NSW NATIONAL PARKS & WILDLIFE SERVICE

River Red Gum Ecological Thinning Trial

Monitoring report 2022

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Cover photo: Two people surveying river red gum forest. Emma Gorrod.

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Contents

Key Results

The key results for the effect of ecological thinning on each monitoring variable analysed in this report are listed below. Each variable was sampled either annually or every 5 years in a subplot that had an appropriate spatial scale to detect the effects of thinning. No ecological thinning was undertaken on control plots. Statistically significant effects of ecological thinning are shaded grey (significance level 0.05–0.1 stated explicitly, otherwise $p<0.05$). Where effects of thinning were specific to particular combinations of Site Quality, pre-thinning tree density or time, they were described. All magnitudes of difference from controls are for 5 years post-thinning (2021–22 surveys) unless otherwise stated.

Tree mortality	
Tree mortality	Marginally significant ($p = 0.08$) effect of ecological thinning that **increased** tree mortality by 3–12% (1.5–6 additional dead trees out of 50) relative to control plots.
Large tree mortality	**No statistically significant effect of ecological thinning.**
Tree growth	
Tree diameter growth rate	Ecological thinning: • **Increased** the growth rates of trees that were 200 millimetres diameter at breast height prior to thinning by approximately 1 to 3 millimetres per year relative to controls 5 years post-thinning. • **Decreased** the growth rates of trees that were 1000 millimetres diameter at breast height prior to thinning by approximately –1 to –4 millimetres per year relative to controls 5 years post-thinning.
Tree height growth rate	Ecological thinning **increased** average tree height by 2.5–5 metres relative to controls 5 years post-thinning.
Tree size class structure	
Count of live large trees	**No statistically significant effect of ecological thinning.**
Proportion of trees that were large	Ecological thinning initially **increased** the proportion of trees occurring in large diameter size classes due to the removal of small trees, however this effect diminished over time and was a maximum of 11% higher (per hectare) than control 5 years post-thinning.
Coppice	Ecological thinning **increased** the abundance of stems that were <10 centimetres diameter at breast height due to coppiced stems arising from cut stumps and damaged or pushed over saplings. The greatest magnitude of effect was in drier Site Quality 2 plots that had very high initial tree density, with approximately 330–450 coppiced stems more than controls (per 0.1 hectares).
Hollow-bearing tree development	
Tree crown area	Ecological thinning caused an initial **decrease** in tree crown area, but a subsequent faster **rate of increase** than trees in control plots. Five years post-thinning there was no difference in the average canopy area in thinned and control plots.
Count of hollow-bearing trees	No hollow-bearing trees were removed by thinning operations and there was **no statistically significant effect of ecological thinning**.

Tree canopy health	
Proportion of tree crown that is live	Ecological thinning caused an **increase** in average proportion of individual tree crowns that contained live foliage by 2.5–7% in drier Site Quality 2 plots and also in wetter Site Quality 1 plots with very high initial tree density.
Foliage Projective Cover (FPC)	Light ecological thinning (~25% of trees removed) initially caused a small **increase** in remotely sensed FPC relative to control plots, but this increase diminished over time and was not significant 5 years post-thinning. Heavy ecological thinning (~75% of trees removed) caused a significant and substantial (5–13%) **decrease** in FPC relative to control plots, and the difference was sustained for 5 years post-thinning.
Recruitment	
Germinants	The data for germinant presence and germinant abundance were not able to be modelled due to the prevalence of zeros in the dataset. However, the raw data did not provide evidence that ecological thinning had an effect on germinant occurrence or abundance.
Seedlings	Ecological thinning caused an **increase** of 200–1,000 seedlings (per 0.04-hectare subplot) in drier Site Quality 2 plots that had very low to moderate initial tree density. Ecological thinning caused a temporary **decrease** of approximately 35 seedlings (per 0.04-hectare subplot) in wetter Site Quality 1 plots that had very low initial tree density 4 years post-thinning.
Saplings	Ecological thinning generally **decreased** abundance of saplings by 6–22 saplings (per 0.04-hectare subplot) relative to controls. However, in drier Site Quality 2 plots with moderate to very high initial tree density ecological thinning **increased** abundance of saplings by 5–32 saplings (per 0.04-hectare subplot).
Structural diversity	
Midstorey structural diversity	No evidence of an effect of ecological thinning, however no statistical analyses were conducted due to a lack of data. Only 3 midstorey shrub species were recorded on fewer than a quarter of 9-hectare plots across all surveys, and tended to occur on the same plots over time.
Understorey structural diversity	Marginally significant ($p = 0.05$) effect of ecological thinning that **decreased** variation in understorey height in most plot types (by 9%) but **increased** it in drier Site Quality 2 plots with very high initial tree density (by 20%).
Coarse Woody Debris (CWD)	
Volume of CWD	**No statistically significant effect of ecological thinning.**
Heterogeneity of CWD size	**No statistically significant effect of ecological thinning.**
Leaf litter	
Heterogeneity of leaf litter cover	Marginally significant ($p = 0.08$) effect ecological thinning that changed over time, resulting in a 1–10% **increase** in leaf litter heterogeneity (per 0.01-hectare subplot) in some heavily thinned plots in some years.
Heterogeneity of leaf litter depth	**No statistically significant effect of ecological thinning.**
Standing dead trees	
Count of standing dead trees	**No statistically significant effect of ecological thinning.**

Fuel hazard	
Overall fuel hazard	**No statistically significant effect of ecological thinning.**
Litter depth	Marginally significant ($p = 0.07$) effect of ecological thinning that caused both **increases and decreases** of 3–4 millimetres in leaf litter depth in some circumstances.
Litter cover	Ecological thinning initially **increased** litter cover on some plot types. Five years post-thinning, the only significant difference from controls was a **decrease** of 5% (per 0.04-hectare subplot) in wetter Site Quality 1 plots with very high initial tree density.
Surface fuel hazard	**No statistically significant effect of ecological thinning.**
Live near surface vegetation	Ecological thinning initially **decreased** live near surface vegetation cover, and subsequently **increased** live near surface vegetation cover by 1–12% (per 0.04-hectare subplot) in wetter Site Quality 1 plots. Ecological thinning **increased** live near surface vegetation cover in drier Site Quality 2 plots with very high initial tree density plots by 1–6% (per 0.04-hectare subplot).
Dead near surface vegetation	Ecological thinning had an effect on dead near surface vegetation cover that depended on thinning intensity, Site Quality and initial tree density. One year post-thinning, ecological thinning **increased or decreased** dead near surface vegetation cover up to 4% (per 0.04-hectare subplot) relative to controls in different circumstances, but these effects diminished over time and were a maximum of 1.2% difference 5 years post-thinning.
Near surface fuel hazard	**No statistically significant effect of ecological thinning.**
Combined surface fuel hazard	**No statistically significant effect of ecological thinning.**
Live elevated vegetation cover	Ecological thinning likely temporarily reduced live vegetation cover in the elevated stratum by 3–5% (per 0.04-hectare subplot), however a statistical model was not able to be fitted to these data.
Dead elevated vegetation cover	No evidence in the data that ecological thinning affected dead elevated vegetation cover (per 0.04-hectare subplot), however a statistical model was not able to be fitted to these data.
Elevated fuel hazard	**No statistically significant effect of ecological thinning.**
Bat species	
Bat species richness	No evidence of an effect of ecological thinning, although statistical analyses were not undertaken as most bat species were recorded on most plots and a statistical model was not able to be fitted to these data.
Bat species diversity	Heavy intensity ecological thinning (~75% of trees removed) **increased** Hill-Shannon bat diversity by the equivalent of 1–1.8 equally abundant species per night in Site Quality 1 plots with very high initial tree density. Moderate intensity thinning (~50% of trees removed) temporarily increased bat diversity in some Site Quality 2 plots 3 years post-thinning.

Activity of all bat species	Ecological thinning **increased** total bat activity by a maximum of approximately 300 calls per night relative to control plots. However, this increase was only statistically different from controls in some years due to annual fluctuations.
Activity of clutter specialist bat species	Ecological thinning initially **decreased** clutter specialist activity by 3–11 calls per night in some plot types relative to controls. Five years post-thinning, there were no significant differences from controls.
Activity of clutter avoider bat species	Ecological thinning **increased** clutter avoider activity. The magnitude of the effect changed over time and was highest in the most recent year with a modelled average of 38–149 additional calls per night relative to controls.
Bird species	
Abundance of bird species	Ecological thinning **increased** bird abundance between 3 and 5 years post-thinning. Five years post-thinning the only statistically significant difference relative to controls was an additional 13 birds (per 20-minute survey of 2 hectares) in wetter Site Quality 1 plots with very high initial tree density.
Bird species richness	Marginally significant ($p = 0.06$) effect of ecological thinning on bird species richness. For most plot types, thinning caused an **increase** in richness with a maximum of 5 additional species (per 20-minute survey of 2 hectares) relative to controls in the most recent survey year. However, prior to the most recent year, thinning caused a **decrease** of 2 species in wetter Site Quality 1 plots with very high initial tree density.
Bird species diversity	Ecological thinning initially **decreased** bird Hill-Shannon diversity in drier Site Quality 2 plots with moderate to very high initial tree density by the equivalent of 2 equally abundant species (per 20-minute survey of 2 hectares) relative to controls. Subsequently, moderate and heavy intensity ecological thinning **increased** bird diversity in all site types and the magnitude of change increased over time to a maximum of 3.3 more than controls.
Foraging activity of bird species	Raw data provide evidence that bird activity increased in most microhabitat locations in thinned plots, relative to control plots, but statistical analyses were not undertaken.
Threatened birds	Twelve threatened bird species were recorded. These opportunistic data were sparse and not appropriate for statistical analyses.
Gliders	
Count of glider feed trees	**No statistically significant effect of ecological thinning.**
Predators	
Abundance of fox scats	Insufficient fox scats were recorded to enable statistical analyses.
Vascular plants	
Exotic plant species diversity	Heavy and moderate intensity ecological thinning (>50% of trees removed) caused an initial **increase** in exotic plant Hill-Shannon diversity by the equivalent of up to 6.6 equally abundant species (per 0.04-hectare subplot) in drier Site Quality 2 plots. The increase was maintained for very low to moderate initial tree density plots but declined over time for high initial tree density plots.
Exotic plant species richness	Ecological thinning **increased** exotic plant species richness on most plot types in most years by up to 11 additional species (per 0.04-hectare subplot) relative to controls, with the exception of wetter Site Quality 1 plots with very low initial

	tree density 4 years post-thinning that had up to 6 **fewer** exotic plant species. Results were highly variable over time.
Exotic plant cover	Ecological thinning caused a significant **increase** in exotic vegetation cover on most plot types. The greatest magnitude of increase was 2.1% (per 0.04-hectare subplot) in wetter Site Quality 1 plots 3 years post-thinning, but the difference from controls diminished over time.
Native plant species diversity	Ecological thinning **increased** native plant Hill-Shannon diversity in some plot types by a maximum of the equivalent of 4.4 equally abundant species (per 0.04-hectare subplot). However, the significant differences from controls changed over time and by plot type. In addition, thinning **decreased** native plant diversity in wetter Site Quality 1 plots with very high initial density by the equivalent of one species for 3 years.
Native plant richness	There was a significant effect of ecological thinning on native plant species richness, however there was uncertainty about the nature and magnitude of the effect due to high levels of year-to-year variation related to climate and flooding. - In drier Site Quality 2 plots an initial **increase** relative to controls of approximately 3 species (per 0.04-hectare subplot) diminished over time. - In wetter Site Quality 1 plots with very low initial density, the difference from controls increased over time to 6 species (per 0.04-hectare subplot) 5 years post-thinning.
Native plant cover	Ecological thinning initially **decreased** native plant cover in wetter Site Quality 1 plots. Between the 2 most recent survey periods thinning **increased** cover on all plot types, with a maximum of 13–17% higher cover (per 0.04-hectare subplot) than control plots.
Threatened plants	Insufficient data were collected for statistical analyses, but raw data suggest it was unlikely that ecological thinning had a negative effect on floating swamp wallaby grass.

1. Introduction

1.1 Ecological thinning trial

The aims and details of the experimental design are fully described in *Ecological thinning trial in New South Wales and Victorian River Red Gum forests: Experimental design and monitoring plan* (OEH 2012), which was included in Appendix 1 of *Public Environment Report: Ecological thinning trial in New South Wales River Red Gum forests* (OEH 2014) as part of the Commonwealth approval under the *Environment Protection and Biodiversity Conservation Act 1999*. The experimental design is also detailed in Gorrod et al. (2017) and summarised briefly below.

Aims of the trial

The ecological thinning trial aims to learn about the effectiveness of ecological thinning for addressing a range of conservation concerns associated with widespread high tree density stands and canopy dieback in *Eucalyptus camaldulensis* (river red gum) forests. Conservation concerns in high tree density stands are related to high competition for water and other resources. Within-stand competition is likely to be higher in stands with lower water availability, and is likely to increase with increasing tree density. Ecological thinning may reduce competition by reducing stand density while retaining and enhancing biodiversity and habitat features.

The trial's hierarchy of aims are:

- The primary aim for the trial is to determine whether any of several levels of ecological thinning positively affect biodiversity, canopy condition and resilience to epidemic river red gum mortality within all stands of river red gum forests, and whether these effects depend on water availability and initial tree density.
- The secondary aim for the trial is to determine whether any of several levels of ecological thinning positively affect characteristics of the stands that are reasonably expected to lead to the primary aim, and whether these effects depend on water availability and initial tree density. For example, hollow-bearing tree recruitment levels, and understorey species diversity.
- The tertiary aim for the trial is to determine whether any of several levels of ecological thinning positively affect characteristics of the trees that are reasonably expected to lead to the secondary aim, and whether these effects depend on water availability and initial tree density. For example, tree diameter growth rates, tree diameter distribution diversity, crown shape and health.

Ecological thinning trial sites

The number and location of ecological thinning trial sites were selected to represent a spectrum of within-stand competition, occurring in a range of tree densities and 2 levels of long-term water availability. A total of 22 sites were located in the Millewa precinct of the Murray Valley National Park in New South Wales (Figure 1).

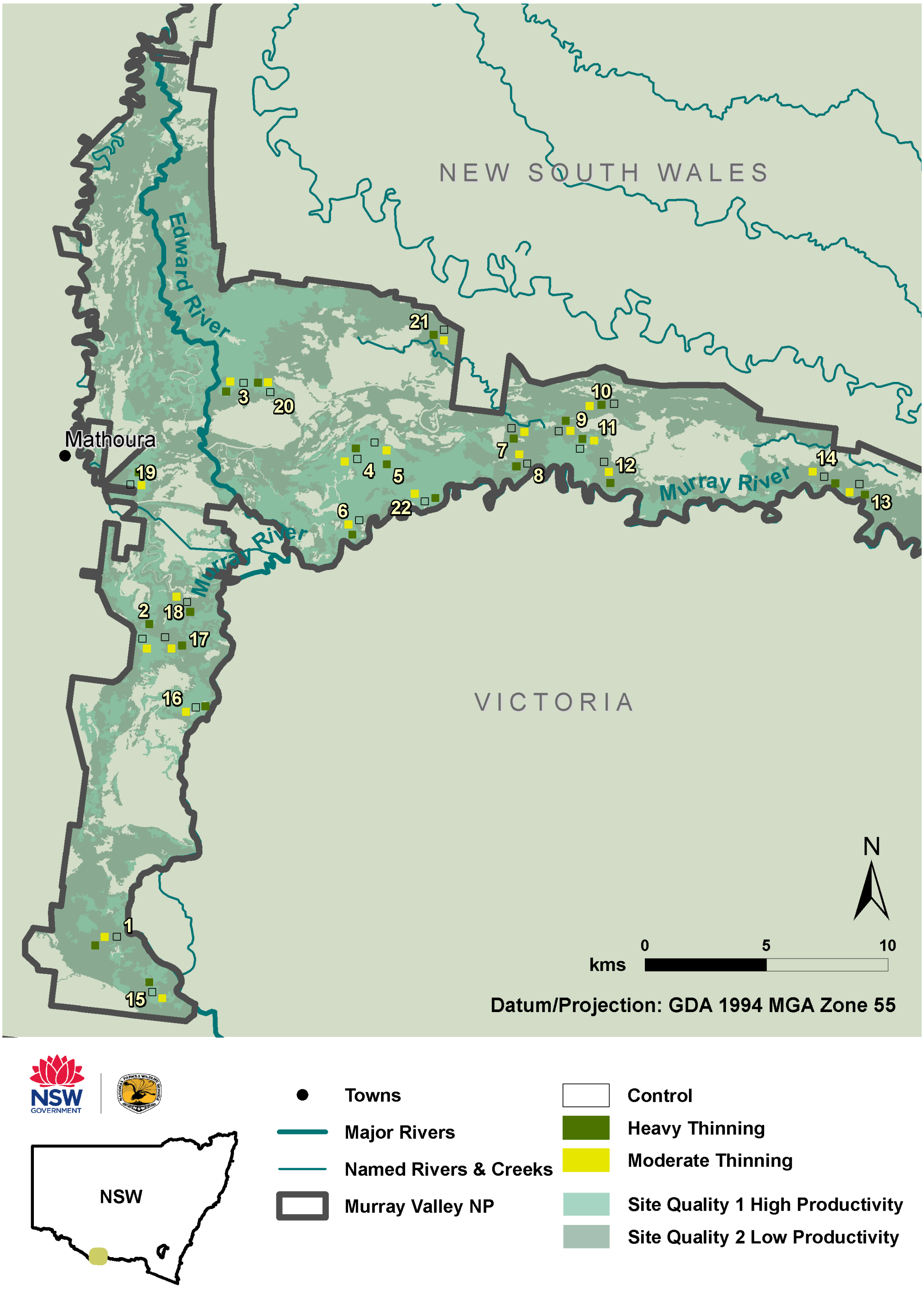

Figure 1 Locations of ecological thinning sites

NP = national park; SQ = Site Quality

The locations of sites with a range of pre-thinning tree densities were selected using tree density mapping of the Murray Valley National Park (Bowen et al. 2012). More sites were selected in high tree density stands because they were the focus of management interest (Table 1). A surrogate for water availability called Site Quality was also used to inform the locations of sites. Site Quality is derived from tree height mapping (Baur 1984): Site Quality 1 (SQ1) is associated with increased long-term water availability and taller trees than Site Quality 2 (SQ2). Sites were evenly divided among the 2 Site Quality classes (Table 1).

Table 1 Intended number of sites across a spectrum of stem density (Bowen et al. 2012) and a surrogate of water availability (Site Quality)

	<200 stems/ha	200–400 stems/ha	>400 stems/ha	Total
Site Quality 1	2	4	5	11
Site Quality 2	2	4	5	11
Total	**4**	**8**	**10**	**22**

Each site consisted of three 9-hectare (ha) treatment plots. The 3 treatment plots were intended to be similar to each other prior to thinning. All plots were 300 x 300 metres (m) and the distance between plots within a site was between 100 and 300 metres. The size of the plot minimised edge effects from the surrounding forest and enabled detection of responses in all of the vegetation, flora and fauna parameters of interest.

Field data for tree density

Field data for initial (pre-thinning) tree density was collected in 2015, in which all trees >10 centimetre (cm) diameter at breast height (dbh) were counted in two 20 x 50 m plots in each 9-hectare plot. These data indicated that measured tree density may have poor correspondence with mapped tree density.

Additional field data for tree density was subsequently collected in 2016 and 2017, in which trees of all sizes were counted in an additional eight 20 x 50 m plots in each 9-hectare plot. For some 9-hectare plots (10 out of 44), these data were collected after thinning had been completed, in which case all recent stumps were counted and the height and diameter of each stump was measured. Taper equations were used to allocate stumps to tree size classes.

These data provided estimates of pre-thinning tree density, which indicated that the tree density mapping did not reliably represent on-ground density (OEH 2018).

Pre-thinning tree density

The field data for tree density showed that thinning treatment plots were located in a wide range of initial tree densities, from about 250 trees per hectare to 1,850 trees per hectare (Figure 2). The majority of plots had tree densities between 400 and 1,000 trees per hectare. The average tree density across all plots was 740 trees per hectare.

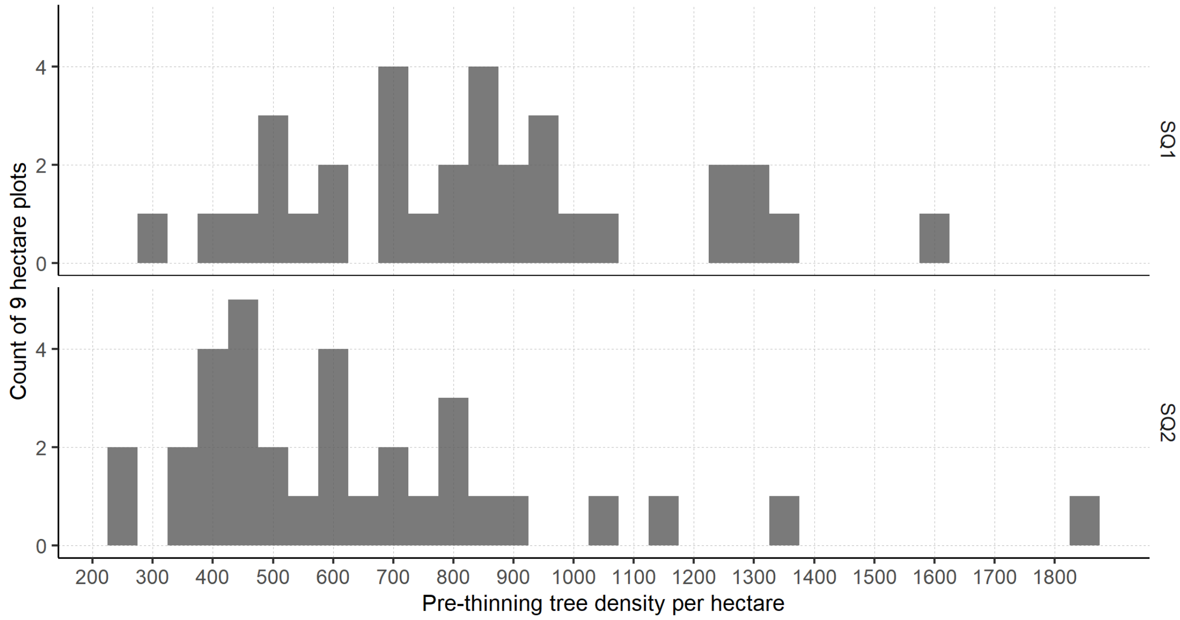

Figure 2 Count of 9-hectare plots with different pre-thinning tree densities per hectare

Each bar represents a range of 50 trees (for example, the left-most bar in Site Quality 2 represents the count of 9-hectare plots that had pre-thinning tree density of 225–275 per hectare)

There were some differences between the Site Qualities. The majority of plots in Site Quality 1 had tree densities of between about 500 and 1,000 trees per hectare, about one-quarter of plots had more than 1,000 trees per hectare, and very few plots had low tree densities. The average tree density in Site Quality 1 plots was 830 trees per hectare.

The majority of Site Quality 2 plots had tree densities of between about 350 and 800 trees and only 4 plots in Site Quality 2 had initial tree densities greater than 1,000 trees. The average tree density in Site Quality 2 plots was 580 trees per hectare.

1.2 Ecological thinning treatments

Thinning treatments: spacings

Three ecological thinning treatments were planned in the trial (Table 2): control, moderate thinning and heavy thinning. At each site, one 9-hectare plot was randomly assigned to each of the 3 thinning treatments.

Table 2 Ecological thinning treatments

Treatment	Specifics	Rationale
Control	No action	Enable comparison with thinning treatments.
Moderate thinning	7 m spacings between retained trees	Widest spacings likely to be implemented in commercial silviculture (7.3 m, Baur 1984), and substantially wider than most silvicultural thinning treatments (3–4 m, Schonau & Coetzee 1989).

Treatment	Specifics	Rationale
Heavy thinning	15 m spacings between retained trees	Equivalent to the crown diameter (approximately 17 m) of a large *Eucalyptus camaldulensis* tree (>80 cm dbh*), to facilitate development of branches and spreading crowns that may lead to hollow development.

*diameter at breast height

Thinning prescriptions included a number of environmental protections. The following trees were retained in all treatments:

- all trees with dbh >40 centimetres
- all trees with a visible hollow (minimum opening of 5 centimetres)
- all dead trees with a dbh of >20 centimetres.

Retention of all trees with these properties aimed to maintain the current quantity and distribution of trees with important habitat values, and trees with the potential to develop hollows over the coming decades.

In addition, buffer zones, in which all trees were retained, were placed around drainage lines and cultural heritage features.

No prescriptions were given for the treatment of trees with <10 centimetres dbh and therefore retention was variable among plots.

The spacings method of thinning involved selecting a tree for retention, measuring 7 metres or 15 metres from the trunk of that tree, and selecting another tree for retention, and so on.

Within the 10–40 centimetres dbh size class, trees with the following features were preferentially selected for retention:

- structurally viable trunk and root attachment
- strong lateral branching (that may develop into spreading, branching form)
- healthy crown
- larger dbh.

Thinning using prescribed spacings and retention of all large and habitat trees was selected to increase the proportion of trees in larger size classes, as well as to increase the abundance of branching trees that are likely to become hollow bearing in the future.

NPWS staff marked-up each 9-hectare plot according to these protections and prescriptions, marking all trees to be retained.

Contractors implemented the thinning operations. Between retained trees, all trees with dbh between 10 and 40 centimetres were removed. Following felling, each stump was painted with Roundup Biactive® within 5 minutes to restrict coppicing. The felling method minimised damage to retained trees.

Thinning treatments: total tree density change

After thinning operations were completed, tree density surveys were repeated. From the field data, tree density change was estimated for all thinned plots (Figure 3). As noted above, some plots were surveyed only once and stumps were used to estimate the change in density.

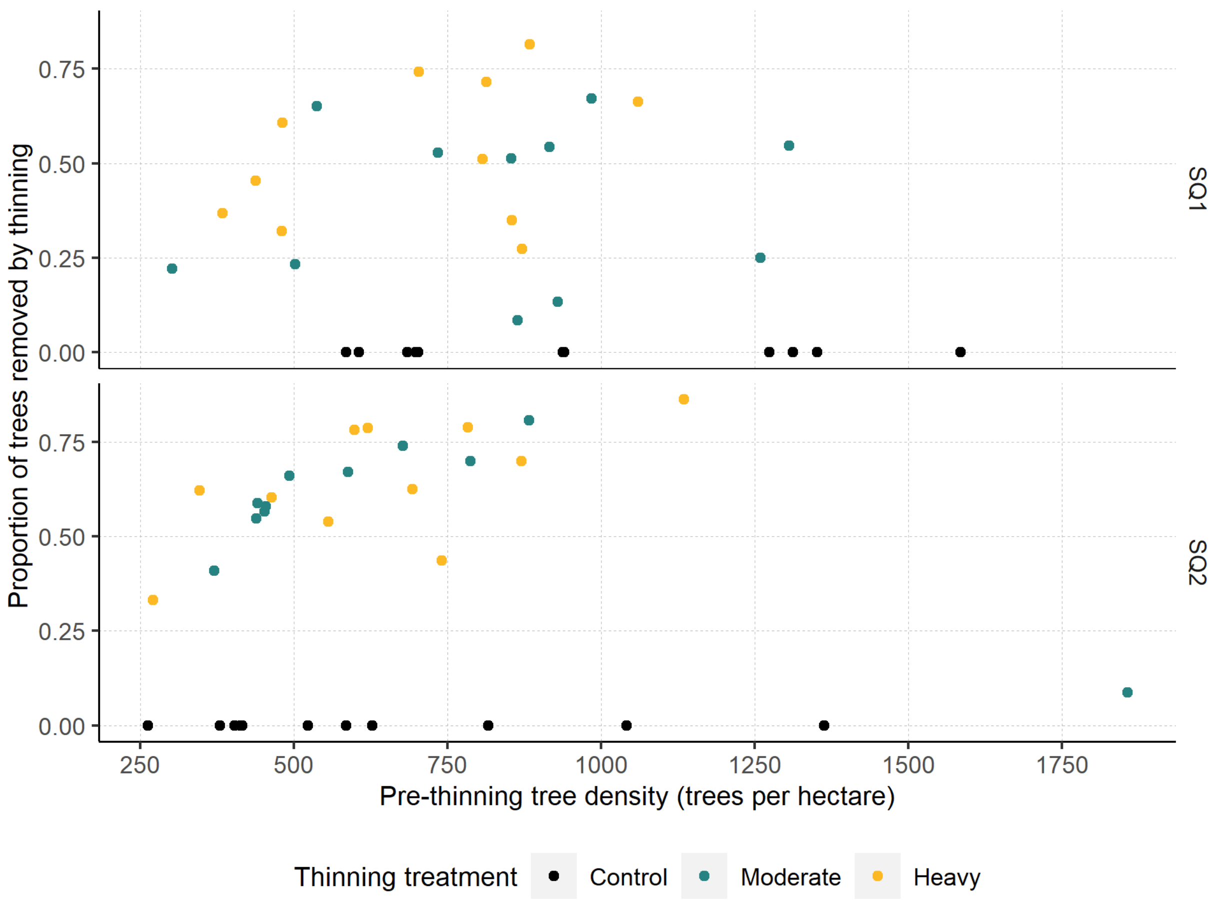

Figure 3 **Pre-thinning tree density and proportion of trees removed, by thinning treatment**

Among Site Quality 1 plots, the proportion of trees removed was not dependent on the starting density (indicated by the vertical spread of points for any given pre-thinning density). For example, there were 4 plots with pre-thinning tree densities of around 500 trees per hectare, which had between 25% and 70% of trees removed by thinning.

Among Site Quality 2 plots, the proportion of trees removed tended to increase with increasing starting density. For example, all plots with starting densities of around 500 trees per hectare had between 55% and 70% of trees removed by thinning.

The proportion of total trees removed was not distinct among the moderate and heavy thinning treatment prescriptions.

Thinning treatments: tree size class

The proportion of small (<20 cm dbh) trees that was removed did not differ substantially among thinning treatment categories (Figure 4). These size classes were by far the most abundant, contributing substantially to total tree density.

A higher proportion of 20–40 cm dbh trees tended to be removed in the heavy thinning treatments than in moderate thinning treatments (Figure 4).

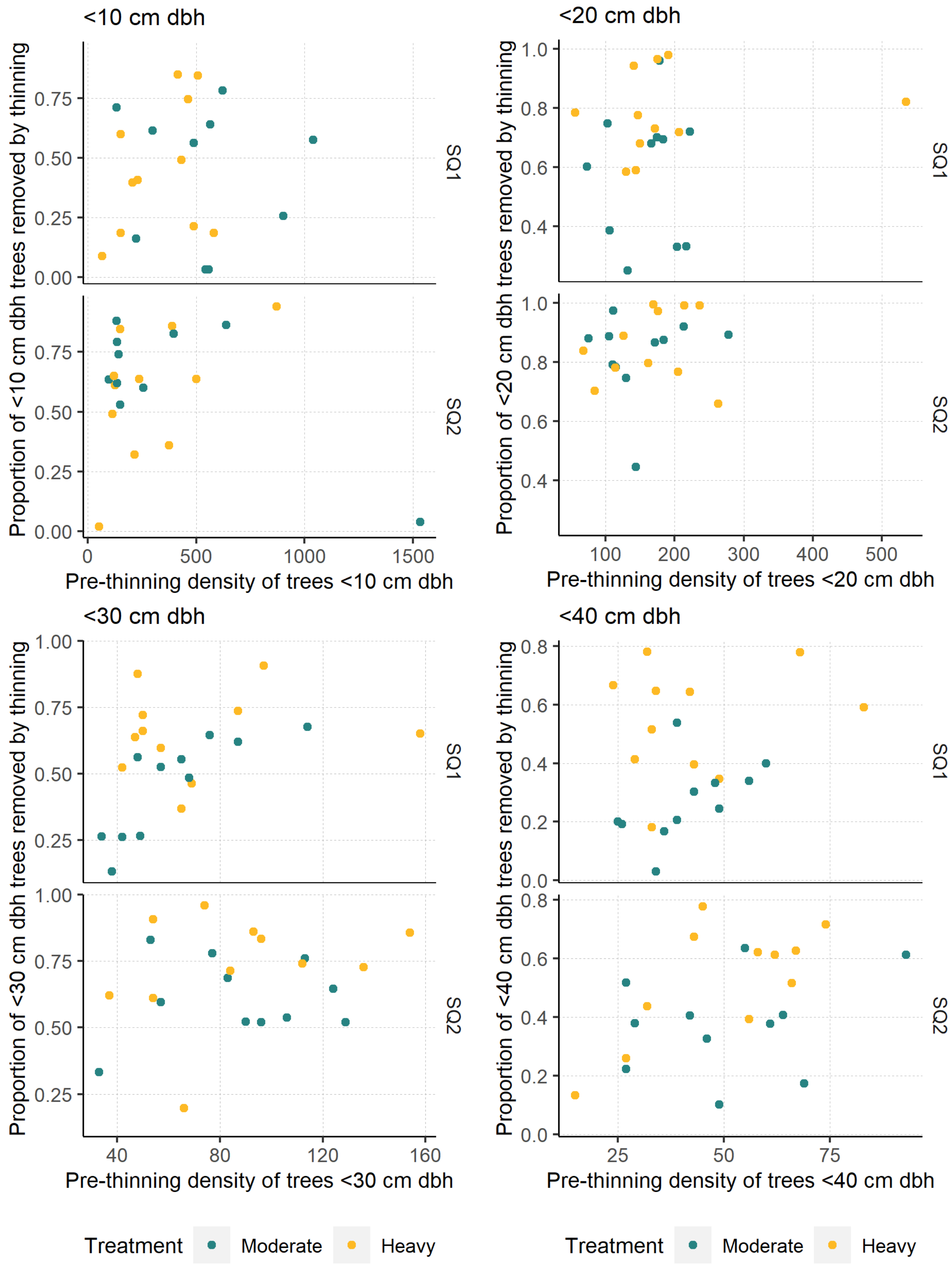

Figure 4 Change in density of different sized trees due to thinning

Thinning treatments: thinning intensity

The proportion of 30–40 cm dbh trees that were removed was lower in moderately thinned plots than heavily thinned plots. However, the proportion of smaller trees that were removed was not distinct among treatment protocols, and these smaller trees tended to be the most abundant.

Characterising thinning treatments in terms of the proportional change in total tree density may yield more nuanced information about the effects of thinning in river red gum forest, than the 3 categories of treatment by spacings. Further, proportional change in total tree density can be coupled with data about pre-thinning tree density to improve understanding of the effects of ecological thinning under different starting conditions.

1.1 Hypotheses

Prior to implementing ecological thinning treatments, a series of hypotheses were specified about the effects of ecological thinning on individual tree features, tree population characteristics, forest structure and site features; flow-on effects to indigenous and non-indigenous flora and fauna; and any processes or disturbances associated with implementing the treatments.

It was hypothesised that the effects of ecological thinning would be greatest at plots for which ecological thinning caused the greatest decrease in competition for water, nutrient and space resources. These plots would have high initial tree densities, low post-treatment densities and high levels of water availability. Information concerning the rationale or conceptual process model underpinning each hypothesis, as well as any available published evidence supporting each hypothesis, was provided in the experimental design and monitoring plan (OEH 2012).

Prior to thinning, and for 5 years post-thinning, monitoring data have been collected to evaluate each hypothesis. Each year the trends for each of these parameters was analysed.

Effects of ecological thinning on tree populations and forest structure:

- 1a. Increased survival and growth rates of retained trees.
- 1b. Increased number and proportion of trees occurring in large diameter size classes.
- 1c. Increased spread and hollow-development rates of retained trees.
- 1d. Increased tree canopy health (proportion of potential crown that is live) of retained trees.
- 1e. Increased recruitment of tree seedlings in early post-treatment years.
- 1f. Increased survival of seedlings (<1.37 metres tall) and saplings (>1.37 metres tall, <10 centimetres dbh).
- 1g. Increased structural diversity of midstorey and understorey strata.
- 1h. Higher levels of coarse woody debris (45–50 tonnes/hectare) maintained in long term.
- 1i. Increased heterogeneity in cover and depth of forest litter in the long term.
- 1j. Decreased persistence of dead trees (stags) in the short term.
- 1k. Increased fuel and fire risk.

Effects of ecological thinning on mammalian and avian diversity:

- 2a. Increased diversity of bat species, and increased levels of site utilisation by bat species.

2b. Increased abundance and frequency of foraging activity by woodland bird species.

2c. Increased abundance of gliders.

2d. Increased abundance of predators, in particular foxes.

Effects of ecological thinning on vascular plant diversity:

3a. Increased diversity and cover of exotic plant species in understorey in the short term, decreasing in the long term.

3b. Increased diversity and abundance of native plant species.

1.2 Monitoring

For each hypothesis, one or more monitoring variables were defined, and a monitoring protocol was designed to survey each variable at an appropriate spatial scale. Consequently, the size and number of monitoring subplots within each 9-hectare treatment plot varied (Figure 5). For example, in each 9-hectare treatment plot birds were surveyed within a single 2-hectare monitoring subplot and floristics were surveyed in three 0.04-hectare monitoring subplots. Details for each monitoring variable are given in the experimental design and monitoring plan (OEH 2012) and are summarised in the results section for each variable in this report.

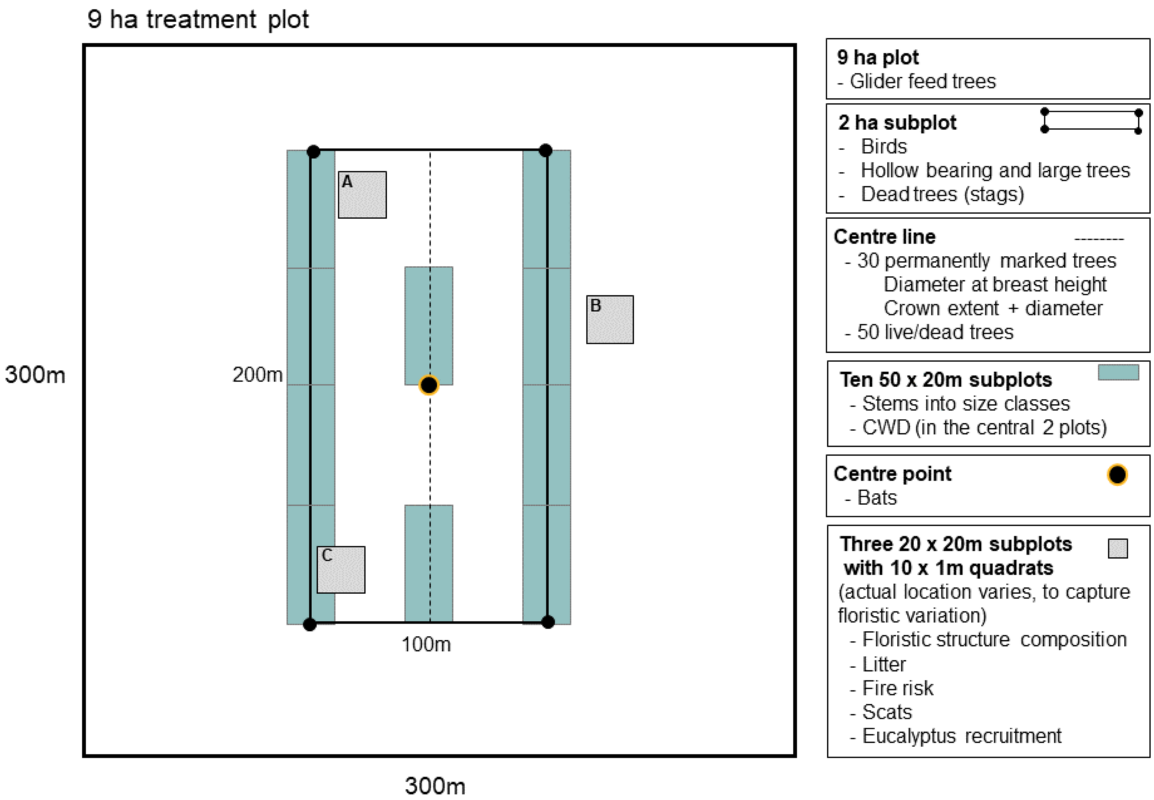

Figure 5 Schematic layout of monitoring subplots within each 9-hectare plot

1.3 Ecological thinning trial to date

Pre-thinning monitoring

Half of the sites (1–12) were first surveyed in 2012–13. These data are not included in this report.

Pre-thinning surveys were undertaken on all sites between September 2015 and February 2016. All variables were measured in this survey period. Results were described in the *River red gum pre-ecological thinning monitoring report 2017* (OEH 2017).

These data are referred to as the 2015–16 or pre-thinning survey period in this report.

Thinning treatments

Thinning treatments commenced in April 2016. Half of the treatment plots were thinned prior to a major flood event in September 2016, in which all control and treatment plots were inundated. Thinning treatments recommenced in February 2017 and were completed in August 2017.

All Site Quality 1 plots that were thinned prior to the flood had a lower proportion of trees removed than Site Quality 1 plots that were thinned after the flood (indicated by the horizontal spread of points in Figure 6).

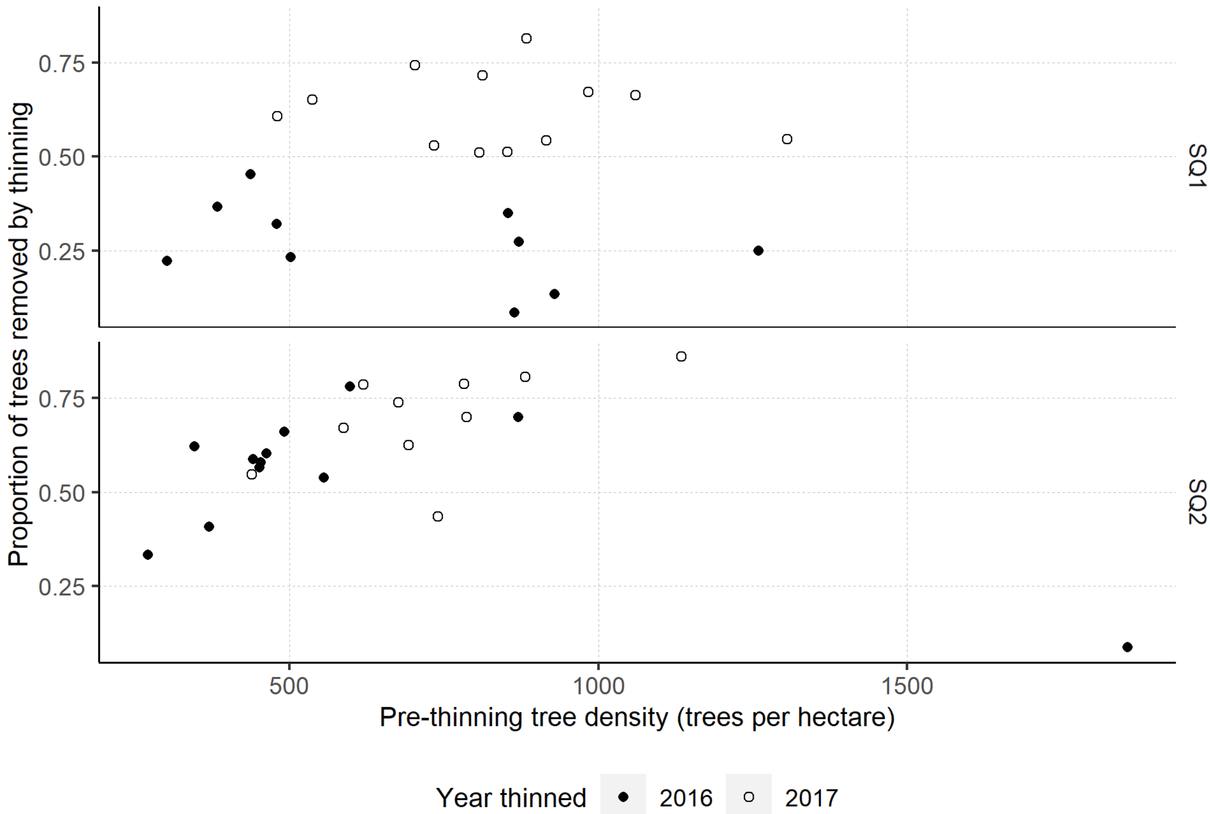

Figure 6 Proportion of trees removed relative to year of thinning

Post-thinning monitoring

First post-thinning monitoring 2017–18

The first round of post-thinning monitoring commenced in October 2017 and was completed in February 2018. All variables were measured in this survey period. The results of the first post-thinning monitoring are described in the *River red gum ecological thinning trial monitoring report 2018* (OEH 2018).

These data are referred to as the 2017–18 survey period in this report.

Second post-thinning monitoring 2018–19

The second round of post-thinning monitoring commenced in October 2018 and was completed in February 2019. A subset of variables were measured in the 2018–19 survey period and the results of this monitoring are described in the *River red gum ecological thinning trial monitoring report 2019* (OEH 2019).

These data are referred to as 2018–19 survey period in this report.

Third post-thinning monitoring 2019–20

The third round of post-thinning monitoring commenced in October 2019 and was completed in February 2020. A subset of variables were measured in the 2019–20 survey period and the results of this monitoring are described in *River red gum ecological thinning trial monitoring report 2020* (Gorrod et al. 2020).

These data are referred to as the 2019–20 survey period in this report.

Fourth post-thinning monitoring 2020–21

The fourth round of post-thinning monitoring commenced in October 2020 and was completed in February 2021. A subset of variables were measured in the 2020–21 survey period and the results of this monitoring were described in *River red gum ecological thinning trial monitoring report 2021* (Gorrod et al. 2021).

These data are referred to as the 2020–21 survey period in this report.

Fifth post-thinning monitoring 2021–22

The fifth round of post-thinning monitoring commenced in November 2021 and was completed in August 2022. The timing of these surveys was later than the spring-summer surveys of previous years due to COVID travel restrictions and extensive flooding. All variables were measured in the 2021–22 survey period and the results of this monitoring are described in this report. However, vegetation surveys were not able to be conducted on floristic subplots with more than 30% standing floodwater present and therefore 30 out of 198 floristic subplots were not surveyed in 2021–22. Further, 42% out of 66 plots were not surveyed for bats due to restricted access around the time of the full moon. All other surveys were completed for tree, tree density, coarse woody debris and bird variables.

These data are referred to as the 2021–22 survey period in this report.

Sequence of events

As a result of the 2016 flood event, the sequence of flooding and thinning differed among sites (Figure 7). Flooding occurred in 2021 that delayed the commencement of monitoring of the fifth post-thinning survey.

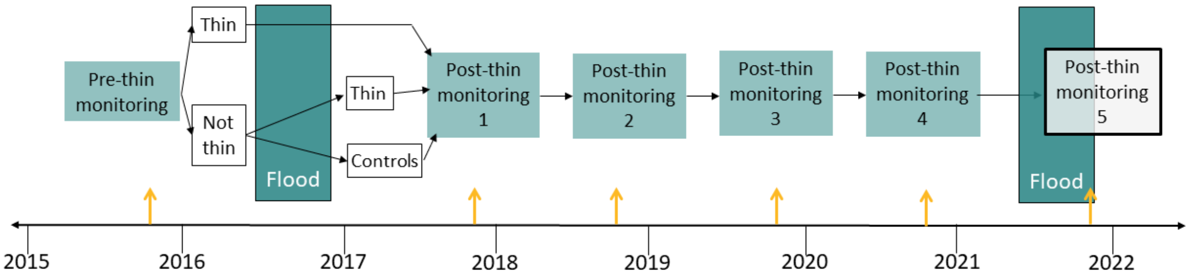

Figure 7 Sequence of monitoring, thinning and flood events

The amount of time that elapsed between thinning implementation and the first post-thinning monitoring varied among sites, and also differed among monitoring variables. For example, time since thinning at the time of survey was between one and 22 months for the tree parameters; and 4 and 30 months for the floristics. The effects of these differences are taken into account by including a continuous measure of 'time since thinning' (in decimal years) in analyses.

