctv2 + (1 | site)	7	-5096.01	10206.26	4078.15	0.00
	Ranlya	**zi-bino**	**financial_year_fctv2 + (1 | line)**	**13**	**-883.00**	**1792.81**	**0.00**	**1.00**
		binomial	financial_year_fctv2 + (1 | site/line)	8	-1122.33	2260.98	468.17	0.00
		binomial	financial_year_fctv2 + (1 | line)	7	-1133.16	2280.56	487.75	0.00
		binomial	financial_year_fctv2 + (1 | site)	7	-1227.85	2469.95	677.14	0.00
WARO Area	**All species**	**zi-bino**	**financial_year_fctv2 + (1 | site/line)**	**12**	**-5630.47**	**11285.48**	**0.00**	**1.00**
		binomial	financial_year_fctv2 + (1 | site/line)	7	-7269.76	14553.7	3268.22	0.00
		binomial	financial_year_fctv2 + (1 | line)	6	-7300.28	14612.71	3327.23	0.00
		binomial	financial_year_fctv2 + (1 | site)	6	-8494.06	17000.27	5714.79	0.00
	Celver	**zi-bino**	**financial_year_fctv2 + (1 | site)**	**11**	**-2331.97**	**4686.40**	**0.00**	**1.00**
		binomial	financial_year_fctv2 + (1 | site/line)	7	-2585.41	5185.00	498.61	0.00
		binomial	financial_year_fctv2 + (1 | line)	6	-2620.54	5253.22	566.82	0.00
		binomial	financial_year_fctv2 + (1 | site)	6	-2970.41	5952.97	1266.57	0.00
	Dolsco	**zi-bino**	**financial_year_fctv2 + (1 | site/line)**	**12**	**-3149.00**	**6322.56**	**0.00**	**1.00**
		binomial	financial_year_fctv2 + (1 | site/line)	7	-4506.63	9027.46	2704.90	0.00
		binomial	financial_year_fctv2 + (1 | line)	6	-4521.26	9054.68	2732.12	0.00
		binomial	financial_year_fctv2 + (1 | site)	6	-5154.1	10320.36	3997.80	0.00

Management area	Plant species	Distribution	Formula	df	logLik	AICc	ΔAICc	weight
	Ranlya	**zi-bino**	**financial_year_fctv2 + (1 | site/line)**	**12**	**-1182.12**	**2388.79**	**00.00**	**1.00**
		binomial	financial_year_fctv2 + (1 | site/line)	7	-1837.03	3688.25	1299.46	0.00
		binomial	financial_year_fctv2 + (1 | line)	6	-1844.99	3702.13	1313.34	0.00
		binomial	financial_year_fctv2 + (1 | site)	6	-1957.75	3927.64	1538.86	0.00

Table A3.7. Summary of the raw mean proportion of browsed alpine plants for all species combined and each indicator species (Celver: *Celmisia verbascifolia*, Dolsco: *Dolichoglottis scorzoneroides*, Ranlya: *Ranunculus lyallii*) and associated standard deviation (±SD) per survey period with the number of surveyed transects (No line).

Management area	Survey period	No line	All species browsed	Celver browsed	Dolsco browsed	Ranlya browsed
Wapiti Area	2005 - 2006	60	0.19 ± 0.18	0.15 ± 0.17	0.31 ± 0.27	0.09 ± 0.15
	2007 - 2008	60	0.12 ± 0.14	0.08 ± 0.15	0.21 ± 0.25	0.07 ± 0.13
	2011 - 2012	60	0.05 ± 0.08	0.02 ± 0.05	0.12 ± 0.21	0.04 ± 0.15
	2014 - 2017	100	0.17 ± 0.16	0.14 ± 0.19	0.30 ± 0.28	0.11 ± 0.17
	2019 - 2020	100	0.18 ± 0.15	0.16 ± 0.18	0.32 ± 0.28	0.13 ± 0.15
	2023 - 2024	80	0.08 ± 0.09	0.08 ± 0.1	0.19 ± 0.25	0.01 ± 0.04
Murchison Mountains	2005 - 2006	20	0.00 ± 0.02	0.02 ± 0.08	0.00 ± 0.01	0.00 ± 0.00
	2007 - 2008	20	0.00 ± 0.01	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.01
	2011 - 2012	20	0.01 ± 0.02	0.01 ± 0.02	0.01 ± 0.04	0.00 ± 0.01
	2016 - 2019	50	0.10 ± 0.13	0.07 ± 0.12	0.14 ± 0.24	0.17 ± 0.24
	2022 - 2023	50	0.18 ± 0.16	0.16 ± 0.18	0.29 ± 0.26	0.16 ± 0.23
WARO Area	2005 - 2006	120	0.23 ± 0.20	0.19 ± 0.23	0.35 ± 0.27	0.11 ± 0.15
	2007 - 2009	120	0.08 ± 0.12	0.05 ± 0.10	0.12 ± 0.18	0.04 ± 0.06
	2011 - 2013	120	0.03 ± 0.06	0.03 ± 0.07	0.05 ± 0.10	0.02 ± 0.07
	2016 - 2018	119	0.10 ± 0.15	0.07 ± 0.16	0.19 ± 0.24	0.08 ± 0.16
	2021 - 2022	119	0.16 ± 0.17	0.14 ± 0.22	0.27 ± 0.27	0.08 ± 0.12

Table A3.8. Results from Tukey Post-hoc analysis of models predicting the change in the proportion of alpine plant browse over time (survey period) for all species combined and each indicator species (Celver: *Celmisia verbascifolia*, Dolsco: *Dolichoglottis scorzoneroides*, Ranlya: *Ranunculus lyallii*) in each management areas (Murchison Mountains, Wapiti Area and WARO Area). For each survey period, emmean values, standard error (SEM), lower confidence limits (asymp.LCL) and upper confidence limits (asymp.UCL) are provided with associated compact letter displaying pair-wise comparisons.

Management area	Plant species	Survey period	emmean	SEM	asymp.LCL	asymp.UCL	Letters
Murchison Mountains	All species	2005 - 2006	-4.57	0.41	-5.62	-3.52	a
		2007 - 2008	-3.57	0.48	-4.81	-2.32	b
		2011 - 2012	-5.02	0.42	-6.11	-3.94	a
		2016 - 2019	-2.78	0.37	-3.73	-1.83	b
		2022 - 2023	-2.02	0.37	-2.96	-1.07	c
	Celver	2005 - 2006	-4.62	0.63	-6.25	-3.00	a
		2007 - 2008	-1.83	0.79	-3.86	0.20	c
		2011 - 2012	-5.50	0.82	-7.62	-3.39	a
		2016 - 2019	-3.56	0.6	-5.09	-2.03	b
		2022 - 2023	-2.62	0.59	-4.14	-1.09	c
	Dolsco	2005 - 2006	-3.16	0.56	-4.61	-1.71	a
		2007 - 2008	-2.99	1.25	-6.21	0.23	abcd
		2011 - 2012	-1.89	0.54	-3.26	-0.51	b
		2016 - 2019	-1.08	0.47	-2.29	0.14	c
		2022 - 2023	-0.29	0.47	-1.51	0.92	d
	Ranlya	2007 - 2008	-2.47	0.7	-4.2	-0.73	ab
		2011 - 2012	-4.25	0.76	-6.13	-2.37	a
		2016 - 2019	-1.85	0.47	-3.03	-0.68	b
		2022 - 2023	-1.98	0.47	-3.15	-0.81	b
Wapiti Area	All species	2005 - 2006	-1.79	0.17	-2.23	-1.35	e
		2007 - 2008	-2.12	0.17	-2.56	-1.68	c
		2011 - 2012	-2.68	0.17	-3.13	-2.22	a
		2014 - 2017	-1.54	0.17	-1.98	-1.10	f
		2019 - 2020	-1.89	0.17	-2.33	-1.46	d
		2023 - 2024	-2.44	0.17	-2.88	-2.00	b
	Celver	2005 - 2006	-2.49	0.27	-3.19	-1.79	b
		2007 - 2008	-2.27	0.27	-2.98	-1.56	c
		2011 - 2012	-4.10	0.30	-4.88	-3.32	a
		2014 - 2017	-2.01	0.26	-2.70	-1.31	d
		2019 - 2020	-2.12	0.26	-2.82	-1.43	c
		2023 - 2024	-2.55	0.27	-3.25	-1.85	b

Management area	Plant species	Survey period	emmean	SEM	asymp.LCL	asymp.UCL	Letters
	Dolsco	2005 - 2006	-0.74	0.12	-1.05	-0.44	b
		2007 - 2008	-1.14	0.12	-1.45	-0.83	a
		2011 - 2012	-1.30	0.13	-1.64	-0.95	a
		2014 - 2017	-0.19	0.11	-0.49	0.11	c
		2019 - 2020	-1.11	0.12	-1.41	-0.80	a
		2023 - 2024	-1.12	0.12	-1.44	-0.79	a
	Ranlya	2005 - 2006	-1.29	0.24	-1.92	-0.65	e
		2007 - 2008	-2.47	0.25	-3.13	-1.81	abc
		2011 - 2012	-1.65	0.25	-2.31	-0.99	de
		2014 - 2017	-2.33	0.22	-2.91	-1.74	b
		2019 - 2020	-2.06	0.22	-2.64	-1.48	cd
		2023 - 2024	-3.08	0.33	-3.94	-2.21	a
WARO Area	All species	2005 - 2006	-1.28	0.16	-1.68	-0.88	d
		2007 - 2009	-2.21	0.16	-2.61	-1.81	b
		2011 - 2013	-2.97	0.16	-3.39	-2.56	a
		2016 - 2018	-2.20	0.16	-2.60	-1.80	b
		2021 - 2022	-1.84	0.16	-2.24	-1.44	c
	Celver	2005 - 2006	-1.41	0.29	-2.15	-0.66	e
		2007 - 2009	-2.30	0.29	-3.05	-1.55	d
		2011 - 2013	-2.79	0.3	-3.55	-2.03	b
		2016 - 2018	-3.08	0.29	-3.83	-2.33	a
		2021 - 2022	-2.50	0.29	-3.25	-1.76	c
	Dolsco	2005 - 2006	-0.57	0.18	-1.03	-0.12	d
		2007 - 2009	-1.34	0.18	-1.80	-0.89	b
		2011 - 2013	-2.25	0.18	-2.72	-1.78	a
		2016 - 2018	-1.25	0.18	-1.71	-0.80	b
		2021 - 2022	-0.89	0.18	-1.34	-0.44	c
	Ranlya	2005 - 2006	-1.79	0.15	-2.17	-1.40	d
		2007 - 2009	-2.79	0.16	-3.19	-2.38	b
		2011 - 2013	-3.21	0.19	-3.70	-2.71	a
		2016 - 2018	-2.19	0.15	-2.58	-1.79	c
		2021 - 2022	-1.99	0.15	-2.37	-1.60	cd