1.4 Climate and flooding

Flooding

River red gum forests are flood-dependent ecosystems that require inundation approximately 7–9 years out of every 10 years. River regulation caused a substantial reduction in frequency and duration of flooding and also changed the seasonality of flooding (Bren 1988).

Higher than average water release from Yarrawonga Reservoir in mid-2021 resulted in flooding throughout the surveyed area (Figure 8). These levels persisted until late September 2021, returning to water release amounts similar to previous years in early 2022. During this fifth-year post-thinning survey, vegetation monitoring was not able to be conducted on 15% of floristic plots that were flood-affected. In addition, 42% of bat surveys were not able to be completed due to access issues.

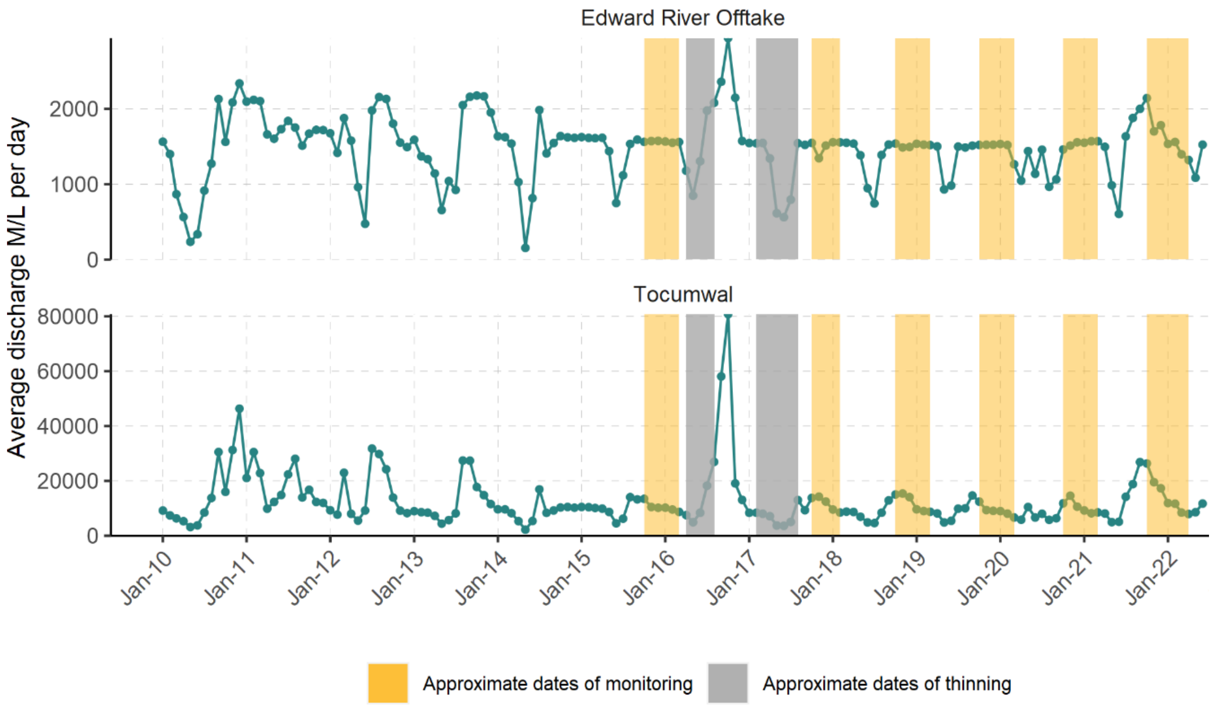

Figure 8 Average daily discharge (in megalitres) through Tocumwal and Edwards River Offtake, averaged per month

Source: Murray–Darling Basin Authority, River Murray Data, accessed 15/06/2022.

Rainfall

Rainfall is winter-dominant at Mathoura. In autumn and winter 2021, rainfall was relatively high when compared the previous years (Figure 10). During the fifth-year post-thinning survey period in spring and summer, rainfall was higher and more variable when compared to previous survey periods. There were peaks in precipitation in November 2021 and April 2022.

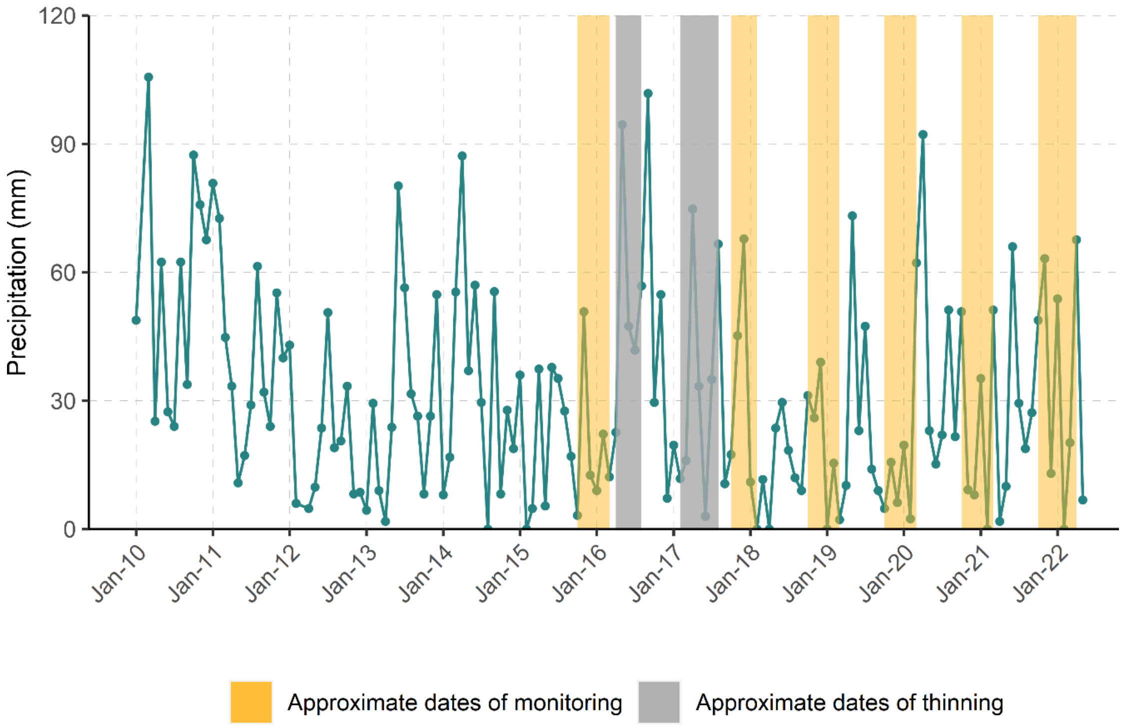

Figure 9 Total monthly precipitation at Mathoura
Source: Australian Bureau of Meteorology, gauge no. 074129, accessed 31/03/2021.

Evapotranspiration

Minimum evapotranspiration values in winter 2021 were comparable with the previous decade, but maximum evapotranspiration values in the summers of 2020–21 and 2021–22 were lower than in the previous 6 summers (Figure 10).

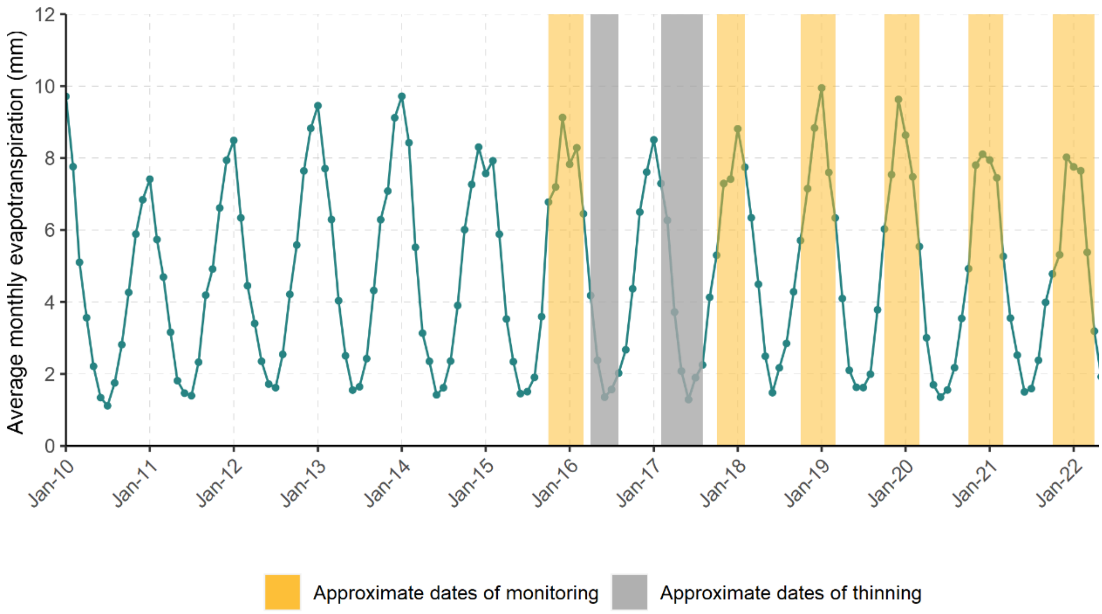

Figure 10 Monthly precipitation minus evapotranspiration at Deniliquin airport
Source: Australian Bureau of Meteorology, gauge no. 074258, accessed 31/03/2021.

1.5 This report

The analyses in this report seek to explore the effects of ecological thinning on a range of variables.

This report describes the fifth post-thinning monitoring data that were collected in 2021–22 and compares them with data collected in previous years.

As specified in the experimental design and monitoring plan (OEH 2012), variables that are expected to change from year-to-year were monitored annually (Table 3) and variables that are expected to change over longer time frames were monitored every 5 years (Table 4). In the 2021–22 surveys, all variables were monitored.

Photographs of a selection of sites in each survey year are included in the separate Appendices document.

Table 3 Variables monitored annually

Variable
Tree diameter at breast height over bark (trees ≥10 cm dbh)
Live/dead status of 50 trees (trees ≥10 cm dbh)
Tree crown extent
Foliage projective cover (Landsat derived)
Occurrence of seedlings
Occurrence of saplings
Cover of litter
Depth of forest leaf litter
Bat species richness and diversity; use level by individual and all species
Occurrence of woodland bird species
Fox scat evidence
Richness and cover of exotic plant species
Richness and cover of native plant species
Photo points
Fuel assessment

Table 4 Variables monitored 5-yearly

Variable
Distribution of trees amongst size classes
Number of trees with hollows
Number of trees with glider notches
Opaque crown (m^2)
Cover, abundance and height of dominant species in understorey strata
Count of standing dead trees (stags)
Volume of coarse woody debris (>10 cm diameter)

Variable
Survival of trees ≥80 cm dbh
Tree height

Hypothesis evaluation

The evidence for each hypothesis is summarised in the results section for each monitoring variable in this report.

Plate 1 People walking through river red gum forest. Nicholas Chu

2. Methods

2.1 Data analysis approach

An estimation approach to analyses was used to interpret the recorded data and detect effects of thinning.

Data analysis for each monitoring variable was undertaken to estimate the following:

- the direction of change over time
- the magnitude of change over time
- differences in the direction and/or magnitude of change between control plots and plots that were thinned
- the degree to which any effect of thinning was dependent on thinning intensity (the proportion of trees removed)
- the degree to which any effect of thinning depended on the initial density of trees or Site Quality
- the level of confidence in results.

Confidence about changes in monitoring variables is drawn from the following sources:

- variability in the raw data
- any difficulties in finding relationships between the monitoring variable and the explanatory variables (that is, model convergence issues)
- how well the model fits all parts of the range of raw data values (that is, residual tests)
- how likely it is that the data would have occurred by random chance (that is, p values)
- the width of confidence intervals.

A separate Appendices document contains information about these sources of information and describes confidence in the model for each monitoring variable.

In this approach, the statistical significance (‘p value’) generated for a regression model is only one piece of information used to draw conclusions about the importance of ecological thinning for the ecological and biodiversity features of interest.

All analyses were conducted in the R statistical environment (R Core Team 2022).

2.2 Data summaries

In this report, raw data are presented in at least one figure, like the example in Figure 11 below. Other summary figures and tables are provided where relevant.

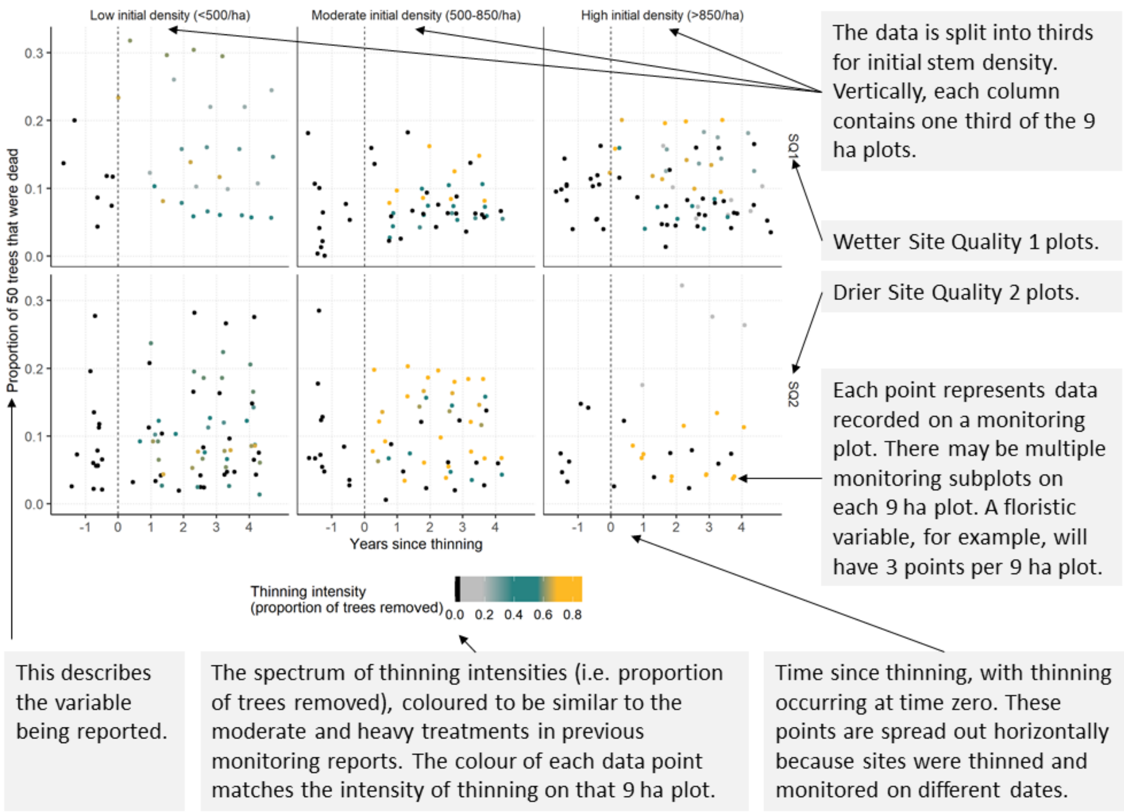

Figure 11 Generic raw data figure

2.3 Modelling

Frequentist and Bayesian models

Regression models estimate the extent to which different values of explanatory variables are associated with different values of the response (monitoring) variable, while accounting for known variation in the data.

Regression models calculate the line (or plane) that minimises the distance to each response variable data point. The slope (or shape) and location of the line (or plane) are determined by the values of the explanatory variables. Once the line (or plane) has been calculated, it can be used to predict what the value of the response variable may be for particular values of explanatory variables.

Frequentist regression (generalised linear mixed effects models) gives a single point estimate for each explanatory variable, by finding the value that minimises the amount of error in the data (called ordinary least squares).

In Bayesian regression modelling, a range of possible fits for each explanatory variable are explored. The result is a *distribution* for the explanatory variables that is proportional to the likelihood of the data. This allows the influence of each explanatory variable on the monitoring variable to be assessed while taking into account background variability. These distributions are called credible intervals.

Frequentist regression results can be re-sampled many times using bootstrapping procedures, also resulting in distributions of explanatory variables. These distributions are called confidence intervals or prediction intervals. Confidence intervals can be used to show the likely range of values that the *average* could take. Prediction intervals show the range of values future *individual observations* could take. Prediction intervals account for the variation in the average plus the variation in individual observations, and thus are always wider than confidence intervals.

While the frequentist and Bayesian estimates are calculated differently, they both provide estimates of uncertainty around the relationship between each explanatory variable and the response variable.

When a credible, prediction or confidence interval for a model coefficient does not include zero, there is high confidence that the explanatory variable has had an effect on the response variable.

Frequentist models were used for most response variables, in conjunction with bootstrapping (1000 simulations) where possible. Bayesian models were used in all cases where the response variable was a category.

Regression models were implemented in R statistical environment, using the packages lme4 and glmmTMB for frequentist models and brms for Bayesian models.

Response variables

Monitoring (response) variables can be continuous numbers, proportions, counts or categories. Each type of variable differs in terms of the likely spread of values, and the amount of variation expected to occur around each value.

Regression is most useful in detecting the effects of thinning when the likely spread and variation (that is, distribution) of response variable values are specified.

There are 2 features of regression models that are used to specify the distribution of the response variable: family and link.

The family specifies the expected relationship between the mean (average) value and the variance of the response variable.

The link function allows the relationship between the response variable and the explanatory variables to be something other than a simple linear form. It is similar to transforming the raw response variable data (for example, taking the log of each response value), but instead transforms the modelled average of the response. Other modelled values are predicted around the mean in accordance with their family characteristics.

In cases where there was uncertainty about which family and link function may have been appropriate, multiple models were run and their performance compared.

Explanatory variables

There were 4 explanatory variables of primary interest. Three of them were continuous predictors:

- initial tree density – total number of trees (>1.37 metres in height) per hectare (log-transformed)
- thinning intensity – proportion of trees removed (scale of 0–1)
- years elapsed since thinning commenced on the site (that is, same date for all three 9-hectare plots on the site, including the control). The difference in dates was calculated as the number of years elapsed (as decimal years).

The fourth explanatory variable indicative of long-term water availability, Site Quality, was a categorical predictor.

All models also included additional explanatory variables that account for the fact that measurements within a given site or plot may not be independent samples (that is, they may be spatially and/or temporally auto-correlated), which could influence interpretation of the main explanatory variables and their significance. These additional variables are called random effects. Models included random effects across site (where there was one estimate per 9-hectare plot) or site and plot (where there were multiple estimates per 9-hectare plot). A random effect was also included for survey year, to account for the fact that data collected in a particular survey season are more likely to be similar to each other than those collected in other years.

For each response variable, the first model that was attempted included all possible interactions between all main explanatory variables (Table 5). In order to allow for the effect of the continuous predictors to be relationships other than a straight line, polynomial terms were included.

Table 5 All explanatory variables and interactions for inclusion in regression models

Model term	Effect being tested	Comment
Site Quality	Does the value of the response variable depend on whether it is in Site Quality 1 or Site Quality 2?	Each of these terms are independent of all other terms in the model
Initial tree density	Does the value of the response variable differ depending on pre-thinning tree density?	
Initial tree density^2	Does the value of the variable differ depending on pre-thinning tree density, such that the variable does not increase (or decrease) at a constant rate with increasing tree density?	
Years elapsed	Does the value of the response variable change over time? Although this is calculated as time 'since thinning', when it is included in the model on its own (that is, no interaction with thinning intensity), it is determining whether there is change over time, irrespective of thinning.	
Years elapsed^2	Does the value of the response variable change over time, such that the variable does not necessarily increase (or decrease) at a constant rate as time goes on?	
Thinning intensity	Does the value of the response variable differ depending on the intensity of thinning that was applied?	
Thinning intensity^2	Does the value of the response variable differ depending on thinning intensity, such that the variable does not increase (or decrease) at a constant rate with increasing intensity?	
Initial tree density * Site Quality Initial tree density^2 * Site Quality	Does the response variable depend on initial tree density in a way that differs among Site Qualities?	These terms account for background interactions that are not related to thinning
Years elapsed * Site Quality Years elapsed^2 * Site Quality	Does the response variable change over time in a way that differs among the Site Qualities?	
Initial tree density * years elapsed	Does the relationship between the response variable and initial tree density change over time?	

Model term	Effect being tested	Comment
Initial tree density * years elapsed * Site Quality	Does the relationship between the response variable and initial tree density change over time in a way that differs among Site Qualities?	
Thinning intensity * Site Quality Thinning intensity^2 * Site Quality	Does the effect of thinning differ among Site Qualities; and does the effect of increasing thinning intensity in either Site Quality increase (or decrease) the response variable at a rate that is not constant (for example does moderate thinning lead to a greater increase (or decrease) than either light or heavy thinning)?	These interactions give detailed information about the possible effects of thinning
Thinning intensity * initial tree density	Does the effect of thinning depend on initial tree density?	
Thinning intensity * years elapsed	Does the effect of thinning change over time?	
Thinning intensity * initial tree density * Site Quality	Does the effect of thinning depend on initial tree density in a way that differs among the Site Qualities?	
Thinning intensity * years elapsed * Site Quality	Does the effect of thinning change over time in a way that differs among the Site Qualities?	
Thinning intensity * initial tree density * years elapsed * Site Quality	Does the effect of thinning intensity depend on initial tree density and change over time in a way that differs among the Site Qualities?	
Site	To account for the fact that plots within the same site are likely to be more similar to each other than they are to other sites.	These are random effects to account for temporal and spatial auto-correlation
9-hectare plot, subplot	To account for the fact that sites, plots and subplots are likely to be similar each time they are surveyed.	
Year factor (survey year)	To account for differences across survey seasons – due primarily to different hydro-climatic conditions.	

Sometimes there were 2 or more equally plausible sets of relationships between response and explanatory variables, and it was not possible to define the most appropriate model for the raw data. In these cases, simpler models were subsequently attempted by removing one or more interaction terms, or removing the random effect of survey year. The intention was not to find the 'best' model that explained the most variation in the data with the fewest terms, but rather to find the model that could fit the response data and contained as much information as possible about the effects of ecological thinning and the extent to which those effects may be dependent on initial tree density, time since thinning and/or Site Quality.

Assessing model fit

How well the model fits the raw data can be described in a number of ways, many of which involve looking at the difference between raw values and the model's fitted line (or plane). These differences are called residuals. For example, if the residuals are small for small values of the response variable but large for high values of the response variable, it can indicate that the model might not be a good representation of relationships for the full range of raw response variable data values.

An extension of the comparison of differences between raw and fitted values is to assume that the model is correct and use it to simulate new data with the same mean and variance as the raw data. Simulating many new datasets generates a likely spread of data around the fitted values, which can be compared with the actual spread of data around the fitted values.

The fit of all models was assessed using examination of raw and simulated residuals (using the DHARMa package in R) to determine whether they met assumptions of homogeneity of variance, collinearity, and outliers. In cases where 2 models had similar residuals, they were compared using Akaike Information Criteria.

The model with the best fit for each response variable is reported in the results section of this report. The Appendices contain details about which models were trialled for each response variable, residual plots for the reported model, and a description of the level of confidence in the reported model.

Assessing statistical significance of explanatory variables

Because there were numerous terms in each model that contained information about each explanatory variable, it was difficult to use the model coefficients and estimates of significance to draw conclusions about the strength of relationships between response and explanatory variables. For example, in a model that contained all the terms in Table 5, there were 9 terms that included thinning intensity, only some of which may have shown statistical significance. The Appendices contain the coefficients and significance values for each term in each model.

Likelihood ratio tests compare the goodness of fit of 2 models. If one model is superior at explaining variation in the response data, then its goodness of fit is higher. A model that contains all possible combinations of explanatory variables (full model) can be compared with a model that contains all combinations of explanatory variables *except one* (say, thinning intensity) (null model) via a likelihood ratio test. If there is little difference in the ability of the 2 models to explain variation in the response data, then the likelihood ratio test will be non-significant. If the test is not significant, then the explanatory variable that was removed is unlikely to be a strong predictor of the response variable. On the other hand, if the explanatory variable was important for explaining variation in the response data, then there will be a significant difference between the models.

Null model comparisons were conducted using bootstrapped likelihood ratio tests for each of the main explanatory effects as well as for interactions involving thinning intensity. The significance levels are reported in a table. The actual p values were reported for each null model comparison, and a threshold of $p = 0.05$ was used for ascribing statistical significance.

Instead of likelihood ratio tests, Bayesian models used leave one out cross validation to estimate out of sample prediction accuracy using the log-likelihood evaluations of the posterior simulations to compare the candidate model with null models. These comparisons calculate a difference in expected log-predictive density (ELPD) and a standard error for this difference. Where the difference in ELPD is much larger than the estimated standard error of the difference there is much better predictive performance. We reported the ratio of the ELPD difference to its standard error and used an absolute value of 4 or greater as an indicator of significant change in predictive performance.

Visualising modelled relationships

The modelled relationships between explanatory variables and the response variable are represented in Figure 12. The figure shows the modelled values of the response variable (on the original scale after removing any link function or transformation that had been applied, unless otherwise stated) for different values of the explanatory variables. The figure also shows bootstrapped 95% confidence intervals (generated from 999 simulations), which were generated from the model for specific values of explanatory variables, generic levels of variation representing differences among site and 9-hectare plot, and specific levels of variation in each survey year (where survey year was included as a random effect).

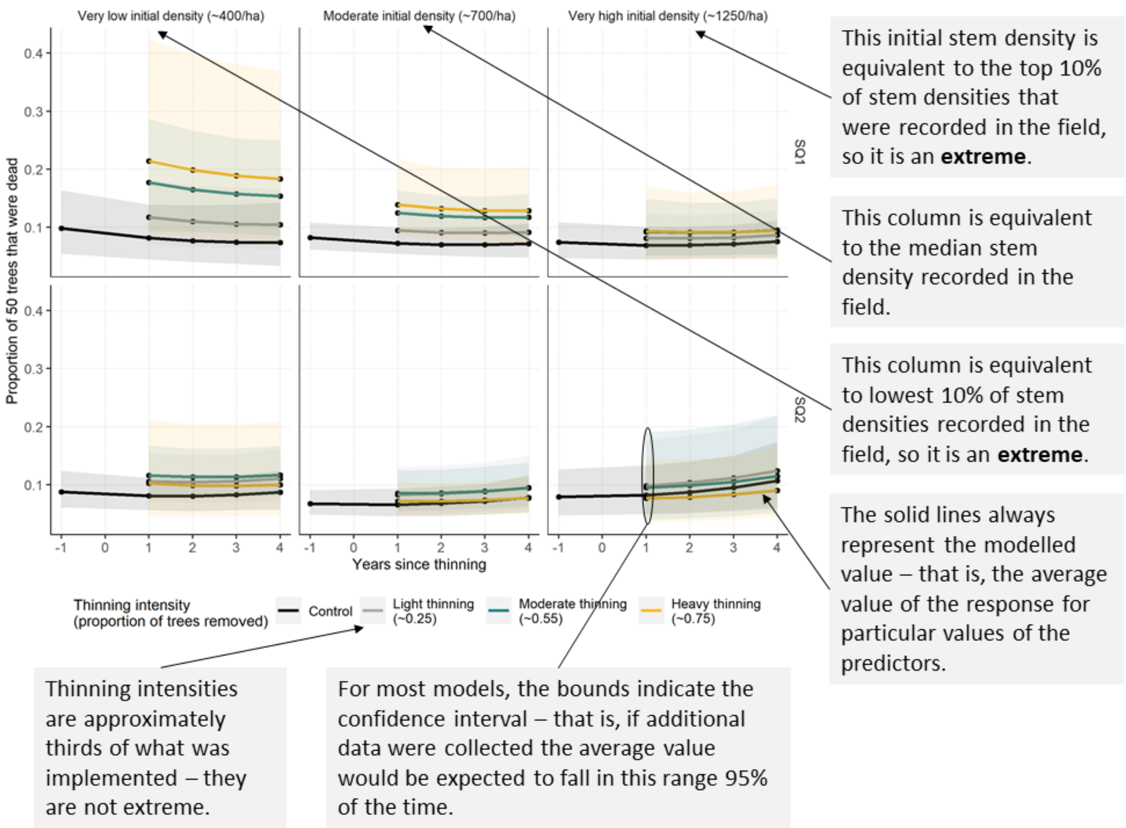

Figure 12 Explanation of model results figure

Note that the figures and text descriptions are on the scale of the response variable, unless stated otherwise. A statistically significant effect may not appear so in the figure, with confidence intervals overlapping all means, particularly where there was a significant interaction but no significant main effects.

Assessing magnitude of effects

It may be difficult to determine the exact magnitude of difference between the value of the response variable in control and thinned plots from the model results figure. The exact differences are presented in an effect size table for 5 years post-thinning (the most recent survey year) only (Figure 13). In cases where the confidence interval for thinned plots does not include the fitted value for control plots, it is likely that there has been an effect of thinning. This is indicated by both the interval values being either positive or negative.

Site quality		Site Quality 1			Site Quality 2		
Initial stem density		400/ha	700/ha	1250/ha	400/ha	700/ha	1250/ha
Thinning intensity	Low intensity	+1.5 +0.1 to +3.0	+1.4 +0.3 to +2.4	+1.2 0.0 to +2.5	+0.4 -0.8 to +1.7	+0.5 -1.1 to +2.1	+0.7 -1.2 to +2.6
	Mod intensity	+2.2 +0.3 to +4.2	+1.8 +0.8 to +2.8	+1.5 -0.1 to +3.1	+1.1 0.0 to +2.3	+1.5 +0.2 to +2.7	+1.8 -0.5 to +4.2
	High intensity	+1.7 -1.4 to +4.7	+1.2 -0.6 to +2.9	+0.7 -1.9 to +3.3	+1.7 -1.0 to +4.3	+2.2 +0.9 to +3.4	+2.6 +0.4 to +4.9

For each level of site quality and initial stem density, this is the **difference** between the modelled value of the response variable on **control plots** and the modelled value of the response variable on **plots with different thinning intensities**.

This value is the difference between the modelled value of the response variable on control plots and the lower 95% prediction interval.

This value is the difference between the modelled value of the response variable on control plots and the upper 95% prediction interval.

When the range of predicted values on thinned plots does not include the modelled value for control plots, there is likely to be an effect of thinning and the cell is highlighted. **This is the case when BOTH UPPER AND LOWER predicted values are either positive or negative.**

These values are for FIVE YEARS post thinning – reflecting the most recent surveyed values. This may not be the year in which the greatest effect of thinning was likely to occur.

Figure 13 Explanation of effect size table

Data limitations

Using the available data for initial tree density and thinning intensity (proportion of trees removed) is likely to improve learning about the effects of ecological thinning. However, as the plots in each Site Quality class were not evenly distributed across the spectrums of initial tree density and thinning intensity, fewer datapoints were available for some combinations of Site Quality, initial tree density and thinning intensity. Consequently, model predictions for the following combinations were likely to have higher levels of uncertainty:

1. Control plots in Site Quality 1 with low tree density stands.
2. Low intensity thinning (<40% of trees removed) in stands with moderate to high initial tree density in Site Quality 2.

3. Results: Tree survival

3.1 Tree mortality

Hypothesis	1a. Ecological thinning will cause increased survival (decreased mortality) of retained trees.
Key result	Marginally significant ($p = 0.08$) effect of ecological thinning that **increased** tree mortality by 3–12% (1.5–6 additional dead trees out of 50) relative to control plots.

Data collection

Dead trees were defined as those with no live foliage and included ringbarked trees.

Tree survival was measured as the proportion of trees that were dead. In each 9-hectare treatment plot 50 trees with ≥10 centimetres diameter at breast height were assigned as either live or dead, along a north–south transect (the centre line in Figure 5). Tree survival was surveyed annually.

Data summary

Prior to ecological thinning, the proportion of dead trees was similar for all treatment types, averaging at about 9% of trees (Figure 14). Four (out of 66) 9-hectare plots had 20–30% dead trees prior to thinning.

Across all years and plots, the proportion of trees that were dead ranged from 0% to 56% (0 to 28 dead trees out of 50 trees, respectively), with an average of 10% (5 dead trees). Only 3 plots had rates of mortality over 30%. The proportion of dead trees showed little evidence of change over time (Figure 14). Mortality was highest in plots that had low initial densities (Figure 14).

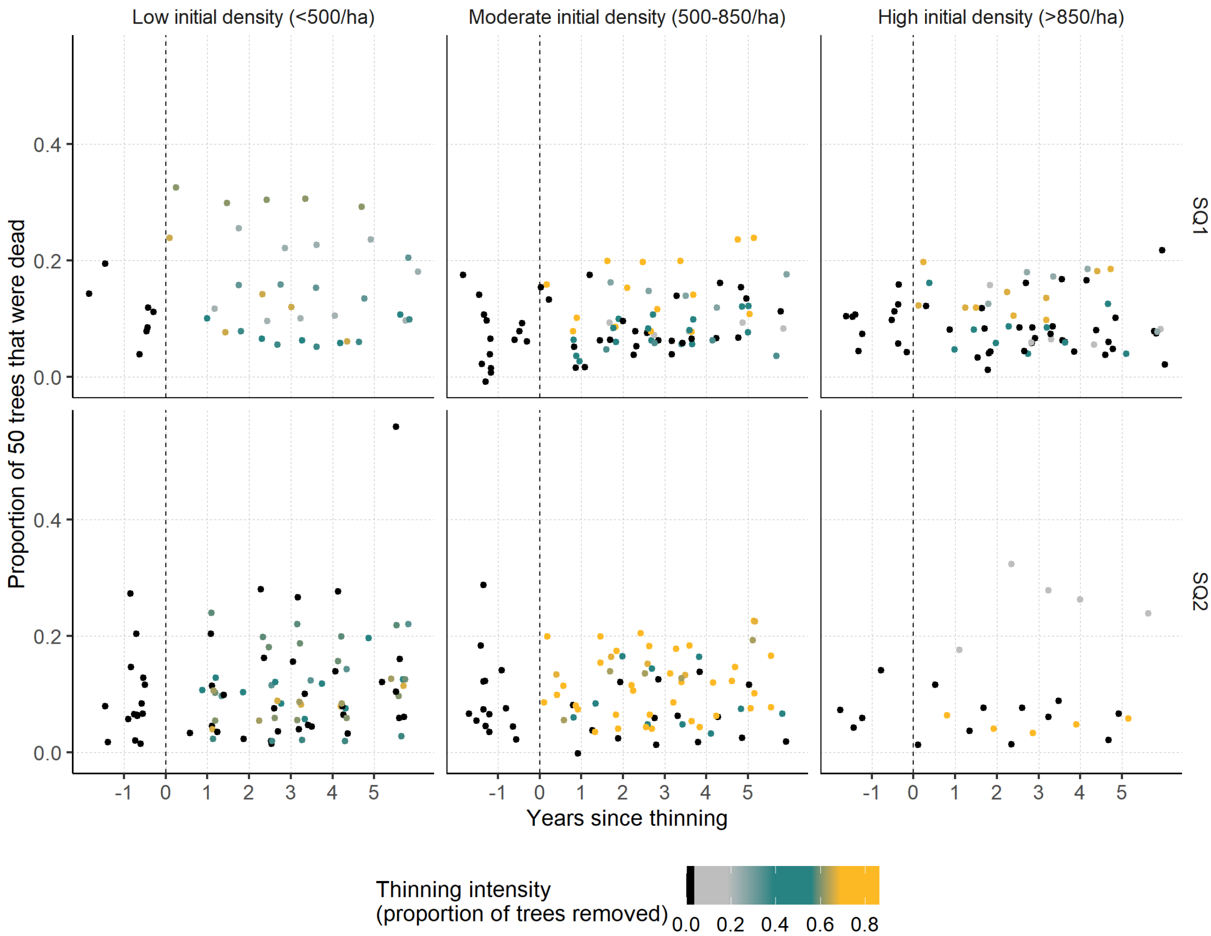

Figure 14 Data for proportion of 50 trees that were dead in each 9-hectare plot

Model results

Tree mortality was analysed as the proportion of trees that were dead using a binomial distribution (see Appendices). The model did not include four-way interaction between Site Quality, initial tree density, time since thinning and thinning intensity, or three-way interaction between initial tree density, time since thinning and thinning intensity, but included all other two-way and three-way interactions. Random effects of survey year, site and 9-hectare plot were included.

Modelled values of mortality in control plots were between 6 and 12% in all initial tree density and Site Quality combinations over time (Figure 15). There was a small increase in mortality over time, but this was not statistically significant (Table 6, Figure 15).

There was some evidence of an effect of thinning on tree mortality with thinned plots having higher proportions of dead trees (3–12% higher or 1.5 to 6 additional dead trees out of 50) compared to control plots (Figure 15, Table 7). However, the level of statistical significance was slightly higher than 5% for this effect (p = 0.08, Table 6).

The modelled effects of thinning on mortality were higher for wetter (SQ1) than drier (SQ2) plots but these were not statistically significantly different (Table 6, Figure 15). Any differences in the effect of thinning among initial tree densities and time since thinning were not statistically significant (Table 6).

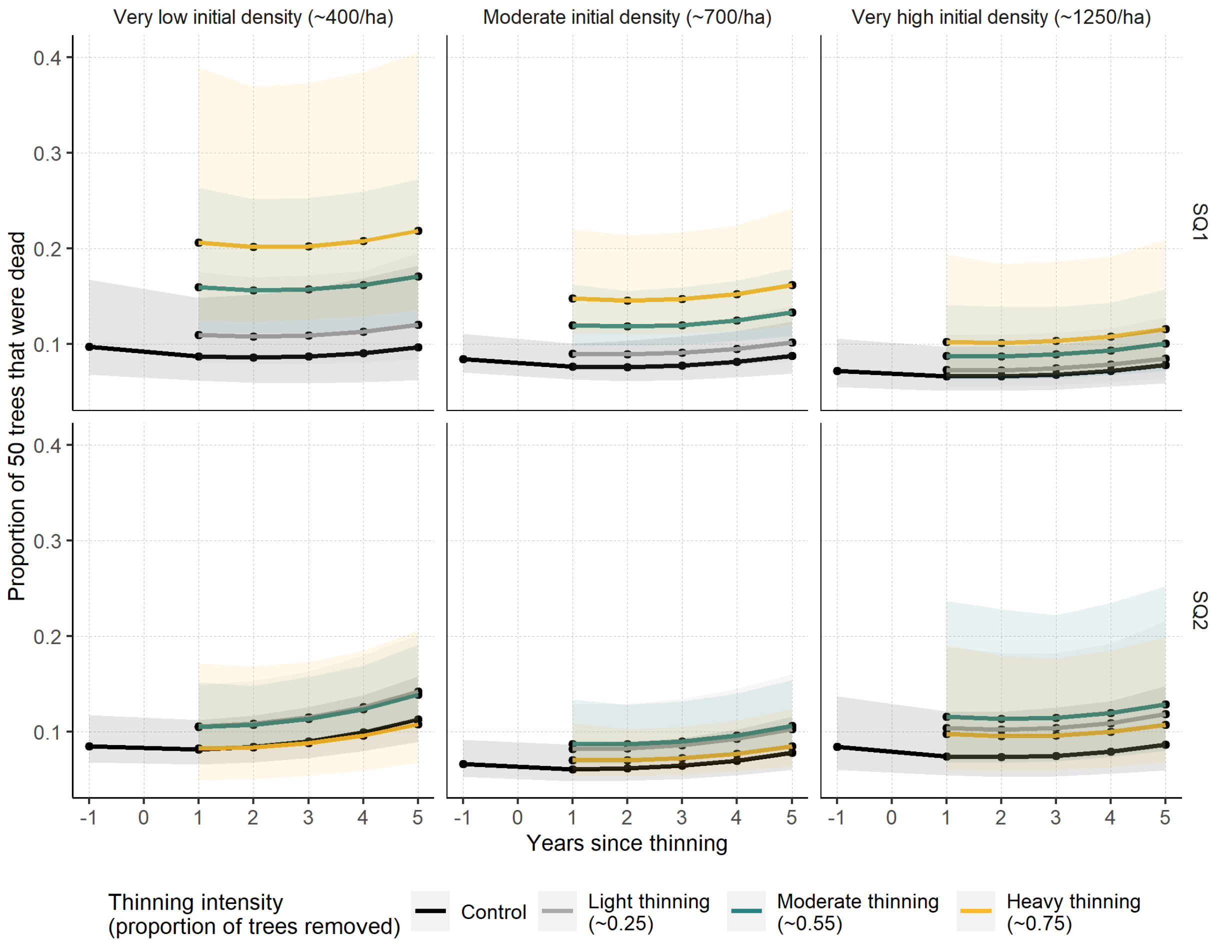

Figure 15 Modelled values and 95% confidence intervals for proportion of 50 trees that were dead in each 9-hectare plot

Table 6 Statistical significance of explanatory variables on tree mortality (proportion of trees that were dead)

	Bootstrapped likelihood ratio test significance	Description
Site Quality	0.62	Mortality did not differ among Site Qualities
Initial tree density	0.61	Mortality did not depend on initial tree density
Time since thinning	0.21	Mortality did not change over time
Thinning intensity	0.08	Mortality may have been affected by thinning intensity
Does the effect of thinning intensity vary depending on:		
• Site Quality	0.48	The effect of thinning on mortality did not depend on Site Quality
• Initial tree density	0.72	The effect of thinning on mortality did not depend on initial tree density

• Time since thinning	0.94	The effect of thinning on mortality did not change over time
• Site Quality **and** initial tree density **and** time since thinning	NA	Four-way interaction was not included in the model

Table 7 Estimated effect sizes for tree mortality (proportion of trees that were dead) 5 years post-thinning, showing difference between fitted values and 95% confidence intervals in thinned plots relative to control plots

Site Quality		Site Quality 1			Site Quality 2		
Thinning intensity		Low intensity	Mod intensity	High intensity	Low intensity	Mod intensity	High intensity
Initial tree density	Very low (400/ha)	+0.02 –0.02 to +0.09	+0.07 +0.02 to +0.17	+0.12 +0.04 to +0.31	+0.03 +0.003 to +0.09	+0.03 +0.002 to +0.08	0.00 –0.04 to +0.10
	Moderate (700/ha)	+0.01 –0.01 to +0.05	+0.04 +0.02 to + 0.09	+0.07 +0.03 to + 0.15	+0.02 –0.003 to +0.08	+0.03 +0.002 to +0.07	0.00 –0.02 to +0.04
	Very high (1250/ha)	+0.01 –0.02 to +0.05	+0.02 –0.01 to +0.08	+0.04 –0.004 to +0.13	+0.03 –0.01 to +0.13	+0.04 –0.01 to +0.16	+0.02 –0.02 to +0.11

Hypothesis evaluation

The hypothesis that thinning would increase survival of trees was not supported by the data. There was evidence that ecological thinning had an unexpected detrimental effect on tree survival rates. As data included trees of all sizes (greater than 10 centimetres dbh), more information is required to determine whether ecological thinning affected survival rates of particular sized trees. Below we analyse a separate dataset to determine whether ecological thinning affected mortality of large trees.

3.2 Large tree mortality

Hypothesis	1a (additional). Ecological thinning will cause increased survival (decreased mortality) of retained large trees.
Key result	**No evidence of an effect of ecological thinning on large tree mortality.**

Data collection

Large trees were defined as having a diameter at breast height of 80 centimetres or more. Dead large trees were defined as large trees with no live foliage and included ringbarked trees.

Large tree mortality was surveyed by assessing all large trees as live or dead in the central 2-hectare subplot in each 9-hectare plot (the 2-hectare plot in Figure 5).

Large trees were surveyed in 2015–16 prior to thinning; in 2017–18 one year post-thinning; and in 2021–22 five years post-thinning.

Data summary

Across all years and subplots, the total number of large trees ranged from 1 to 78, averaging 25, with the proportion of these trees that were dead ranging from 0 to 100%, with an average of 30%. The proportion of large dead trees appeared to decrease slightly over time (Figure 16).

Prior to ecological thinning, the proportion of large dead trees was higher in drier (SQ2) than wetter (SQ1) plots with moderate and high initial tree densities (Figure 16). In Site Quality 1, 50% or more of the total number of large trees were dead in only 3 (out of 33) 2-hectare subplots, whereas in Site Quality 2 this was 12 (out of 33). Prior to thinning, the total number of large trees in each subplot differed, ranging from 2 to 72, averaging 19 large trees.

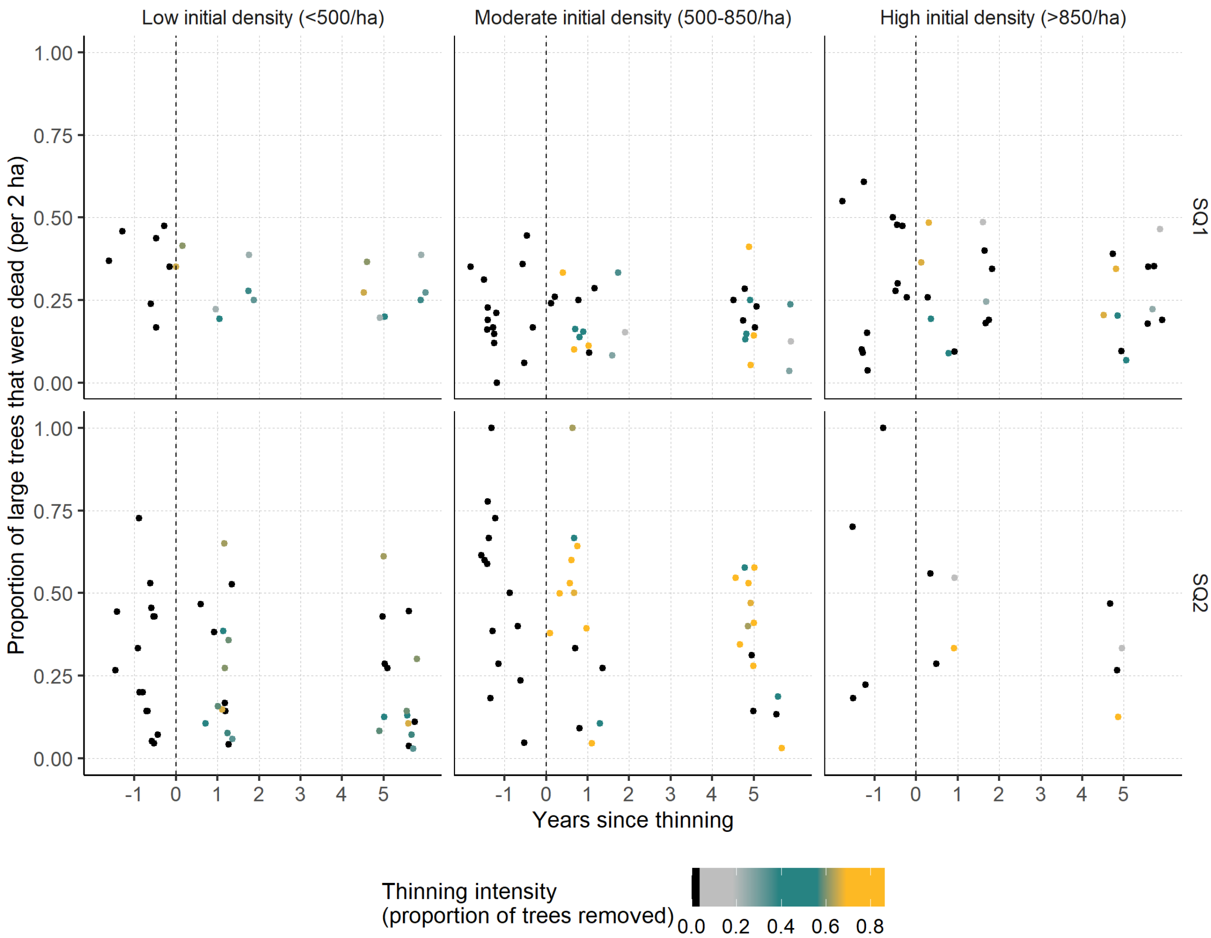

Figure 16 Data for proportion of large trees that were dead in each 2-hectare subplot

Model results

Large tree mortality was analysed as the proportion of large trees that were dead (see Appendices). The model did not include four-way interaction between Site Quality, initial tree density, time since thinning and thinning intensity, or three-way interaction between initial tree density, time since thinning and thinning intensity, but included all other two-way and three-way interactions. There was large variation in the total number of large trees within each 2-hectare subplot (10–78 trees), which was accounted for in the model by using a binomial distribution which weights the total number of trees when considering the number of dead trees. Random effects of year, site and 9-hectare plot were included.