Appendix 4 – Model selection and analyses of alpine plant abundance (Q4)

Table A4.1. Candidate model sets to investigate alpine plant abundance over time as evaluated by comparing corrected Akaike's Information Criterion (AICc). The family error distribution (negative binomial: ng bino, zero-inflated negative binomial: zi-ng bino), log likelihood (logLik), differences in model AICc value from the best model (ΔAICc), degrees of freedom (df) and Akaike weights are shown for each model. The best model for each response variable (in bold) were identified using ΔAICc and model diagnostics.

Management area	Plant species	Distribution	Formula	df	logLik	AICc	ΔAICc	weight
Murchison Mountains	All species	**ng bino**	**financial_year_fctv2 + (1 | site/line)**	**8**	**-1027.91**	**2072.78**	**0.00**	**1**
		zi-ng bino	financial_year_fctv2 + (1 | site/line)	13	-1027.91	2084.33	11.55	0
		ng bino	financial_year_fctv2 + (1 | line)	7	-1036.38	2087.51	14.73	0
		ng bino	financial_year_fctv2 + (1 | site)	7	-1074.12	2162.98	90.20	0
	Celver	ng bino	financial_year_fctv2 + (1 | site/line)	8	-922.22	1861.39	0.00	0.7
		ng bino	**financial_year_fctv2 + (1 | line)**	**7**	**-924.20**	**1863.13**	**1.74**	**0.29**
		zi-ng bino	financial_year_fctv2 + (1 | site/line)	13	-922.22	1872.93	11.54	0
		ng bino	financial_year_fctv2 + (1 | site)	7	-981.06	1976.86	115.47	0
	Dolsco	**ng bino**	**financial_year_fctv2 + (1 | site/line)**	**8**	**-780.88**	**1578.78**	**0.00**	**0.76**
		zi-ng bino	financial_year_fctv2 + (1 | site/line)	13	-776.36	1581.41	2.63	0.2
		ng bino	financial_year_fctv2 + (1 | line)	7	-785.11	1585.01	6.23	0.03
		ng bino	financial_year_fctv2 + (1 | site)	7	-843.72	1702.23	123.44	0
	Ranlya	ng bino	financial_year_fctv2 + (1 | site/line)	8	-565.71	1148.73	0.00	0.95
		ng bino	**financial_year_fctv2 + (1 | line)**	**7**	**-569.94**	**1154.87**	**6.14**	**0.04**
		zi-ng bino	financial_year_fctv2 + (1 | site/line)	13	-565.71	1160.86	12.14	0
		ng bino	financial_year_fctv2 + (1 | site)	7	-657.64	1330.29	181.56	0