Modelled average values of large tree mortality in control plots were between 22 and 46% in all initial tree density and Site Quality combinations over time. Generally, large tree mortality was greater in drier (SQ2) than wetter (SQ1) plots, although this was not statistically significant (Table 8, Figure 17). There was a decrease in large tree mortality over time, but this was not statistically significant (Table 8, Figure 17).

There was no evidence of an effect of thinning on large tree mortality in 2-hectare subplots with moderate initial tree density (Table 6, Table 8). There was some evidence of an effect of thinning in subplots with very low and very high initial density, but this was not statistically significant (Table 9, Figure 17).

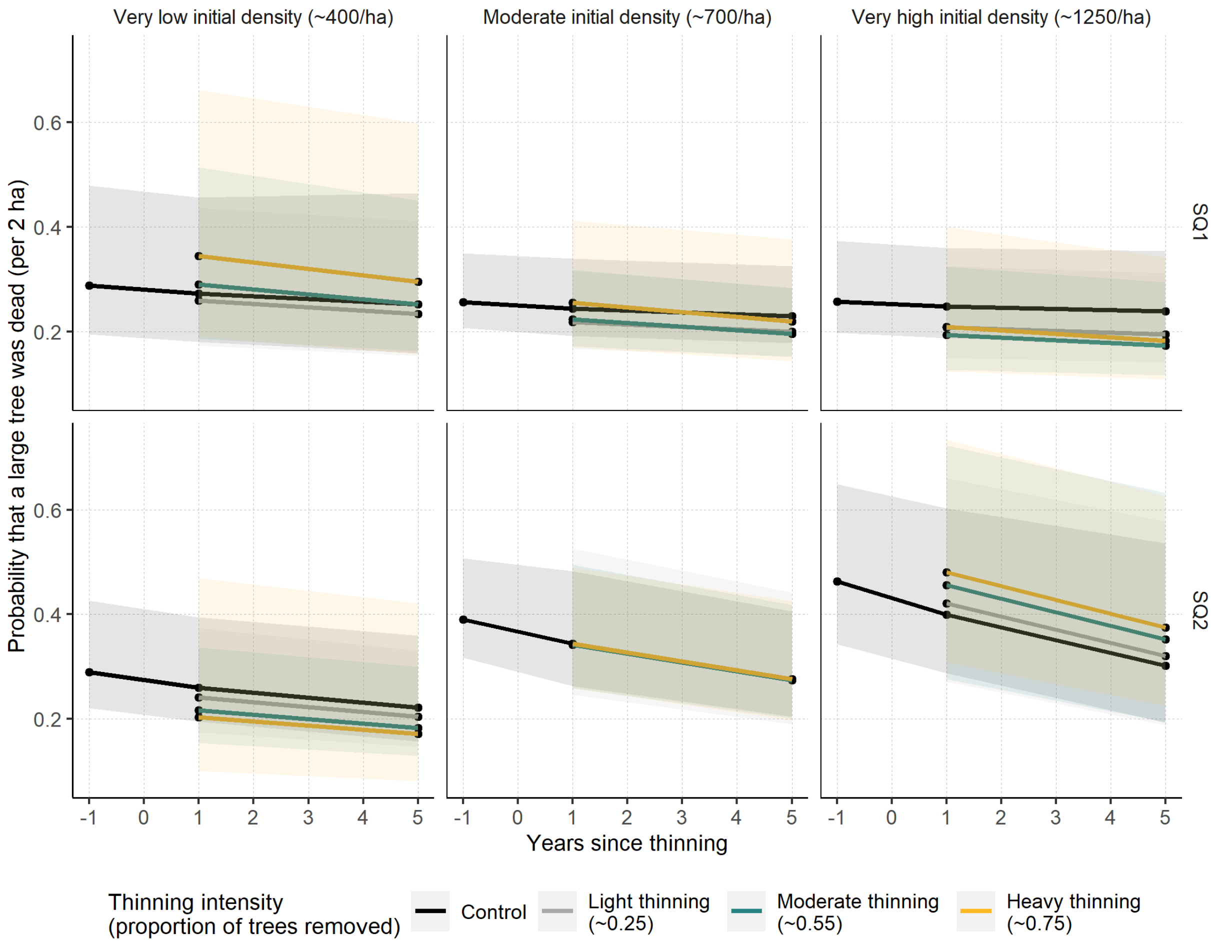

Figure 17 Modelled values and 95% confidence intervals for proportion of large trees that were dead in each 2-hectare subplot

Table 8 Statistical significance of explanatory variables on large tree mortality (proportion of large trees that were dead)

	Bootstrapped likelihood ratio test significance	Description
Site Quality	0.59	Large tree mortality did not differ among Site Qualities
Initial tree density	0.83	Large tree mortality did not depend on initial tree density
Time since thinning	0.47	Large tree mortality did not change over time
Thinning intensity	0.95	Large tree mortality was not affected by thinning intensity
Does the effect of thinning intensity vary depending on:		
• Site Quality	1.00	The effect of thinning on large tree mortality did not depend on Site Quality
• Initial tree density	0.49	The effect of thinning on large tree mortality did not depend on initial tree density
• Time since thinning	0.89	The effect of thinning on large tree mortality did not change over time
• Site Quality **and** initial tree density **and** time since thinning	NA	Four-way interaction was not included in the model

Table 9 Estimated effect sizes for large tree mortality (proportion of large trees that were dead) 5 years post-thinning, showing difference between fitted values and 95% confidence intervals in thinned plots relative to control plots

Site Quality		Site Quality 1			Site Quality 2		
Thinning intensity		Low intensity	Mod intensity	High intensity	Low intensity	Mod intensity	High intensity
Initial tree density	Very low (400/ha)	–0.02 –0.10 to +0.16	0.00 –0.09 to +0.20	+0.05 –0.09 to +0.35	–0.02 –0.07 to +0.11	–0.04 –0.09 to +0.08	–0.05 –0.14 to +0.20
	Moderate (700/ha)	–0.03 –0.08 to +0.05	–0.03 –0.08 to +0.05	–0.01 –0.09 to +0.15	–0.01 –0.09 to +0.16	–0.01 –0.08 to +0.14	0.00 –0.08 to +0.15
	Very high (1250/ha)	–0.05 –0.10 to +0.07	–0.07 –0.12 to +0.05	–0.06 –0.13 to +0.10	+0.02 –0.11 to +0.28	+0.05 –0.11 to +0.33	+0.08 –0.08 to +0.33

Hypothesis evaluation

The hypothesis that ecological thinning would improve survival of large trees was not supported by the data. However, there was no evidence that ecological thinning had a detrimental effect on survival of large trees.

4. Results: Tree growth

4.1 Tree diameter growth rates

Hypothesis	1a. Ecological thinning will increase growth rates of retained trees.
Key result	Ecological thinning: • **Increased** the growth rates of trees that were 200 millimetres diameter at breast height prior to thinning by approximately 1 to 3 millimetres per year relative to controls 5 years post-thinning • **Decreased** the growth rates of trees that were 1000 millimetres diameter at breast height prior to thinning by approximately –1 to –4 millimetres per year relative to controls 5 years post-thinning.

Data collection

Within each 9-hectare treatment plot, 30 trees that were >100 millimetres diameter at breast height were randomly selected along a north–south transect in the centre of the plot (the centre line in Figure 5). These 30 trees were permanently marked and surveyed for diameter at breast height to the nearest millimetre each survey. A single observer conducted all measurements on all surveys.

Tree diameter growth rates were measured annually, over 6 survey years.

Out of 1,980 permanently marked trees, 20 died since the 2015–16 surveys. Replacement trees were selected that were a similar diameter to the dead trees. Replacement trees were included in these analyses.

The average annual growth rate (millimetres per year) was calculated for each tree from change in diameter at breast height between the first observation date (this was in 2015–16, prior to ecological thinning, for all trees except the replacement trees) until the most recent observation date (in 2021–22). For multi-stemmed trees, the total diameter was calculated by taking the square root of the sum of each diameter squared. Trees with a differing number of stems between years were excluded from analyses.

Data summary

In wetter (SQ1) plots growth rates typically ranged from 0 to 10 millimetres per year, with an average of 4.7 millimetres per year (Figure 18). In drier (SQ2) plots, growth rates tended to be lower, with a typical range of 0 to 8 millimetres per year, and an average of 3.2 millimetres per year. Growth rates between 10 and 25 millimetres per year were most often recorded for smaller trees (Figure 19). Negative growth rates were most often recorded on larger trees, primarily due to bark loss.

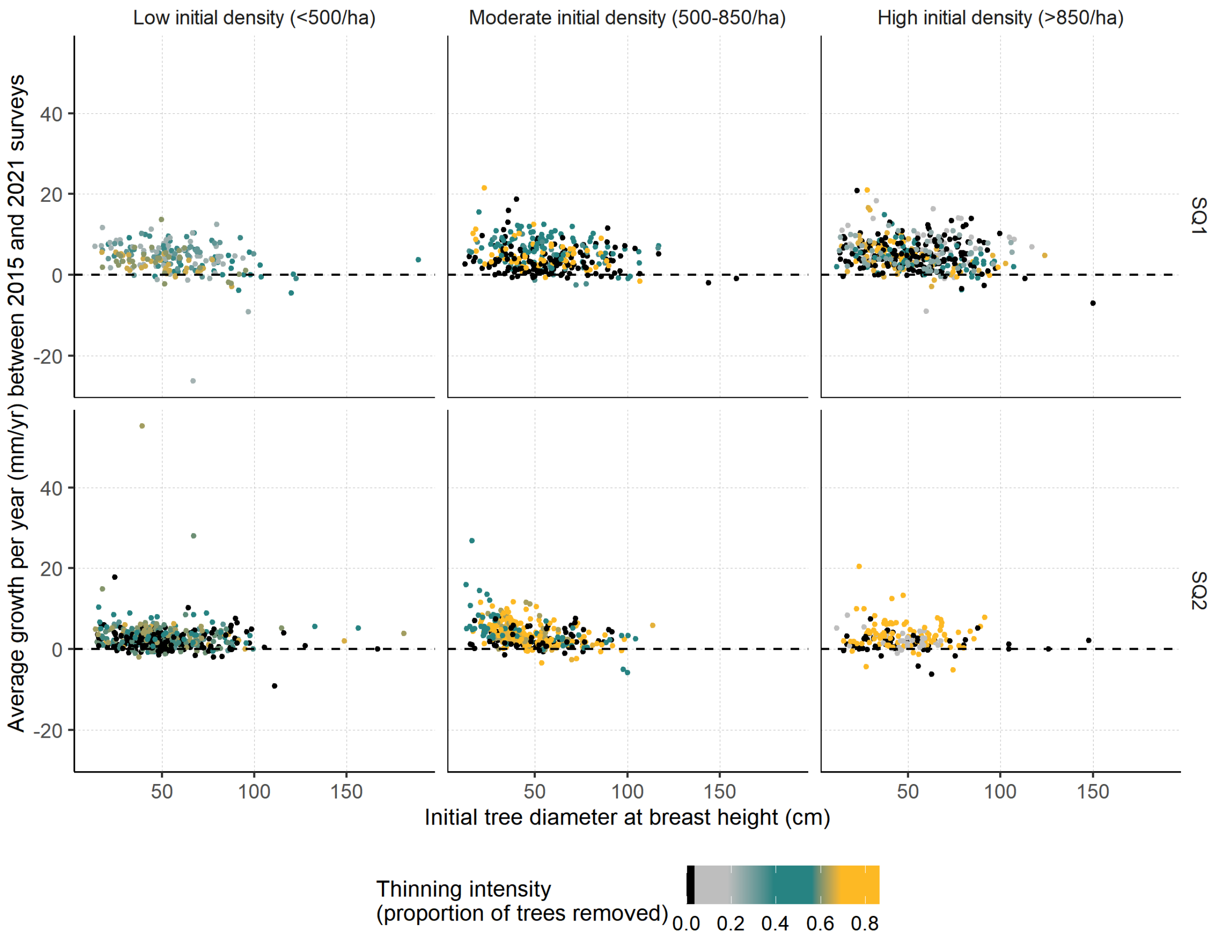

Figure 18 Data summary for average tree growth per year (millimetres per year) between first measurement (predominantly 2015–16 pre-thinning) and 2021–22 survey dates

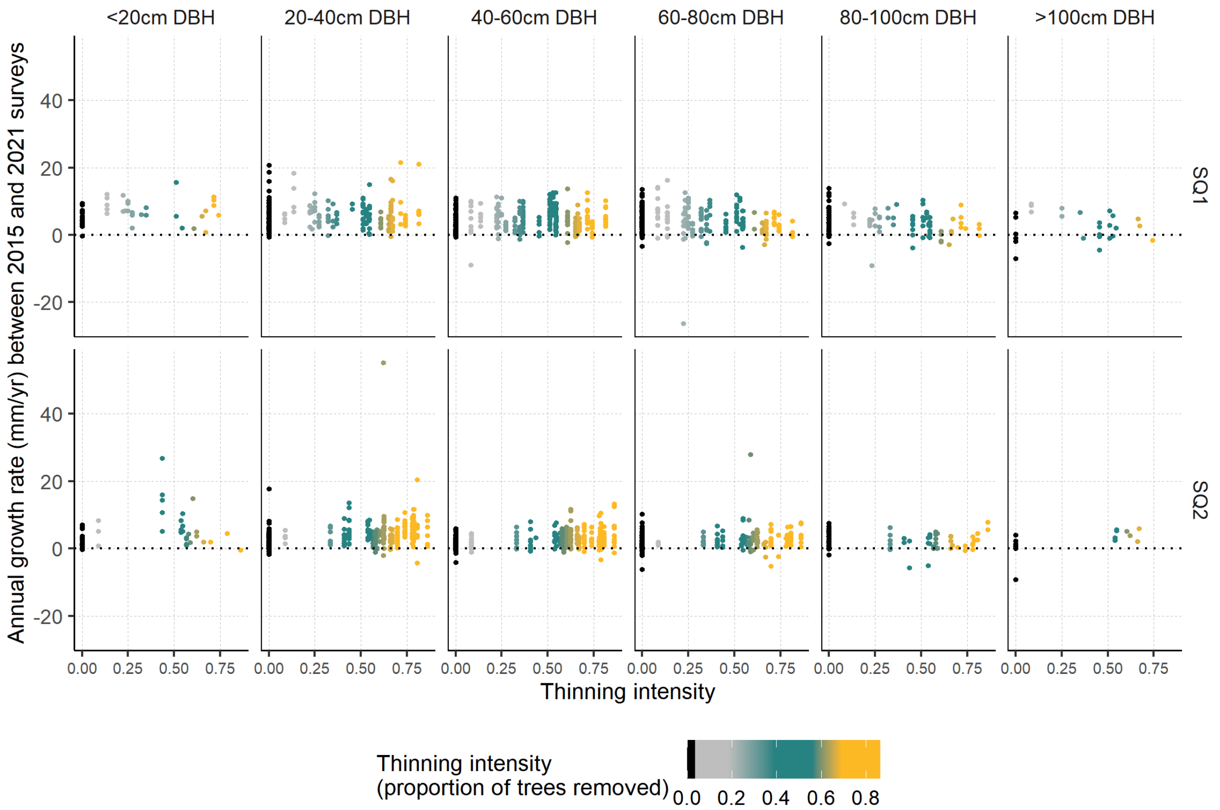

Figure 19 Data for tree annual growth rates by thinning intensity, by tree size class and Site Quality

Model results

Annual tree growth was modelled using a Gaussian distribution with 2 outliers removed: one value of –26 millimetres per year; and one value of 55 millimetres per year (see Appendices). The predictors in the model were initial diameter at breast height of the tree, initial tree density of the 9-hectare plot, thinning intensity and Site Quality. A four-way interaction between all predictors was not included, but all other two- and three-way interactions were included. Random effects of site and 9-hectare plot were included.

Independent of ecological thinning, there was evidence that annual growth rate was higher in wetter (SQ1) sites than drier (SQ2) sites. Further, growth rate varied with initial tree density in a way that differed among Site Qualities (Figure 20, Table 10).

There was evidence that ecological thinning had a significant impact on annual tree growth rates, but the effect of thinning differed for trees of different sizes (Figure 20, Table 10). The effect on small trees was to increase the growth rate (Figure 20). For example, the growth rates of trees 200 millimetres diameter at breast height increased by approximately 1.1 to 4.5 millimetres per year (Table 11). The effect on large trees was to decrease the growth rate. However, this was only statistically significant for wetter (SQ1) plots with moderate initial tree density for which the growth rates of trees 1,000 millimetres diameter at breast height decreased by –2.5 millimetres per year (Table 12).

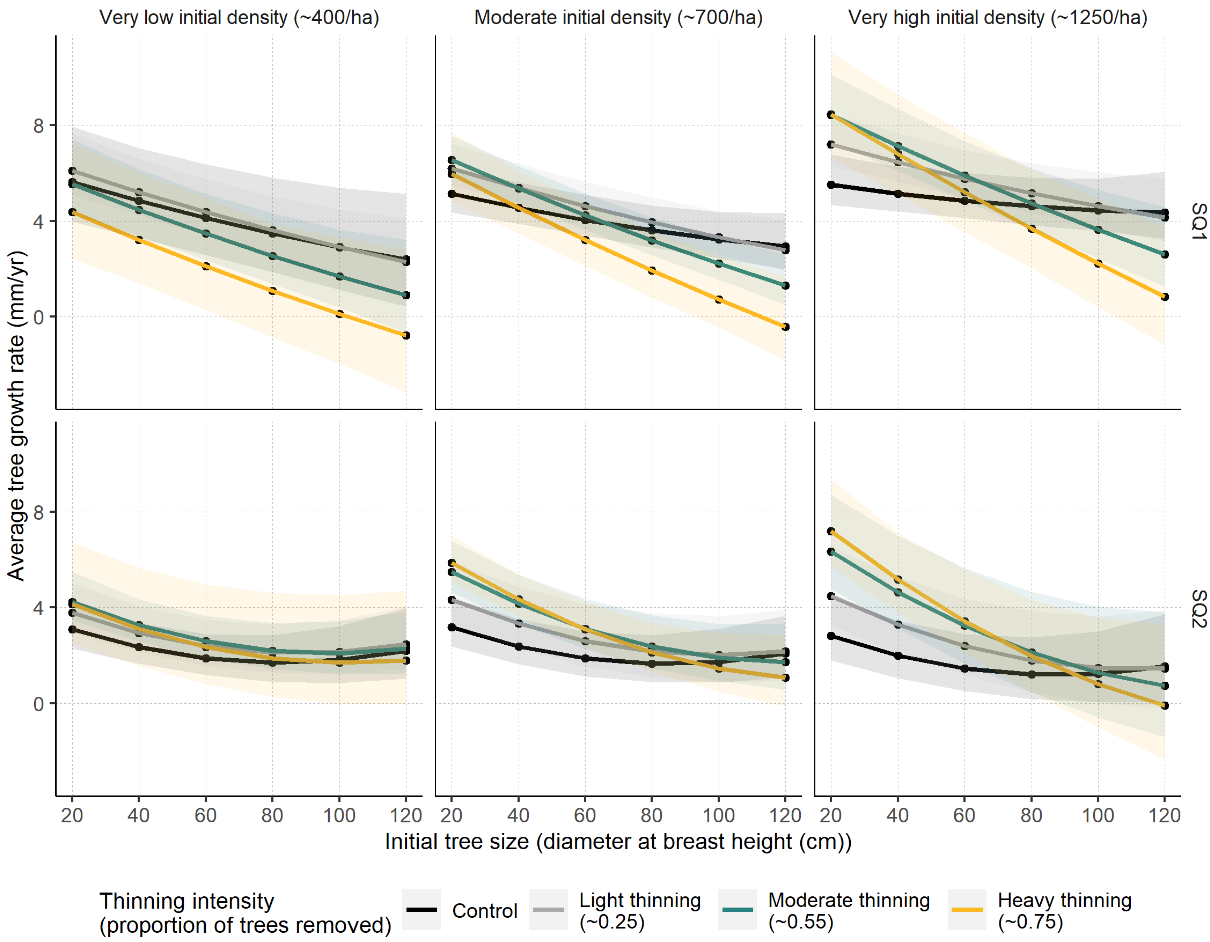

Figure 20 Modelled values and 95% confidence intervals for annual tree growth rates in relation to initial tree size

Table 10 Statistical significance of explanatory variables on average annual tree growth

	Bootstrapped likelihood ratio test significance	Description
Site Quality	0.01	Annual tree growth varied between Site Qualities
Initial tree density	0.25	Annual tree growth did not depend on initial tree density
Initial tree diameter	0.01	Annual tree growth varied with initial tree diameter
Thinning intensity	0.01	Ecological thinning had a significant effect on annual tree growth
Does the effect of thinning intensity vary depending on:		
• Site Quality	0.39	The effect of ecological thinning did not depend on Site Quality
• Initial tree density	0.18	The effect of ecological thinning did not depend on initial tree density

	Bootstrapped likelihood ratio test significance	Description
• Initial tree diameter	0.01	The effect of ecological thinning depended on initial tree size
• Site Quality **and** initial tree density **and** initial tree diameter	Not modelled	

Table 11 Estimated effect sizes post-thinning of annual tree growth rates for trees that were 200 mm diameter at breast height at first measurement, showing difference between fitted values and 95% confidence intervals in thinned plots relative to control plots

Site Quality		Site Quality 1			Site Quality 2		
Thinning intensity		Low intensity	Mod intensity	High intensity	Low intensity	Mod intensity	High intensity
Initial tree density	Very low (400/ha)	+0.5 –0.6 to +2.0	–0.1 –1.3 to +1.8	–1.3 –3.2 to +1.6	+0.7 –0.1 to +2.1	+1.1 +0.4 to +2.4	+1.1 –0.6 to +3.6
	Moderate (700/ha)	+1.1 +0.4 to +2.1	+1.4 +0.7 to +2.4	+0.8 –0.3 to +2.6	+1.2 +0.1 to +2.7	+2.3 +1.5 to +3.6	+2.7 +1.9 to +3.8
	Very high (1250/ha)	+1.7 +0.8 to +2.9	+2.9 +1.8 to +4.6	+2.9 +1.2 to +5.5	+1.6 +0.4 to +3.7	+3.5 +2.0 to +5.9	+4.4 +2.9 to +6.5

Table 12 Estimated effect sizes of tree growth rates for trees that were 1000 mm diameter at breast height prior at first measurement, showing difference between fitted values and 95% confidence intervals in thinned plots relative to control plots

Site Quality		Site Quality 1			Site Quality 2		
Thinning intensity		Low intensity	Mod intensity	High intensity	Low intensity	Mod intensity	High intensity
Initial tree density	Very low (400/ha)	0.0 –1.1 to +1.6	–1.2 –2.5 to +0.7	–2.8 –4.9 to +0.4	+0.3 –0.6 to +1.7	+0.3 –0.6 to +1.6	–0.1 –1.8 to +2.7
	Moderate (700/ha)	+0.1 –0.6 to +1.2	–1.0 –1.7 to +0.1	–2.5 –3.7 to –0.7	+0.3 –0.8 to +1.9	+0.2 –0.8 to +1.6	–0.3 –1.2 to +1.2
	Very high (1250/ha)	+0.2 –0.7 to +1.6	–0.8 –2.0 to +0.8	–2.2 –4.0 to +0.4	+0.2 –1.2 to +2.4	0.0 –1.8 to +2.8	–0.4 –2.3 to +2.3

Hypothesis evaluation

The hypothesis was partially supported by the data, as there was evidence that growth rates of smaller trees increased where initial tree density was moderate to very high. However, there was evidence that the growth rates of larger trees declined as a result of ecological thinning, which may be detrimental to the recruitment of additional large and hollow-bearing trees in river red gum forests.

4.2 Tree height growth rates

Hypothesis	1a. Ecological thinning will increase growth rates of retained trees.
Key result	Ecological thinning **increased** average tree height by 2.5–5 metres relative to controls 5 years post-thinning.

Data collection

In the 2020–21 and 2021–22 monitoring surveys, the height of all trees in each three 0.04-hectare subplots per 9-hectare plot (see 20 x 20 metre subplots in Figure 5) were measured to the nearest 10 centimetres using a laser hypsometer. Saplings in the midstorey stratum (with at least a 3 metre gap between the top of their tree canopy and the bottom of the upper stratum canopy) were not included. Where more than 10 trees occurred in a 0.04-hectare subplot, 10 trees were measured that represented the range of tree heights present. In 2021–22, 15% of 0.04-hectare subplots were not able to be surveyed due to flooding.

Data summary

Tree height was between approximately 8 and 38 metres in wetter (SQ1) plots and was between approximately 5 and 30 metres in drier (SQ2) sites (Figure 21).

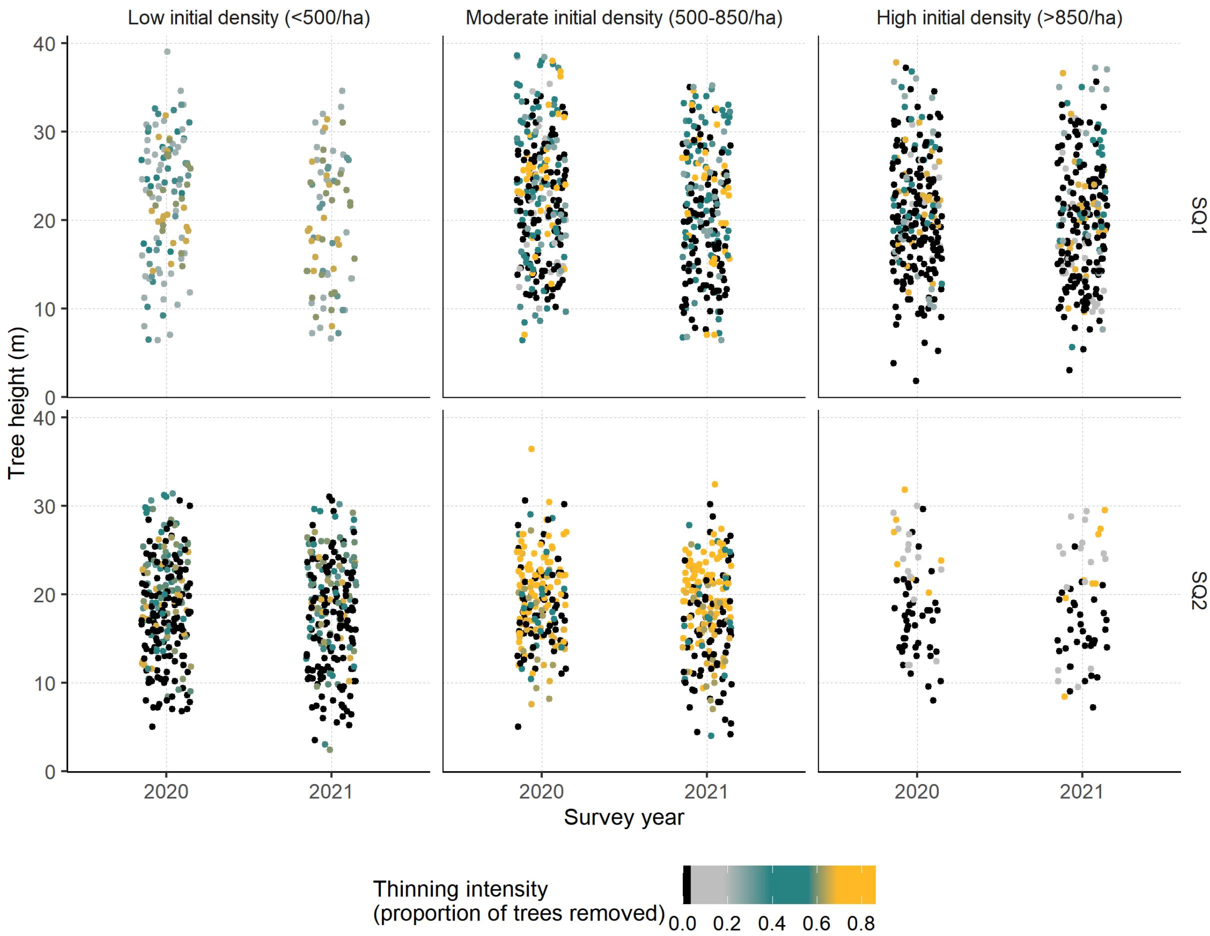

Figure 21 Data for tree height (in metres) by survey year

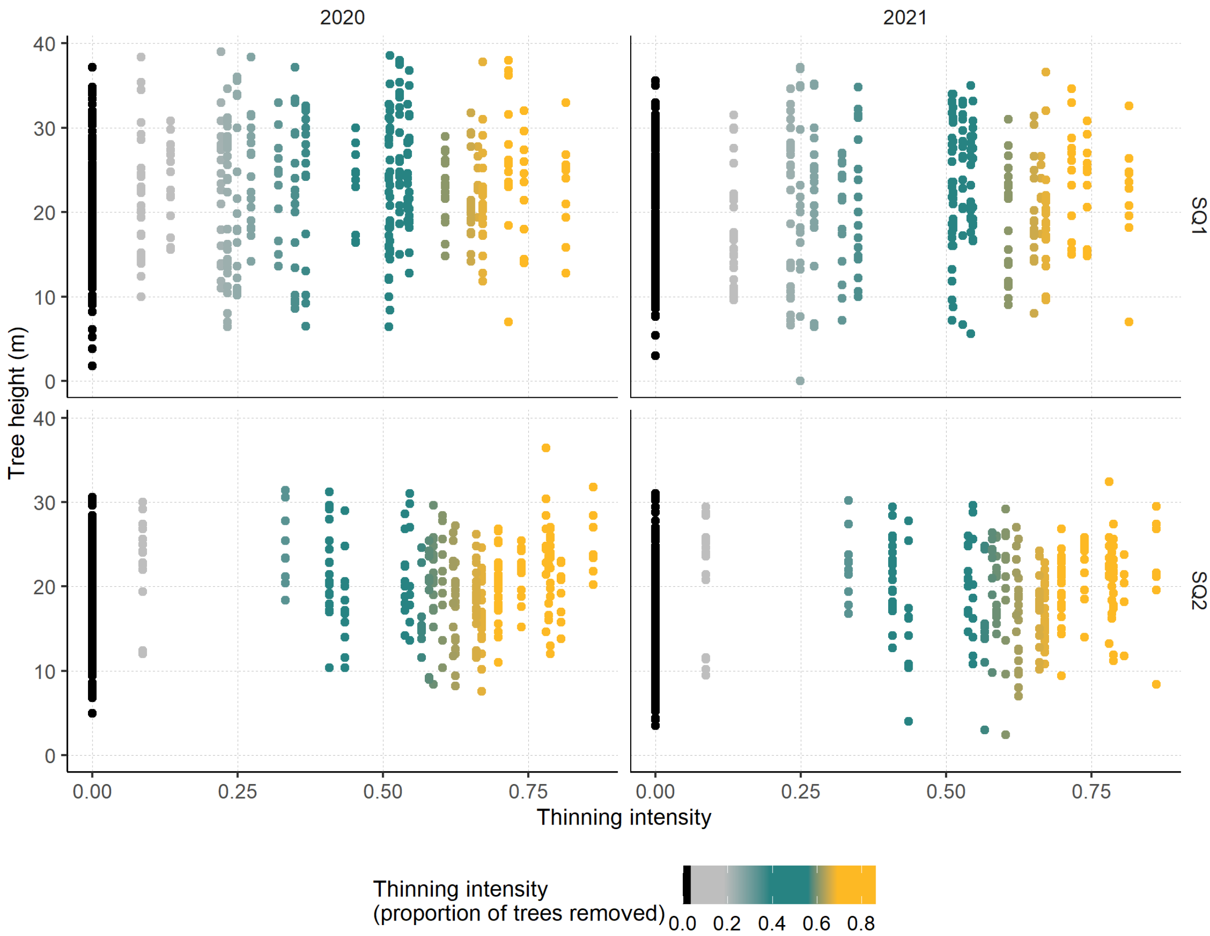

Figure 22 Data for individual tree height, not including information about initial tree density

Model results

Tree height was modelled using a Gaussian distribution (see Appendices). The model for tree height did not include four-way interaction between Site Quality, initial tree density, time since thinning and thinning intensity, but included all two-way and three-way interactions. Random effects of 9-hectare plot and subplot were included to account for spatial autocorrelation and repeat sampling.

In the absence of ecological thinning, tree height differed between Site Qualities (Table 14, Figure 23), with average tree heights of 18.5–24.3 metres and 16.1–22.6 metres in Site Quality 1 and 2 respectively. Tree height did not vary with initial tree density but generally declined slightly over time. This may be due to the inclusion of more shorter trees in the upper stratum in 2021–22.

There was evidence that ecological thinning increased average tree height by approximately 2.5 to 6.2 metres (Table 14), and that this effect was statistically significant (Table 13). Variations in the effect of thinning among in different Site Quality and initial tree density conditions were not statistically significant, and the effect did not change over time.

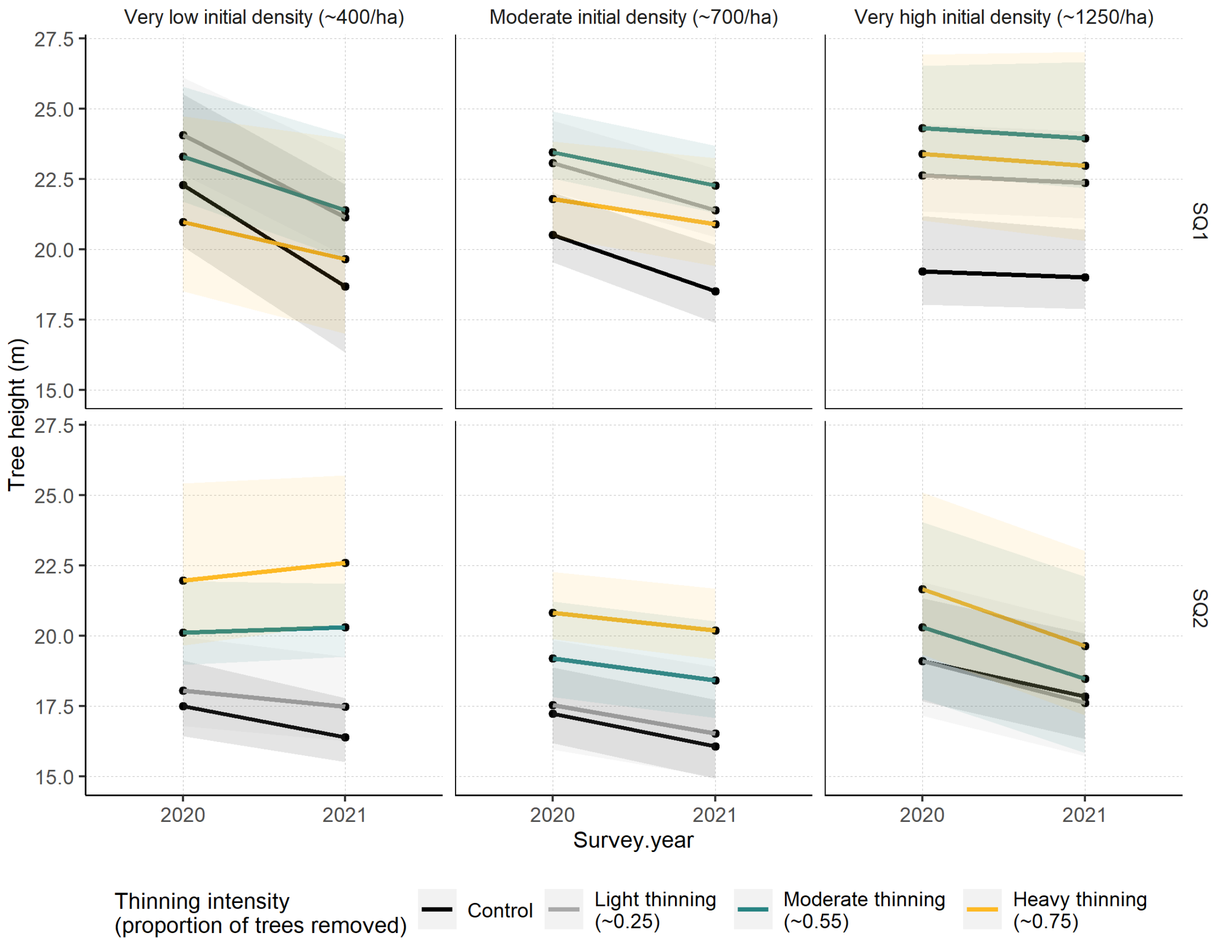

Figure 23 Modelled values and confidence intervals for average tree height

Table 13 Statistical significance of explanatory variables on tree height

	Bootstrapped likelihood ratio test significance	Description
Site Quality	0.01	Tree height differed among Site Qualities
Initial tree density	0.09	Tree height may have depended on initial tree density
Time since thinning	0.02	Tree height changed over time
Thinning intensity	0.01	Ecological thinning had a significant effect on tree height
Does the effect of thinning intensity vary depending on:		
• Site Quality	0.29	The effect of ecological thinning did not depend on Site Quality, initial tree density or time since thinning
• Initial tree density	0.30	
• Time since thinning	0.11	
• Site Quality **and** initial tree density **and** time since thinning	Not modelled	

Table 14 Estimated effect sizes for tree height, showing difference between fitted values and 95% confidence intervals in thinned plots relative to control plots

Site Quality		Site Quality 1			Site Quality 2		
Thinning intensity		Low intensity	Mod intensity	High intensity	Low intensity	Mod intensity	High intensity
Initial tree density	Very low (400/ha)	+2.5 +1.1 to +4.7	+2.7 +1.0 to +5.4	+1.0 –1.7 to +5.3	+1.1 –0.2 to +2.9	+3.9 +2.9 to +5.5	+6.2 +4.0 to +9.3
	Moderate (700/ha)	+2.9 +1.9 to +4.4	+3.8 +2.8 to +5.2	+2.4 +0.9 to +4.7	+0.5 –1.1 to +2.8	+2.4 +1.0 to +4.5	+4.1 +3.1 to +5.6
	Very high (1250/ha)	+3.4 +2.1 to +5.2	+4.9 +3.2 to +7.7	+4.0 +1.3 to +8.0	–0.2 –2.1 to +2.6	+0.6 –2.0 to +4.2	+1.8 –0.7 to +5.2

Hypothesis evaluation

The data provided evidence in support of this hypothesis, with ecological thinning causing increased tree height growth rates. The data included trees of all sizes, and it was not possible to determine whether changes in tree height vary with tree size.

5. Results: Tree size class structure

5.1 Count of large live trees

Hypothesis	1b. Ecological thinning will increase the number of trees occurring in large diameter size classes.
Key result	**No evidence of statistically significant effect of ecological thinning.**

Data collection

Large live trees were defined as trees that had a diameter at breast height of 80 centimetres or more and that have some live foliage.

All large live trees were counted in the central 2-hectare subplot in each 9-hectare plot (see Figure 5). Surveys were conducted prior to thinning in 2015–16, one year post-thinning in 2017–18 and 5 years post-thinning in 2021–22. The same observers conducted surveys in 2015–16 and 2017–18; different observers conducted the most recent surveys.

Data summary

Prior to ecological thinning the average number of large live trees within a 2-hectare subplot was 13 (range 0–60). Prior to thinning, the number of large live trees in Site Quality 1 subplots was greater than in Site Quality 2 subplots, averaging 18 and 9 trees respectively (Figure 24). The number of large live trees appeared to increase over time (Figure 24).

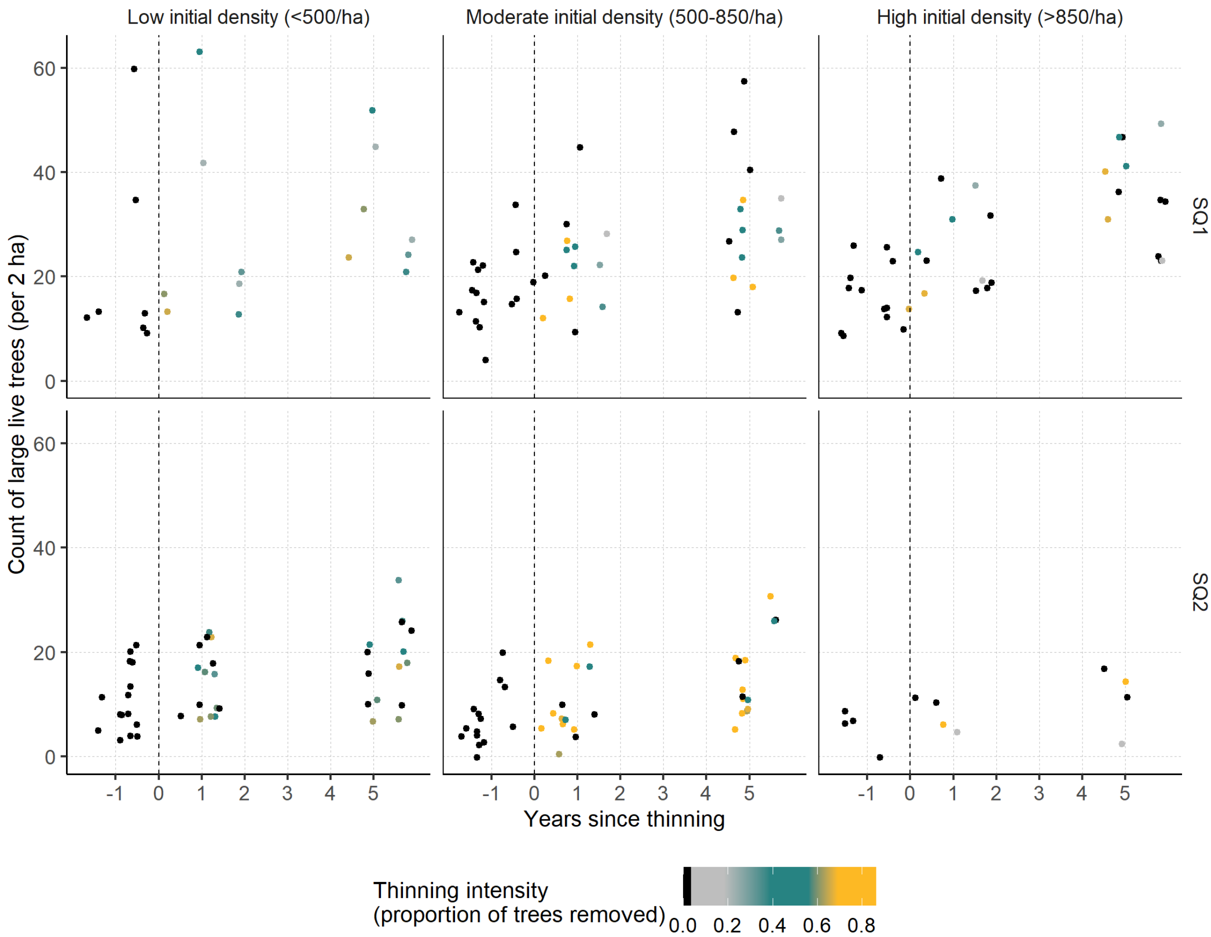

Figure 24 Data for count of large live trees per 2-hectare subplot

Model results

The number of large trees per 2-hectare subplot was modelled using a Poisson distribution (see Appendices). The model did not include four-way interaction between Site Quality, initial tree density, time since thinning and thinning intensity, or three-way interaction between initial tree density, time since thinning and thinning intensity, but included all other two-way and three-way interactions. Random effects for survey year, site and 9-hectare plot were included in the model.

In the absence of ecological thinning, the modelled values of average number of large live trees were significantly higher in wetter (SQ1) than drier (SQ2) plots (Table 15, Figure 25). The modelled values increased over time but did not vary with initial tree density.

In Site Quality 1, there was some evidence that ecological thinning reduced the number of large live trees, particularly in subplots with very low initial tree density (Figure 25), but this was not statistically significant (Table 15, Table 16). There was no evidence of an effect of thinning on the number of the large live trees in Site Quality 2 subplots (Table 6, Table 15, Table 16).

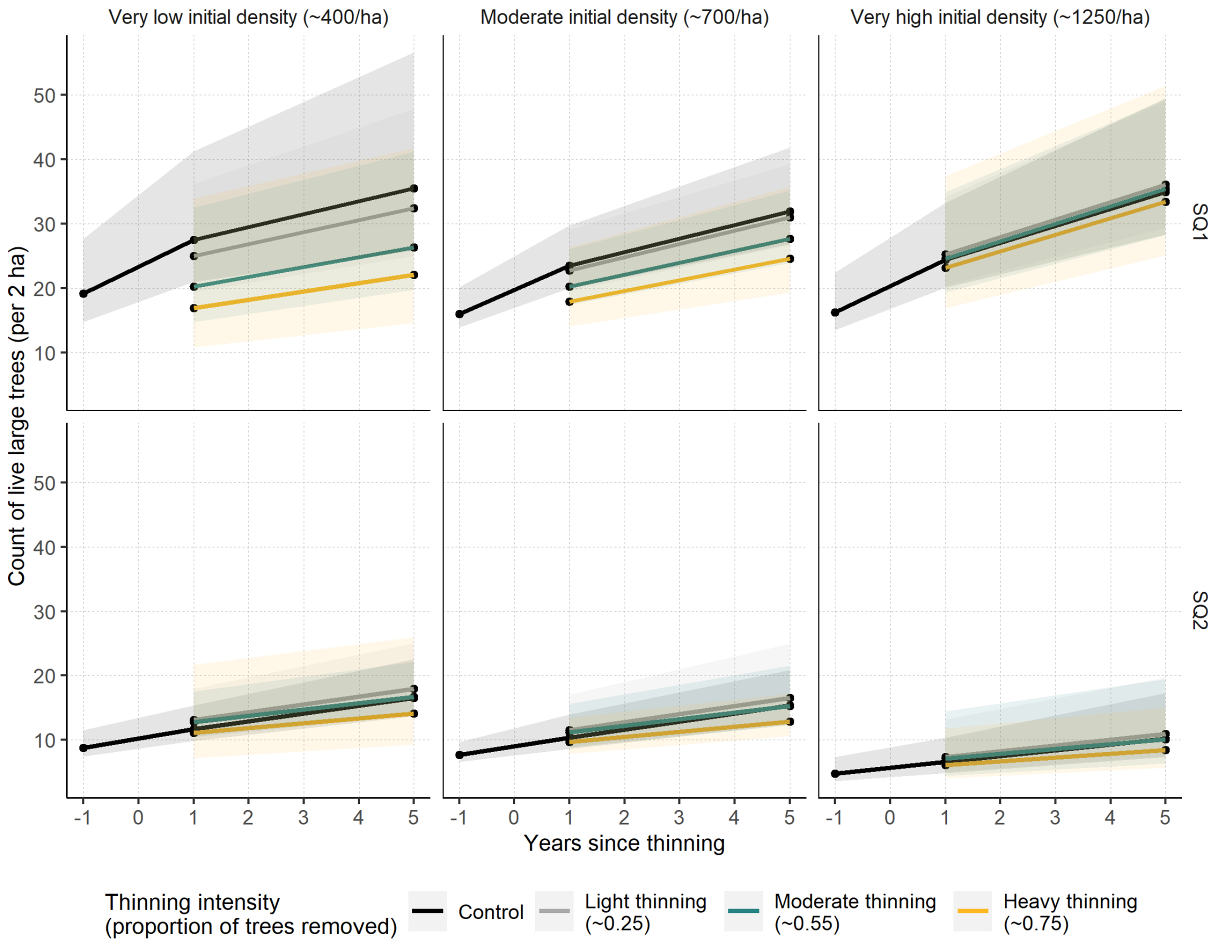

Figure 25 **Modelled values and 95% confidence intervals for count of large live trees per 2-hectare subplot**

Table 15 **Statistical significance of explanatory variables on count of large live trees per 2-hectare subplot**

	Bootstrapped likelihood ratio test significance	Description
Site Quality	0.01	The number of large live trees differed among Site Qualities
Initial tree density	0.18	The number of large live trees did not depend on initial tree density
Time since thinning	0.02	The number of large live trees changed over time
Thinning intensity	0.71	The number of large live trees was not affected by thinning intensity
Does the effect of thinning intensity vary depending on:		
• Site Quality	0.53	The effect of thinning on the number of large live trees did not depend on Site Quality

	Bootstrapped likelihood ratio test significance	Description
• Initial tree density	0.54	The effect of thinning on the number of large live trees did not depend on initial tree density
• Time since thinning	0.75	The effect of thinning on the number of large live trees did not change over time
• Site Quality **and** initial tree density **and** time since thinning	NA	Four-way interaction was not included in the model

Table 16 Estimated effect sizes for count of large live trees per 2-hectare subplot 5 years post-thinning, showing difference between fitted values and 95% confidence intervals in thinned plots relative to control plots

Site Quality		Site Quality 1			Site Quality 2		
Thinning intensity		Low intensity	Mod intensity	High intensity	Low intensity	Mod intensity	High intensity
Initial tree density	Very low (400/ha)	–3.1 –10.6 to +12.3	–9.2 –15.7 to +5.7	–13.5 –21.0 to +6.2	+1.4 –2.0 to +8.5	+0.1 –2.7 to +5.6	–2.4 –7.2 to +9.4
	Moderate (700/ha)	–0.9 –5.3 to +7.3	–4.3 –8.0 to +3.2	–7.4 –12.6 to +3.8	+1.2 –2.7 to +9.6	0.0 –3.1 to +6.2	–2.4 –4.8 to +1.9
	Very high (1250/ha)	+1.2 –5.5 to +14.1	+0.5 –6.7 to +14.3	–1.5 –9.8 to +16.6	+0.8 –2.8 to +9.5	–0.1 –3.8 to +9.3	–1.8 –4.5 to +4.8

Hypothesis evaluation

There was no evidence to support the hypothesis that ecological thinning increased the number of large trees within 5 years. In contrast, ecological thinning reduced the number of large live trees in some plot types, but the difference was not statistically significant from controls. Longer time frames are likely to be required to assess this hypothesis due to the long-lived nature of *Eucalyptus camaldulensis*.

5.2 Proportion of trees occurring in large diameter size classes

Hypothesis	1b. Ecological thinning will increase the proportion of trees occurring in large diameter size classes.
Key result	Ecological thinning initially **increased** the proportion of trees occurring in large diameter size classes due to the removal of small trees, however this effect diminished over time and was a maximum of 11% higher (per hectare) than control 5 years post-thinning.

Data collection

Tree size class distribution data were collected on ten 20 x 50 metre subplots per 9-hectare plot (see Figure 5).

In the pre-thinning surveys and immediate post-thinning surveys (in 2015–16 and 2016–17) tree density data was collected in ten 20 x 50 metre subplots in each 9-hectare plot, but the densities of trees <10 centimetres diameter at breast height were not included in 2 of the subplots. Densities of trees in this size class were scaled to be equivalent to sampling 10 subplots. Multi-stemmed trees were counted as individuals, in the size class of the largest tree at breast height.

In the 5-year post-thinning surveys (2021–22), each tree >1.37 metres in height was counted and allocated to a size class within each subplot. Multi-stemmed trees were counted as a single individual, with each tree allocated to a size class based on stem diameter at breast height, allowing calculation of both tree and stem density. Large multi-stemmed trees were defined as having at least one stem >80 centimetres dbh. Similarly, coppiced stems that were more than 1.37 metres in height were also counted as a single individual with each coppiced tree allocated to a size class.

Control plots were all surveyed twice: in 2015–16 and 2021–22.

Thirty-four (out of 44) thinned plots were surveyed 3 times: prior to thinning in 2015–16, immediately post-thinning in 2016–17 and 5 years post-thinning in 2021–22.

Ten (out of 44) thinned plots were surveyed immediately post-thinning in 2016–17 and 5 years post-thinning in 2021–22. In these plots, the width and height of each new stump was recorded and tapering equations were used to estimate pre-thinning densities.

Data summary – tree size

The total stem count per 0.1 hectare includes each individual stem in multi-stemmed trees and coppiced stumps/saplings as individuals. The highest densities (>150 per 0.1 hectare) of very small stems (<5 centimetres diameter at breast height) almost exclusively occurred in thinned plots (Figure 26). Densities of stems between 10 and 40 centimetres in diameter at breast height, which were removed during the thinning operations, were lower in thinned plots than control plots.

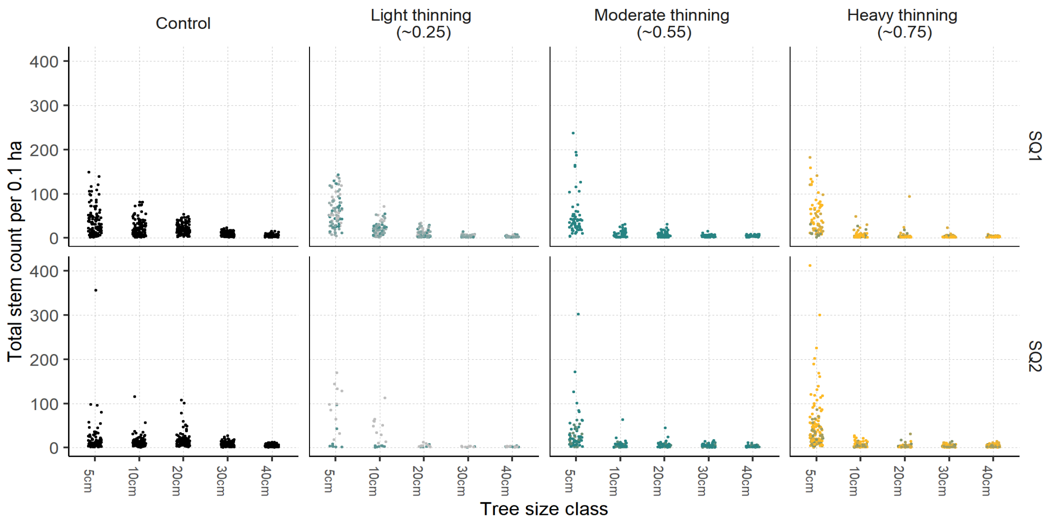

Figure 26 Data for tree density (per 0.1 hectare) in size classes that were modified by ecological thinning, including coppiced stems

Note that tree size classes are not equal. Labels on the x axis indicate the maximum diameter for each class. 2021–22 data only.

Densities of stems that were not affected by thinning operations (>40 centimetres diameter at breast height) were similar among control and thinned plots (Figure 27). The maximum number of stems of the larger size classes was 9 per 0.1 hectare. Smaller stems were more abundant than larger stems, with very few trees >100 centimetres diameter at breast height recorded.

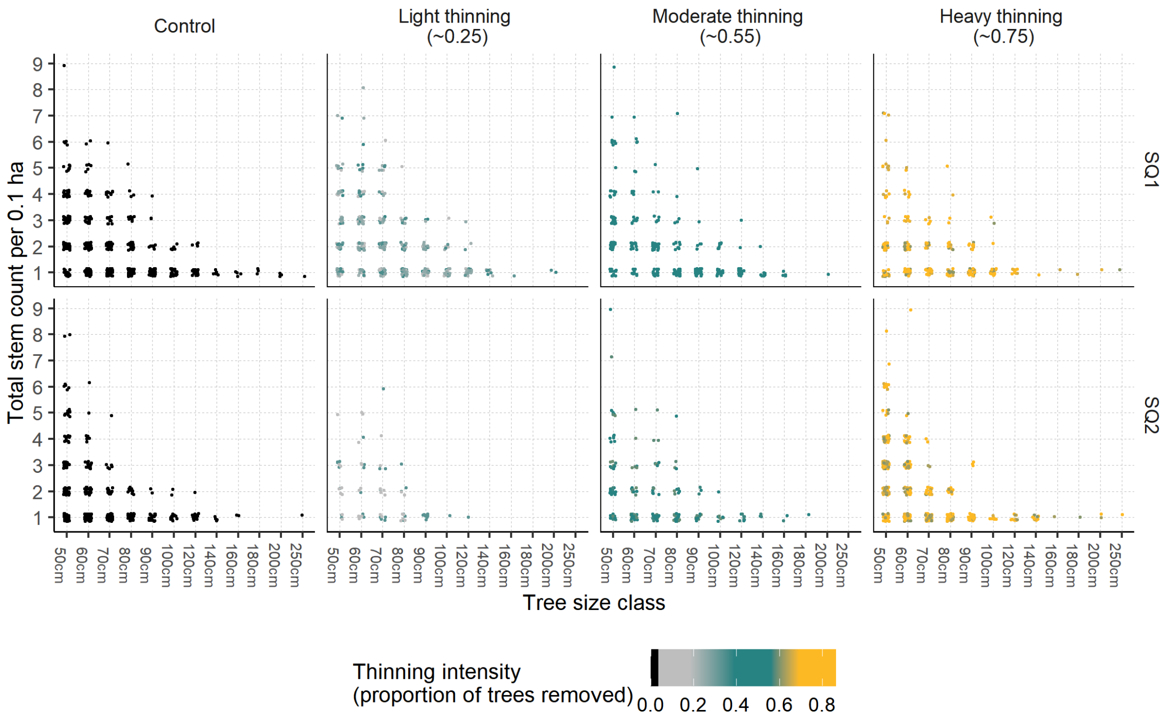

Figure 27 Data for tree density (per 0.1 hectares) in size classes that were not affected by ecological thinning.

Note that tree size classes are not equal. Labels on the x axis indicate the maximum diameter for each class. 2021–22 data only.

Data summary – proportion of trees that were large

Prior to thinning, the proportion of trees (that is, multi-stemmed trees counted as individuals) within a plot that were in large size classes ranged from 0 to 7.6%, averaging 2.0%. Prior to thinning, the proportion of trees that were in large size classes decreased with increasing initial tree density and was higher in wetter (SQ1) plots than drier (SQ2) plots (Figure 28).

Immediately following thinning, the proportion increased (Figure 28), as would be expected following the removal of smaller trees. Control plots were not surveyed in this immediate post-thinning period, as we would not expect any substantial change to have occurred. Five years after thinning, the proportion of large trees had decreased, though it remained slightly higher than pre-thinning levels (Figure 28). In general, plots that were subject to heavy thinning had a higher proportion of total trees that were large (Figure 28).

There was substantial variation in the total number of trees within each plot (131–1856 trees).

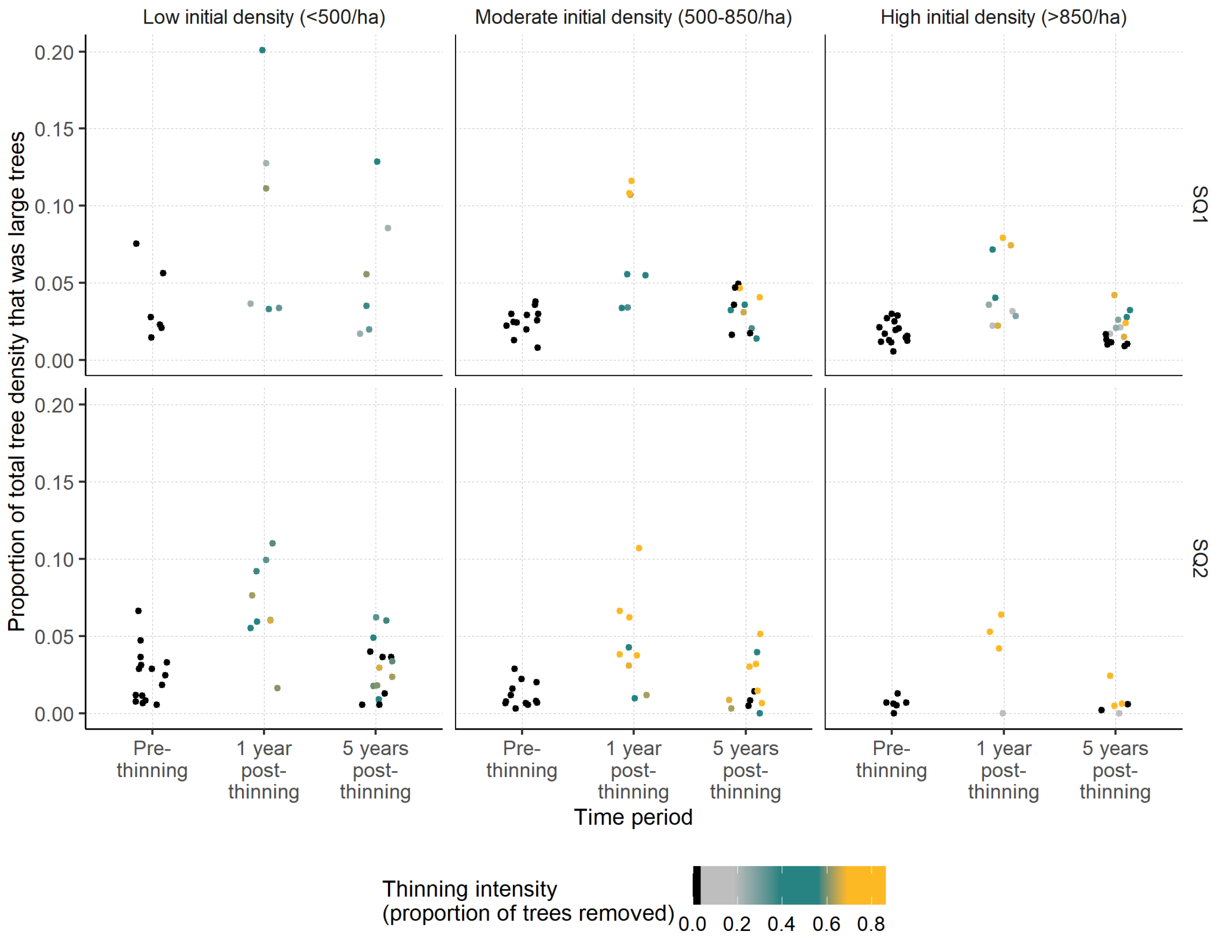

Figure 28 Proportion of trees occurring in large diameter size classes per 9-hectare plot

Model results

The proportion of trees occurring in large diameter size classes was analysed using a beta distribution with a logit link (see Appendices). The model for proportion of trees occurring in large diameter size classes did not include time since thinning as a continuous variable due to the variable dates of survey between 2015 and 2017. However, the model did include survey year as a random effect. The model included interactions between, thinning intensity, initial tree density and Site Quality. Random effects of year, site and 9-hectare plot were included. These data could have been analysed using a binomial distribution, with the response variable as the ratio of large trees (≥80 cm dbh) to small trees (<80 cm dbh), which would account for the variation in total number of trees using weights. However, this would require removal of the fixed effect initial tree density to avoid duplication of this value (as both an explanatory variable and in the weights function) in control plots. Given we were interested in the effects of initial tree density, we used a beta distribution and retained initial tree density as a fixed effect.

Modelled values of proportion of trees occurring in large diameter size classes in control plots were between 0.4 and 6.1% in all initial tree density and Site Quality combinations over time. The highest modelled value was 25.7%, and this was predicted in heavily thinned plots with very low initial tree density, immediately after thinning.

The proportion of trees occurring in large diameter size classes was significantly greater in Site Quality 1 than Site Quality 2 plots, and was highest in very low initial tree density plots (Figure 29, Table 17). The modelled values for proportion of trees occurring in large diameter size classes changed significantly between time periods (Table 17), increasing initially (2017–18 survey), and then decreasing (2021–22 survey), but remaining higher than 2015–16 values (Figure 29).

There was a significant effect of thinning on proportion of trees occurring in large diameter size classes, though this varied with initial tree density (Figure 29, Table 17, Table 18). All heavily thinned plots had a significant increase in the proportion of large trees compared to control plots, with effect sizes varying from 1 to 11%, with the greatest effect occurring in very low initial density plots in Site Quality 1 (Figure 29, Table 18). In Site Quality 1, moderately thinned plots also had a significantly higher proportion of large trees (1–4% increase), but in Site Quality 2, an increase was only seen in very low initial density plots (Table 18). The effects of thinning were more pronounced in the period immediately post-thinning (Figure 29), compared to the effect values reported here (Table 18) for 5 years post-thinning.

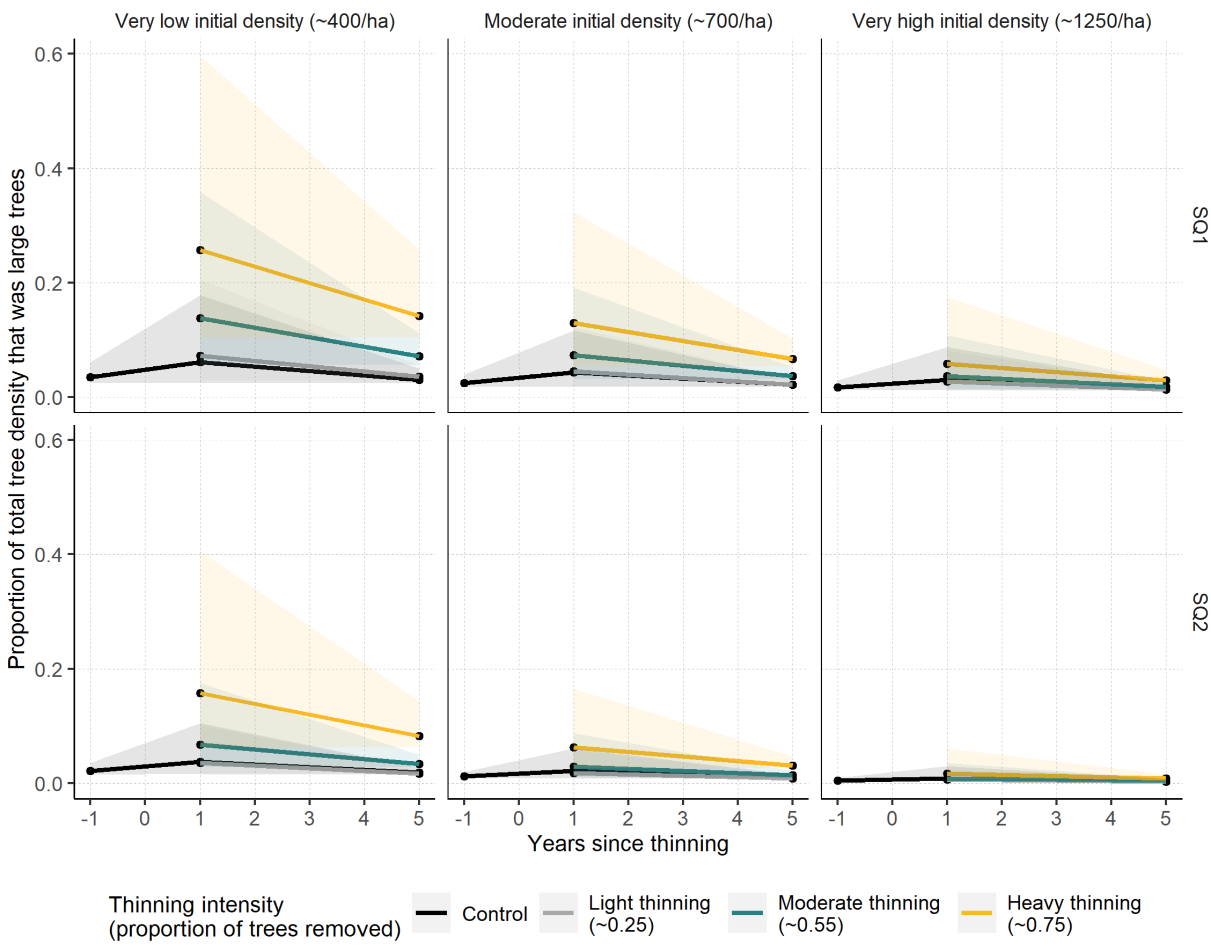

Figure 29 Modelled values and 95% confidence intervals for proportion of trees occurring in large diameter size classes per 9-hectare plot

Table 17 Statistical significance of explanatory variables on proportion of trees occurring in large diameter size classes per 9-hectare plot

	Bootstrapped likelihood ratio test significance	Description
Site Quality	0.01	The proportion of trees occurring in large diameter size classes differed among Site Qualities
Initial tree density	0.01	The proportion of trees occurring in large diameter size classes depended on initial tree density
Time since thinning	NA	This variable was not included in the model
Thinning intensity	0.01	The proportion of trees occurring in large diameter size classes was affected by thinning intensity
Time period	0.01	The proportion of trees occurring in large diameter size classes varied between pre-thinning, post-thinning, and 5 years post-thinning
Does the effect of thinning intensity vary depending on:		
• Site Quality	0.37	The effect of thinning on the proportion of trees occurring in large diameter size classes did not depend on Site Quality
• Initial tree density	0.02	The effect of thinning on the proportion of trees occurring in large diameter size classes depended on initial tree density
• Time since thinning		This variable was not included in the model
• Site Quality **and** initial tree density **and** time since thinning	NA	Four-way interaction was not included in the model

Table 18 Estimated effect sizes for proportion of trees occurring in large diameter size classes (presented as percentage) per 9-hectare plot 5 years post-thinning, showing difference between fitted values and 95% confidence intervals in thinned plots relative to control plots

Site Quality		Site Quality 1			Site Quality 2		
Thinning intensity		Low intensity	Mod intensity	High intensity	Low intensity	Mod intensity	High intensity
Initial tree density	Very low (400/ha)	+1.0 –0.1 to +2.6	+4.0 +2.6 to +8.2	+11.0 +7.5 to +22.8	0.0 –0.6 to +0.6	+1.0 +0.8 to +3.0	+6.0 +4.2 to +12.4
	Moderate (700/ha)	0.0 –0.1 to +1.2	+2.0 +1.1 to +3.3	+5.0 +3.3 to +8.2	0.0 –0.3 to +0.4	0.0 +0.1 to +1.1	+2.0 +1.6 to +3.7
	Very high (1250/ha)	0.0 +0.1 to +1.1	+1.0 +0.4 to +1.9	+2.0 +1.2 to +3.7	0.0 +0.2 to +0.6	0.0 +0.3 to +0.8	+1.0 +0.6 to +1.5

Hypothesis evaluation

There was support for the hypothesis that thinning would cause an increase in the proportion of trees in large size classes. This effect was produced by reducing the number of trees in small size classes, not by increasing the number of trees in large size classes. Five years after thinning, the number of trees in small size classes had substantially increased on many thinned plots due to coppice (see below), therefore there may not be support for this hypothesis in the long term.

5.3 Coppice

Hypothesis	No hypothesis relating to coppice was formulated prior to thinning. The thinning prescription included spraying cut stumps with Roundup Biactive® and it was assumed that substantial coppice growth would not occur.
Key result	Ecological thinning **increased** the abundance of stems that were <10 centimetres diameter at breast height due to coppiced stems arising from cut stumps and damaged or pushed over saplings. The greatest magnitude of effect was in drier Site Quality 2 plots that had very high initial tree density, with approximately 330–450 coppiced stems more than controls (per 0.1 hectares).

Data collection

The number of coppiced stems arising from cut stumps and pushed over saplings were counted in ten 0.1-hectare subplots on each 9-hectare plot (see 20 x 50 metre subplots in Figure 5). For each stump or pushed over tree with coppice, the number of sapling-sized (>1.37 metres in height) stems arising were counted.

Comprehensive data for coppice were collected for the first time in the 2020–21 survey season.

Plate 2 Coppiced stems greater than 1.37 metres in height observed in 2021–22. Josie Lange

Data summary

Coppice that was greater than 1.37 metres in height was observed on most 9-hectare plots that had undergone ecological thinning. The average number of coppiced stems counted per 0.1-hectare subplot on both Site Quality classes was approximately 22, and the range was 0–341.

Most coppiced stems were less than 5 centimetres in diameter at breast height; however up to 20 coppiced stems that were >5 centimetres diameter at breast height were recorded in 41 (out of 44) 9-hectare plots. Further, 12 (out of 44) 9-hectare plots had one or 2 coppiced stems >10 centimetres diameter at breast height recorded.

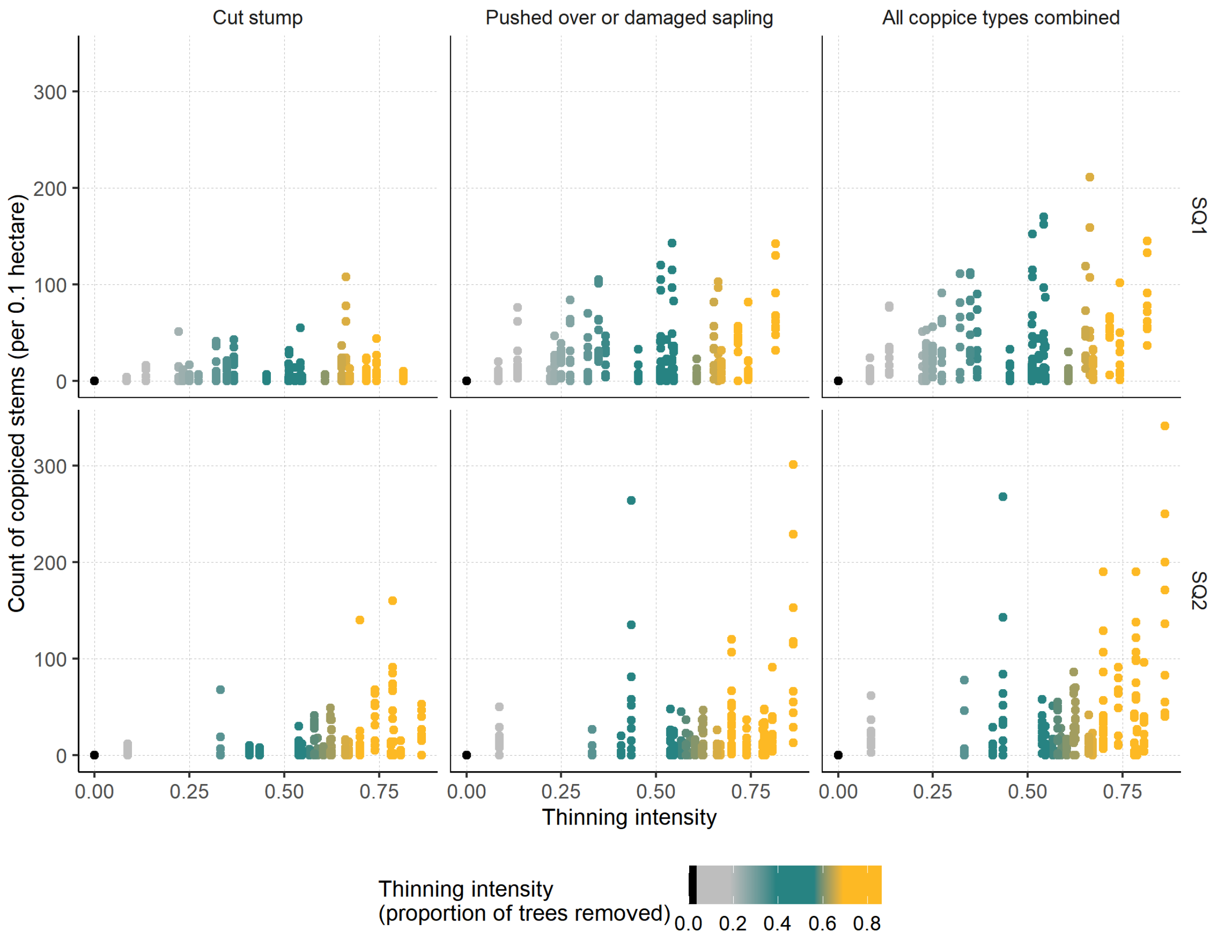

Figure 30 Data for count of coppiced stems (seedling and sapling-sized) arising from cut stumps and pushed over saplings per 0.04-hectare subplot

Data only recorded in 2020–21 and 2021–22 survey seasons.

Model results

The total count of coppiced stems greater than 1.37 metres in height per 0.1-hectare subplot was modelled using a negative binomial distribution (see Appendices). The data for control plots, which all had counts of zero, were excluded from the model. A four-way interaction between all predictors was not included, but all two- and three-way interactions between initial tree density, Site Quality, thinning intensity and time since thinning were included. Random effects for site and 9-hectare plot were included.

Modelled results were plotted on the log scale (Figure 31), as the confidence interval bounds for counts of coppiced stems were very wide (up to 39,000 coppiced stems) making it difficult to visualise differences among treatments. However, the modelled results were presented on the count scale in Table 20.

There was evidence that ecological thinning caused increased coppice in all site types (Figure 31), and significance did not depend on thinning intensity (Table 19).

The strongest coppice response occurred in drier (SQ2) plots that had very high initial tree density prior to moderate or heavy thinning, with a modelled average of 330–450 coppiced stems per 0.1 hectare (Figure 31, Table 20).

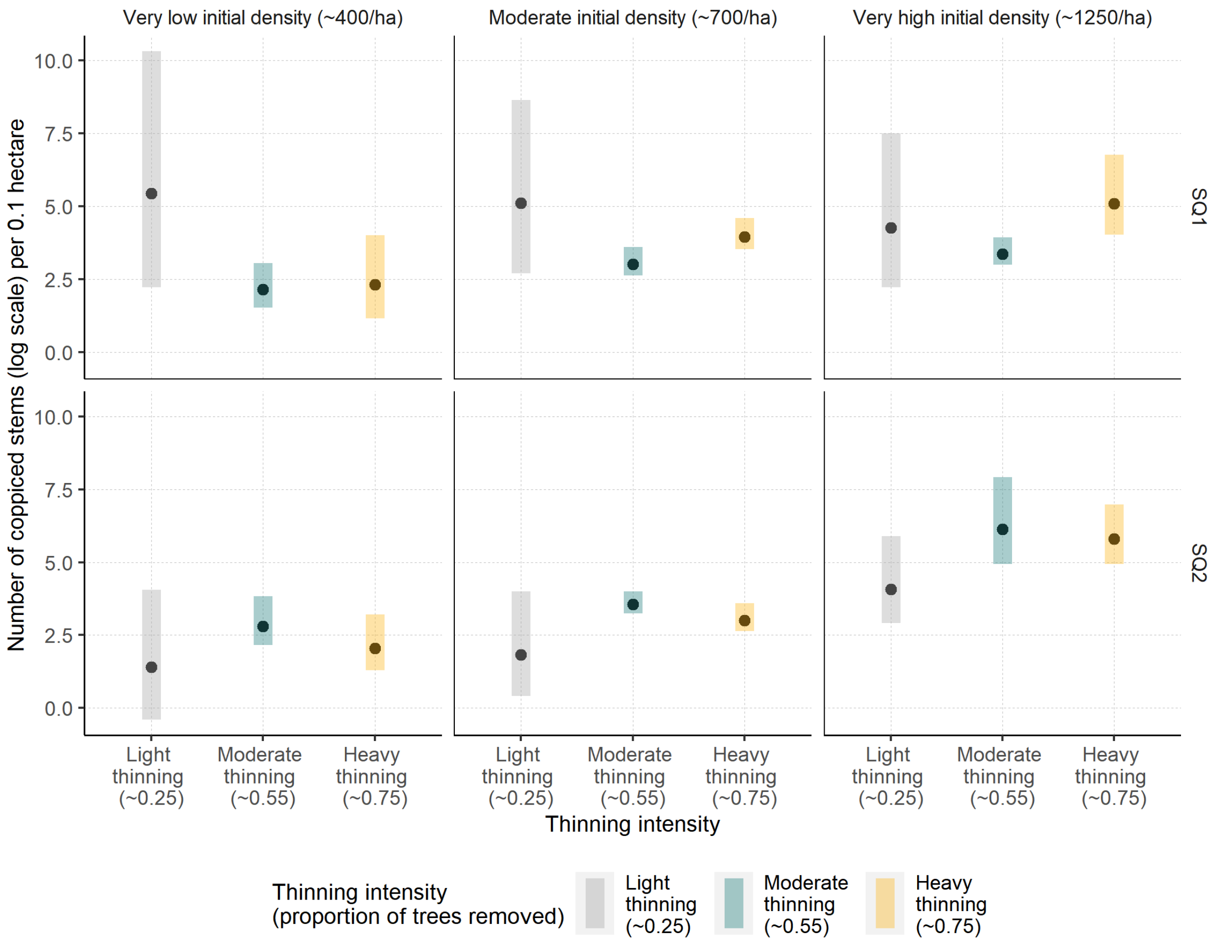

Figure 31 Modelled values and confidence intervals for abundance of coppiced stems arising from stumps and pushed over or damaged saplings

Table 19 Statistical significance of explanatory variables on abundance of coppiced stems arising from stumps and pushed over saplings among thinned plots (not including control plots that all had zero coppice)

	Bootstrapped likelihood ratio test significance	Description
Site Quality	0.33	Coppice abundance was not significantly different among Site Qualities
Initial tree density	0.07	There was some evidence that coppice abundance depended on initial tree density
Time since thinning	0.15	Coppice abundance did not depend on time since thinning
Thinning intensity (not including control plots)	0.34	Coppice abundance in thinned plots did not depend on the intensity of thinning
Does the effect of thinning intensity vary depending on:		

	Bootstrapped likelihood ratio test significance	Description
• Site Quality	0.37	The effect of thinning on coppice abundance did not vary with Site Quality
• Initial tree density	0.56	The effect of thinning on coppice abundance did not depend on initial tree density
• Time since thinning	0.38	The effect of thinning on coppice abundance did not change over time
• Site Quality **and** initial tree density **and** time since thinning	1.00	The effect of thinning on coppice abundance did not vary with Site Quality, initial tree density and time since thinning

Table 20 Estimates of effect sizes for abundance of coppiced stems arising from pushed over saplings and stumps (difference from control value of zero) 5 years post-thinning

Site Quality		Site Quality 1			Site Quality 2		
Thinning intensity		Low intensity	Mod intensity	High intensity	Low intensity	Mod intensity	High intensity
Initial tree density	Very low (400/ha)	+233 +7 to +59383	+9 +5 to +20	+10 +3 to +63	+1 +1 to +66	+8 +8 to +50	+3 +3 to +27
	Moderate (700/ha)	+167 +12 to +9771	+20 +14 to +35	+52 +33 to +104	+6 +1 to +60	+35 +27 to +55	+20 +14 to +35
	Very high (1250/ha)	+71 +7 to +2606	+29 +20 to +51	+162 +57 to +952	+59 +18 to +404	+459 +133 to +2889	+328 +149 to +1178

Hypothesis evaluation

There was evidence that ecological thinning caused a substantial coppice response, particularly from damage to saplings. Coppiced stems are likely to increase total tree density in thinned stands. Coppiced stems are also likely to compete with retained trees for moisture, nutrient and space, which may affect retained tree growth rates.

6. Results: Hollow-bearing tree development

6.1 Tree canopy spread

Hypothesis	1c. Ecological thinning will increase canopy spread of retained trees.
Key result	Ecological thinning caused an initial **decrease** in tree crown area, but a subsequent faster **rate of increase** than trees in control plots. Five years post-thinning there was no difference in the average canopy area in thinned and control plots.

Data collection

Trees that have a highly branched structure, with many limbs extending from the trunk, are more likely to become hollow bearing than straight trees with a small crown. Tree canopy area is indicative of the extent of tree branching.

Tree canopy spread was approximated using the opaque area occupied by individual tree crowns. It was measured on 30 permanently marked trees (>10 cm diameter at breast height, selected randomly along a central north–south transect) in each 9-hectare plot (see Figure 5) by estimating the distance between the canopy edges in 2 perpendicular planes (Figure 32). The 2 distances were used as diameters to calculate the area of an oval, which approximated the area of the tree canopy. For example, a tree canopy with a diameter of 15 metres on its longest axis and 9 metres on its short axis would have an area of 106 m^2.

Tree canopy dimensions were measured 3 times: prior to thinning in 2015–16, approximately one year post-thinning in 2017–18 and approximately 5 years post-thinning in 2021–22.

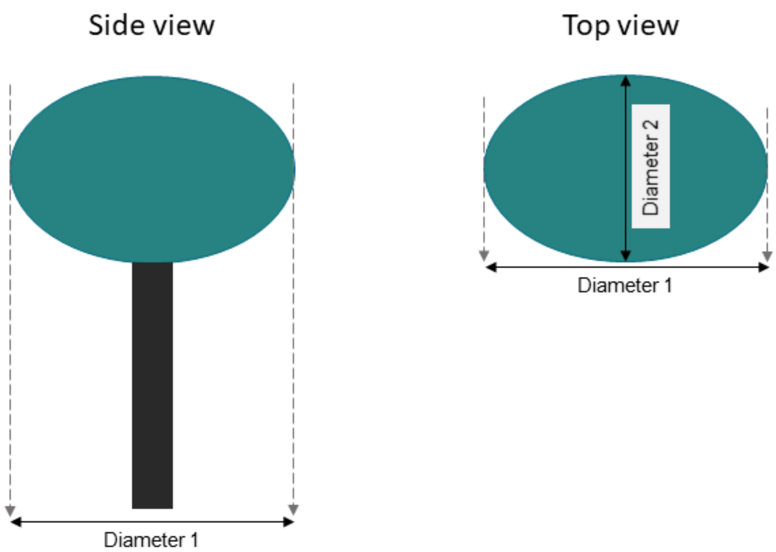

Figure 32 Schematic representation of tree crown area measurement

Data summary

Tree crown area most commonly ranged from 10–100 m², with values up to 350 m² recorded on both Site Qualities. Areas greater than 180 m² were recorded less often in pre-thinning 2015–16 surveys than they were in subsequent years.

Average tree crown area was 3.5–5.5 m² higher in wetter (SQ1) than drier (SQ2) sites. Maximum tree crown area was 373 m² and the minimum was less than 1 metre².

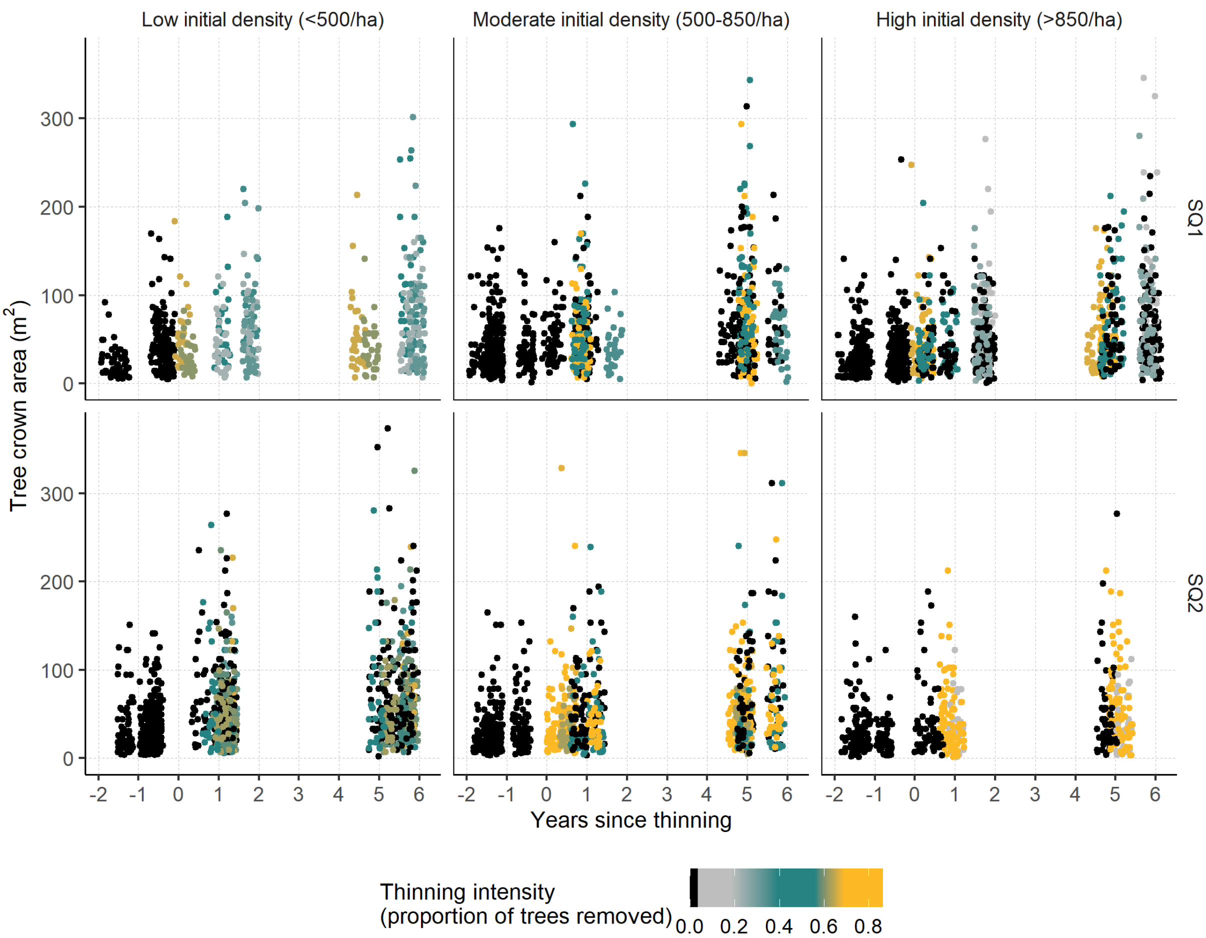

Figure 33 Data for tree canopy area for 30 permanently marked trees in each 9-hectare plot

Model results

Tree crown area was modelled by taking the log (natural base) of the value for each tree and using a Gaussian distribution (see Appendices). All predictors and interactions, and 4 random effects (year factor, site, 9-hectare plot and tree) were included in the model.

In the absence of ecological thinning, tree crown area was higher in wetter (SQ1) than drier (SQ2) sites, was higher in sites that had low pre-thinning tree density and increased over time (Figure 34). All of these differences were statistically significant (Table 19).

The effect of ecological thinning was statistically significant (Table 19), however confidence intervals were all wide, which caused uncertainty about the magnitude of change relative to controls (Figure 34, Table 20). For most site types, ecological thinning caused an initial decrease in tree crown area in 2017–18. Tree crown area increased in all site types (including controls) between 2017–18 and 2021–22. The effect of ecological thinning over this time period was to increase the rate of increase in tree crown area in thinned plots relative to controls, with the exception of Site Quality 1 plots with very high initial tree density. Despite the increased rate of growth, in 2021–22 there were no significant differences in tree crown area between thinned and control plots.

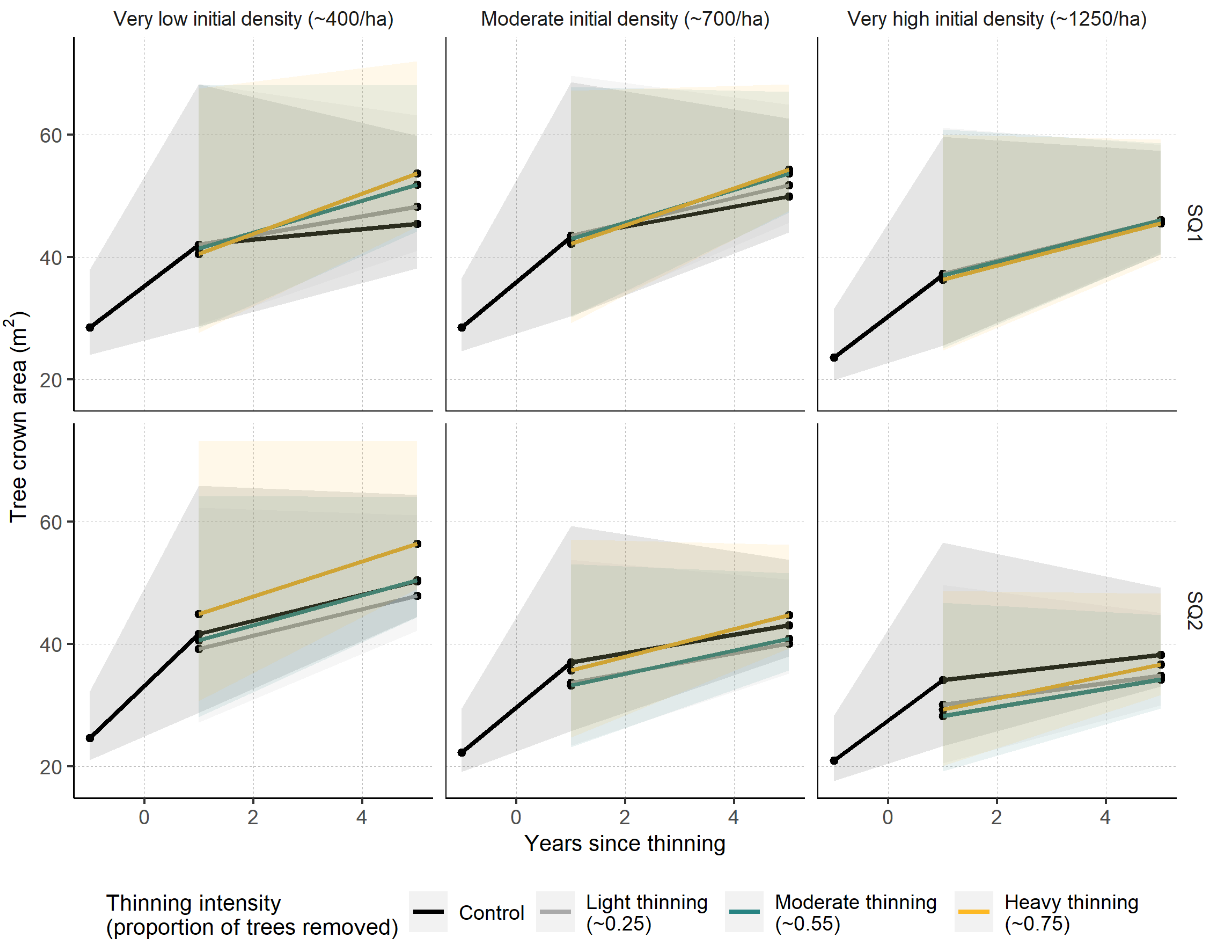

Figure 34 Modelled values and 95% confidence intervals for tree canopy area for 30 permanently marked trees in each 9-hectare plot

Table 21 Statistical significance of explanatory variables on tree canopy area for 30 permanently marked trees in each 9-hectare plot

	Bootstrapped likelihood ratio test significance	Description
Site Quality	0.01	Tree crown area differed among Site Qualities
Initial tree density	0.01	Tree crown area depended on initial tree density
Time since thinning	0.01	Tree crown area changed over time
Thinning intensity	0.02	Tree crown area was affected by ecological thinning
Does the effect of thinning intensity vary depending on:		

	Bootstrapped likelihood ratio test significance	Description
• Site Quality	0.01	The effect of ecological thinning on tree crown area varied with Site Quality
• Initial tree density	0.06	There was some evidence that the effect of thinning depended on initial tree density
• Time since thinning	0.01	The effect of thinning changed over time
• Site Quality **and** initial tree density **and** time since thinning	0.02	The effect of thinning depended on additional interactions with the 3 other predictors

Table 22 Estimated effect sizes for tree canopy area for 30 permanently marked trees in each 9-hectare plot 5 years post-thinning, showing difference between fitted values and 95% confidence intervals in thinned plots relative to control plots

Site Quality		Site Quality 1			Site Quality 2		
Thinning intensity		Low intensity	Mod intensity	High intensity	Low intensity	Mod intensity	High intensity
Initial tree density	Very low (400/ha)	+3.0 –3.5 to +14.3	+6.9 –1.6 to +19.7	+8.9 –0.7 to +26.4	–2.6 –12.2 to +13.3	+0.2 –9.6 to +16.8	+6.7 –4.1 to +25.1
	Moderate (700/ha)	+2.0 –8.1 to +18.0	+4.0 –6.0 to +21.1	+4.8 –6.1 to +22.9	–3.2 –10.8 to +9.5	–2.4 –9.9 to +9.5	+1.8 –5.3 to +14.8
	Very high (1250/ha)	+0.6 –9.0 to +17.3	+0.6 –7.7 to +16.2	0.0 –7.3 to +15.7	–3.7 –11.0 to +8.7	–4.3 –12.2 to +8.5	–1.6 –10.1 to +13.1

Hypothesis evaluation

There was some support for the hypothesis that ecological thinning would increase canopy spread of retained trees, with the canopy area of trees in thinned plots increasing at a faster rate than trees in control plots between 2017–18 and 2021–22. However, in 2021–22 there was no difference in the average canopy area. Longer time frames may be required to evaluate this hypothesis.