Management area	Plant species	Distribution	Formula	df	logLik	AICc	ΔAICc	weight
Wapiti Area	All species	**ng bino**	**financial_year_fctv2 + (1 | site/line)**	**9**	**-2784.41**	**5587.23**	**0.00**	**1**
		zi-ng bino	financial_year_fctv2 + (1 | site/line)	15	-2784.41	5599.91	12.68	0
		ng bino	financial_year_fctv2 + (1 | line)	8	-2809.60	5635.52	48.29	0
		ng bino	financial_year_fctv2 + (1 | site)	8	-2891.86	5800.04	212.81	0
	Celver	**zi-ng bino**	**financial_year_fctv2 + (1 | site/line)**	**15**	**-2501.98**	**5035.03**	**0.00**	**1**
		ng bino	financial_year_fctv2 + (1 | site/line)	9	-2517.31	5053.03	17.99	0
		ng bino	financial_year_fctv2 + (1 | line)	8	-2542.93	5102.17	67.14	0
		ng bino	financial_year_fctv2 + (1 | site)	8	-2681.27	5378.85	343.82	0
	Dolsco	**zi-ng bino**	**financial_year_fctv2 + (1 | site/line)**	**15**	**-2084.74**	**4200.57**	**0.00**	**1**
		ng bino	financial_year_fctv2 + (1 | site/line)	9	-2100.29	4218.99	18.42	0
		ng bino	financial_year_fctv2 + (1 | line)	8	-2113.68	4243.68	43.11	0
		ng bino	financial_year_fctv2 + (1 | site)	8	-2263.69	4543.7	343.13	0
	Ranlya	ng bino	financial_year_fctv2 + (1 | site/line)	9	-1717.64	3453.67	00.00	0.96
		ng bino	**financial_year_fctv2 + (1 | line)**	**8**	**-1722.1**	**3460.53**	**6.85**	**0.03**
		zi-ng bino	financial_year_fctv2 + (1 | line)	14	-1717.63	3464.21	10.54	0
		ng bino	financial_year_fctv2 + (1 | site)	8	-1974.07	3964.46	510.78	0
WARO Area	All species	**zi-ng bino**	**financial_year_fctv2 + (1 | site/line)**	**13**	**-3558.78**	**7144.19**	**0.00**	**1**
		ng bino	financial_year_fctv2 + (1 | site/line)	8	-3584.98	7186.21	42.02	0
		ng bino	financial_year_fctv2 + (1 | line)	7	-3618.47	7251.13	106.94	0
		ng bino	financial_year_fctv2 + (1 | site)	7	-3648.86	7311.9	167.71	0
	Celver	**zi-ng bino**	**financial_year_fctv2 + (1 | site/line)**	**13**	**-2855.85**	**5738.32**	**0.00**	**1**
		ng bino	financial_year_fctv2 + (1 | site/line)	8	-2879.41	5775.06	36.73	0
		ng bino	financial_year_fctv2 + (1 | line)	7	-2913.67	5841.54	103.21	0

Management area	Plant species	Distribution	Formula	df	logLik	AICc	ΔAICc	weight
		ng bino	financial_year_fctv2 + (1 | site)	7	-3014.40	6042.99	304.66	0
	Dolsco	zi-ng bino	financial_year_fctv2 + (1 | site/line)	13	-2516.80	5060.26	0.00	1
		ng bino	financial_year_fctv2 + (1 | site/line)	8	-2534.15	5084.56	24.30	0
		ng bino	**financial_year_fctv2 + (1 | line)**	**7**	**-2549.61**	**5113.42**	**53.16**	**0**
		ng bino	financial_year_fctv2 + (1 | site)	7	-2734.90	5484.01	423.75	0
	Ranlya	zi-ng bino	financial_year_fctv2 + (1 | site/line)	13	-2313.33	4653.31	0.00	1
		ng bino	**financial_year_fctv2 + (1 | site/line)**	**8**	**-2354.13**	**4724.52**	**71.20**	**0**
		ng bino	financial_year_fctv2 + (1 | line)	7	-2374.60	4763.40	110.09	0
		ng bino	financial_year_fctv2 + (1 | site)	7	-2562.28	5138.75	485.44	0

Table A4.2. Candidate model sets for the relationship between alpine plant abundance and proportion of plant browse as evaluated by comparing corrected Akaike's Information Criterion (AICc). All models were fitted with a normal distribution with alpine plant abundance log transformed. The log likelihood (logLik), differences in model AICc value from the best model (ΔAICc), degrees of freedom (df) and Akaike weights are shown for each model The best model for each response variable (in bold) were identified using ΔAICc and model diagnostics.

Plant species	Formula	df	logLik	AICc	ΔAICc	weight
All species	**management_area + Prop_Browse_All + (1 | site/line) + (1 | financial_year_fctv2)**	**8**	**-1080.03**	**2176.18**	**0.00**	**0.46**
	management_area * Prop_Browse_All + (1 | site/line) + (1 | financial_year_fctv2)	10	-1078.48	2177.14	0.96	0.29
	Prop_Browse_All + (1 | site/line) + (1 | financial_year_fctv2)	6	-1082.67	2177.41	1.22	0.25
	management_area + Prop_Browse_All + (1 | line) + (1 | financial_year_fctv2)	7	-1148.32	2310.72	134.54	0.00
	management_area * Prop_Browse_All + (1 | line) + (1 | financial_year_fctv2)	9	-1146.37	2310.9	134.71	0.00
	Prop_Browse_All + (1 | line) + (1 | financial_year_fctv2)	5	-1156.90	2323.85	147.67	0.00
Celver	**management_area + Prop_Browse_Celver + (1 | site/line) + (1 | financial_year_fctv2)**	**8**	**-1317.35**	**2650.83**	**0.00**	**0.81**
	management_area * Prop_Browse_Celver + (1 | site/line) + (1 | financial_year_fctv2)	10	-1317.02	2654.23	3.40	0.15
	Prop_Browse_Celver + (1 | site/line) + (1 | financial_year_fctv2)	6	-1322.41	2656.9	6.07	0.04
	management_area + Prop_Browse_Celver + (1 | line) + (1 | financial_year_fctv2)	7	-1377.50	2769.1	118.27	0.00
	management_area * Prop_Browse_Celver + (1 | line) + (1 | financial_year_fctv2)	9	-1377.44	2773.03	122.2	0.00
	Prop_Browse_Celver + (1 | line) + (1 | financial_year_fctv2)	5	-1392.00	2794.05	143.23	0.00
Dolsco	**management_area * Prop_Browse_Dolsco + (1 | site/line) + (1 | financial_year_fctv2)**	**10**	**-1241.24**	**2502.71**	**0.00**	**0.96**
	management_area + Prop_Browse_Dolsco + (1 | site/line) + (1 | financial_year_fctv2)	8	-1247.13	2510.41	7.70	0.02
	Prop_Browse_Dolsco + (1 | site/line) + (1 | financial_year_fctv2)	6	-1249.32	2510.73	8.03	0.02
	management_area * Prop_Browse_Dolsco + (1 | line) + (1 | financial_year_fctv2)	9	-1268.00	2554.2	51.49	0.00
	management_area + Prop_Browse_Dolsco + (1 | line) + (1 | financial_year_fctv2)	7	-1273.94	2561.99	59.28	0.00
	Prop_Browse_Dolsco + (1 | line) + (1 | financial_year_fctv2)	5	-1279.17	2568.41	65.7	0.00
Ranlya	**Prop_Browse_Ranlya + (1 | site/line) + (1 | financial_year_fctv2)**	**6**	**-1042.32**	**2096.73**	**0.00**	**0.57**
	management_area + Prop_Browse_Ranlya + (1 | site/line) + (1 | financial_year_fctv2)	8	-1040.77	2097.69	0.96	0.36