6.2 Count of hollow-bearing trees

Hypothesis	1c. Ecological thinning will increase hollow-development rates of retained trees.
Key result	No hollow-bearing trees were removed by thinning operations and there was **no statistically significant effect of ecological thinning**.

Data collection

Hollow-bearing trees were defined as any tree with at least one hollow with an entrance size of at least 5 centimetres that was visible from the ground.

All hollow-bearing trees were counted in the central 2-hectare subplot in each 9-hectare plot (see Figure 5). Surveys were conducted prior to thinning in 2015–16, one year post-thinning in 2017–18 and 5 years post-thinning in 2021–22. The same observers conducted surveys in 2015–16 and 2017–18; different observers conducted the most recent surveys.

Data summary

Prior to ecological thinning the average number of hollow-bearing trees within a 2-hectare subplot was 19 (range 3–34). Prior to thinning, the number of hollow-bearing trees in Site Quality 1 subplots was greater than in Site Quality 2 subplots, averaging 22 and 16 trees respectively (Figure 35). Over time, the number of hollow-bearing trees appeared to change, although not consistently; increasing in some treatment groups and decreasing in others (Figure 35).

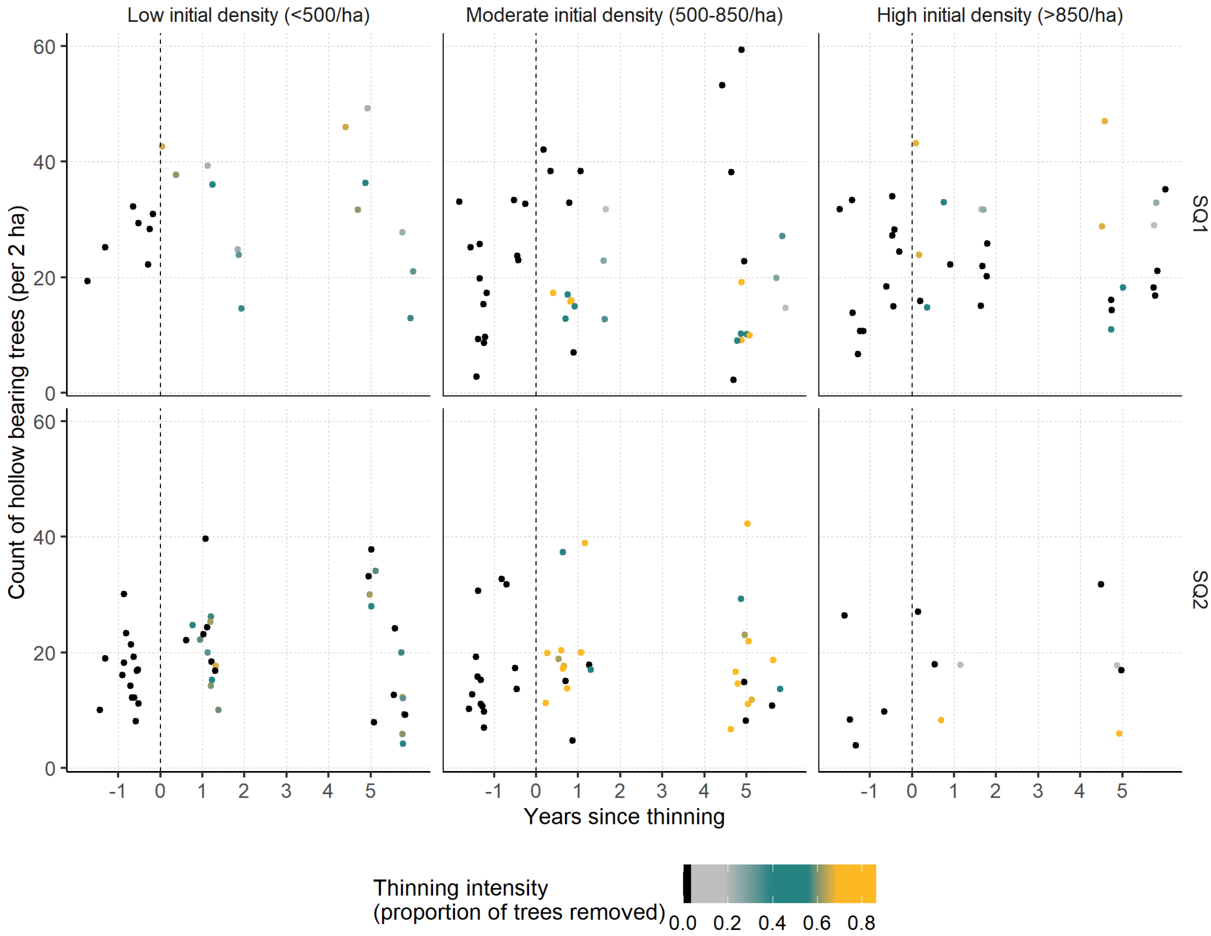

Figure 35 Data for count of hollow-bearing trees per 2-hectare subplot

Model results

Number of hollow-bearing trees was modelled using a Poisson distribution (see Appendices). The model did not include four-way interaction between Site Quality, initial tree density, time since thinning and thinning intensity, but included all two-way and three-way interactions. Random effects for site and 9-hectare plot were included.

In the absence of ecological thinning, there were more hollow-bearing trees in Site Quality 1 plots than Site Quality 2 plots (Figure 34), though this was not statistically significant (Table 21). The number of hollow-bearing trees did not vary significantly with initial tree density. Change over time was statistically significant (Table 21), but the direction and magnitude of change was not consistent among site conditions (Figure 34). This difference may be related to measurement uncertainty associated with inconsistent detection of hollows between monitoring surveys.

In the fifth year after thinning in Site Quality 1 there were fewer hollow-bearing trees in thinned plots than control plots, but none of the differences were statistically significant (Table 22). There were fewer hollow-bearing trees in thinned plots in Site Quality 2 that had low and moderate tree density prior to thinning and were heavily thinned, but this effect was not statistically significant (Table 21, Table 22).

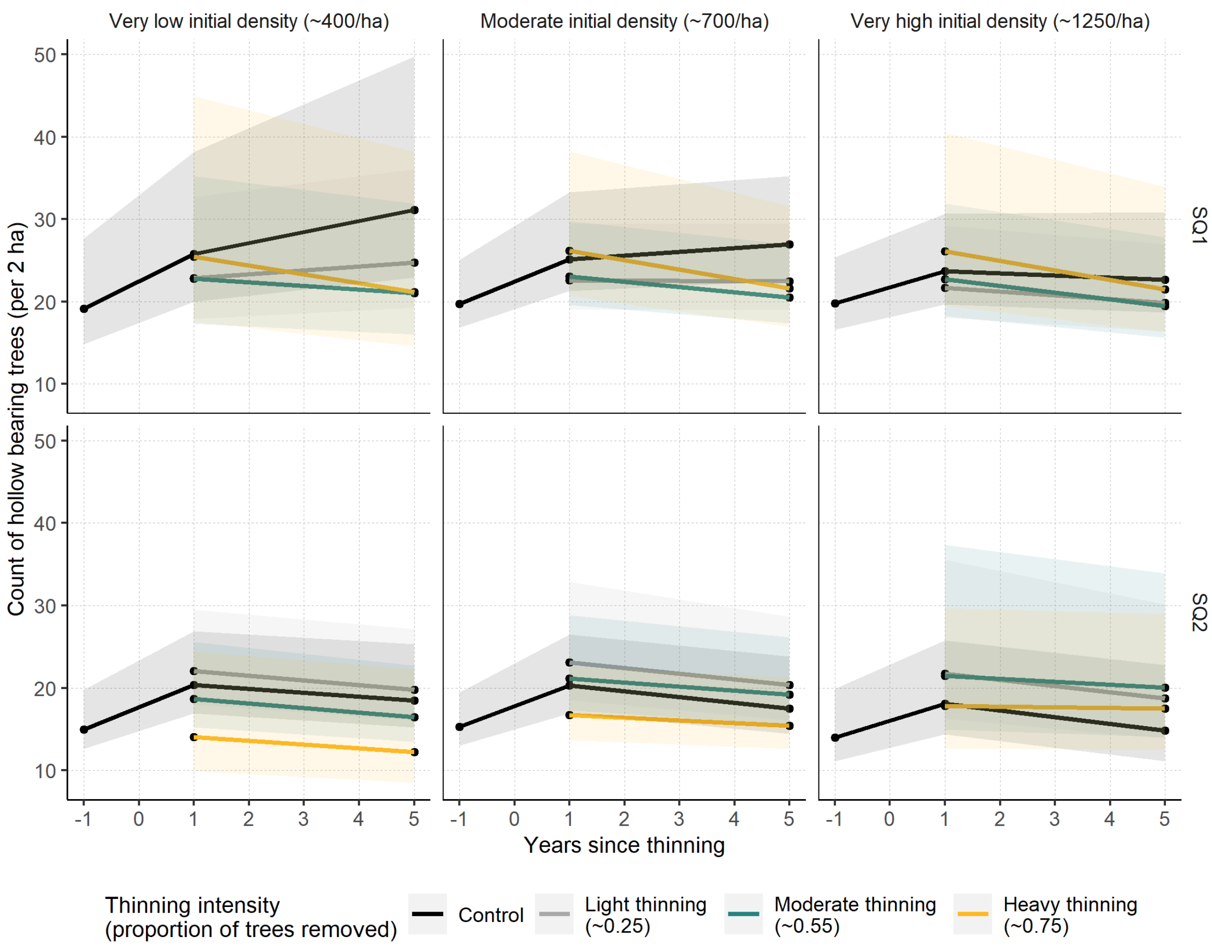

Figure 36 **Modelled values and 95% confidence intervals for count of hollow-bearing trees per 2-hectare subplot**

Table 23 Statistical significance of explanatory variables on count of hollow-bearing trees per 2-hectare subplot

	Bootstrapped likelihood ratio test significance	Description
Site Quality	0.45	The number of hollow-bearing trees did not differ among Site Qualities
Initial tree density	0.88	The number of hollow-bearing trees did not depend on initial tree density
Time since thinning	0.01	The number of hollow-bearing trees changed over time
Thinning intensity	0.41	The number of hollow-bearing trees was not affected by thinning intensity
Does the effect of thinning intensity vary depending on:		
• Site Quality	0.13	The effect of thinning on the number of hollow-bearing trees did not depend on Site Quality
• Initial tree density	0.63	The effect of thinning on the number of hollow-bearing trees did not depend on initial tree density
• Time since thinning	0.20	The effect of thinning on the number of hollow-bearing trees did not change over time
• Site Quality **and** initial tree density **and** time since thinning	NA	Four-way interaction was not included in the model

Table 24 Estimated effect sizes for count of hollow-bearing trees per 2-hectare subplot 5 years post-thinning, showing difference between fitted values and 95% confidence intervals in thinned plots relative to control plots

Site Quality		Site Quality 1			Site Quality 2		
Thinning intensity		Low intensity	Mod intensity	High intensity	Low intensity	Mod intensity	High intensity
Initial tree density	Very low (400/ha)	–6.4 –11.9 to +5.0	–10.1 –15.1 to +0.8	–10.0 –16.5 to +7.1	+1.3 –2.5 to +8.6	–2.1 –5.0 to +4.2	–6.3 –10.0 to +3.8
	Moderate (700/ha)	–4.5 –7.9 to +2.5	–6.5 –9.6 to 0.0	–5.3 –10.0 to +4.6	+2.8 –1.4 to +11.2	+1.7 –1.9 to +8.7	–2.1 –4.9 to +3.7
	Very high (1250/ha)	–2.8 –6.3 to +4.3	–3.2 –7.1 to +5.2	–1.2 –6.4 to +11.3	+3.9 –1.0 to +15.3	+5.2 –0.8 to +19.1	+2.7 –2.3 to +14.1

Hypothesis evaluation

There was no evidence to support the hypothesis that ecological thinning increased hollow-development rates of retained trees 5 years post-thinning.

7. Results: Tree canopy health

7.1 Proportion of tree crown that is live

Hypothesis	1d. Ecological thinning will increase tree canopy health of retained trees.
Key result	Ecological thinning caused an **increase** in average proportion of individual tree crowns that contained live foliage by 2.5–7% in drier Site Quality 2 plots and also in wetter Site Quality 1 plots with very high initial tree density.

Data collection

Within each 9-hectare treatment plot, 30 trees with >10 centimetre diameter at breast height were randomly selected along a north–south transect in the centre of the plot (see Figure 5). These 30 trees were permanently marked and surveyed annually for 6 survey years.

Crown extent is defined as the percentage of the potential crown that contains live foliage, including epicormic growth. The potential crown is estimated from the existing branching structure. Crown extent is sometimes referred to as ‘crown vigour’ in relevant literature. It was visually estimated to the nearest 5% for each of the 30 trees per plot and was analysed as a percentage. The same observer conducted all surveys.

Crown extent assesses the canopy health of individual trees.

Data summary

The vast majority of trees had crown extents between 70 and 100% (Figure 35). Averaging the tree crown extents of the 30 trees within each plot, which was the data used for modelling, showed high average extents. The lowest value was 65% and the majority of values were over 75% (Figure 38). Note that the data suggest that plots with lower averages may have had many trees with high crown extent values and a few trees with low values (Figure 37).

Average tree crown extents were higher in wetter (SQ1) plots than drier (SQ2) plots, but similar across all initial tree densities (Figure 38). Average tree crown extent appeared to increase over time (Figure 38).

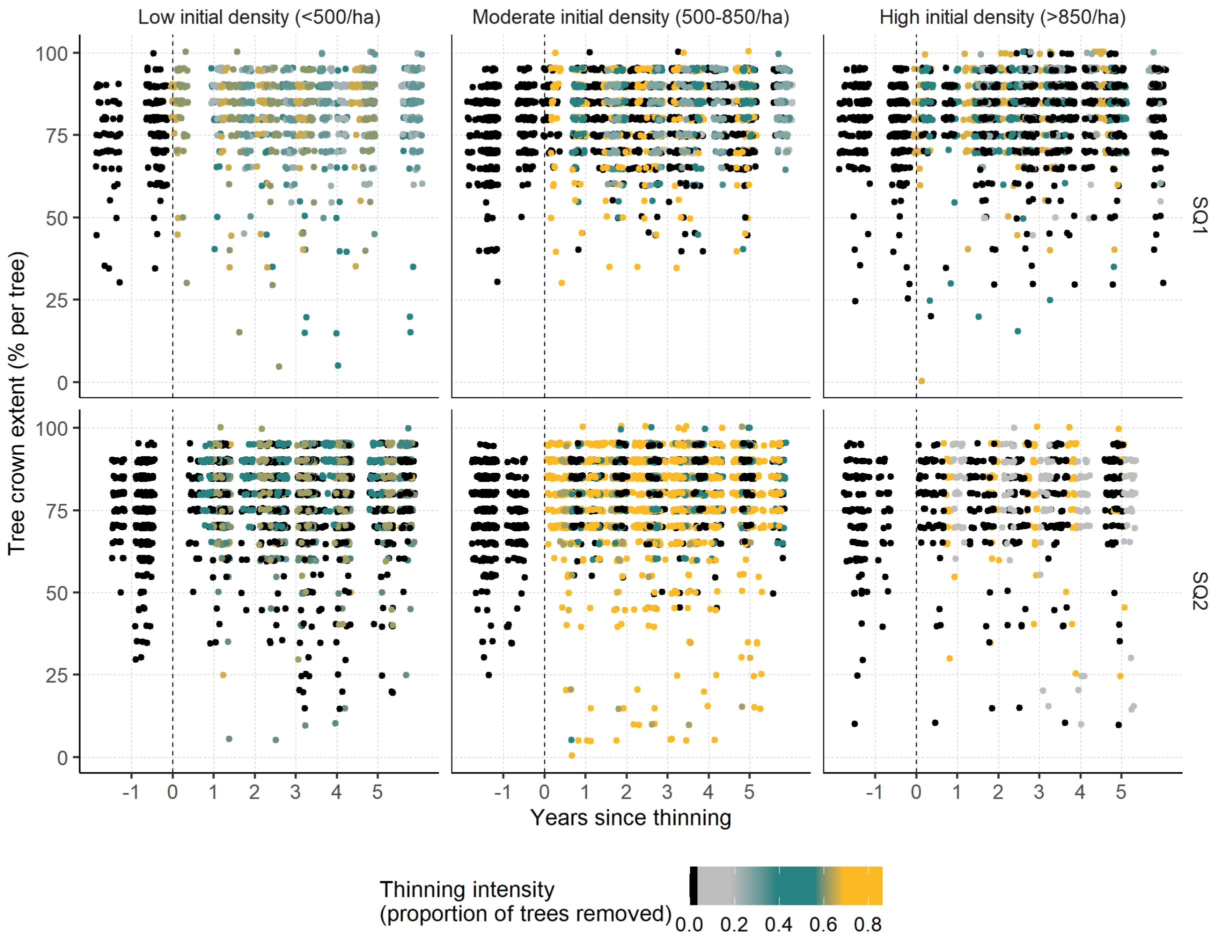

Figure 37 Data for percentage of tree crown extent for 30 trees in each 9-hectare plot

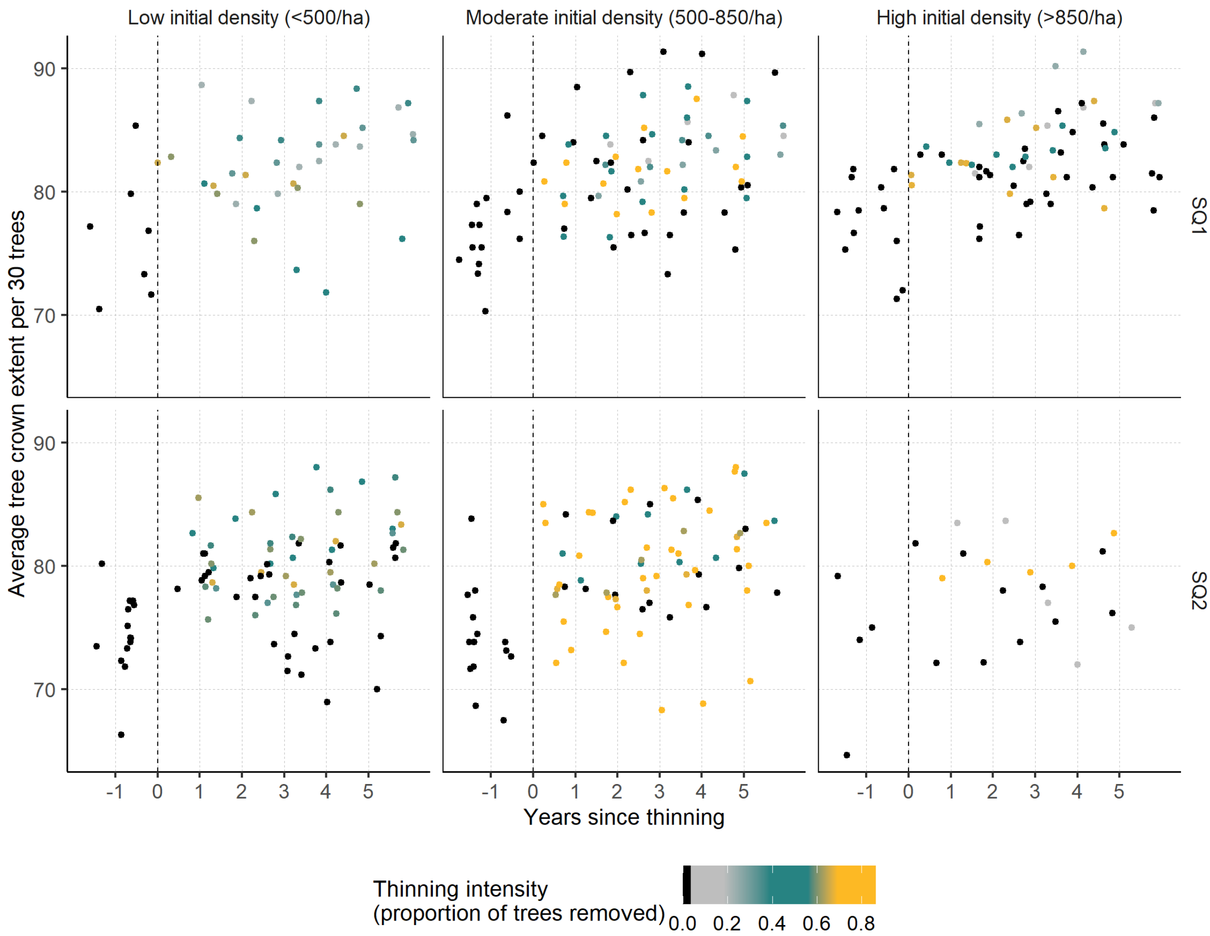

Figure 38 Data for percentage of tree crown extent averaged across 30 trees in each 9-hectare plot

Model results

Tree crown extent was analysed using the average value (from 30 trees) for each 9-hectare plot, as a model could not be fitted to data for all individual trees (see Appendices). Average tree crown extent was modelled as a continuous positive variable, using a Gaussian distribution, and included all interactions between initial tree density, thinning intensity, Site Quality and time since thinning. Random effects for year of survey, site and 9-hectare plot were included.

Modelled values of average tree crown extent were higher in Site Quality 1 plots than Site Quality 2 plots (Figure 39), though were not significantly different (Table 23). Modelled average tree crown extent was similar across all initial tree densities (Figure 39, Table 23). Change over time in average crown extent was statistically significant. Change in tree crown extent in control plots between 2015–16 (pre-thinning) and 2017–18 (one year post-thinning) was likely a response to widespread flooding that occurred in 2016–17 (Figure 8).

Ecological thinning had a statistically significant effect on average crown extent, and the effect of thinning changed over time (Table 23). Control plots showed little change in average tree crown extent between 2017–18 (one year post-thinning) and 2021–22 (5 years post-thinning (Figure 39). Thinning caused crown extent to increase in most plot types, with increasing effect size over time. In the most recent survey year, increases in average extent were between 2.0 and 6.9% (Table 24).

In Site Quality 1 moderate initial tree density plots, there was little evidence of a significant increase in tree crown extent after thinning, and in SQ1 very low initial tree density plots there was some evidence of a negative relationship between thinning and tree crown extent, though this was not significant (Figure 39, Table 24).

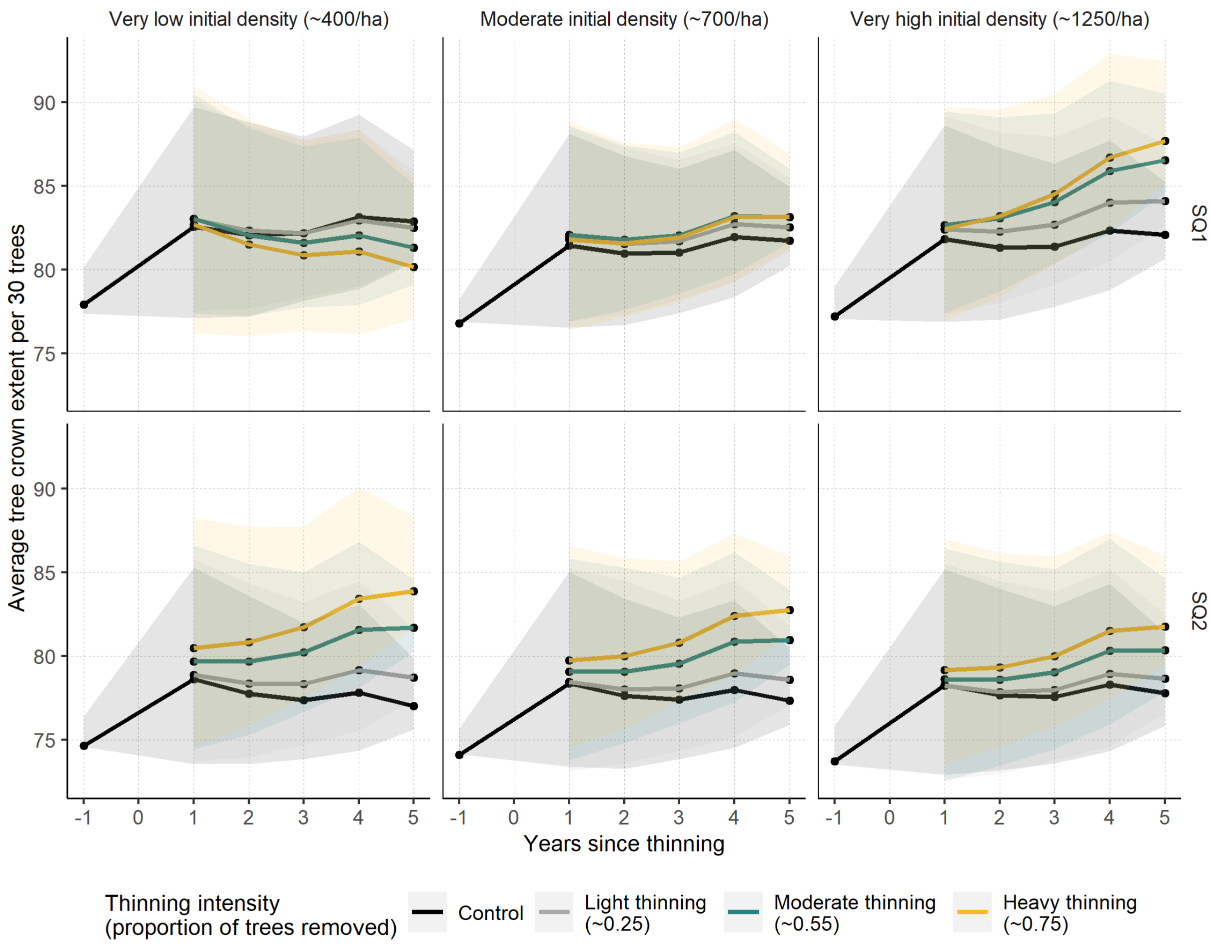

Figure 39 Modelled values and 95% confidence intervals for average tree crown extent (%) per 30 trees

Table 25 Statistical significance of explanatory variables on average tree crown extent (%)

	Bootstrapped likelihood ratio test significance	Description
Site Quality	0.21	Average tree crown extent did not differ by Site Quality
Initial tree density	0.59	Average tree crown extent did not depend on initial tree density
Time since thinning	0.01	Average tree crown extent changed over time
Thinning intensity	0.01	Average tree crown extent was altered by thinning
Does the effect of thinning intensity vary depending on:		

	Bootstrapped likelihood ratio test significance	Description
• Site Quality	0.24	The effect of thinning on average tree crown extent did not differ among Site Qualities
• Initial tree density	0.42	The effect of thinning on average tree crown extent did not differ depending on initial tree density
• Time since thinning	0.01	The effect of thinning on average tree crown extent changed over time
• Site Quality **and** initial tree density **and** time since thinning	0.06	The effect of thinning on average tree crown extent may have varied with Site Quality, initial tree density and time since thinning

Table 26 Estimated effect sizes for average tree crown extent (percentage) 5 years post-thinning, showing difference between fitted values and 95% confidence intervals in thinned plots relative to control plots

Site Quality		Site Quality 1			Site Quality 2		
Thinning intensity		Low intensity	Mod intensity	High intensity	Low intensity	Mod intensity	High intensity
Initial tree density	Very low (400/ha)	–0.4 –2.3 to +3.0	–1.6 –3.8 to +2.2	–2.7 –5.8 to +2.6	+1.7 +0.4 to +4.7	+4.6 +3.2 to +7.5	+6.9 +4.7 to +11.3
	Moderate (700/ha)	+0.8 –0.6 to +3.8	+1.4 –0.1 to +4.3	+1.4 –0.5 to +5.2	+1.3 –0.2 to +4.5	+3.6 +2.2 to +6.6	+5.4 +4.0 to +8.6
	Very high (1250/ha)	+2.0 +0.5 to +5.4	+4.5 +2.5 to +8.4	+5.6 +3.1 to +10.4	+0.9 –1.2 to +4.7	+2.6 +0.1 to +6.9	+4.0 +1.7 to +8.2

Hypothesis evaluation

Data provided evidence to support the hypothesis that thinning would increase tree canopy health in drier (SQ2) sites and wetter (SQ1) plots that had very high tree density prior to thinning. There was no evidence of an effect on SQ1 plots with moderate tree density prior to thinning. There was evidence to suggest that this hypothesis was not supported on SQ1 plots with very low initial tree density, and thinning may have caused a decline in tree crown extent. Hydro-climatic conditions may affect this variable. Longer timeframes may be required to evaluate this hypothesis.

7.2 Remotely sensed canopy cover

Hypothesis	1d. Ecological thinning will increase tree canopy health of retained trees.
Key result	Light ecological thinning (~25% of trees removed) initially caused a small **increase** in remotely sensed FPC relative to control plots, but this increase diminished over time and was not significant 5 years post-thinning. Heavy ecological thinning (~75% of trees removed) caused a significant and substantial (5–13%) **decrease** in FPC relative to control plots, and the difference was sustained for 5 years post-thinning.

Data collection

The Landsat satellite provides remotely sensed images at 30 metre resolution at 16-day intervals. Foliage projective cover (FPC) (Scarth et al. 2008) is a measure of canopy density that is derived from Landsat images. FPC is the percentage of ground area covered by the vertical projection of green foliage of woody vegetation greater than 2 metres in height. In River Red Gum forests, woody vegetation greater than 2 metres in height is almost exclusively composed of *Eucalyptus camaldulensis*. This measure therefore includes the cover of all trees, including saplings. An FPC value is derived for each 30 x 30 metre pixel in a Landsat image and is on a scale from 0 to 1. A value of 1 represents 100% coverage of green foliage.

FPC data were extracted from Landsat images on each cloud-free date between January 2014 and May 2022. Multiple pixels were available per 9-hectare plot for each date, from which the median FPC was calculated for each 9-hectare plot.

In contrast to crown extent, which assesses canopy health of individual trees, FPC is an indicator of the canopy health of trees in a stand.

Data summary

FPC values were higher in wetter (SQ1) sites (with values commonly between approximately 0.2 and 0.6) than drier (SQ2) sites (with values commonly between approximately 0.1 and 0.5) (Figure 40).

FPC values fluctuated with season, and these fluctuations were more pronounced in drier (SQ2) plots. In 2021–22, FPC values tended to be higher than recorded since 2018.

Thinned plots tended to include lower FPC values than were recorded in control plots.

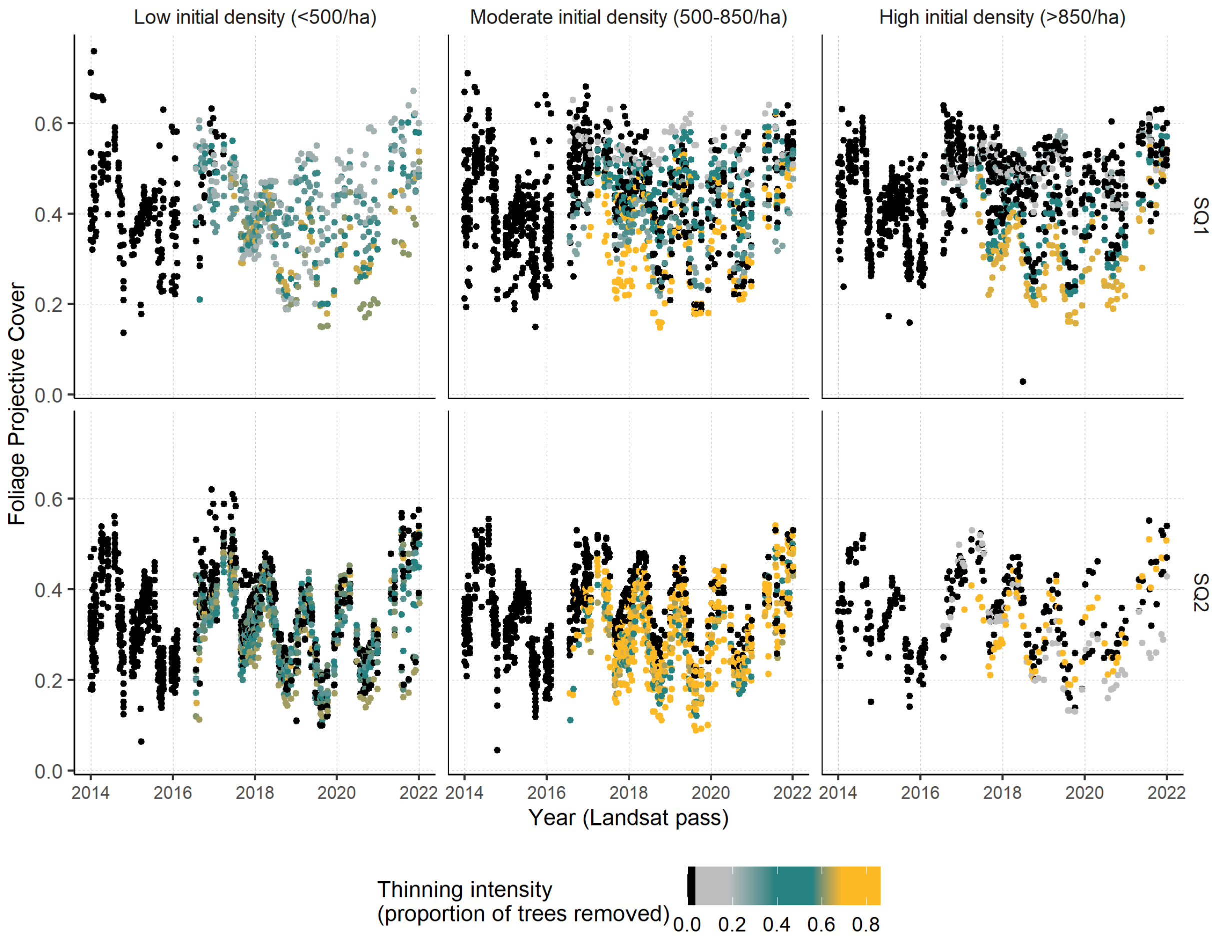

Figure 40 Data for averaged foliage projective cover in each 9-hectare plot

Model results

FPC was analysed as a continuous positive variable, using a Gaussian distribution (see Appendices). The FPC model included Landsat pass instead of time since thinning, and therefore this model does not account for differences in thinning and survey dates among plots. All interactions between initial tree density, thinning intensity, Site Quality and pass were included in the model. Random effects for 9-hectare plot were included but site and year of survey were not.

In the absence of ecological thinning, FPC was significantly higher in wetter sites (SQ1) when compared to drier sites (SQ2) (Table 27). FPC also increased with increasing initial tree density and this effect was statistically significant (Figure 41). FPC changed significantly over time, with the lowest values recorded in 2018, coinciding with drier hydro-climatic conditions.

Ecological thinning had a significant effect on FPC but this effect was dependent on Site Quality, initial tree density and also changed over time (Table 27, Figure 41, Table 28).

Light thinning caused a small initial increase in FPC in all plot combinations, which diminished over time such that there was no significant difference in 2021–22.

Moderate thinning had a variable effect initially, which depended on Site Quality and initial tree density. In the most recent year, FPC was significantly lower in moderately thinned plots than control plots, with the exception of drier (SQ2) plots with moderate and very high initial tree density.

Heavy thinning caused a significant reduction in FPC for all combinations of Site Quality and initial tree density. In the most recent year, FPC values were 0.05–0.13 lower than control plots. The only site type for which modelled FPC values appeared to be converging with control values over time was drier (SQ2) plots with very high initial tree density.

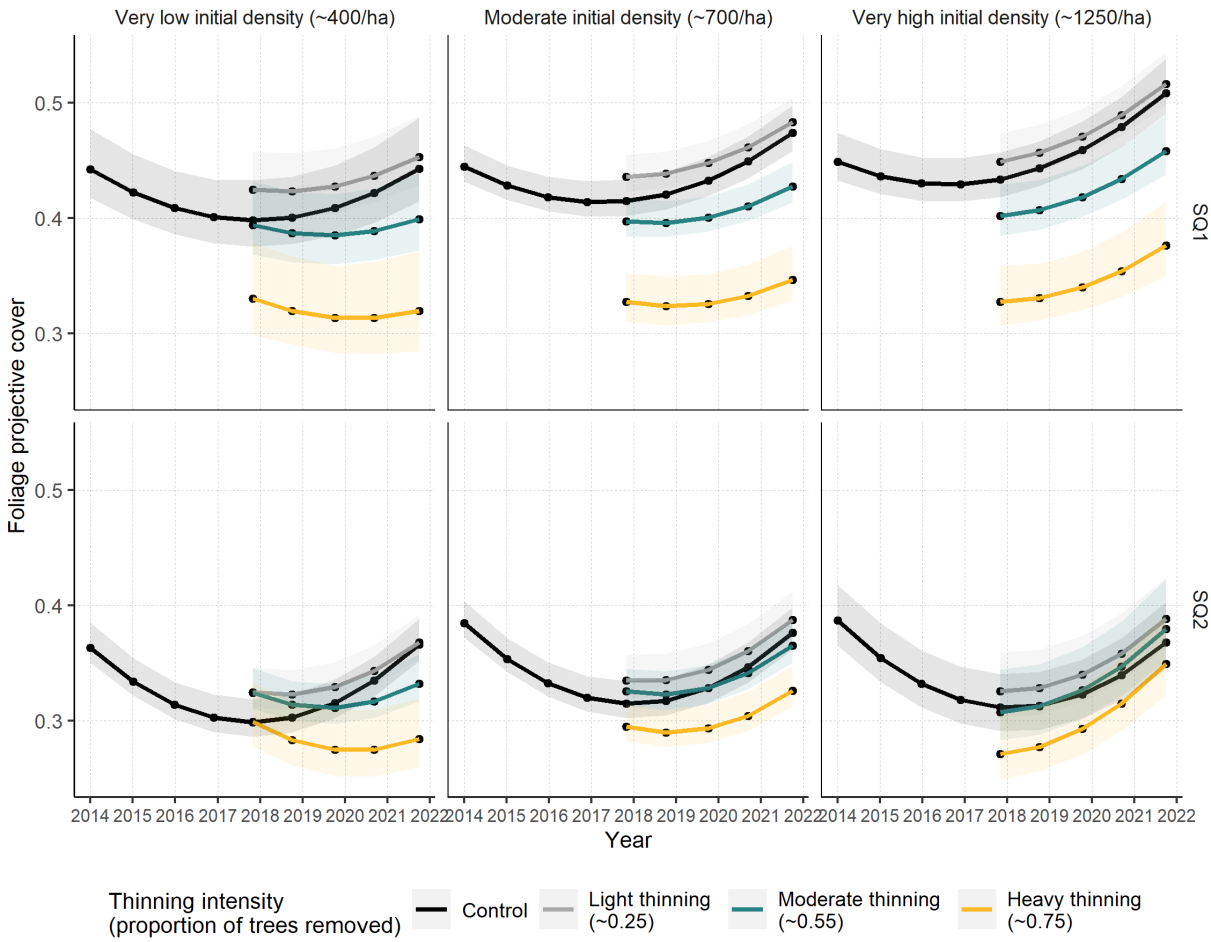

Figure 41 Modelled values and 95% confidence intervals for remotely sensed foliage projective cover in each 9-hectare plot

Table 27 Statistical significance of explanatory variables on remotely sensed foliage projective cover

	Bootstrapped likelihood ratio test significance	Description
Site Quality	0.01	Foliage projective cover differed by Site Quality
Initial tree density	0.01	Foliage projective cover depended on initial tree density
Time	0.01	Foliage projective cover changed over time
Thinning intensity	0.01	Foliage projective cover was altered by thinning

	Bootstrapped likelihood ratio test significance	Description
Does the effect of thinning intensity vary depending on:		
• Site Quality	0.01	The effect of thinning on foliage projective cover differed among Site Qualities
• Initial tree density	0.01	The effect of thinning on foliage projective cover differed depending on initial tree density
• Time	0.01	The effect of thinning on foliage projective cover changed over time
• Site Quality **and** initial tree density **and** time	0.14	The effect of thinning on foliage projective cover did not vary for all combinations of Site Quality, initial tree density and time

Table 28 Estimated effect sizes for foliage projective cover 5 years post-thinning, showing difference between fitted values and 95% confidence intervals in thinned plots relative to control plots

Site Quality		Site Quality 1			Site Quality 2		
Thinning intensity		Low intensity	Mod intensity	High intensity	Low intensity	Mod intensity	High intensity
Initial tree density	Very low (400/ha)	+0.01 –0.01 to +0.05	–0.04 –0.07 to –0.004	–0.12 –0.16 to –0.07	0.00 –0.01 to +0.03	–0.03 –0.05 to –0.01	–0.08 –0.11 to –0.05
	Moderate (700/ha)	+0.01 –0.004 to +0.03	–0.05 –0.06 to –0.03	–0.13 –0.15 to –0.10	+0.01 –0.01 to +0.04	–0.01 –0.03 to +0.01	–0.05 –0.03 to –0.06
	Very high (1250/ha)	+0.01 –0.01 to +0.04	–0.05 –0.07 to –0.02	–0.13 –0.16 to –0.09	+0.02 –0.004 to +0.06	+0.01 –0.02 to +0.06	–0.02 –0.05 to +0.02

Hypothesis evaluation

There was some evidence to support the hypothesis that light-intensity ecological thinning temporarily improved stand-level canopy health in some circumstances. The magnitude of this increase was less than 1%, the duration was 1–2 years, and the difference from controls was uncertain.

For heavy intensity ecological thinning and over the longer term there was no evidence to support this hypothesis.

8. Results: Recruitment

8.1 Germinant occurrence and abundance

Hypothesis	1e. Ecological thinning will increase recruitment of tree seedlings in early post-treatment years.
Key result	The data for germinant presence and germinant abundance were not able to be modelled due to the prevalence of zeros in the dataset. However, the raw data did not provide evidence that ecological thinning had an effect on germinant occurrence or abundance.

Data collection

Germinants were defined as individuals of *Eucalyptus camaldulensis* with cotyledons present.

Germinants were counted in 4 quadrants and summed for each 0.04-hectare subplot (see 20 x 20 metre subplots in Figure 5). Surveys were conducted annually, over 6 survey years. In 2021–22, 15% of 0.04-hectare subplots were not able to be surveyed due to flooding.

Presence of germinants tends to be transient in the few weeks after floodwaters recede. If climatic conditions are too dry the germinants die or if climatic conditions are appropriate they quickly develop into seedlings.

Data summary

In previous surveys, the proportion of 0.04-hectare subplots with at least one germinant recorded ranged from 0 to 17% (Table 29).

In the 2021–22 monitoring surveys, germinants were recorded in more than half of the 0.04-hectare subplots that were surveyed in wetter (SQ1) sites, and approximately one-third of the 0.04-hectare subplots that were surveyed in drier (SQ2) sites. Germinants were recorded in similar proportions of subplots in both control and thinned plots (Figure 42).

Table 29 Count and proportion of 0.04-hectare subplots for which germinants were recorded as present, in each Site Quality and survey year

Site Quality	Survey year	Count of 0.04-hectare subplots with germinants present	Percentage of 0.04-hectare subplots with germinants present
SQ1	2015–16	15 (out of 99)	7.6%
	2017–18	24 (out of 99)	12.1%
	2018–19	22 (out of 99)	11.1%
	2019–20	11 (out of 99)	5.6%
	2020–21	34 (out of 99)	17.2%
	2021–22	41 (out of 76)	53.9%
SQ2	2015–16	0 (out of 99)	0.0%
	2017–18	9 (out of 99)	4.6%

Site Quality	Survey year	Count of 0.04-hectare subplots with germinants present	Percentage of 0.04-hectare subplots with germinants present
	2018–19	1 (out of 99)	0.5%
	2019–20	4 (out of 99)	2.0%
	2020–21	6 (out of 99)	3.0%
	2021–22	30 (out of 93)	32.3%

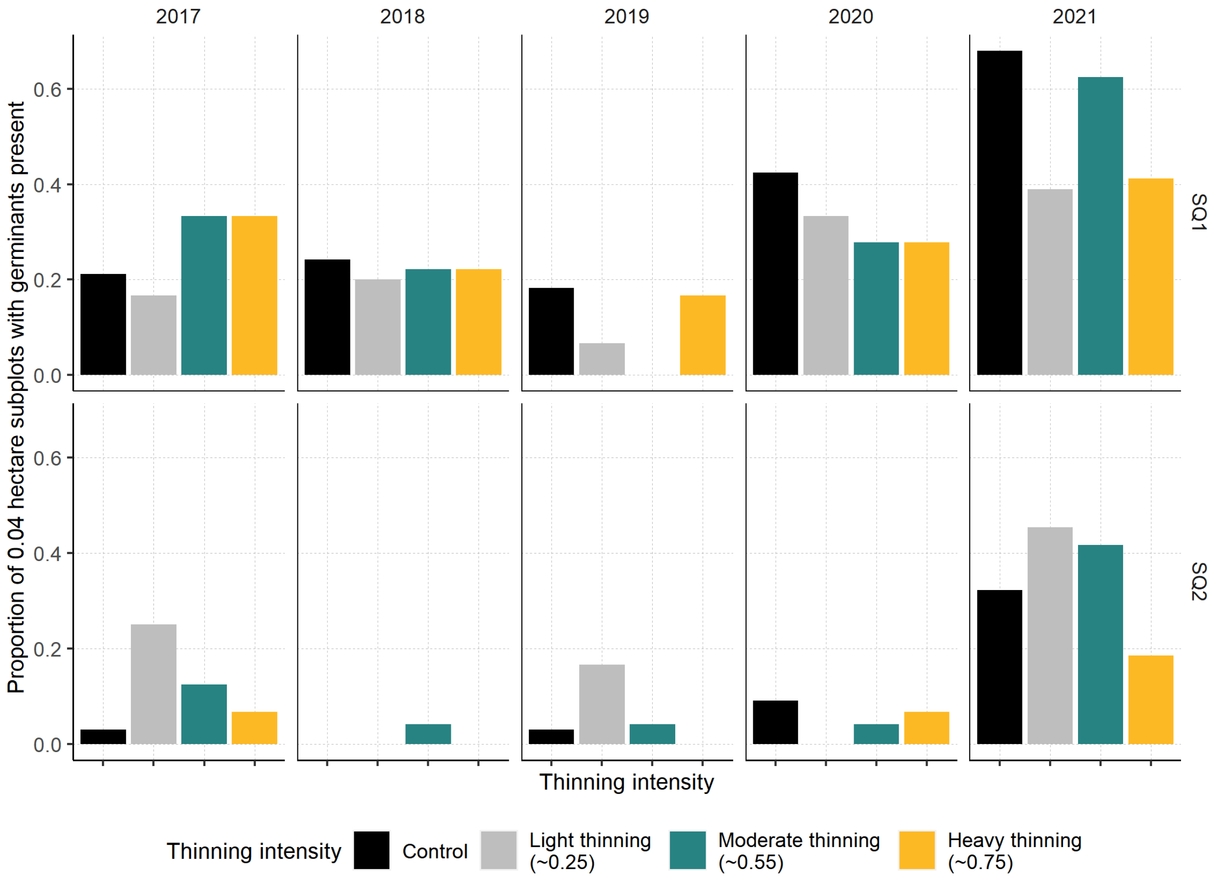

Figure 42 **Data for presence-absence of germinants per 0.04-hectare subplot in post-thinning years**

The most frequently recorded number of germinants on 0.04-hectare subplots was zero. Among plots where germinants were present, the most frequently recorded number of germinants was one. However, germinant abundance was very high on some subplots (Figure 43), including 5 records above 1000 germinants, including a maximum of approximately 3300 germinants per 0.04 hectares. High densities of germinants (>50 germinants per 0.04-hectare subplot) were recorded in both control and thinned plots, with most observations occurring in the 2020–21 and 2021–22 monitoring surveys (Figure 43).

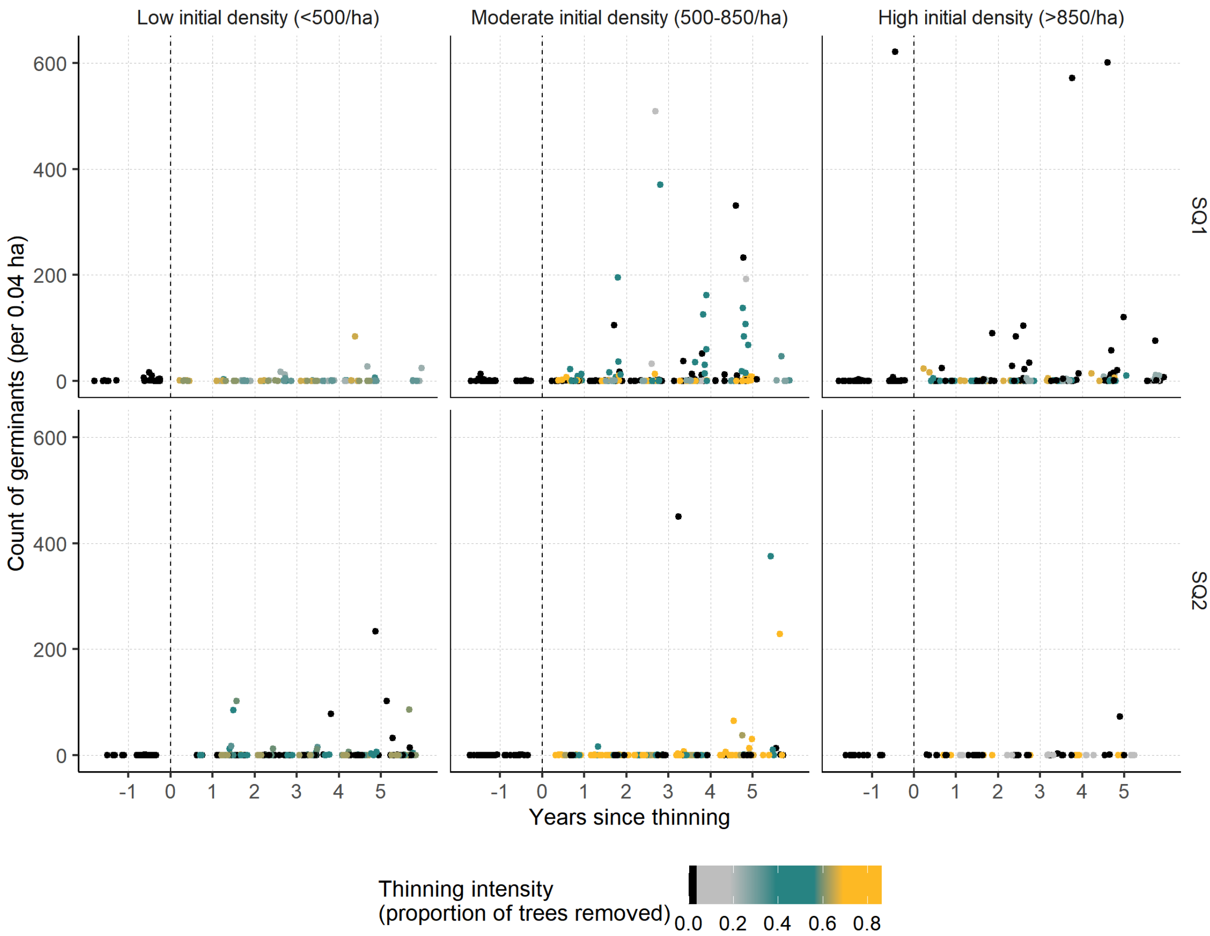

Figure 43 Data summary for abundance of germinants per 0.04-hectare subplot

Five values greater than 1000 were excluded from the figure, that were recorded in control and thinned subplots in 2020 and 2021.

Model results

The data for germinant presence and germinant abundance were not able to be modelled due to the prevalence of zeros in the dataset.

Hypothesis evaluation

There were insufficient data for germinants to inform evaluation of the hypothesis that ecological thinning would increase recruitment of seedlings in early post-thinning years.

8.2 Seedling abundance

Hypothesis	1e. Increased recruitment of tree seedlings in early post-thinning years.
Key result	Ecological thinning caused an **increase** of 200–1000 seedlings (per 0.04-hectare subplot) in drier Site Quality 2 plots that had very low to moderate initial tree density. Ecological thinning caused a temporary **decrease** of approximately 35 seedlings (per 0.04-hectare subplot) in wetter Site Quality 1 plots that had very low initial tree density 4 years post-thinning.

Data collection

Seedlings are defined as *Eucalyptus camaldulensis* recruits that are less than 1.37 metres in height. Seedlings did not include coppiced stems that were seedling sized but emerging from cut stumps or pushed over stems. Seedlings were counted in each of the three 0.04-hectare subplots in the 9-hectare treatment plots (see Figure 5). Surveys were conducted annually, over 6 survey years. In 2021–22, 15% of 0.04-hectare subplots were not able to be surveyed due to flooding.

Data summary

Higher seedling counts were recorded in the most recent survey than previous years (Figure 44). Across all previous years, 22% of 0.04-hectare subplots had zero counts, but in 2021–22 the proportion with zero counts was 13%.

In previous years, the average number of seedlings recorded per 0.04-hectare subplot was between 7.5 and 32. In the most recent survey year, the average number of seedlings recorded in wetter (SQ1) plots was 211 and in drier (SQ2) plots was 297. More than 1000 seedlings were recorded on eight 0.04-hectare subplots in the most recent year, and the maximum was 3290.

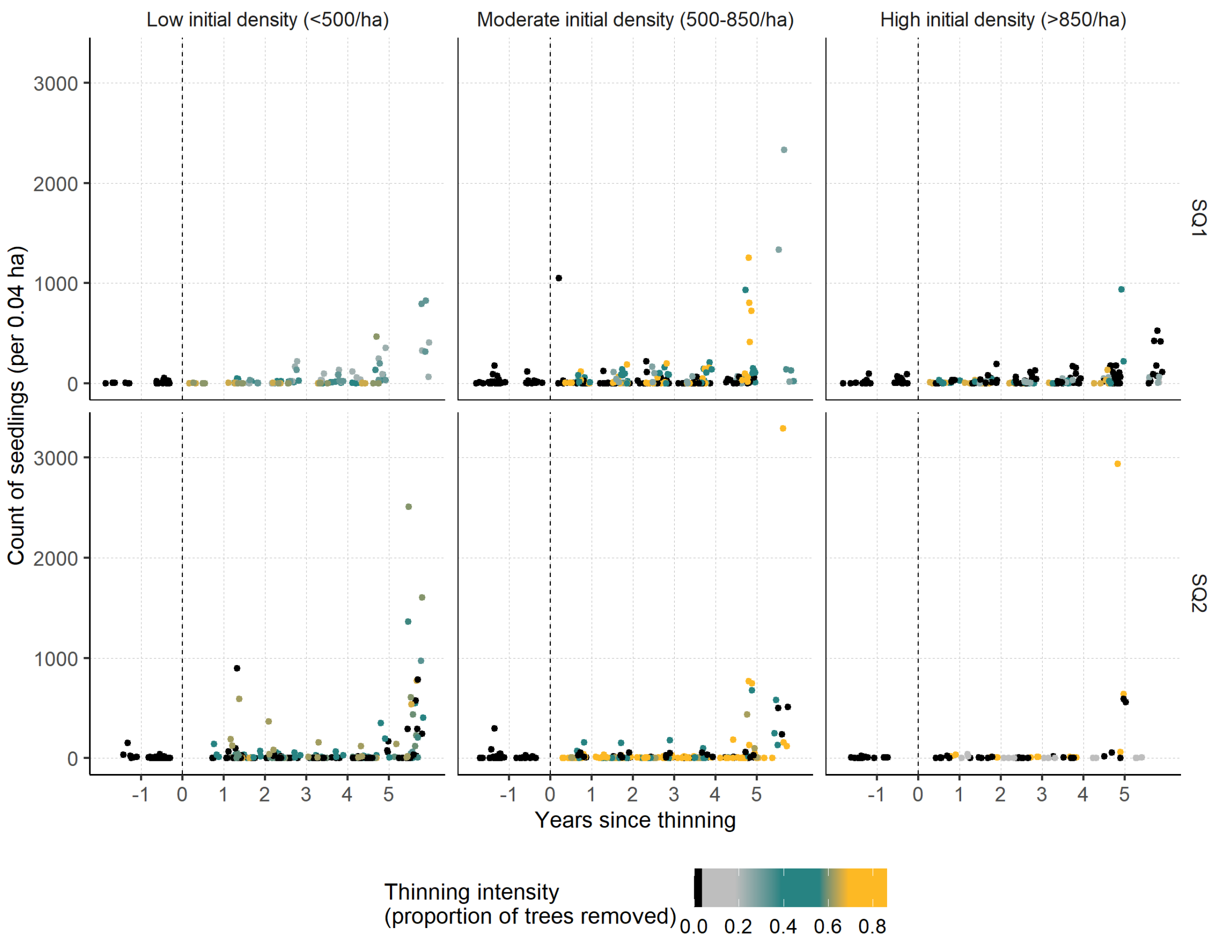

Figure 44 Data for seedling abundance in each 0.04-hectare subplot

Model results

Seedling abundance was modelled using a negative binomial distribution (see Appendices). All predictors were included, except the four-way interaction between initial tree density, years elapsed, thinning intensity and Site Quality. The random effects of survey year, 9-hectare plot and 0.04-hectare subplot were included. The results of the model are presented on a log scale for seedling abundance, as the confidence interval bounds on the original scale were very wide (up to 15,000 seedlings) making it difficult to visualise differences among treatments.

In the absence of ecological thinning, average seedling abundance was slightly higher in wetter (SQ1) sites than drier (SQ2) sites and the difference was statistically significant (Figure 45, Table 30). In wetter (SQ1) sites, seedling abundance was negatively correlated with initial tree density but in drier (SQ2) sites, seedling abundance was positively correlated with initial tree density. Seedling abundance also varied significantly over time.

The effect of ecological thinning on seedling abundance differed among the Site Qualities and also differed depending on pre-thinning tree density. Thinning temporarily reduced seedling abundance in wetter (SQ1) plots that had low initial tree density and moderate or heavy thinning, 3 and 4 years post-thinning. In contrast, thinning increased seedling abundance 4 years post-thinning in wetter (SQ1) plots that had very high initial tree density. Thinning substantially increased seedling abundance 3, 4 and 5 years post-thinning in drier (SQ2) plots that had had very low or moderate tree density prior to thinning. In these plots, thinning increased seedling abundance by 174–830 additional seedlings relative to controls.

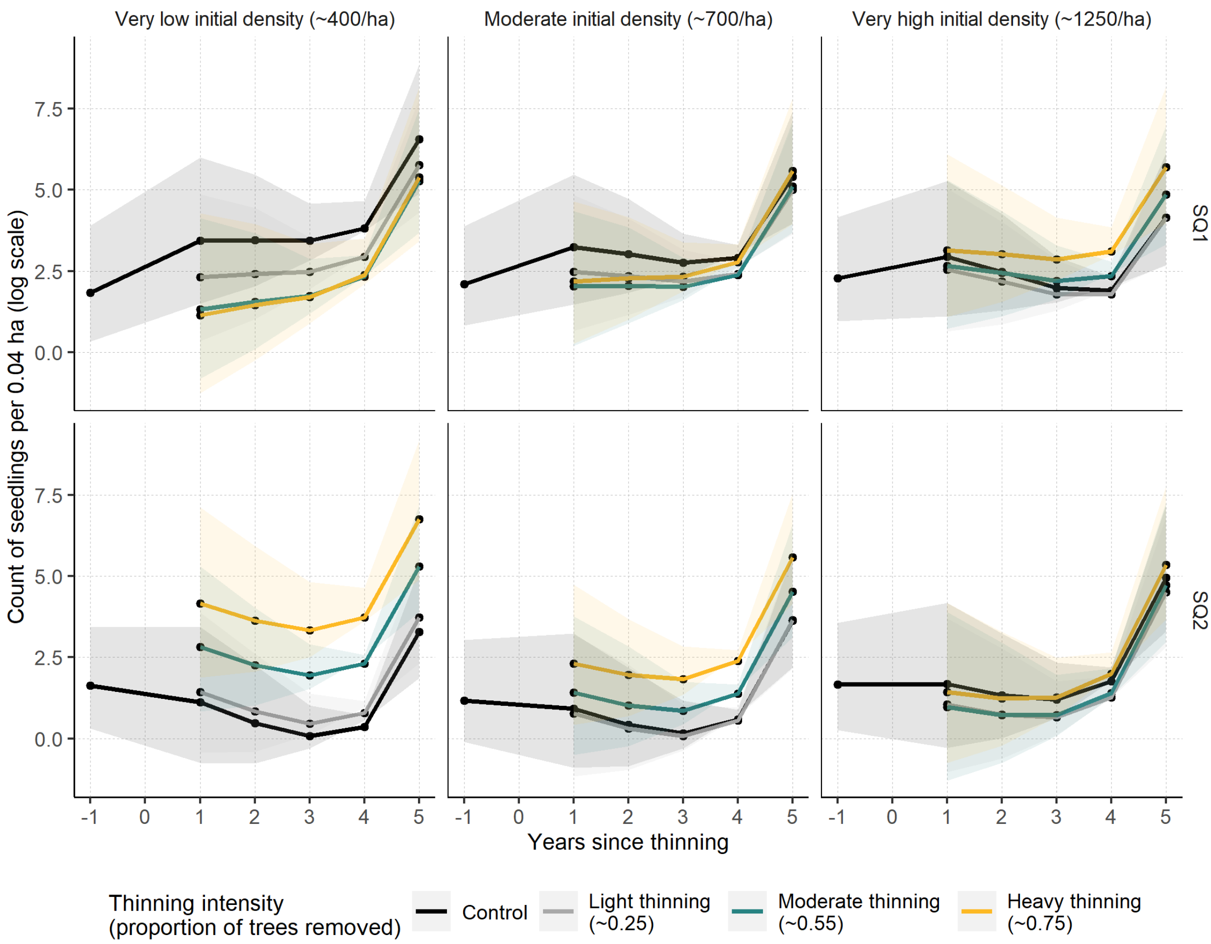

Figure 45 Modelled values and 95% confidence intervals for abundance of seedlings (on the log scale) per 0.04-hectare subplot

Table 30 Statistical significance of explanatory variables on seedling abundance

	Bootstrapped likelihood ratio test significance	Description
Site Quality	0.01	Seedling abundance varied by Site Quality
Initial tree density	0.01	Seedling abundance varied by initial tree density
Time since thinning	0.01	Seedling abundance changed over time
Thinning intensity	0.01	Seedling abundance was affected by thinning intensity
Does the effect of thinning intensity vary depending on:		
• Site Quality	0.01	The effect of thinning varied with Site Quality
• Initial tree density	0.03	There was some evidence that the effect of thinning on seedling abundance may depend on initial tree density
• Time since thinning	0.16	The effect of thinning on seedling abundance did not change over time
• Site Quality **and** initial tree density **and** time since thinning	Not modelled	

Table 31 Estimated effect sizes for seedling abundance in thinned plots relative to control plots, 5 years post-thinning, showing difference between fitted values and 95% confidence intervals in thinned plots relative to control plots

Site Quality		Site Quality 1			Site Quality 2		
Thinning intensity		Low intensity	Mod intensity	High intensity	Low intensity	Mod intensity	High intensity
Initial tree density	Very low (400/ha)	–386 –630 to +1727	–510 –665 to +1052	–486 –674 to +2768	+15 –16 to +254	+174 +22 to +1291	+830 +105 to +9669
	Moderate (700/ha)	–74 –185 to +871	–58 –183 to +1013	+43 –171 to +2269	0 –29 to +294	+55 –16 to +702	+226 +25 to +1834
	Very high (1250/ha)	–1 –49 to +392	+64 –36 to +1001	+232 –11 to +3454	–51 –125 to +775	–31 –122 to +1312	+68 –102 to +2220

Hypothesis evaluation

There was evidence to support the hypothesis that ecological thinning would increase seedling abundance in early post-treatment years in some circumstances. In particular, high densities of seedlings were recruited in drier (SQ2) plots that had very low to moderate tree density prior to thinning. There was also evidence that in other circumstances seedling recruitment was temporarily decreased in thinned plots, although this effect was not sustained over time or in response to favourable hydro-climatic conditions.

8.3 Sapling abundance

Hypothesis	1f. Ecological thinning will increase survival of (naturally occurring) saplings. Note that this hypothesis was not directly assessed – see data collection section below. 1f. (alternative). Ecological thinning will decrease the abundance of naturally occurring saplings in the short term and increase the abundance of naturally occurring saplings in the long term.
Key result	Ecological thinning generally **decreased** abundance of saplings by 6–22 saplings (per 0.04-hectare subplot) relative to controls. However, in drier Site Quality 2 plots with moderate to very high initial tree density ecological thinning **increased** abundance of saplings by 5–32 saplings (per 0.04 hectares).

Data collection

Initial surveys in 2015–16 included tagging all saplings in three 0.04-hectare subplots in each 9-hectare plot (see Figure 5). This proved to be impractical, as it would have required thousands of tags to be deployed across the national park, and ineffective as emus destroyed a substantial proportion of tags. Subsequently, an alternative hypothesis was specified and the abundance of naturally occurring saplings was recorded in three 0.04-hectare subplots in each 9-hectare plot. Saplings were surveyed annually, across 6 survey seasons. In 2021–22, 15% of 0.04-hectare subplots were not able to be surveyed due to flooding.

Saplings are defined as naturally occurring *Eucalyptus camaldulensis* recruits that are more than 1.37 metres in height. Saplings did not include coppiced stems that were emerging from cut stumps or pushed over stems.

Note that the abundance of naturally occurring saplings (response data) is not independent of initial tree density or thinning intensity (predictor data) as saplings are included in tree density and thinning intensity measures. However, we were able to model these data because we obtained response and predictor data in different subplots in each 9-hectare plot.

Data summary

Most subplots had fewer than 50 saplings, though some subplots had over 100 saplings, and one had 200 saplings in the final year of monitoring (Figure 46). Sapling abundance increased with increasing initial tree density, and generally decreased with increasing thinning intensity (Figure 46). There was little evidence of a difference in sapling abundance between Site Qualities (Figure 46).

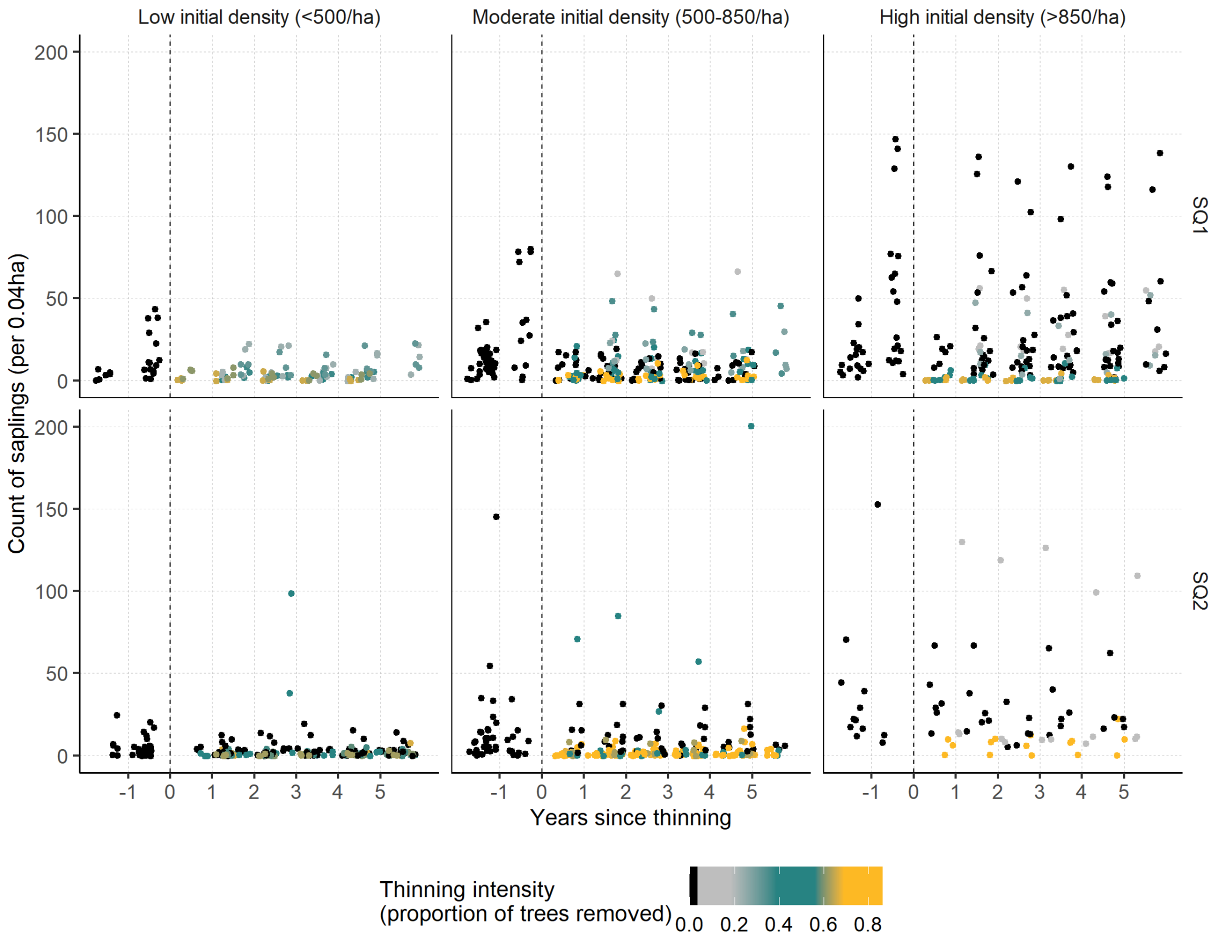

Figure 46 Data for sapling abundance in each 0.04-hectare subplot

Model results

Sapling abundance was modelled using a zero-inflated Poisson distribution (see Appendices). The model for sapling abundance did not include four-way interaction between Site Quality, initial tree density, time since thinning and thinning intensity, but included all two-way and three-way interactions. Random effects of year and subplot were included. The results of the model are presented on a log scale for sapling abundance (Figure 47), as the confidence interval bounds on the original scale were very wide, making it difficult to visualise differences among treatments. The modelled results are presented on the count scale in Table 33. We could not quantify the significance of ecological thinning because it was not possible to fit a model that did not contain this predictor (Table 32). However, there was evidence that ecological thinning had a significant effect because model terms relating to the interaction of thinning with other predictors were statistically significant.

In the absence of thinning, there were significant differences in the abundance of naturally occurring saplings, with higher abundances occurring in wetter (SQ1) plots and plots with higher initial tree density (Figure 47, Table 32). Sapling abundance also changed significantly over time, with minimum values recorded in the 2019–20 survey period on most plot types.

Ecological thinning generally resulted in lower sapling abundance in thinned plots compared to control plots, though this depended on Site Quality and time since thinning (Figure 47, Table 32). Modelled values of sapling abundance in control plots were between 2 and 24 saplings and for thinned subplots were between 0 and 46 (Figure 47).

In wetter (SQ1) subplots, sapling abundance was significantly lower after moderate and high intensity thinning in moderate and very high initial density subplots (Figure 47, Table 33). The magnitude of change was between 6 and 7 fewer saplings in moderate initial density subplots compared to control subplots, and between 19 and 21 fewer saplings in high initial density subplots (Table 33). Similarly, in drier (SQ2) plots there were fewer saplings in moderate and high intensity thinning subplots that had very low and moderate initial densities (Figure 47). However, the magnitude of change was relatively small (2 to 5 fewer saplings) (Table 33).

Light-intensity ecological thinning caused an increase in sapling abundance in drier (SQ2) plots with moderate initial tree density, with an increase of 5 saplings (Table 33). This effect was of a greater magnitude where initial tree density was very high, with light and moderate intensity thinning causing an increase of up to 32 saplings on average (Table 33). This result is likely to have been heavily influenced by 2 subplots which had substantially higher sapling abundance than all other treatments (Figure 46), indicating that high-density recruitment is spatially patchy.

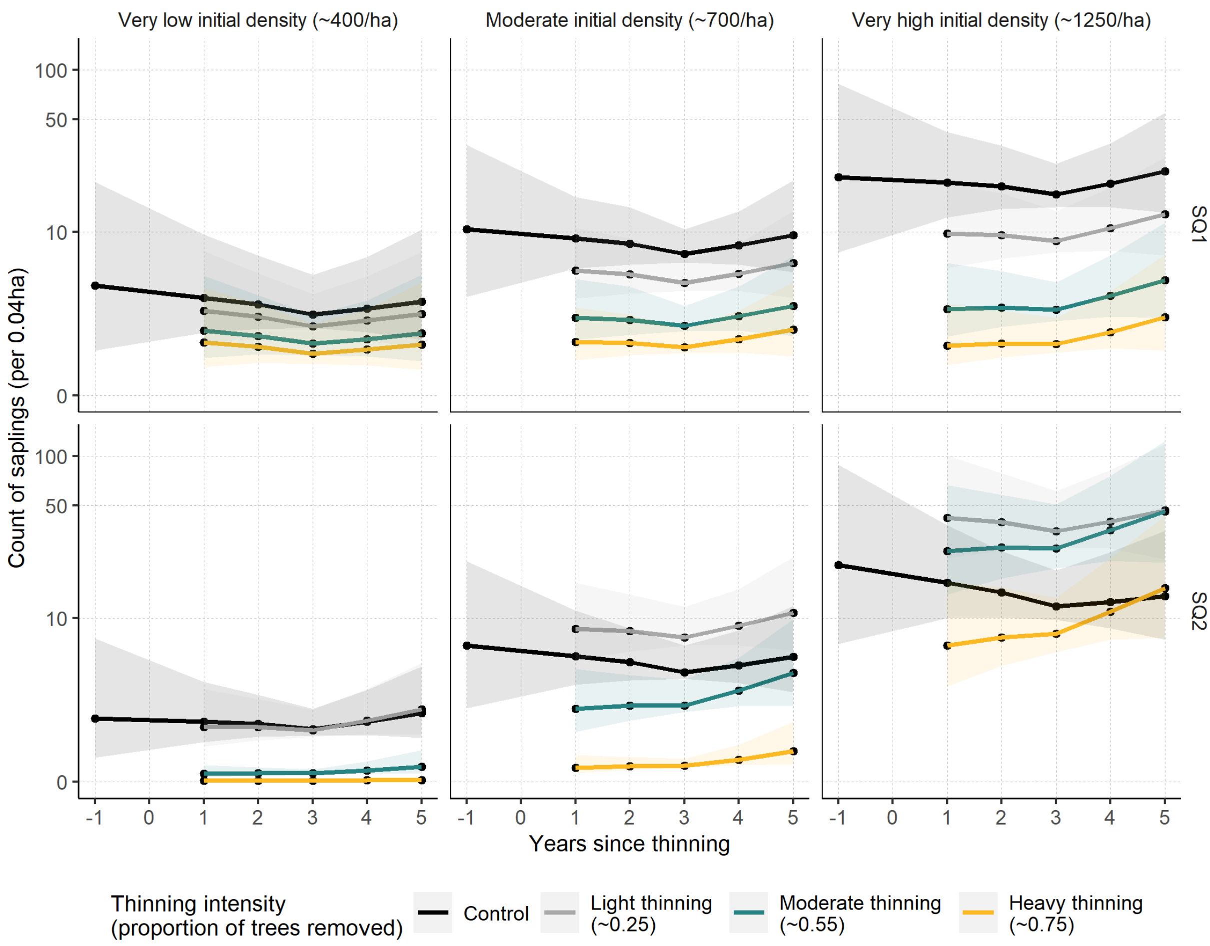

Figure 47 Modelled values and 95% confidence intervals for abundance of saplings per 0.04-hectare subplot, on a log scale

Table 32 Statistical significance of explanatory variables on sapling abundance

	Bootstrapped likelihood ratio test significance	Description
Site Quality	0.01	Sapling abundance differed among Site Qualities
Initial tree density	0.01	Sapling abundance depended on initial tree density
Time since thinning	0.01	Sapling abundance changed over time
Thinning intensity	NA	A model without this term could not be fitted to the data. Therefore, sapling abundance may have depended on thinning intensity
Does the effect of thinning intensity vary depending on:		
• Site Quality	0.01	The effect of thinning on sapling abundance depended on Site Quality
• Initial tree density	0.25	The effect of thinning on sapling abundance did not depend on initial tree density
• Time since thinning	0.01	The effect of thinning on sapling abundance changed over time
• Site Quality **and** initial tree density **and** time since thinning	NA	Four-way interaction was not included in the model

Table 33 Estimated effect sizes for sapling abundance in thinned plots relative to control plots, 5 years post-thinning, showing difference between fitted values and 95% confidence intervals in thinned plots relative to control plots

Site Quality		Site Quality 1			Site Quality 2		
Thinning intensity		Low intensity	Mod intensity	High intensity	Low intensity	Mod intensity	High intensity
Initial tree density	Very low (400/ha)	–0.7 –2.0 to +4.0	–1.5 –2.5 to +1.8	–1.9 –2.8 to +1.3	+0.2 –0.8 to +2.9	–1.9 –2.0 to –1.4	–2.22 –2.24 to –2.15
	Moderate (700/ha)	–3.2 –5.8 to +4.0	–6.3 –7.7 to –2.5	–7.4 –8.4 to –4.8	+5.1 +0.6 to +18.2	–1.3 –3.1 to +4.2	–4.8 –5.2 to –3.8
	Very high (1250/ha)	–10.9 –16.7 to +5.3	–18.9 –21.2 to –12.4	–21.1 –22.5 to –16.7	+32.8 +9.5 to +104.5	+32.2 +8.4 to +109.9	+1.7 –6.2 to +29.4

Hypothesis evaluation

The hypothesis that ecological thinning would increase sapling survival was not assessed. Instead, the data provided some evidence to support the hypothesis that ecological thinning would initially decrease abundance of naturally occurring saplings. It is not yet apparent whether the abundance of saplings will increase over time. The data also provided evidence that, in some circumstances, ecological thinning may cause an increase in sapling abundance.

Plate 3 ***Eucalyptus camaldulensis*** **seedling.** Nicholas Chu

9. Results: Structural diversity

9.1 Structural diversity of the midstorey stratum

Hypothesis	1g. Ecological thinning will increase structural diversity of midstorey strata.
Key result	No evidence of an effect of ecological thinning, however no statistical analyses were conducted due to a lack of data. Only 3 midstorey shrub species were recorded on fewer than a quarter of 9-hectare plots across all surveys, and they tended to occur on the same plots over time.

Data collection

Data were collected annually in three 0.04-hectare subplots per 9-hectare plot (see 20 x 20 metre subplots in Figure 5), over 6 survey seasons. In 2021–22, 15% of 0.04-hectare subplots were not able to be surveyed due to flooding.

All native and exotic plant species were recorded and classified by growth form. Midstorey stratum growth forms were shrubs and did not include saplings of *Eucalyptus camaldulensis*.

Data summary

Three native shrub species (>1.2 metres in height) were recorded in a total of fifteen 9-hectare plots over the 6 survey seasons: *Acacia dealbata* (Silver Wattle), *Exocarpos strictus* (Dwarf Cherry) and *Solanum aviculare* (Kangaroo Apple).

Acacia dealbata was recorded in 2 drier (SQ2) 9-hectare plots in the east of the study area, both of which were heavily thinned (Figure 48). In one of the 9-hectare plots, *A. dealbata* was recorded in two 0.04-hectare subplots prior to thinning, and then after thinning was recorded in either 2 or 3 subplots. In the other 9-hectare plot, *A. dealbata* was not recorded pre-thinning, but was recorded in one subplot in every post-thinning survey.

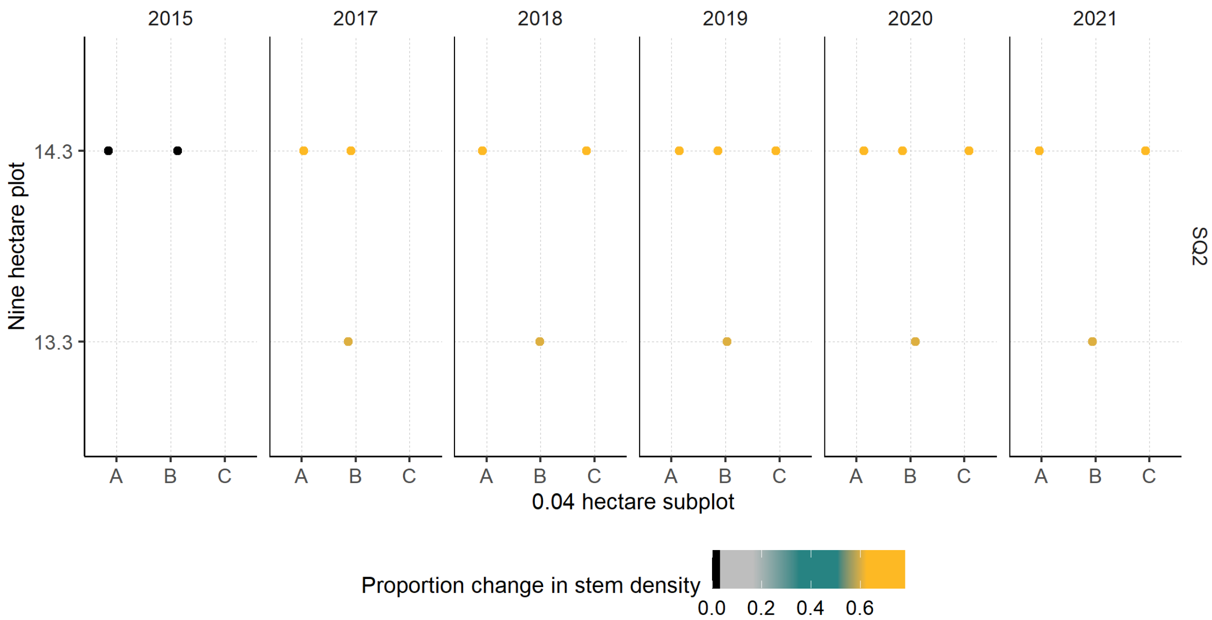

Figure 48 ***Acacia dealbata* records**

Exocarpos strictus was recorded in twelve 9-hectare plots in 6 sites over the 6 survey periods, most of which were in Site Quality 1 (Figure 49). In control plots, *E. strictus* was recorded in same 3 subplots every year (with the exception of one subplot in 2021). In addition, it was recorded on one control subplot as a seedling one year but not subsequently. *E. strictus* was recorded in 9 plots that were thinned. In 3 of the thinned plots, *E. strictus* was recorded prior to thinning but was not recorded in post-thinning years. In the other 6 plots, *E. strictus* was recorded in 2015–16 and all subsequent years (except for one subplot in 2021).

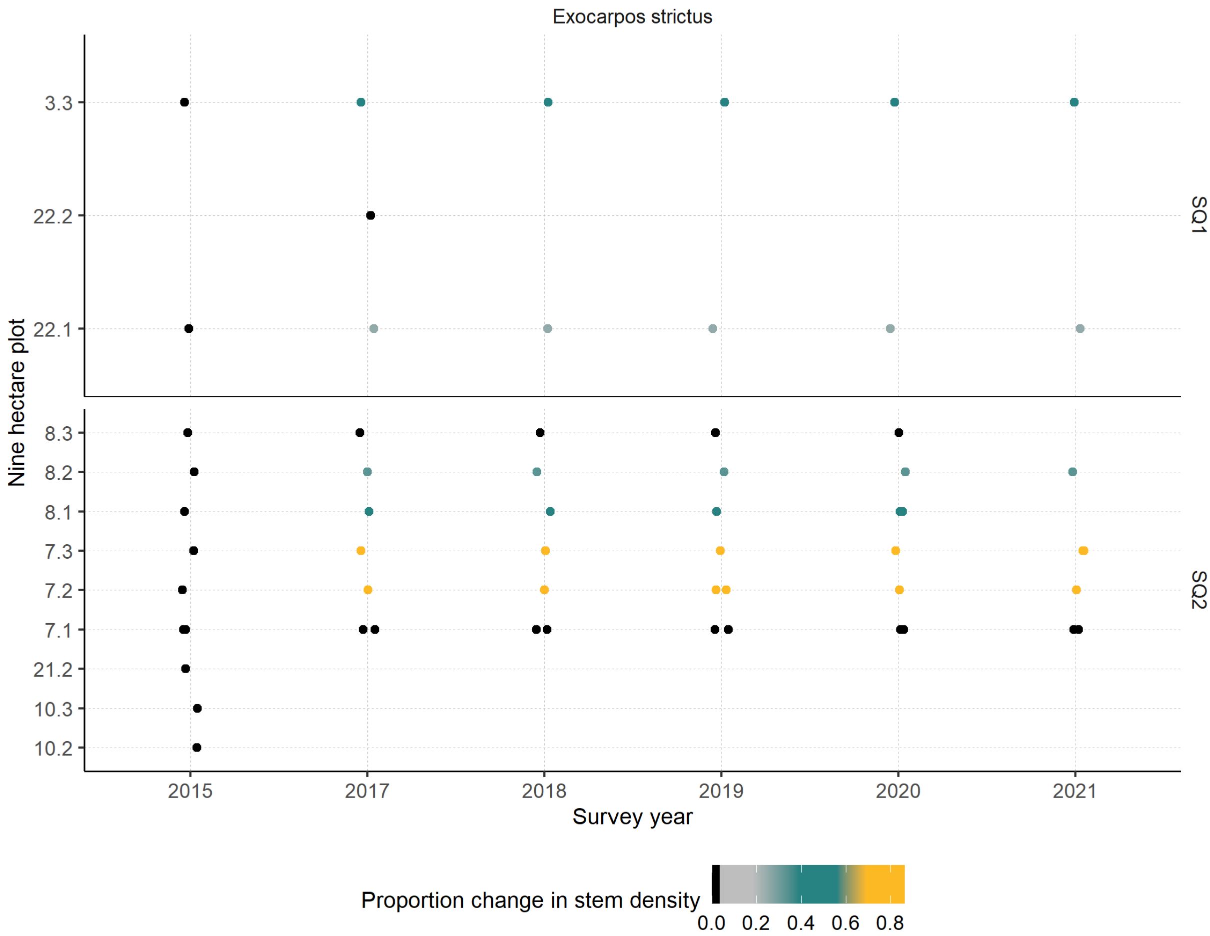

Figure 49 ***Exocarpos strictus* records**

There was only one record of one *Solanum aviculare* seedling in a Site Quality 2 control plot in 2020–21, which was not subsequently recorded.

Hypothesis evaluation

There were insufficient data to conduct statistical analyses.

9.2 Heterogeneity in understorey height

Hypothesis	1g. Ecological thinning will increase the structural diversity of understorey strata.
Key result	Marginally significant ($p = 0.05$) effect of ecological thinning that **decreased** variation in understorey height in most plot types (by 9%) but **increased** it in drier Site Quality 2 plots with very high initial tree density (by 20%).

Data collection

Understorey strata was defined as ground vegetation up to 2 metres in height. Ten measurements of understorey height were taken from a representative range of understorey plants in each of the three 0.04-hectare subplots per 9-hectare treatment plot (see 20 x 20 metre subplots in Figure 5). Understorey height was measured annually, but only in 2020–21 and 2021–22 were individual plant heights measured, allowing the coefficient of variation to be calculated. In 2021–22, 15% of 0.04-hectare subplots were not able to be surveyed due to flooding.

The coefficient of variation (CV) represents the spread of data. CV is calculated by determining the standard deviation of the data and dividing it by the mean of the data. We calculated the CV for the understorey height in each 0.04-hectare subplot. Subplots with a low CV had many similar estimates of understorey height; subplots with a high CV had a range of different height estimates. A CV of 0.5 means that the standard deviation is half of the mean.

Data summary

The coefficient of variation for understorey height ranged from 0.34 to 1.61, with an average of 0.92 (Figure 50). Understorey height CV was highest in moderate initial tree density subplots in both Site Qualities, and appeared to be higher, on average, in Site Quality 1 subplots (Figure 50). There were no obvious consistent differences between thinning intensities or change over time (Figure 50).

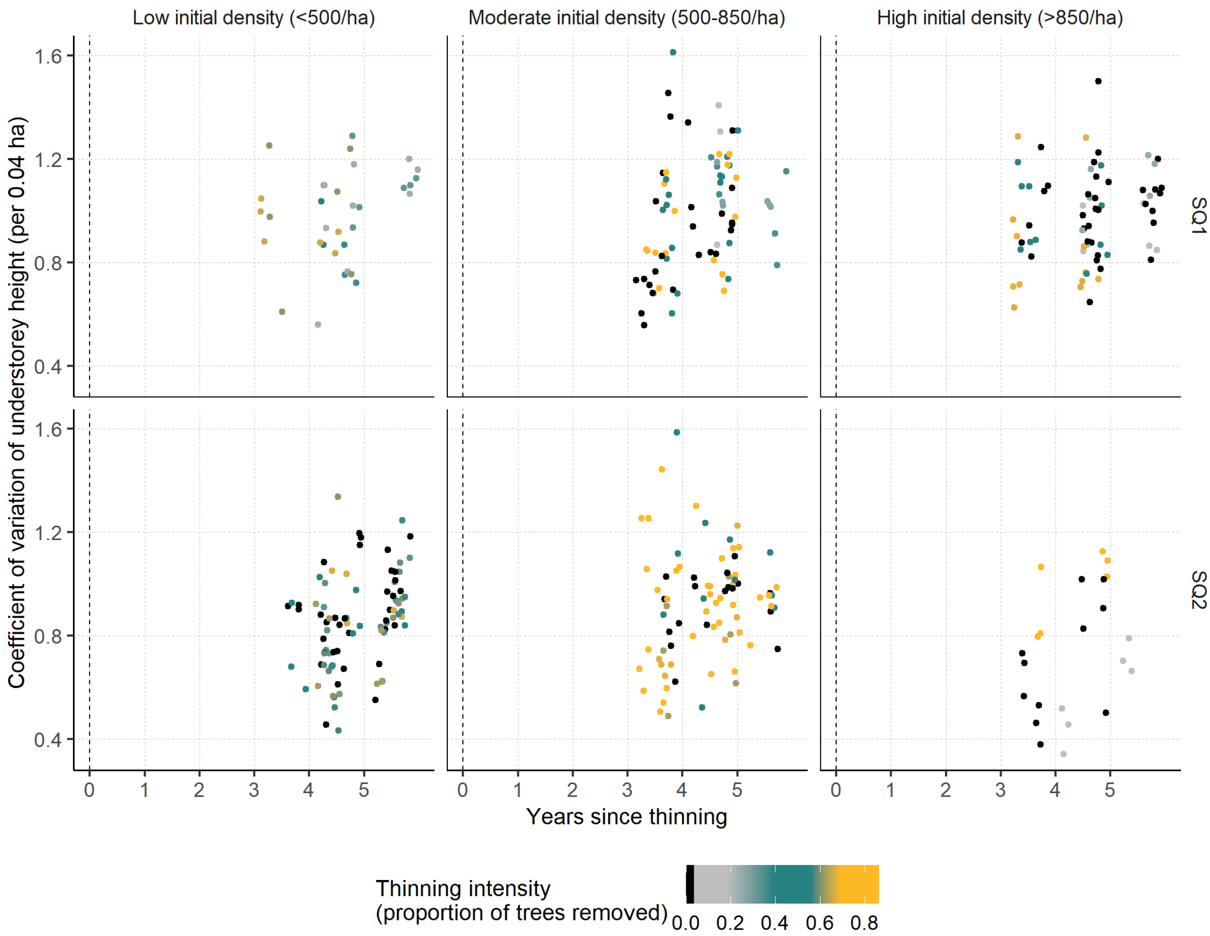

Figure 50 Data for understorey height CV per 0.04-hectare subplot

Model results

Understorey height CV was modelled using a Gaussian distribution with a log link (see Appendices). The model for understorey height CV included a four-way interaction between Site Quality, initial tree density, time since thinning and thinning intensity, as well as all two-way and three-way interactions. A random effect for subplot was included, but site, 9-hectare plot, and survey year were not.

Modelled values of understorey height CV significantly increased from 2020–21 to 2021–22, even in control plots (Table 34, Figure 51), averaging a change of 0.07 metres. The maximum increase (of 0.17 metres) between years was in Site Quality 2 very high initial tree density control plots. Understorey height CV varied with initial tree density and was highest in Site Quality 1 moderate initial tree density sites (Table 34, Figure 51).

There was a significant effect of thinning on understorey height CV, and some evidence (p = 0.07) that this effect varied among Site Qualities (Table 34, Figure 51). In Site Quality 1 subplots, there were no significant, or consistent, effects of thinning on understorey height CV (Table 35, Figure 51). In Site Quality 2 subplots, there was a negative effect of thinning on understorey height CV in very low initial tree density subplots (with the effect significant for heavy thinning). The opposite pattern was apparent in very high initial tree density subplots, with moderate and heavy thinning significantly increasing CV compared to control subplots (Table 35, Figure 51). In Site Quality 2, there was no evidence of an effect of thinning in moderate initial tree density subplots (Table 35, Figure 51).