Plant species	Formula	df	logLik	AICc	ΔAICc	weight
	management_area * Prop_Browse_Ranlya + (1 | site/line) + (1 | financial_year_fctv2)	10	-1040.36	2100.94	4.21	0.07
	management_area + Prop_Browse_Ranlya + (1 | line) + (1 | financial_year_fctv2)	7	-1059.43	2132.98	36.25	0.00
	management_area * Prop_Browse_Ranlya + (1 | line) + (1 | financial_year_fctv2)	9	-1059.01	2136.21	39.48	0.00
	Prop_Browse_Ranlya + (1 | line) + (1 | financial_year_fctv2)	5	-1064.21	2138.49	41.76	0.00

Table A4.3. Conditional model of best fitted models predicting the abundance of alpine plant from the proportion of browse for all species and each indicator species (Celver: *Celmisia verbascifolia*, Dolsco: *Dolichoglottis scorzoneroides*, Ranlya: *Ranunculus lyallii*). See Table for detailed information about the model and selection.

Plant species	Variable	Estimates	Standard error	z value	P-value
All species	(Intercept) *Wapiti Area*	5.234	0.172	30.446	<0.001
	Murchison Mountains	0.458	0.294	1.559	0.119
	WARO Area	-0.214	0.229	-0.933	0.351
	Prop_Browse_All	-0.023	0.111	-0.208	0.835
Celver	(Intercept) *Wapiti Area*	4.553	0.237	19.208	<0.001
	Murchison Mountains	0.524	0.401	1.308	0.191
	WARO Area	-0.593	0.315	-1.884	0.060
	Prop_Browse_Celver	0.290	0.142	2.044	0.041
Dolsco	(Intercept) *Wapiti Area*	3.419	0.234	14.593	<0.001
	Murchison Mountains	0.809	0.406	1.992	0.046
	WARO Area	0.140	0.315	0.444	0.657
	Prop_Browse_Dolsco	-0.032	0.142	-0.227	0.821
	Murchison Mountains:Prop_Browse_Dolsco	0.100	0.383	0.262	0.793
	WARO Area:Prop_Browse_Dolsco	0.743	0.218	3.403	0.001
Ranlya	(Intercept) *Wapiti Area*	3.259	0.143	22.798	<0.001
	Prop_Browse_Ranlya	-0.040	0.145	-0.278	0.781

Table A4.4. Summary of the raw mean abundance of alpine plants for all species combined and each indicator species (Celver: *Celmisia verbascifolia*, Dolsco: *Dolichoglottis scorzoneroides*, Ranlya: *Ranunculus lyallii*) and associated standard deviation (±SD) per survey period with the number of surveyed transects (No line).

Management area	Survey period	No line	All species abundance	Celver abundance	Dolsco abundance	Ranlya abundance
Wapiti Area	2005 - 2006	60	283.28 ± 195.94	161.07 ± 139.86	87.87 ± 93.92	34.35 ± 53.06
	2007 - 2008	60	275.62 ± 189.65	148.92 ± 140.95	90.78 ± 91.09	35.92 ± 49.61
	2011 - 2012	60	250.22 ± 195.34	150.33 ± 147.85	61.63 ± 61.67	38.25 ± 64.1
	2014 - 2017	100	319.64 ± 236.18	198.13 ± 189.21	77.28 ± 104.82	44.23 ± 58.81
	2019 - 2020	100	293.72 ± 216.61	194.24 ± 179.96	63.13 ± 90.06	36.35 ± 49.12
	2023 - 2024	80	294.29 ± 240.22	223.51 ± 227.63	44.25 ± 62.16	26.52 ± 33.23
Murchison Mountains	2005 - 2006	20	432.75 ± 201.77	176.75 ± 141.02	126.4 ± 124.47	129.6 ± 85.03
	2007 - 2008	20	457.75 ± 197.81	159.80 ± 126.03	168.25 ± 138.97	129.7 ± 91.14
	2011 - 2012	20	514.80 ± 214.65	199.50 ± 145.62	174.70 ± 172.94	140.6 ± 100.38
	2016 - 2019	50	455.78 ± 327.39	239.34 ± 184.44	154.00 ± 195.61	67.68 ± 104.62
	2022 - 2023	50	344.14 ± 278.22	219.78 ± 204.97	91.34 ± 125.72	33.02 ± 51.58
WARO Area	2005 - 2006	120	195.19 ± 138.79	83.27 ± 98.91	75.78 ± 92.58	36.15 ± 42.58
	2007 - 2009	120	207.57 ± 165.88	73.23 ± 86.82	89.12 ± 128.01	45.21 ± 47.44
	2011 - 2013	120	221.10 ± 158.72	83.36 ± 95.15	81.17 ± 112.27	56.57 ± 78.55
	2016 - 2018	119	253.51 ± 220.64	127.57 ± 135.29	76.36 ± 119.16	49.10 ± 75.79
	2021 - 2022	119	228.78 ± 224.49	110.13 ± 147.76	72.82 ± 120.81	45.83 ± 56.68

Table A4.5. Results from Tukey Post-hoc analysis of models predicting the change in the abundance of alpine plants over time (survey period) for all species combined and each indicator species (Celver: *Celmisia verbascifolia*, Dolsco: *Dolichoglottis scorzoneroides*, Ranlya: *Ranunculus lyallii*) in each management areas (Murchison Mountains, Wapiti Area and WARO Area). For each survey period, emmean values, standard error (SEM), lower confidence limits (asymp.LCL) and upper confidence limits (asymp.UCL) are provided with associated compact letter displaying pair-wise comparisons.

Management area	Plant species	Survey period	emmean	SEM	asymp.LCL	asymp.UCL	Letters
Murchison Mountains	All species	2005 - 2006	5.62	0.22	5.06	6.17	ab
		2007 - 2008	5.67	0.22	5.11	6.22	ab
		2011 - 2012	5.78	0.22	5.23	6.34	b
		2016 - 2019	5.85	0.21	5.32	6.38	b
		2022 - 2023	5.54	0.21	5.01	6.07	a
	Celver	2005 - 2006	4.92	0.14	4.55	5.29	a
		2007 - 2008	4.82	0.14	4.45	5.19	a
		2011 - 2012	5.03	0.14	4.66	5.40	ab
		2016 - 2019	5.23	0.13	4.90	5.55	b
		2022 - 2023	5.03	0.13	4.7	5.36	a
	Dolsco	2005 - 2006	4.1	0.37	3.15	5.04	a
		2007 - 2008	4.37	0.37	3.43	5.32	ab
		2011 - 2012	4.37	0.37	3.43	5.31	ab
		2016 - 2019	4.60	0.36	3.69	5.52	b
		2022 - 2023	4.13	0.36	3.22	5.05	a
	Ranlya	2005 - 2006	3.33	0.45	2.18	4.48	b
		2007 - 2008	3.28	0.45	2.13	4.43	b
		2011 - 2012	3.35	0.45	2.19	4.50	b
		2016 - 2019	3.45	0.45	2.30	4.6	b
		2022 - 2023	2.74	0.45	1.59	3.89	a
Wapiti Area	All species	2005 - 2006	5.21	0.17	4.78	5.65	ab
		2007 - 2008	5.23	0.17	4.79	5.67	ab
		2011 - 2012	5.06	0.17	4.62	5.5	a
		2014 - 2017	5.50	0.16	5.07	5.93	c
		2019 - 2020	5.37	0.16	4.94	5.79	bc
		2023 - 2024	5.39	0.16	4.96	5.82	bc
	Celver	2005 - 2006	4.28	0.29	3.51	5.05	a
		2007 - 2008	4.07	0.29	3.30	4.84	a
		2011 - 2012	4.09	0.29	3.32	4.86	a
		2014 - 2017	4.61	0.29	3.85	5.37	b
		2019 - 2020	4.54	0.29	3.78	5.30	b
		2023 - 2024	4.69	0.29	3.92	5.45	b