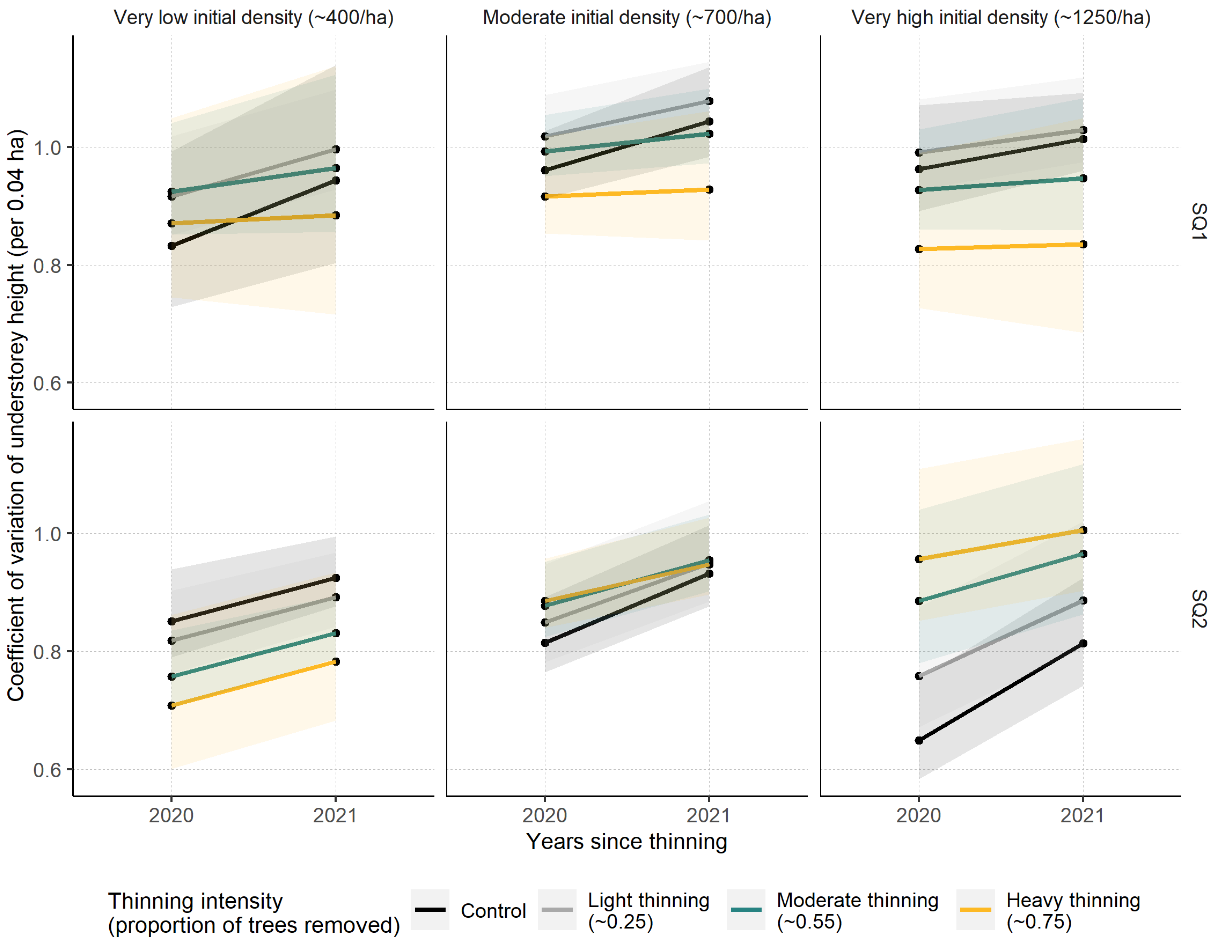

Figure 51 Modelled values and 95% confidence intervals for understorey height CV per 0.04-hectare subplot

Table 34 Statistical significance of explanatory variables on understorey height CV

	Bootstrapped likelihood ratio test significance	Description
Site Quality	0.01	Understorey height CV differed among Site Qualities
Initial tree density	0.02	Understorey height CV depended on initial tree density
Time since thinning	0.02	Understorey height CV changed over time
Thinning intensity	0.05	Understorey height CV was affected by thinning intensity
Does the effect of thinning intensity vary depending on:		
• Site Quality	0.07	The effect of thinning on understorey height CV may have depended on Site Quality

	Bootstrapped likelihood ratio test significance	Description
• Initial tree density	0.14	The effect of thinning on understorey height CV did not depend on initial tree density
• Time since thinning	0.66	The effect of thinning on understorey height CV did not change over time
• Site Quality **and** initial tree density **and** time since thinning	0.50	The effect of thinning was not dependent on additional interactions with the 3 other predictors

Table 35 Estimated effect sizes for understorey height CV in thinned plots 5 years post-thinning, showing difference between fitted values and 95% confidence intervals in thinned plots relative to control plots

Site Quality		**Site Quality 1**			**Site Quality 2**		
Thinning intensity		Low intensity	Mod intensity	High intensity	Low intensity	Mod intensity	High intensity
Initial tree density	Very low (400/ha)	+0.06 −0.01 to +0.16	+0.02 −0.08 to +0.18	−0.06 −0.22 to +0.20	−0.03 −0.08 to +0.05	−0.09 −0.13 to −0.03	−0.14 −0.24 to +0.01
	Moderate (700/ha)	+0.04 −0.01 to +0.10	−0.02 −0.07 to +0.06	−0.11 −0.20 to +0.02	+0.02 −0.05 to +0.12	+0.02 −0.03 to +0.10	+0.02 −0.03 to +0.10
	Very high (1250/ha)	+0.02 −0.04 to +0.11	−0.06 −0.15 to +0.07	−0.17 −0.33 to +0.04	+0.08 −0.004 to +0.21	+0.16 +0.05 to +0.31	+0.20 +0.09 to +0.35

Hypothesis evaluation

There was some evidence to support the hypothesis that ecological thinning increased the structural diversity of understorey strata in plot types with the highest pre-thinning levels of competition for resources: drier (SQ2) sites with very high initial tree density. However, in other plot types the hypothesis was unsupported.

10. Results: Coarse woody debris

10.1 Coarse woody debris volume

Hypothesis	1h. Ecological thinning will result in higher levels of coarse woody debris (45–50 tonnes per hectare or 32–35.5 cubic metres) maintained in the long term.
Key result	**No evidence of a statistically significant effect of ecological thinning.**

Data collection

Coarse woody debris (CWD, logs with diameter >10 centimetres and length >0.5 metres) was measured in two 0.1-hectare subplots within each 9-hectare plot (see the central two 20 x 50 metre plots in Figure 5), by recording the midpoint diameter and length of each log.

Coarse woody debris data were collected pre-thinning (2015–16), one year post-thinning (2017–18) and 5 years post-thinning (2021–22).

The volume of each piece of CWD was calculated and summed to determine volume (cubic metres, m^3) per 0.1 hectare.

Coarse woody debris volume (in cubic metres) can be converted into weight (in tonnes) by multiplying by the specific density of *E. camaldulensis* wood.

Thinning operation protocols stipulated that felled trees would be retained on-site where pre-thinning CWD was below 45–50 tonnes per hectare (equivalent to 32–35.5 cubic metres). No 9-hectare plots had below 45–50 tonnes per hectare prior to thinning, and therefore no additional CWD was retained.

Data summary

Prior to ecological thinning the average volume of CWD in a 0.1-hectare subplot was 12.8 m^3 (that is, 128 m^3 per hectare). Prior to thinning, the volume of CWD in wetter (SQ1) plots was greater than in drier (SQ2), particularly in high initial tree density plots (Figure 52).

Across all years and subplots, there was a wide range of values recorded for volume of CWD (0.3 to 43.7 m^3 per 0.1 hectare), with an average of 13.2 m^3. The volume of CWD showed little evidence of change over time (Figure 52). As for the pre-thinning time period, after thinning the volume of CWD in wetter (SQ1) was greater than in drier (SQ2) sites, particularly in high initial tree density plots (Figure 52).

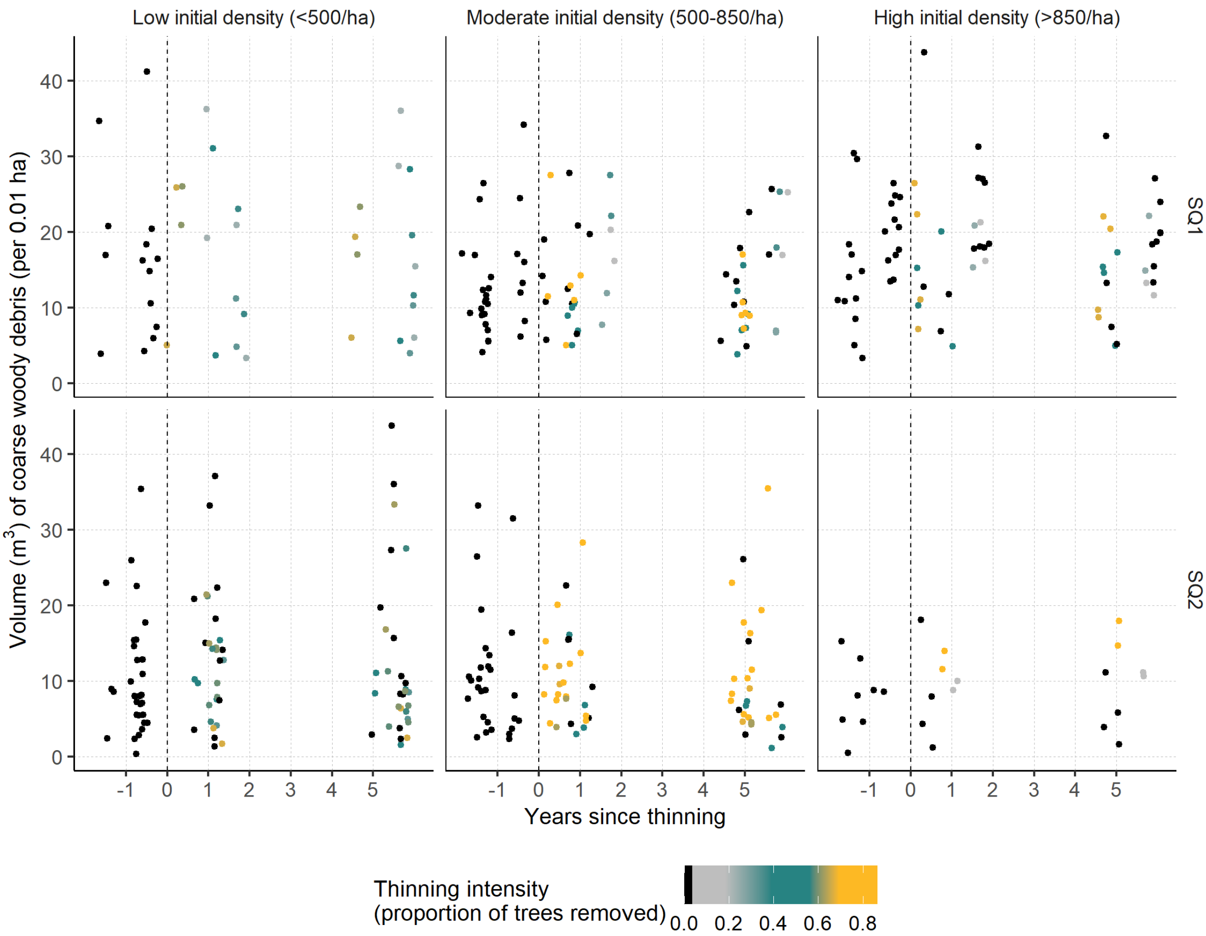

Figure 52 Data for coarse woody debris volume (metres^3) per 0.1-hectare subplot

Model results

CWD volume was modelled using a gamma distribution with a log link (see Appendices). The model did not include four-way interaction between Site Quality, initial tree density, time since thinning and thinning intensity, or three-way interaction between initial tree density, time since thinning and thinning intensity, but included all other two-way and three-way interactions. Random effects for site, 9-hectare plot and 0.1-hectare subplot were included in the model.

The modelled values of CWD volume were higher for wetter (SQ1) sites than drier (SQ2) sites but the difference was not statistically significant (Table 36).

There was a slight decrease in CWD volume over time after thinning, but this effect was not statistically significant (Table 36). Wide confidence intervals around model predictions were due to high variance in the raw data.

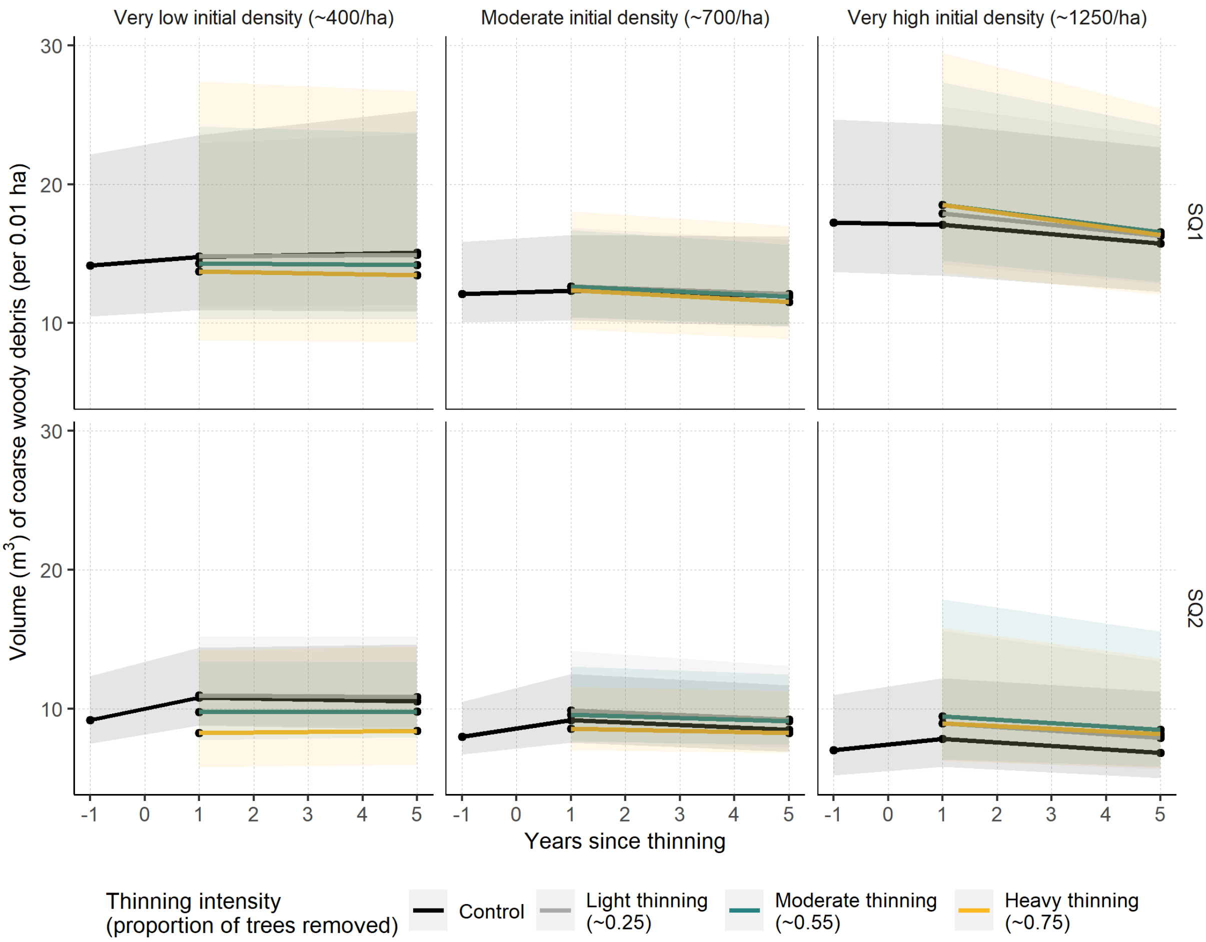

Figure 53 Modelled values and 95% confidence intervals for coarse woody debris volume (metres³) per 0.1-hectare subplot

Table 36 Statistical significance of explanatory variables on coarse woody debris volume (metres³) per 0.1-hectare subplot

	Bootstrapped likelihood ratio test significance	Description
Site Quality	0.17	CWD volume did not differ among Site Qualities
Initial tree density	0.55	CWD volume did not depend on initial tree density
Time	0.64	CWD volume did not change over time
Thinning intensity	0.98	CWD volume was not affected by thinning intensity
Does the effect of thinning intensity vary depending on:		
• Site Quality	0.99	The effect of thinning on CWD volume did not depend on Site Quality
• Initial tree density	0.62	The effect of thinning on CWD volume did not depend on initial tree density

	Bootstrapped likelihood ratio test significance	Description
• Time	0.87	The effect of thinning on CWD volume did not change over time
• Site Quality **and** initial tree density **and** time	NA	Four-way interaction was not included in the model

Table 37 Estimated effect sizes for coarse woody debris volume (metres³) per 0.1-hectare subplot, showing difference between fitted values and 95% confidence intervals in thinned plots relative to control plots

Site Quality		Site Quality 1			Site Quality 2		
Thinning intensity		Low intensity	Mod intensity	High intensity	Low intensity	Mod intensity	High intensity
Initial tree density	Very low (400/ha)	–0.2 –3.8 to +8.5	–0.9 –4.8 to +8.6	–1.6 –6.5 to +11.6	+0.3 –1.8 to +4.6	–0.7 –2.6 to +2.8	–2.1 –4.6 to +3.9
	Moderate (700/ha)	+0.1 –2.0 to +4.1	–0.1 –2.2 to +3.7	–0.5 –3.1 to +5.1	+0.8 –1.3 to +4.6	+0.6 –1.1 to +4.0	–0.2 –1.7 to +2.8
	Very high (1250/ha)	+0.6 –2.9 to +7.7	+0.8 –2.8 to +8.5	+0.6 –3.7 to +9.7	+1.1 –1.2 to +6.6	+1.7 –1.0 to +8.7	+1.3 –1.1 to +6.8

Hypothesis evaluation

There was no evidence that ecological thinning increased coarse woody debris volume.

10.2 Coarse woody debris size heterogeneity

Hypothesis	No hypothesis was specified for heterogeneity in coarse woody debris size, but analyses in 2017–18 suggested that ecological thinning had increased the relative abundance of small pieces of CWD.
Key result	**No evidence of a statistically significant effect of ecological thinning.**

Data collection

Coarse woody debris (CWD, logs with diameter >10 centimetres and length >0.5 metres) were measured in two 0.1-hectare subplots within each 9-hectare plot (see Figure 5), by recording the diameter and length of each log.

Coarse woody debris data were collected pre-thinning (2015–16), one year post-thinning (2017–18) and 5 years post-thinning (2021–22).

The coefficient of variation (CV) represents the spread of data. CV is calculated by determining the standard deviation of the data and dividing it by the mean of the data. We calculated the CV for the diameter of all pieces of CWD in each 0.1-hectare subplot. Subplots with a low CV had many similar sized pieces of coarse woody debris; subplots with a high CV had a range of different sized pieces.

Data summary

Prior to ecological thinning the average coefficient of variation of CWD in a 0.1-hectare subplot was 0.63 (Figure 54). Across all years and subplots, the CV of CWD ranged from 0.25 to 1.13, with an average of 0.64. Only 3 subplots had CV of CWD over 1. Values did not appear to vary substantially by initial tree density, Site Quality, or thinning intensity (Figure 54). CWD CV showed little evidence of change over time (Figure 54).

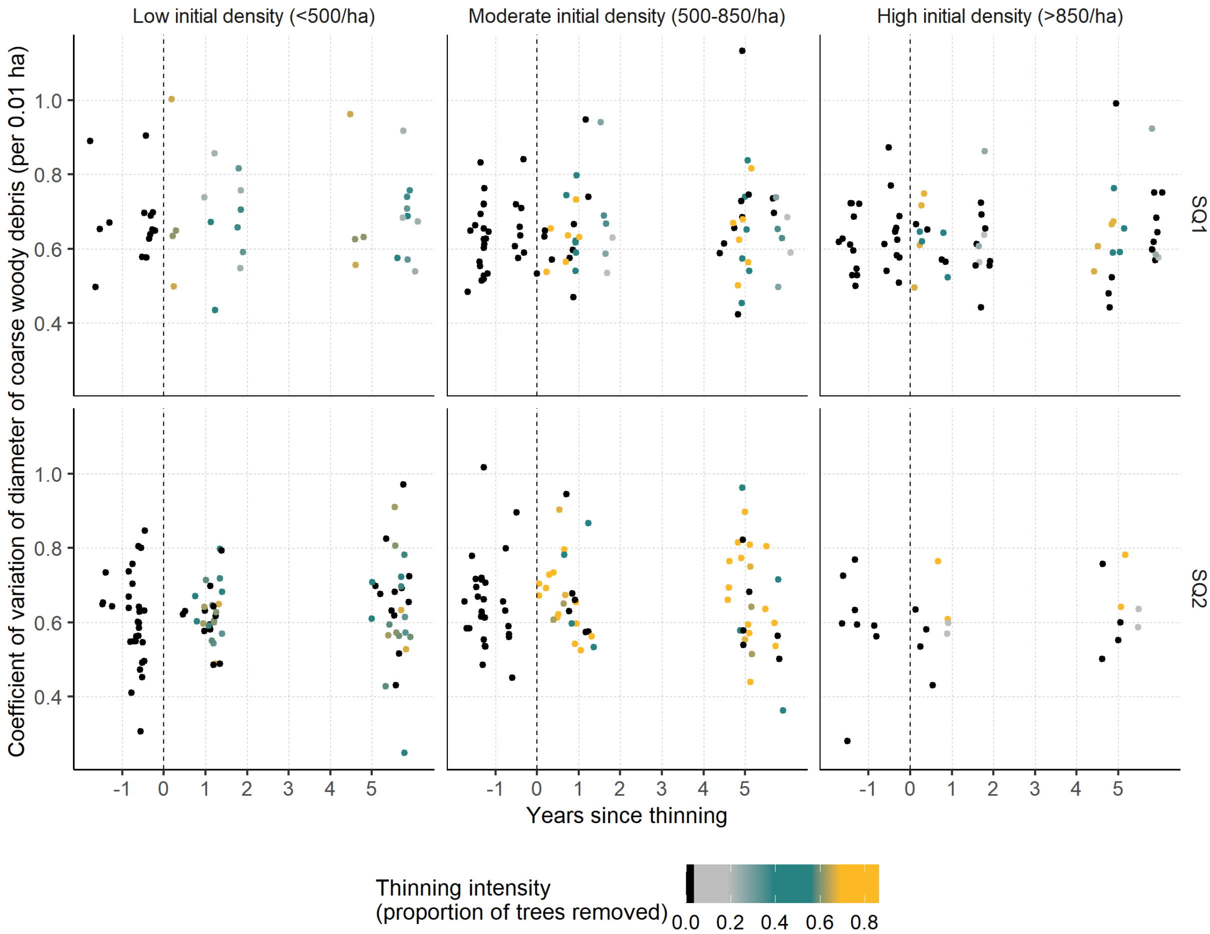

Figure 54 Data for coarse woody debris coefficient of variation in diameter size per 0.1-hectare subplot

Model results

The coefficient of variation of the diameter of CWD pieces was modelled using a gamma distribution with a log link (see Appendices). The model did not include four-way interaction between Site Quality, initial tree density, time since thinning and thinning intensity, or three-way interaction between initial tree density, time since thinning and thinning intensity, but included all other two-way and three-way interactions. The model included random effects of site, 9-hectare plot and 0.1-hectare subplot, but did not include a random effect of survey year.

In the absence of ecological thinning, the CV of CWD was highest in wetter (SQ1) sites with very low initial tree density, but this difference was not statistically significant (Figure 55, Table 38). CV of CWD appeared to increase over time, but this change was not statistically significant.

Ecological thinning increased the heterogeneity of CWD sizes in drier (SQ2) plots with moderate and very high initial tree density (Figure 55) but this was not statistically significant (Table 38, Table 36).

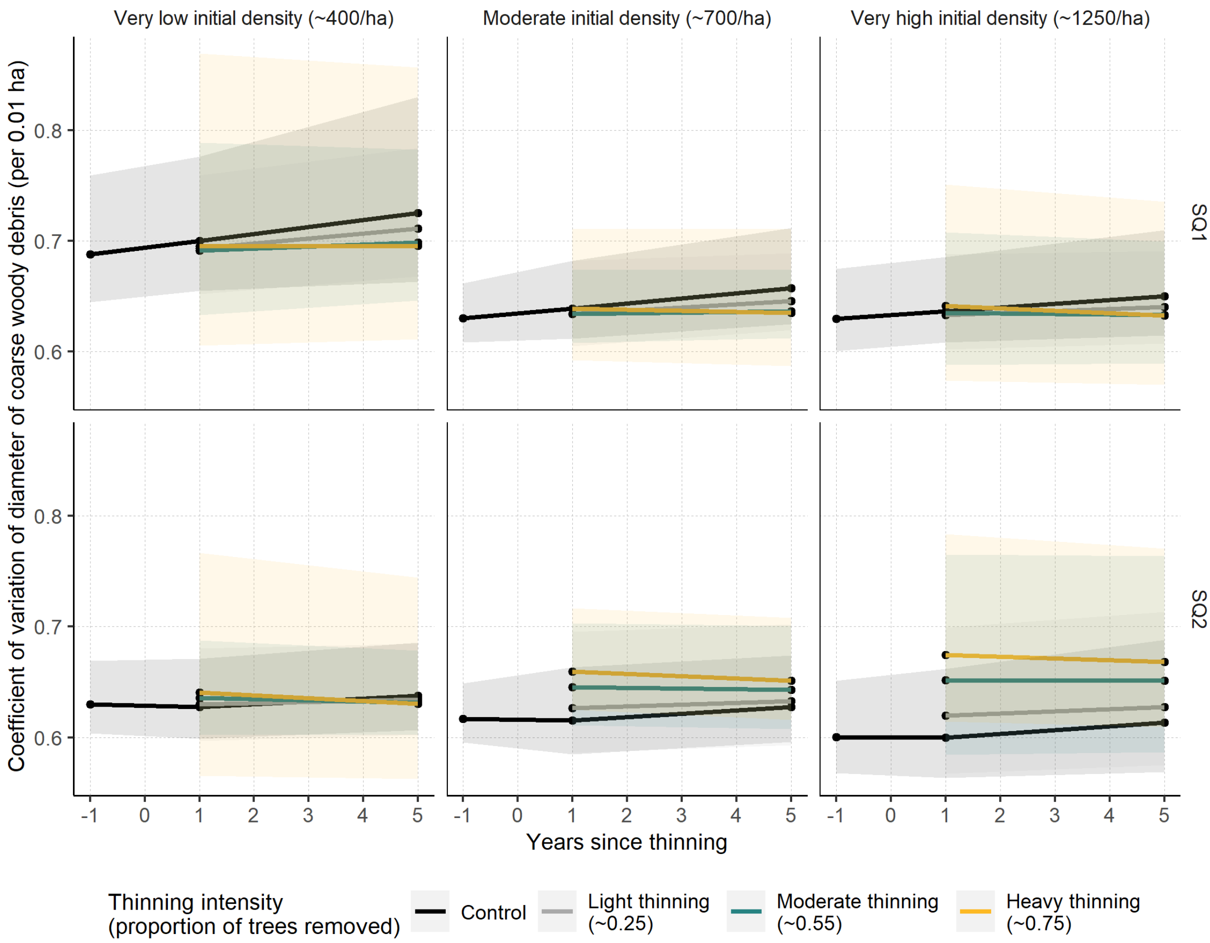

Figure 55 Modelled values and 95% confidence intervals for coarse woody debris coefficient of variation in diameter size per 0.1-hectare subplot

Table 38 Statistical significance of explanatory variables on coarse woody debris coefficient of variation in diameter size per 0.1-hectare subplot

	Bootstrapped likelihood ratio test significance	Description
Site Quality	0.78	CWD CV did not differ among Site Qualities
Initial tree density	0.79	CWD CV did not depend on initial tree density
Time	0.98	CWD CV did not change over time
Thinning intensity	0.92	CWD CV was not affected by thinning intensity
Does the effect of thinning intensity vary depending on:		
• Site Quality	0.83	The effect of thinning on CWD CV did not depend on Site Quality
• Initial tree density	0.80	The effect of thinning on CWD CV did not depend on initial tree density
• Time	0.58	The effect of thinning on CWD CV did not change over time
• Site Quality **and** initial tree density **and** time	NA	Four-way interaction was not included in the model

Table 39 Estimated effect sizes for coarse woody debris coefficient of variation in diameter size per 0.1-hectare subplot, showing difference between fitted values and 95% confidence intervals in thinned plots relative to control plots

Site Quality		Site Quality 1			Site Quality 2		
Thinning intensity		Low intensity	Mod intensity	High intensity	Low intensity	Mod intensity	High intensity
Initial tree density	Very low (400/ha)	–0.01 –0.05 to +0.06	–0.02 –0.07 to +0.06	–0.02 –0.11 to +0.14	–0.01 –0.04 to +0.05	–0.01 –0.04 to +0.04	–0.01 –0.08 to +0.10
	Moderate (700/ha)	–0.01 –0.04 to +0.03	–0.02 –0.05 to +0.01	–0.02 –0.07 to +0.05	0.00 –0.04 to +0.07	+0.01 –0.02 to +0.07	+0.02 –0.01 to +0.08
	Very high (1250/ha)	–0.01 –0.04 to +0.04	–0.02 –0.06 to +0.05	–0.02 –0.08 to +0.09	+0.02 –0.04 to +0.10	+0.04 –0.02 to +0.15	+0.06 –0.001 to +0.16

Hypothesis evaluation

No evidence that ecological thinning affected the variation in size of coarse woody debris.

11. Results: Leaf litter heterogeneity

11.1 Heterogeneity in leaf litter cover

Hypothesis	1i. Ecological thinning will increase heterogeneity in cover of forest litter in the long term.
Key result	Marginally significant (p = 0.08) effect ecological thinning that changed over time, resulting in a 1–10% **increase** in leaf litter heterogeneity (per 0.01-hectare subplot) in some heavily thinned plots in some years.

Data collection

Litter was defined as any dead plant material that was separated from a live plant and included material <1 millimetre in diameter. Note that the definition of litter was refined between 2015 and 2018, which reduced uncertainty in observer estimates.

Litter cover was visually estimated in 10 quadrats (1 x 1 metre) within each of the three 0.04-hectare subplots in each 9-hectare treatment plot (see 20 x 20 metre subplots in Figure 5). Surveys were conducted annually, over 6 survey years. In 2021–22, 15% of 0.04-hectare subplots were not able to be surveyed due to flooding.

The coefficient of variation (CV) represents the spread of data. CV is calculated by determining the standard deviation of the data and dividing it by the mean of the data. We calculated the CV for the litter cover in 10 quadrats in each 0.04-hectare subplot. Subplots with a low CV had many similar estimates of litter cover; subplots with a high CV had a range of different cover estimates.

Data summary

The majority of subplots had a coefficient of variation for litter cover less than 1, with only one subplot having a litter cover CV greater than 1.5, and this occurred at 2 points in time (Figure 56). One subplot had a litter cover CV close of 2.6. Litter cover CV appeared similar in both Site Qualities, being slightly higher in Site Quality 1 subplots (Figure 56). Litter cover CV did not appear to change substantially over time, though was lowest in the last year of monitoring (Figure 56).

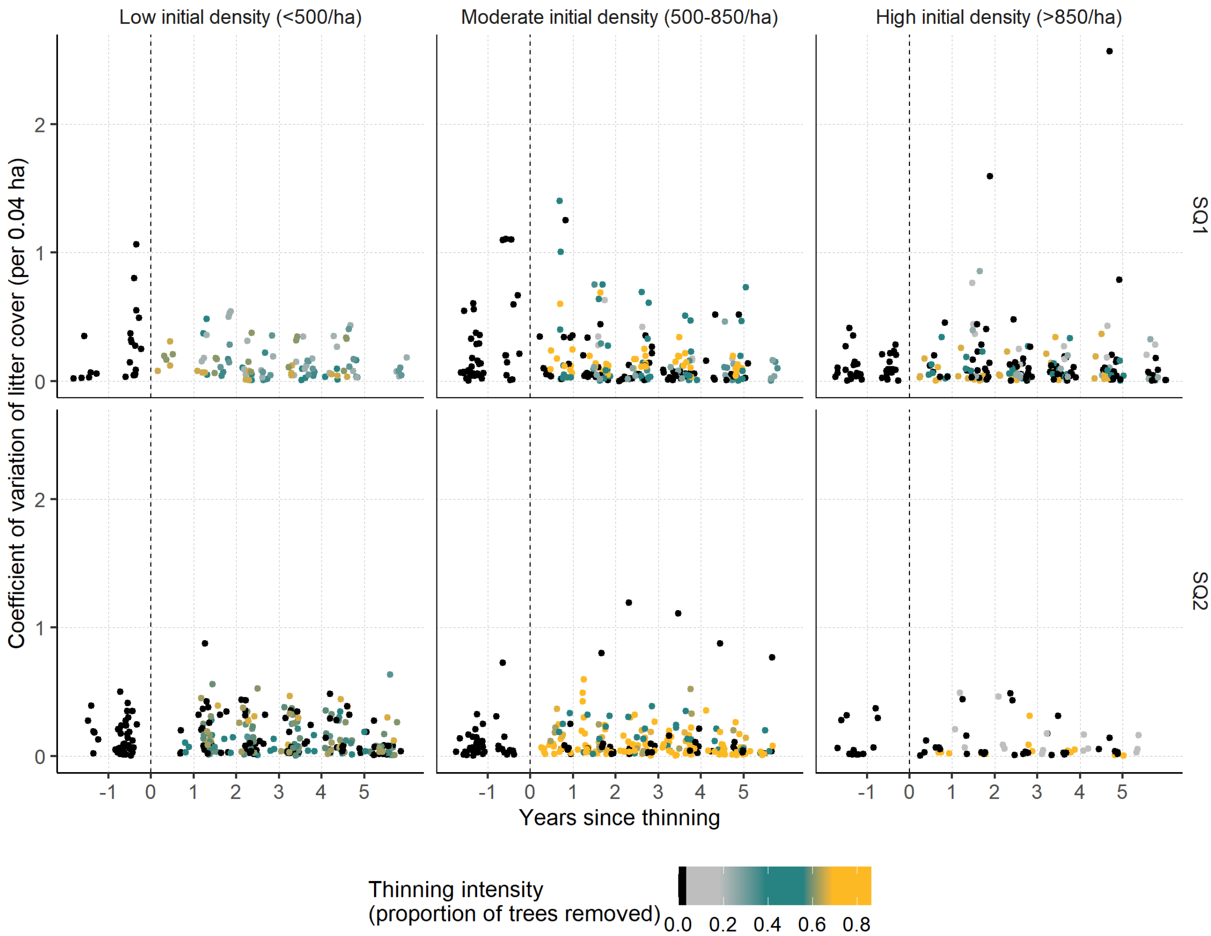

Figure 56 Data for litter cover coefficient of variation in each 0.04-hectare subplot

Model summary

Leaf litter CV was modelled using a gamma distribution with a log link (see Appendices). The model for litter cover CV did not include four-way interaction between Site Quality, initial tree density, time since thinning and thinning intensity, but included all two-way and three-way interactions. A random effect of subplot was included, but random effects of survey year, site and 9-hectare plot were not included.

Modelled values of heterogeneity in litter cover were significantly greater in Site Quality 1 subplots than Site Quality 2 subplots (Table 40, Figure 57). There was a statistically significant effect of initial tree density, but the magnitude of the effect was small.

There was some evidence that the effect of thinning on litter cover CV changed over time ($p = 0.08$) (Table 40, Figure 57). In Site Quality 1 plots that had moderate and very high initial density, litter cover CV was relatively constant over time in thinned plots but declined over time in control plots. Note that where initial density was very high, the increase occurred after an initial decrease. In Site Quality 1 plots that had very low initial density, thinning caused an initial increase in litter CV which was sustained over time. Five years post-thinning, there was a 1–10% increase in heterogeneity of leaf litter cover in these plots (Table 41).

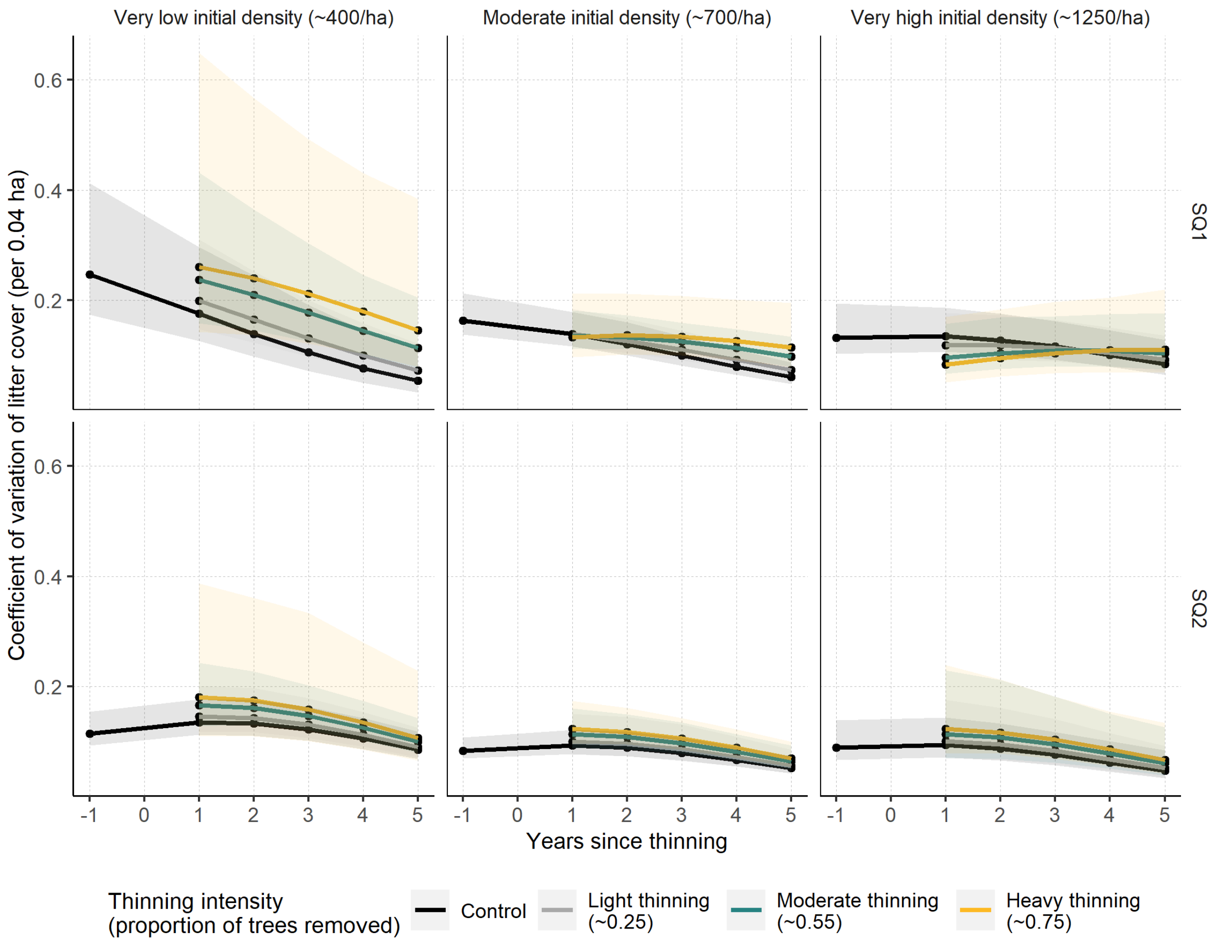

Figure 57 Modelled values and 95% confidence intervals for litter cover CV per 0.04-hectare subplot

Table 40 Statistical significance of explanatory variables on litter cover CV

	Bootstrapped likelihood ratio test significance	Description
Site Quality	0.01	Litter cover CV differed among Site Qualities
Initial tree density	0.04	Litter cover CV depended on initial tree density
Time since thinning	0.01	Litter cover CV changed over time
Thinning intensity	0.35	Litter cover CV was not affected by thinning intensity
Does the effect of thinning intensity vary depending on:		
• Site Quality	0.36	The effect of thinning on litter cover CV did not depend on Site Quality
• Initial tree density	0.78	The effect of thinning on litter cover CV did not depend on initial tree density

	Bootstrapped likelihood ratio test significance	Description
• Time since thinning	0.08	The effect of thinning on litter cover CV may have changed over time
• Site Quality **and** initial tree density **and** time since thinning	NA	Four-way interaction was not included in the model

Table 41 Estimated effect sizes for litter cover CV in thinned plots relative to control plots, 5 years post-thinning, showing difference between fitted values and 95% confidence intervals in thinned plots relative to control plots

Site Quality		Site Quality 1			Site Quality 2		
Thinning intensity		Low intensity	Mod intensity	High intensity	Low intensity	Mod intensity	High intensity
Initial tree density	Very low (400/ha)	+0.02 +0.002 to +0.07	+0.06 +0.03 to +0.16	+0.10 +0.03 to +0.33	0.00 –0.02 to +0.04	+0.01 –0.01 to +0.05	+0.02 –0.02 to +0.14
	Moderate (700/ha)	+0.01 +0.002 to +0.04	+0.04 +0.02 to +0.08	+0.05 +0.02 to +0.14	+0.01 –0.01 to +0.04	+0.01 +0.001 to +0.04	+0.02 +0.01 to +0.05
	Very high (1250/ha)	0.00 –0.02 to +0.05	+0.01 –0.02 to +0.09	+0.02 –0.02 to +0.13	0.00 –0.02 to +0.04	+0.01 –0.01 to +0.08	+0.02 –0.01 to +0.08

Hypothesis evaluation

There was some evidence that ecological thinning increased heterogeneity in leaf litter cover in some circumstances. However, the magnitude of change was small.

11.2 Heterogeneity in leaf litter depth

Hypothesis	1i. Increased heterogeneity in depth of forest litter in the long term.
Key result	**No evidence of a statistically significant effect of ecological thinning.**

Data collection

Litter was defined as any dead plant material that was separated from a live plant and included material <1 millimetre in diameter. Note that the definition of litter was refined between 2015 and 2018, which reduced uncertainty in observer estimates.

Litter depth was measured using the method of Hines et al. (2010). A metal ruler was inserted through the litter until it rested on the soil. A cardboard disc was held gently against the litter and used to mark the height of the litter on the ruler.

Litter depth was measured in the centre of ten 1 x 1 metre quadrats in each 0.04-hectare subplot (see 20 x 20 metre subplots in Figure 5), giving 30 values per 9-hectare plot. Litter depth was averaged for each subplot. Surveys were conducted annually, over 6 survey years. In 2021–22, 15% of 0.04-hectare subplots were not able to be surveyed due to flooding.

The coefficient of variation (CV) represents the spread of data. CV is calculated by determining the standard deviation of the data and dividing it by the mean of the data. We calculated the CV for the litter depth in 10 quadrats in each 0.04-hectare subplot. Subplots with a low CV had many similar estimates of litter depth; subplots with a high CV had a range of different depth estimates.

Data summary

The majority of subplots had a coefficient of variation for litter depth less than 1, with very few having a litter depth CV greater than 1.5 (Figure 58). One subplot had a litter depth CV close to 3. Litter depth CV was similar in both Site Qualities and appeared to decrease slightly over time (Figure 58).

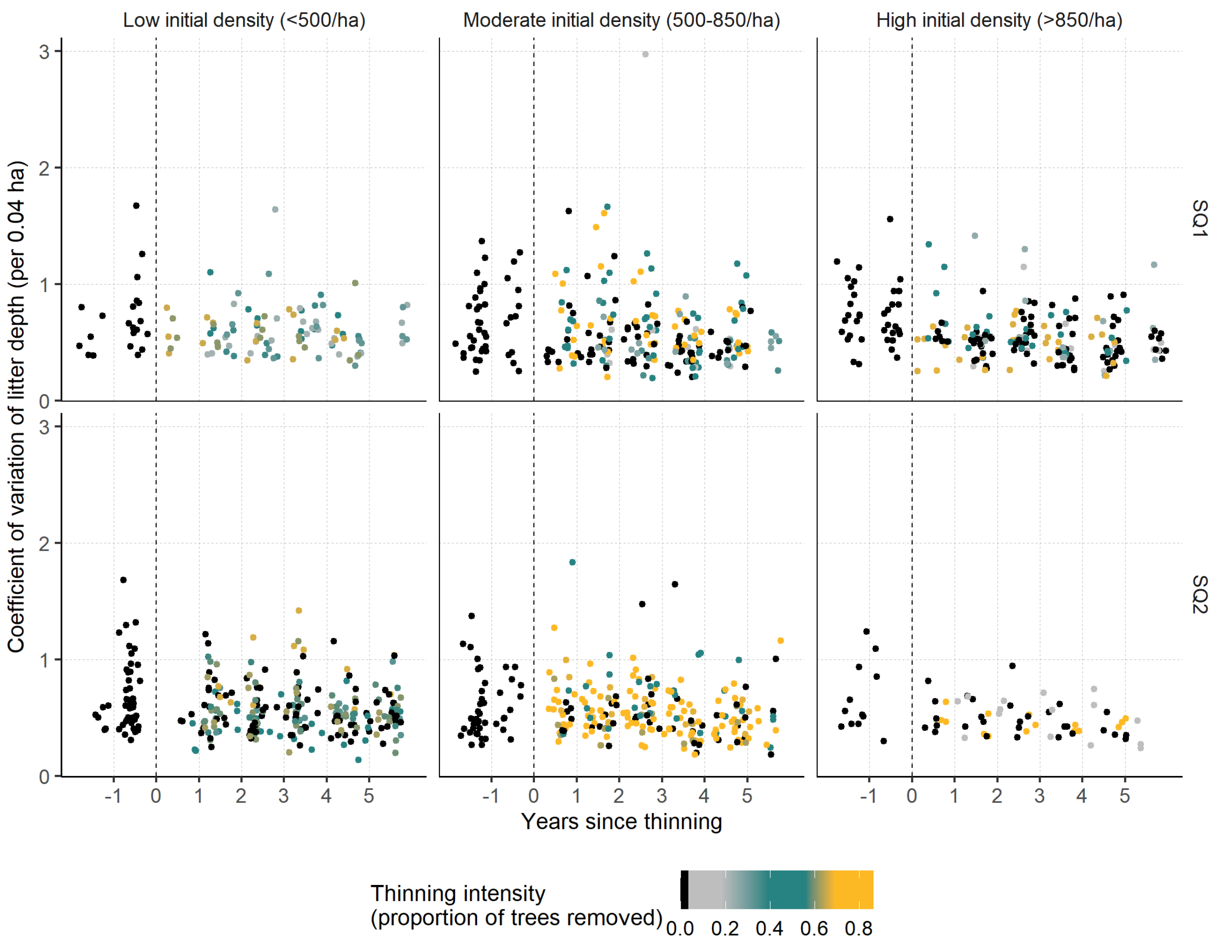

Figure 58 Data for litter depth CV per 0.04-hectare subplot

Model results

Leaf litter CV was modelled using a gamma distribution with a log link (see Appendices). One outlier value (of 2.97) was removed from the data prior to modelling. The model for litter depth CV did not include four-way interaction between Site Quality, initial tree density, time since thinning and thinning intensity, but included all two-way and three-way interactions.

Random effects of survey year and subplot were included, but site and 9-hectare plot were not.

Litter depth CV reduced slightly over time, with minimum values occurring in 2020–21, though the decline was not statistically significant (Table 42, Figure 59). There were no statistically significant differences among Site Qualities or initial tree densities.

Ecological thinning caused heterogeneity in leaf litter depth to increase on most plot types, and the effect was sustained over time. However, in drier plots with very high initial tree density ecological thinning caused litter depth CV to decrease (Figure 59). None of these effects were statistically significant (Table 42, Table 43).