Management area	Plant species	Survey period	emmean	SEM	asymp.LCL	asymp.UCL	Letters
	Dolsco	2005 - 2006	3.09	0.37	2.13	4.06	b
		2007 - 2008	3.15	0.37	2.19	4.12	b
		2011 - 2012	2.74	0.37	1.78	3.71	a
		2014 - 2017	3.17	0.36	2.22	4.12	b
		2019 - 2020	2.97	0.36	2.01	3.92	ab
		2023 - 2024	2.66	0.36	1.71	3.62	a
	Ranlya	2005 - 2006	2.66	0.21	2.11	3.20	ab
		2007 - 2008	2.76	0.21	2.21	3.31	b
		2011 - 2012	2.73	0.21	2.18	3.27	b
		2014 - 2017	2.71	0.2	2.17	3.24	b
		2019 - 2020	2.59	0.20	2.06	3.13	ab
		2023 - 2024	2.47	0.21	1.93	3.01	a
WARO Area	All species	2005 - 2006	5.05	0.15	4.65	5.44	a
		2007 - 2009	5.07	0.15	4.68	5.47	a
		2011 - 2013	5.18	0.15	4.78	5.57	ab
		2016 - 2018	5.27	0.15	4.87	5.66	b
		2021 - 2022	5.06	0.15	4.67	5.46	a
	Celver	2005 - 2006	3.44	0.33	2.58	4.3	a
		2007 - 2009	3.36	0.33	2.5	4.22	a
		2011 - 2013	3.51	0.33	2.65	4.37	ab
		2016 - 2018	3.99	0.33	3.13	4.84	c
		2021 - 2022	3.69	0.33	2.83	4.55	b
	Dolsco	2005 - 2006	3.14	0.26	2.46	3.81	c
		2007 - 2009	3.05	0.26	2.37	3.72	c
		2011 - 2013	2.91	0.26	2.24	3.59	bc
		2016 - 2018	2.70	0.26	2.02	3.37	ab
		2021 - 2022	2.58	0.26	1.90	3.26	a
	Ranlya	2005 - 2006	2.43	0.38	1.45	3.42	a
		2007 - 2009	2.57	0.38	1.58	3.56	ab
		2011 - 2013	2.71	0.38	1.72	3.70	b
		2016 - 2018	2.53	0.38	1.54	3.52	ab
		2021 - 2022	2.50	0.38	1.51	3.49	ab

Appendix 5 – Model selection and analyses of *Ranunculus lyallii* size class (Q5)

Table A5.1. Candidate model sets for the relationship between the proportion of large *Ranunculus lyallii* (size class: 8cm or more) and harvest rate, deer pellet groups or proportion of browsed Ranlya as evaluated by comparing corrected Akaike's Information Criterion (AICc). The model with the lowest AICc value for each response variable was chosen as the best model. The log likelihood (logLik), differences in model AICc value from the best model (ΔAICc), degrees of freedom (df) and Akaike weights are shown for each model. The best model for each predictor (in bold) were identified using ΔAICc and model diagnostics.

Formula	df	logLik	AICc	ΔAICc	weight
management_area * harvest_km_10000_730 + (1 | area/line) + (1 | financial_year_fctv2)	**9**	**-3364.8**	**6747.79**	**0**	**1**
harvest_km_10000_730 + (1 | site/line) + (1 | financial_year_fctv2)	5	-3394.74	6799.55	51.76	0
management_area + harvest_km_10000_730 + (1 | site/line) + (1 | financial_year_fctv2)	7	-3393.05	6800.22	52.43	0
harvest_km_10000_730 + (1 | line) + (1 | financial_year_fctv2)	4	-3478.1	6964.25	216.46	0
management_area * deer_pellets + (1 | site/line) + (1 | financial_year_fctv2)	**9**	**-3482.99**	**6984.17**	**236.38**	**0**
deer_pellets + (1 | area/line) + (1 | financial_year_fctv2)	5	-3503.56	7017.17	269.38	0
management_area + deer_pellets + (1 | site/line) + (1 | financial_year_fctv2)	7	-3502.21	7018.54	270.75	0
management_area * Prop_Browse_Ranlya + (1 | site/line) + (1 | financial_year_fctv2)	**9**	**-3520.81**	**7059.85**	**312.06**	**0**
1 + (1 | site/line) + (1 | financial_year_fctv2)	4	-3571.41	7150.87	403.08	0
Prop_Browse_Ranlya + (1 | site/line) + (1 | financial_year_fctv2)	5	-3571.41	7152.89	405.1	0
management_area + Prop_Browse_Ranlya + (1 | site/line) + (1 | financial_year_fctv2)	7	-3569.85	7153.84	406.05	0
deer_pellets + (1 | line) + (1 | financial_year_fctv2)	4	-3582.3	7172.63	424.84	0
Prop_Browse_Ranlya + (1 | line) + (1 | financial_year_fctv2)	4	-3653.29	7314.63	566.84	0

Table A5.2. Conditional model of best fitted models predicting the proportion of large *Ranunculus lyallii* (size class: 8 cm or more) from harvest rate, deer pellet groups or the proportion of browsed Ranlya. See Table A5.1 for detailed information about the model selection.

Variable of interest	Variable	Estimates	Standard error	z value	P-value
Harvest rate	(Intercept) *Wapiti Area*	-0.885	0.520	-1.701	0.089
	Murchison Mountains	0.010	0.801	0.012	0.990
	WARO Area	-0.657	0.760	-0.865	0.387
	harvest_km_10000_730	-0.032	0.006	-5.817	<0.001
	Murchison Mountains : harvest_km_10000_730	0.095	0.028	3.449	0.001
	WARO Area : harvest_km_10000_730	0.045	0.006	7.121	<0.001
Deer pellet groups	(Intercept) *Wapiti Area*	-1.533	0.493	-3.112	0.002
	Murchison Mountains	1.350	0.734	1.839	0.066
	WARO Area	0.425	0.747	0.569	0.569
	deer_pellets	-0.021	0.024	-0.889	0.374
	Murchison Mountains : deer_pellets	-0.125	0.054	-2.325	0.020
	WARO Area : deer_pellets	-0.178	0.029	-6.165	<0.001
Browsed Ranlya	(Intercept) *Wapiti Area*	-1.738	0.494	-3.519	<0.001
	Murchison Mountains	1.416	0.741	1.911	0.056
	WARO Area	0.563	0.748	0.752	0.452
	Prop_Browse_Ranlya	1.217	0.220	5.530	<0.001
	Murchison Mountains : Prop_Browse_Ranlya	-0.064	0.382	-0.169	0.866
	WARO Area : Prop_Browse_Ranlya	-2.585	0.288	-8.988	<0.001

Table A5.3. Raw mean of proportion of large *Ranunculus lyallii* (size class: 8 cm or more) with standard deviation (±SD) and results from Tukey Post-hoc analysis of models predicting the change in the proportion of large *Ranunculus lyallii* in each management areas (Murchison Mountains, Wapiti Area and WARO Area) over time (survey period). For each survey period, emmean values, standard error (SEM), lower confidence limits (asymp.LCL) and upper confidence limits (asymp.UCL) are provided with associated compact letter displaying pair-wise comparisons.

Management area	Survey period	Raw means	emmean	SEM	asymp.LCL	asymp.UCL	Letters
Murchison Mountains	2007 - 2008	0.73 ± 0.28	1.14	0.32	0.36	1.93	c
	2011 - 2012	0.76 ± 0.22	1.15	0.31	0.37	1.94	c
	2016 - 2019	0.66 ± 0.29	0.71	0.31	-0.07	1.49	b
	2022 - 2023	0.50 ± 0.31	-0.17	0.31	-0.95	0.62	a
Wapiti Area	2007 - 2008	0.25 ± 0.28	-0.44	0.35	-1.33	0.44	c
	2011 - 2012	0.31 ± 0.32	-0.28	0.35	-1.17	0.61	c
	2014 - 2017	0.22 ± 0.27	-1.93	0.34	-2.82	-1.05	b
	2019 - 2020	0.15 ± 0.21	-2.82	0.35	-3.71	-1.93	a
	2023 - 2024	0.12 ± 0.18	-3.06	0.35	-3.97	-2.15	a
WARO Area	2007 - 2009	0.31 ± 0.31	-1.50	0.35	-2.36	-0.63	a
	2011 - 2013	0.35 ± 0.31	-1.16	0.35	-2.02	-0.30	b
	2016 - 2018	0.39 ± 0.32	-0.84	0.35	-1.70	0.03	c
	2021 - 2022	0.32 ± 0.32	-1.26	0.35	-2.13	-0.40	b

Table A5.4. Candidate model sets to investigate the proportion of large *Ranunculus lyallii* (size class: 8cm or more) over time as evaluated by comparing corrected Akaike's Information Criterion (AICc). The family error distribution (binomial, zero-inflated binomial: zi-bino), log likelihood (logLik), differences in model AICc value from the best model (ΔAICc), degrees of freedom (df) and Akaike weights are shown for each model. The best model for each response variable (in bold) were identified using ΔAICc and model diagnostics.

Management area	Distribution	Formula	df	logLik	AICc	ΔAICc	weight
Murchison Mountains	binomial	financial_year_fctv2 + (1 | area/line)	6	-693.3	1399.51	0	0.81
	binomial	financial_year_fctv2 + (1 | line)	5	-695.96	1402.55	3.04	0.18
	zi-bino	financial_year_fctv2 + (1 | area/line)	10	-693.3	1409.08	9.57	0.01
	binomial	financial_year_fctv2 + (1 | area)	5	-824.94	1660.52	261.01	0
Wapiti Area	zi-bino	financial_year_fctv2 + (1 | area/line)	12	-1182.66	2390.13	0	1
	binomial	financial_year_fctv2 + (1 | area/line)	7	-1229.08	2472.44	82.3	0
	binomial	financial_year_fctv2 + (1 | line)	6	-1251.39	2514.99	124.85	0
	binomial	financial_year_fctv2 + (1 | area)	6	-1540.24	3092.7	702.56	0
WARO Area	zi-bino	financial_year_fctv2 + (1 | area/line)	10	-1589.17	3198.84	0	1
	binomial	financial_year_fctv2 + (1 | area/line)	6	-1605.58	3223.35	24.51	0
	binomial	financial_year_fctv2 + (1 | line)	5	-1657.65	3325.44	126.6	0
	binomial	financial_year_fctv2 + (1 | area)	5	-1899.69	3809.52	610.68	0