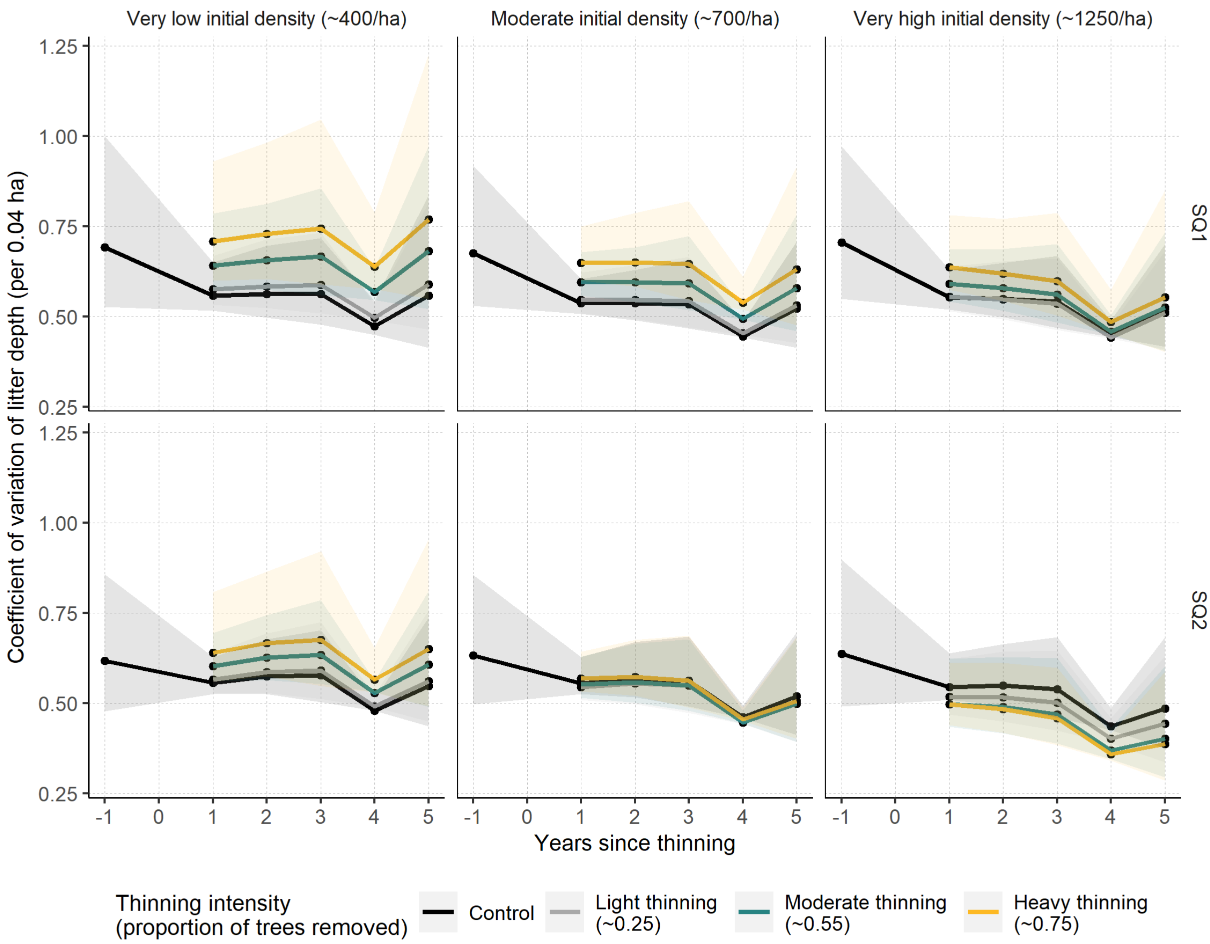

Figure 59 Modelled values and 95% confidence intervals for litter depth CV per 0.04-hectare subplot

Table 42 Statistical significance of explanatory variables on litter depth CV

	Bootstrapped likelihood ratio test significance	Description
Site Quality	0.51	Litter depth CV did not differ among Site Qualities
Initial tree density	0.22	Litter depth CV did not depend on initial tree density

	Bootstrapped likelihood ratio test significance	Description
Time since thinning	0.14	Litter depth CV did not change over time
Thinning intensity	0.47	Litter depth CV was not affected by thinning intensity
Does the effect of thinning intensity vary depending on:		
• Site Quality	0.48	The effect of thinning on litter depth CV did not depend on Site Quality
• Initial tree density	0.49	The effect of thinning on litter depth CV did not depend on initial tree density
• Time since thinning	0.85	The effect of thinning on litter depth CV did not change over time
• Site Quality **and** initial tree density **and** time since thinning	NA	Four-way interaction was not included in the model

Table 43 Estimated effect sizes for litter depth CV in thinned plots 5 years post-thinning, showing difference between fitted values and 95% confidence intervals in thinned plots relative to control plots

Site Quality		Site Quality 1			Site Quality 2		
Thinning intensity		Low intensity	Mod intensity	High intensity	Low intensity	Mod intensity	High intensity
Initial tree density	Very low (400/ha)	+0.03 –0.10 to +0.26	+0.12 –0.04 to +0.41	+0.21 –0.01 to +0.67	+0.01 –0.10 to +0.21	+0.06 –0.06 to +0.26	+0.10 –0.06 to +0.40
	Moderate (700/ha)	+0.01 –0.09 to +0.19	+0.06 –0.06 to +0.26	+0.11 –0.04 to +0.40	–0.02 –0.13 to +0.17	–0.02 –0.13 to +0.16	–0.01 –0.12 to +0.16
	Very high (1250/ha)	–0.01 –0.11 to +0.16	+0.01 –0.12 to +0.21	+0.03 –0.12 to +0.33	–0.05 –0.15 to +0.14	–0.09 –0.20 to +0.11	–0.10 –0.20 to +0.10

Hypothesis evaluation

There was some support for the hypothesis that ecological thinning increased heterogeneity in leaf litter depth, with the modelled effect of ecological thinning on many plot types increased heterogeneity in litter depth. However, the effect was not statistically significant.

12. Results: Standing dead trees

12.1 Count of standing dead trees

Hypothesis	1j. Decreased persistence of dead trees (stags) in the short term.
Key result	**No evidence of a statistically significant effect of ecological thinning.**

Data collection

Standing dead trees (stags) were defined as any tree with a diameter at breast height of at least 40 centimetres with no live foliage.

All standing dead trees were counted in the central 2-hectare subplot in each 9-hectare plot (see Figure 5). Surveys were conducted prior to thinning in 2015–16, one year post-thinning in 2017–18 and 5 years post-thinning in 2021–22. The same observers conducted surveys in 2015–16 and 2017–18; different observers conducted the most recent surveys.

Data summary

Prior to ecological thinning the average number of stags in a 2-hectare subplot, across all initial tree densities, was 10 (range 0–26). After thinning, the average number of stags was 12 (range 0–38). Wetter (SQ1) plots had a slightly higher average number of stags (14 stags) than drier (SQ2) plots (9 stags) per 2 hectares, being most pronounced in low and high initial density sites (Figure 60). There appeared to be a slight increase in the number of stags one year after thinning, before reducing in the final year of monitoring (Figure 60). There was no obvious effect of thinning on the number of stags (Figure 60).

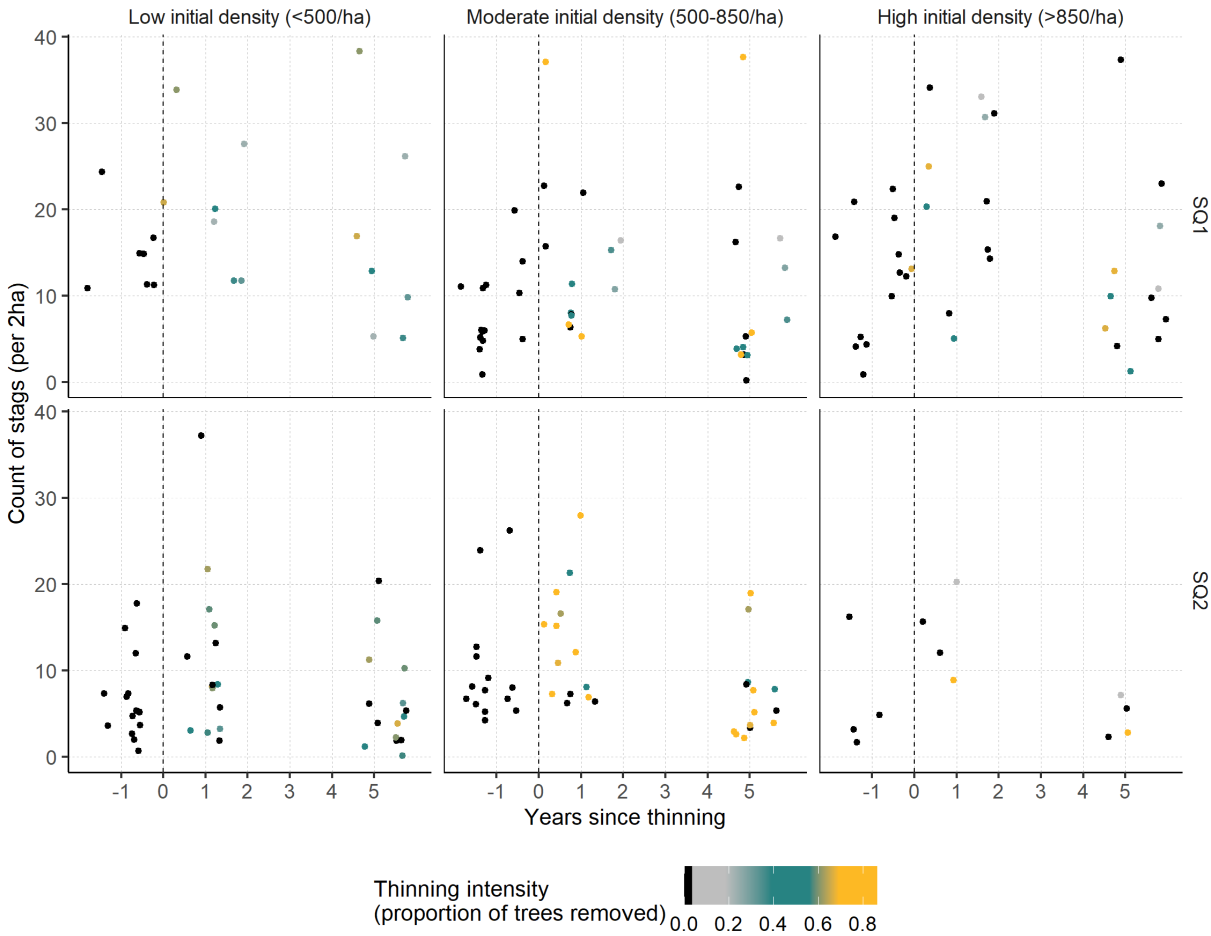

Figure 60 Data for count of standing dead trees per 2-hectare subplot

Model results

Number of stags was modelled using a Poisson distribution (see Appendices). The model did not include four-way interaction between Site Quality, initial tree density, time since thinning and thinning intensity, or three-way interaction between initial tree density, time since thinning and thinning intensity, but included all other two-way and three-way interactions. Random effects for year, site, and 2-hectare subplot were included.

In the absence of ecological thinning, the modelled data suggested there were more stags in Site Quality 1 subplots than Site Quality 2 subplots (Figure 61), and this was statistically significant (Table 44). The number of stags did not vary significantly with initial tree density (Figure 61, Table 44). There was a significant change in the number of stags over time (Table 44), decreasing between the first year following thinning and the final year of monitoring (Figure 61).

Heavy thinning in Site Quality 1 plots that had very low initial tree density had higher densities of stags (Figure 61, Table 45). The modelled increase was 8 stags per 2 hectares, however it was not statistically significant (Table 44, Table 45). There was no evidence of an effect of thinning on the number of stags in other treatments (Figure 61, Table 44, Table 45).

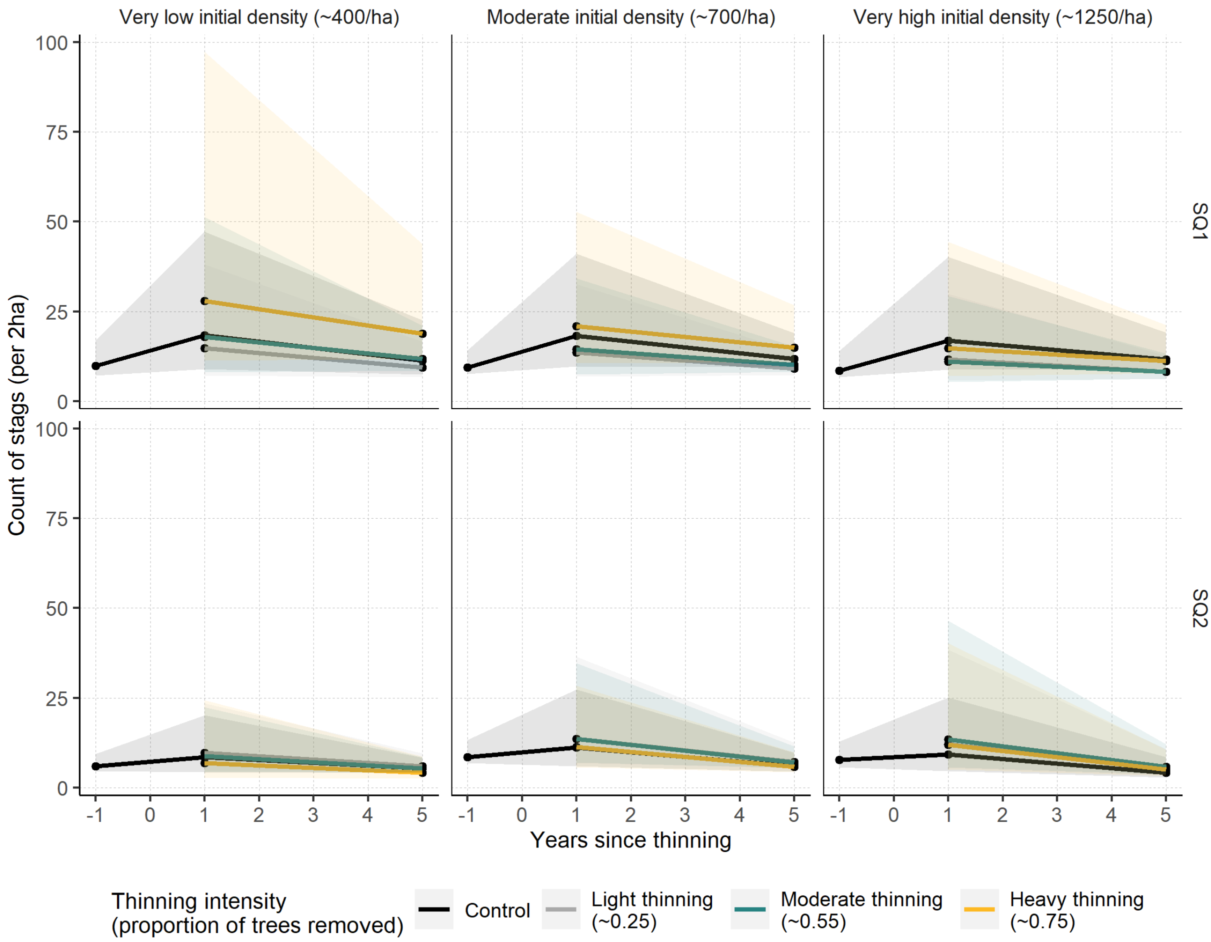

Figure 61 Modelled values and 95% confidence intervals for count of standing dead trees per 2-hectare subplot

Table 44 Statistical significance of explanatory variables on count of standing dead trees per 2-hectare subplot

	Bootstrapped likelihood ratio test significance	Description
Site Quality	0.01	Number of stags differed among Site Qualities
Initial tree density	0.55	Number of stags did not depend on initial tree density
Time since thinning	0.02	Number of stags changed over time
Thinning intensity	0.33	Number of stags did not depend on thinning intensity
Does the effect of thinning intensity vary depending on:		
• Site Quality	0.18	The effect of thinning on number of stags did not depend on Site Quality
• Initial tree density	0.39	The effect of thinning on number of stags did not depend on initial tree density

	Bootstrapped likelihood ratio test significance	Description
• Time since thinning	0.89	The effect of thinning on number of stags did not change over time
• Site Quality **and** initial tree density **and** time since thinning	NA	Four-way interaction was not included in the model

Table 45 Estimated effect sizes for count of standing dead trees per 2-hectare subplot 5 years post-thinning, showing difference between fitted values and 95% confidence intervals in thinned plots relative to control plots

Site Quality		Site Quality 1			Site Quality 2		
Thinning intensity		Low intensity	Mod intensity	High intensity	Low intensity	Mod intensity	High intensity
Initial tree density	Very low (400/ha)	–2.0 –4.6 to +5.2	+0.4 –2.8 to +9.7	+7.5 +0.5 to +32.5	+0.6 –0.7 to +4.2	0.0 –1.2 to +3.1	–1.2 –2.7 to +3.4
	Moderate (700/ha)	–2.8 –4.6 to +1.9	–1.8 –3.6 to +3.4	+3.1 –1.0 to +14.9	+1.2 –0.5 to +6.6	+1.0 –0.5 to +5.5	–0.2 –1.6 to +3.9
	Very high (1250/ha)	–3.5 –5.4 to +1.0	–3.6 –5.5 to +1.6	–0.5 –3.9 to +9.5	+1.2 –0.6 to +6.6	+1.6 –0.4 to +7.9	+1.0 –0.9 to +6.4

Hypothesis evaluation

Observer error in detecting and counting standing dead trees over a large area is likely to have been the primary cause of differences in stag counts among years. Raw data suggested that the hypothesis may have been supported for heavy intensity ecological thinning on some wetter (SQ1) plots, but this effect was not statistically significant.

13. Results: Fuel hazard

Fuel hazard was assessed using the method of Hines et al. (2010). In this method, overall fuel hazard is determined from the assessment of 4 fuel hazard assessment components that are associated with vegetation strata from the forest floor to the canopy (Figure 62).

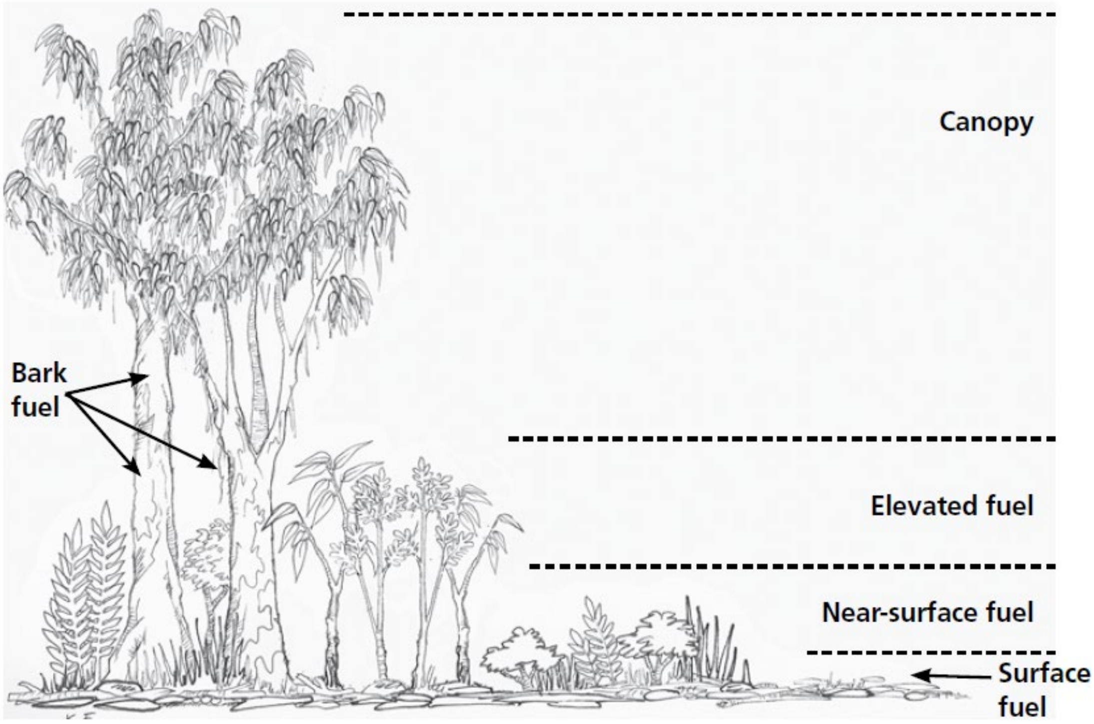

Figure 62 Fuel hazard assessment components (Hines et al. 2010)

The first component is *surface fuel hazard*, which is determined using estimates of litter cover and litter depth.

The second component is *near surface fuel hazard*, which is determined using estimates of live and dead ground vegetation cover.

These 2 components are combined into an overall surface fuel hazard category.

The third component is *elevated fuel hazard*, which is determined using estimates of live and dead elevated vegetation cover.

The fourth component is *bark fuel hazard* (all plots were in the low to moderate category).

All 4 components are combined into an *overall fuel hazard category*.

Results for overall fuel hazard are presented first, and then the other 4 components are presented in order below. The underpinning data (litter, vegetation cover, etc.) is reported prior to the hazard assessment for each component.

The Hines et al. (2010) method specifies subjective evaluation of categories for some aspects of fuel hazard assessment; for example, distinguishing between 'Soil surface occasionally visible through litter bed' or 'Litter well connected. Little bare soil'. Where possible, these subjective assessments have been replaced with objective quantitative categories, detailed below.

13.1 Overall fuel hazard

Hypothesis	1k. Ecological thinning will increase fuel and fire risk.
Key result	**No evidence of a statistically significant effect of ecological thinning.**

Data collection

Data were collected from three 0.04-hectare subplots per 9-hectare treatment plot (see 20 x 20 metre subplots in Figure 5) for all components of fuel hazard assessment in accordance with Hines et al. (2010). Fuel hazard was assessed annually, over 6 survey years. In 2021–22, 15% of 0.04-hectare subplots were not able to be surveyed due to flooding.

Overall fuel hazard is determined from the hazard assessments of 4 components of fuel hazard: combined surface and near surface hazard category; the elevated fuel hazard category; and bark hazard (Table 46). Bark hazard was in the same category (low to moderate) on all plots. The analyses and results for all other components are described in following sections.

Overall fuel hazard is scored on a scale with 5 categories, from low to extreme (Table 46). For example, if the elevated fuel hazard on a plot was Medium and the combined surface and near surface fuel hazard on a plot was High, then the overall fuel hazard category was Medium.

Table 46 Overall fuel hazard assessment categories (from Hines et al. 2010)

L = Low, M = Moderate, H = High, VH = Very High, E = Extreme

1	2	3 Combined surface and near surface fuel hazard				
Bark hazard	**Elevated fuel hazard**	**L**	**M**	**H**	**VH**	**E**
Low and moderate	L	L	M	M	H	H
	M	L	M	M	H	H
	H	L	M	H	VH	VH
	VH	VH	VH	VH	VH	VH
	E	E	E	E	E	E

Data summary

Overall fuel hazard scores were most commonly in the moderate and high categories for all combinations of Site Quality and initial tree density (Figure 65). The proportion of plots in each category did not appear to change substantially over time. The proportion of plots that were in the high overall fuel hazard category was slightly higher on heavily thinned plots than control plots in the most recent survey year (Figure 64, Figure 65).

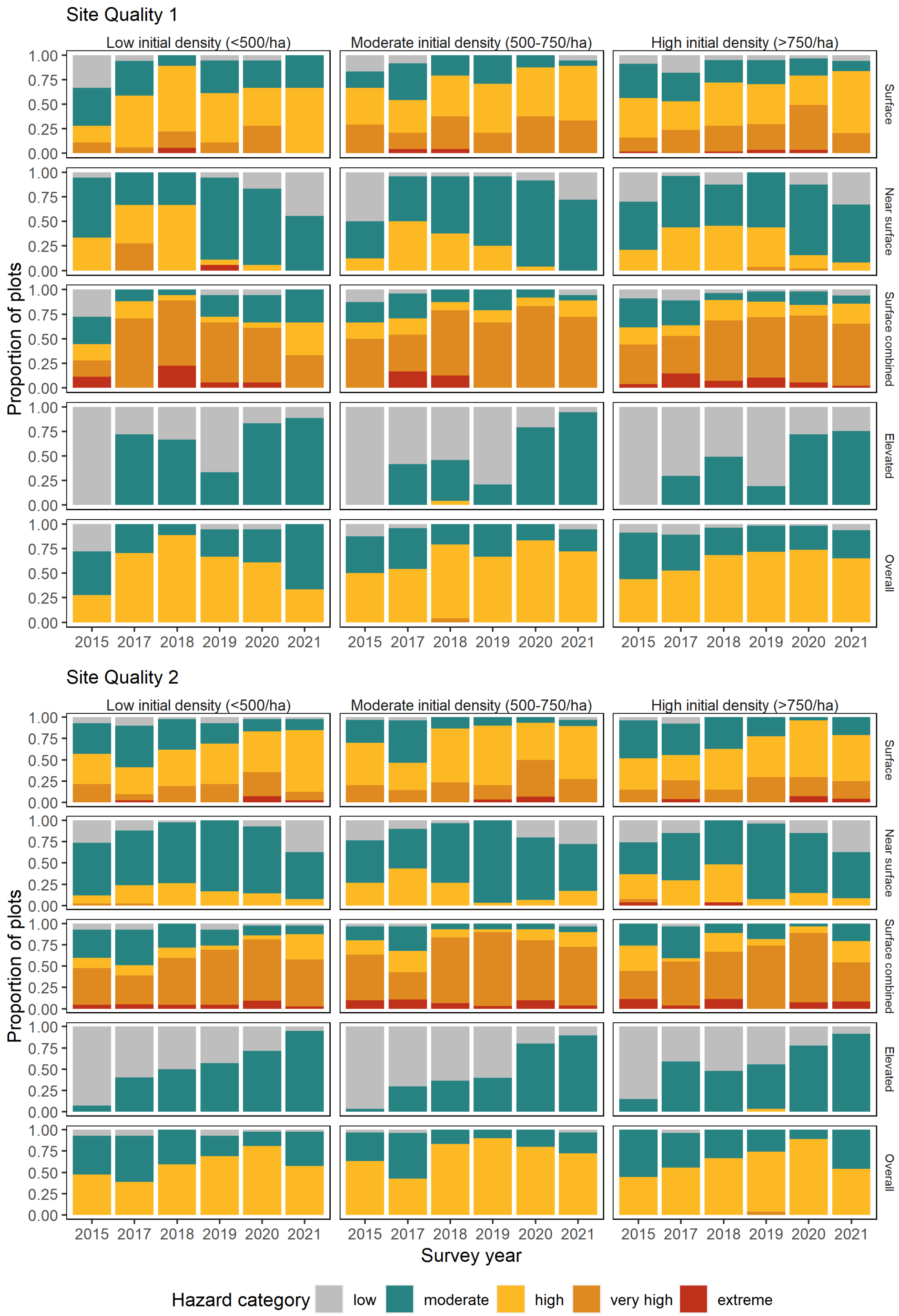

Figure 63 Proportion of 9-hectare treatment plots in each fuel hazard assessment category, by initial tree density, survey year and Site Quality

Figure 64 Proportion of 9-hectare treatment plots in each fuel hazard assessment category, by thinning intensity, survey year and Site Quality

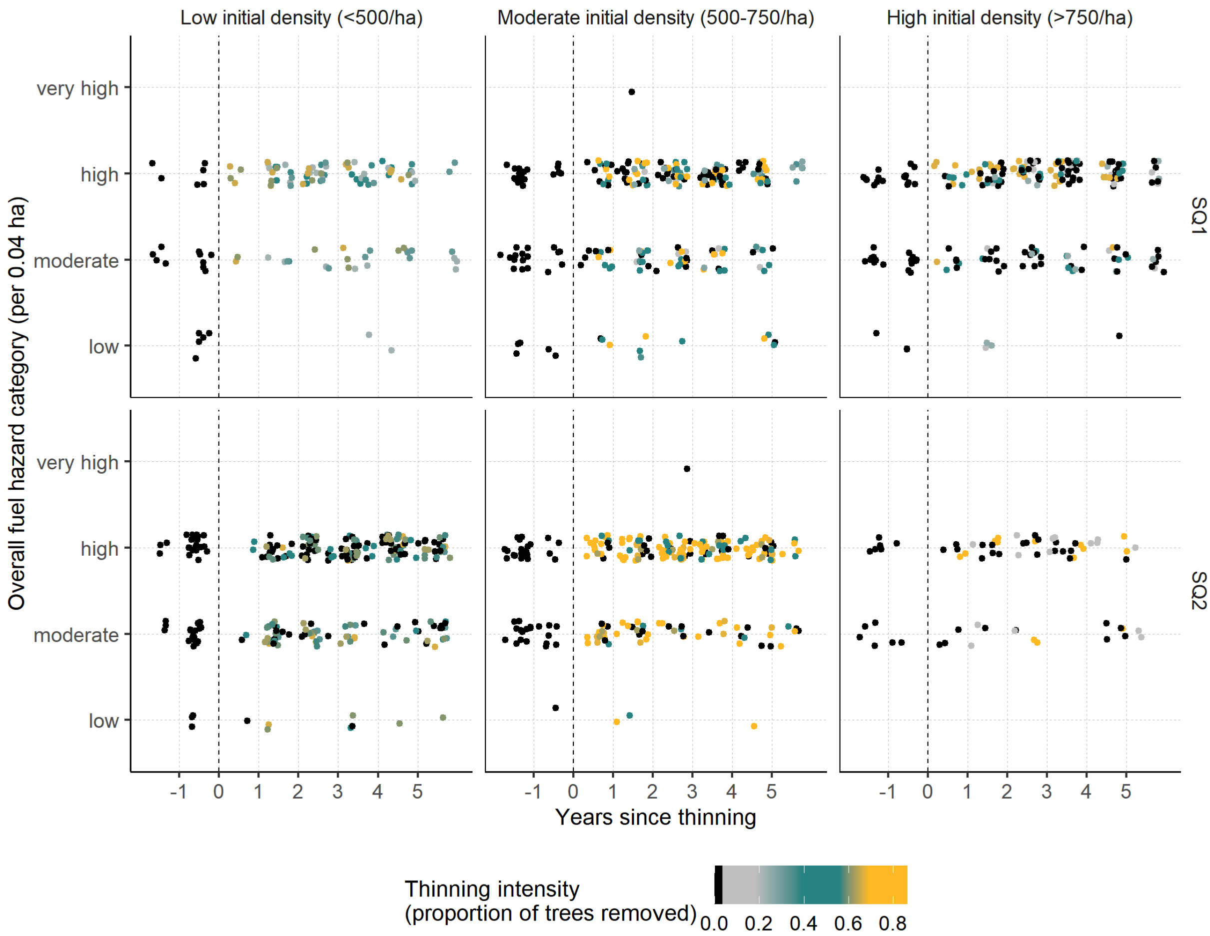

Figure 65 Scores for overall fuel hazard

Model results

Overall fuel hazard category was modelled using a Bayesian cumulative ordinal model, a type of regression that calculates the probability of data belonging to a set of ordered categories (see Appendices). The model for overall fuel hazard category included all interactions between Site Quality, initial tree density, thinning intensity, and time since thinning. The model also included 4 random effects: site, 9-hectare plot, 0.04-hectare subplot and survey year.

There was no evidence of pre-existing differences among plots with different Site Quality or initial tree densities, and no evidence that overall fuel hazard changed over time (Figure 66, Table 47).

Immediately after thinning, overall fuel hazard was lower in thinned plots than control plots in drier (SQ2) sites (increased probability of being in the moderate rather than high hazard category, particularly for moderate thinning intensity) (Figure 66). This decrease was not statistically significant (Table 47).

Five years after thinning, heavily thinned plots had a higher modelled probability of being in the high overall fuel hazard category than control plots in the most recent year (Figure 66), however this increase was not statistically significant (Table 47).

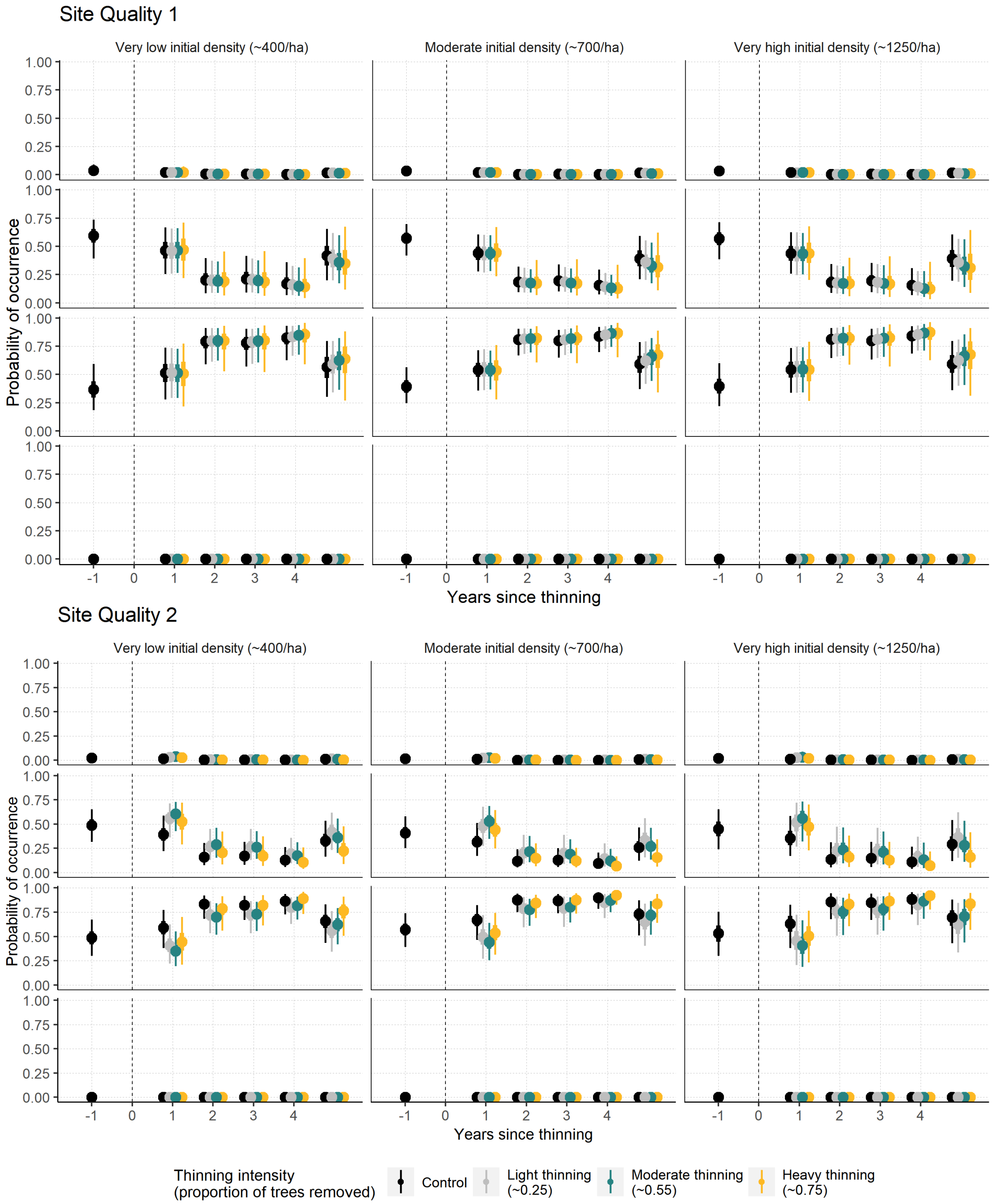

Figure 66 Modelled probability of being in each of the overall fuel hazard categories ± 50% and 95% bootstrapped credible intervals for ecological thinning treatment, survey year and Site Quality

Table 47 Statistical significance of explanatory variables on overall fuel hazard ratings

Evidence of statistical significance for ELPD ratio >4

Model term	ELPD ratio	Comment
Site Quality	1.04	No effect of Site Quality on overall fuel hazard ratings
Initial tree density	0.09	Some evidence that overall fuel hazard ratings varied with initial tree density
Time since thinning	0.11	No effect of time since thinning on overall fuel hazard ratings
Thinning intensity	0.80	No effect of thinning intensity on overall fuel hazard ratings
Does the effect of thinning intensity vary depending on:		
• Site Quality	1.86	The effect of thinning intensity on overall fuel hazard ratings did not depend on Site Quality
• Initial tree density	0.37	The effect of thinning intensity on overall fuel hazard ratings did not depend on initial tree density
• Time since thinning	0.60	The effect of thinning intensity on overall fuel hazard ratings did not change over time
• Site Quality **and** initial tree density **and** time since thinning	0.20	The effect of thinning intensity on overall fuel hazard ratings did vary independently for all combinations of Site Quality, initial tree density and time since thinning

Hypothesis evaluation

Ecological thinning initially slightly decreased overall fuel hazard in drier (SQ2) plots relative to control plots. In the most recent year, heavy intensity thinning plots had slightly increased overall fuel hazard on both Site Qualities. However, these effects were small in magnitude and not statistically significant.

13.2 Surface fuel hazard: litter depth

Hypothesis	1k. Ecological thinning will increase fuel and fire risk: ecological thinning will increase litter depth.
Key result	Marginally significant ($p = 0.07$) effect of ecological thinning that caused both **increases** and **decreases** of 3–4 millimetres in leaf litter depth in some circumstances.

Data collection

Litter was defined as any dead plant material that was separated from a live plant and included material <1 millimetre in diameter. Note that the definition of litter was refined between 2015 and 2018, which reduced uncertainty in observer estimates.

Litter depth was measured using the method of Hines et al. (2010). A metal ruler was inserted through the litter until it rested on the soil. A cardboard disc was held gently against the litter and used to mark the height of the litter on the ruler.

Litter depth was measured in the centre of ten 1 x 1 metre quadrats in each 0.04-hectare subplot (see 20 x 20 metre subplots in Figure 5). Litter depth was averaged for each subplot. Litter depth was surveyed annually, over 6 survey years. In 2021–22, 15% of 0.04-hectare subplots were not able to be surveyed due to flooding.

Data summary

Litter depth ranged from 0 to 95.1 millimetres, averaging 19.4 millimetres, but was generally less than 40 millimetres (Figure 67). Average litter depth was similar in all Site Quality and initial tree density combinations, but lowest in high initial tree density, Site Quality 2 subplots (Figure 67). There was little apparent change over time in average litter depth, although fewer high values were recorded in the most recent survey year (Figure 67).

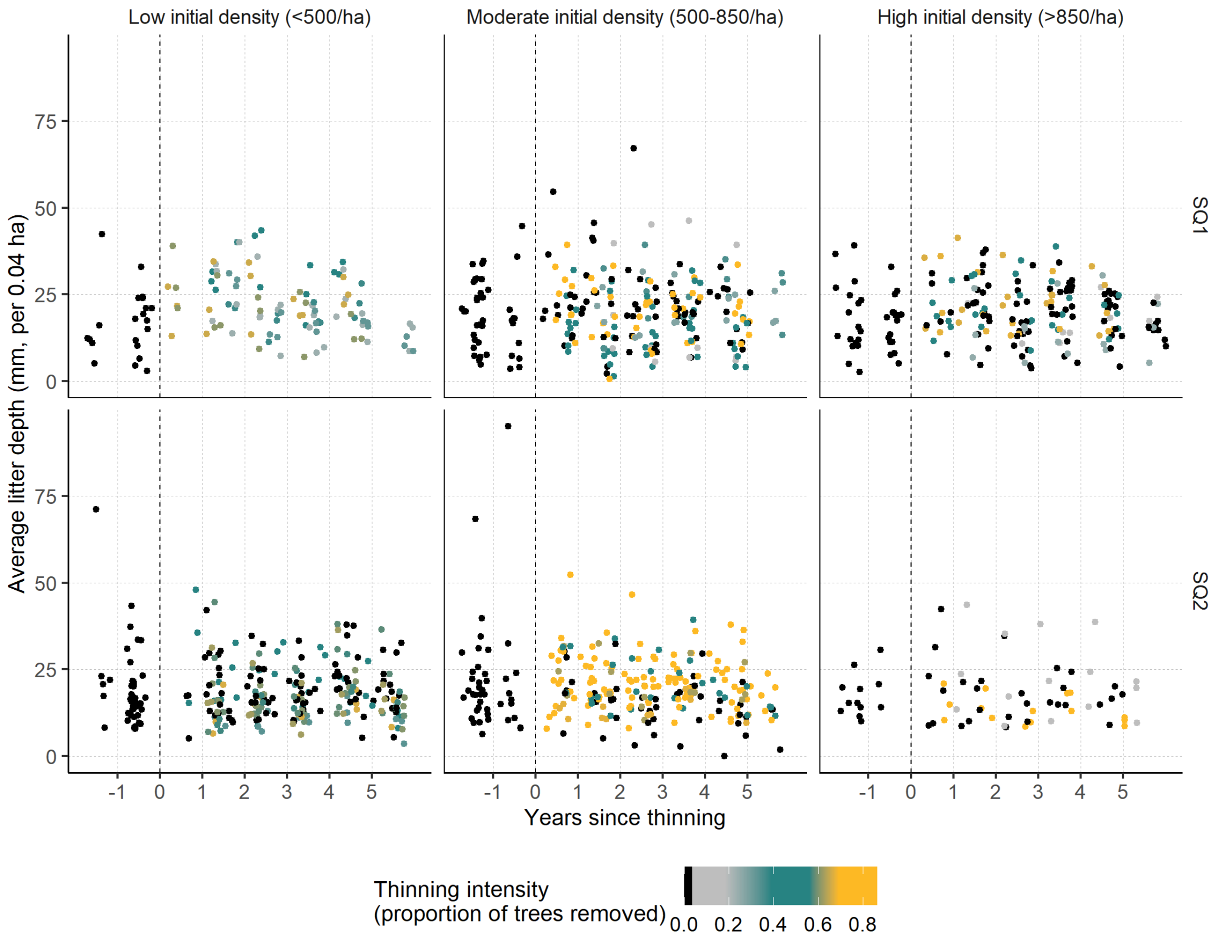

Figure 67 Data for average litter depth (mm) per 0.04-hectare subplot

Model results

Average litter depth was modelled using a log transformation and a Gaussian distribution (see Appendices). The reported model did not include four-way interaction between Site Quality, initial tree density, time since thinning and thinning intensity, or three-way interaction between initial tree density, time since thinning and thinning intensity. The model included all other two-way and three-way interactions. Random effects for 9-hectare plot, 0.04-hectare subplot and survey year were included, but a random effect for site was not.

In the absence of ecological thinning, there was some evidence ($p = 0.059$) that leaf litter depth was 1–2 millimetres greater in drier (SQ2) sites than wetter (SQ1) sites. There was no evidence that leaf litter depth varied with initial tree density (Figure 68, Table 48). Litter depth fluctuated over time, but this effect was not statistically significant.

There was some evidence ($p = 0.059$) that there was a significant effect of thinning intensity that differed among Site Qualities (Table 48). However, the only predicted circumstances under which thinned plots differed substantially from control plots were for extreme values of initial tree density (Figure 68). In the most recent surveys (5 years post-thinning) the magnitude of difference was an increase or decrease of 3–4 millimetres relative to control plots (Table 49).

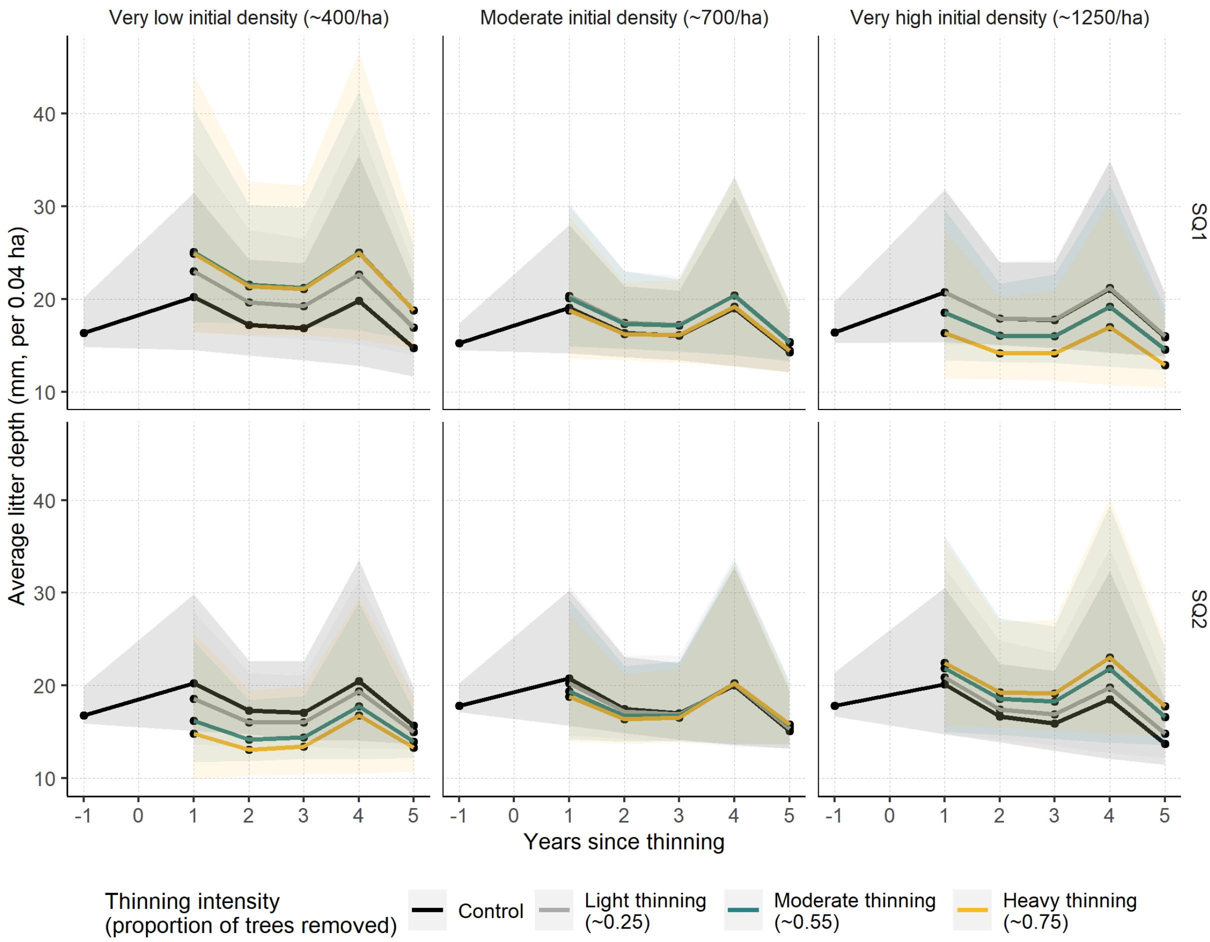

Figure 68 Modelled values and 95% confidence intervals for average litter depth (millimetres) per 0.04-hectare subplot

Table 48 Statistical significance of explanatory variables on litter depth

	Bootstrapped likelihood ratio test significance	Description
Site Quality	0.06	Some evidence that litter depth may have differed among Site Qualities
Initial tree density	0.44	Litter depth did not depend on initial tree density
Time since thinning	0.46	Litter depth did not change over time
Thinning intensity	0.13	Litter depth was not affected by thinning intensity
Does the effect of thinning intensity vary depending on:		
• Site Quality	0.06	Some evidence that the effect of thinning on litter depth may have depended on Site Quality
• Initial tree density	0.11	The effect of thinning on litter depth did not depend on initial tree density

	Bootstrapped likelihood ratio test significance	Description
• Time since thinning	0.33	The effect of thinning on litter depth did not change over time
• Site Quality **and** initial tree density **and** time since thinning	NA	Four-way interaction was not included in the model

Table 49 Estimated effect sizes for litter depth in thinned plots 5 years post-thinning, showing difference between fitted values and 95% confidence intervals in thinned plots relative to control plots

Site Quality		Site Quality 1			Site Quality 2		
Thinning intensity		Low intensity	Mod intensity	High intensity	Low intensity	Mod intensity	High intensity
Initial tree density	Very low (400/ha)	+2.2 –0.7 to +8.9	+4.0 +0.8 to +11.1	+4.0 –0.1 to +13.3	–0.7 –2.5 to +3.2	–1.7 –3.4 to +1.6	–2.4 –5.0 to +3.1
	Moderate (700/ha)	+1.1 –1.0 to +5.5	+1.1 –0.9 to +5.3	+0.2 –2.2 to +5.4	+0.3 –1.8 to +5.2	+0.6 –1.4 to +5.3	+0.7 –1.4 to +4.8
	Very high (1250/ha)	+0.1 –2.0 to +4.7	–1.4 –3.5 to +3.0	–3.1 –5.5 to +2.2	+1.1 –1.5 to +7.0	+2.9 –0.1 to +10.3	+4.1 +0.9 to +11.1

Hypothesis evaluation

The data and modelling results suggest that the hypothesis may be correct for a small subset of thinned sites, but thinning may also have caused the opposite to occur in other plots. Overall, ecological thinning is unlikely to have had an impact on average litter depth for the majority of sites.

13.3 Surface fuel hazard: litter cover

Hypothesis	1k. Ecological thinning will increase fuel and fire risk: ecological thinning will increase litter cover.
Key result	Ecological thinning initially **increased** litter cover on some plot types. Five years post-thinning, the only significant difference from controls was a **decrease** of 5% (per 0.04-hectare subplot) in wetter Site Quality 1 plots with very high initial tree density.

Data collection

Litter was defined as any dead plant material that was separated from a live plant and included material <1 millimetre in diameter. Note that the definition of litter was refined between 2015 and 2018, which reduced uncertainty in observer estimates.

Litter cover was visually estimated in three 0.04-hectare subplots in each 9-hectare treatment plot (see 20 x 20 metre subplots in Figure 5). Litter depth was surveyed annually, over 6 survey years. In 2021–22, 15% of 0.04-hectare subplots were not able to be surveyed due to flooding.

Data summary

Most subplots had litter cover occupying greater than 75% of the subplot area, some had litter cover less than 50% and very few had less than 25% litter cover (Figure 69). Litter cover increased over time (Figure 69). Site Quality 1 subplots had less litter cover than Site Quality 2 subplots (Figure 69). There were no obvious effects of thinning on litter cover (Figure 69).

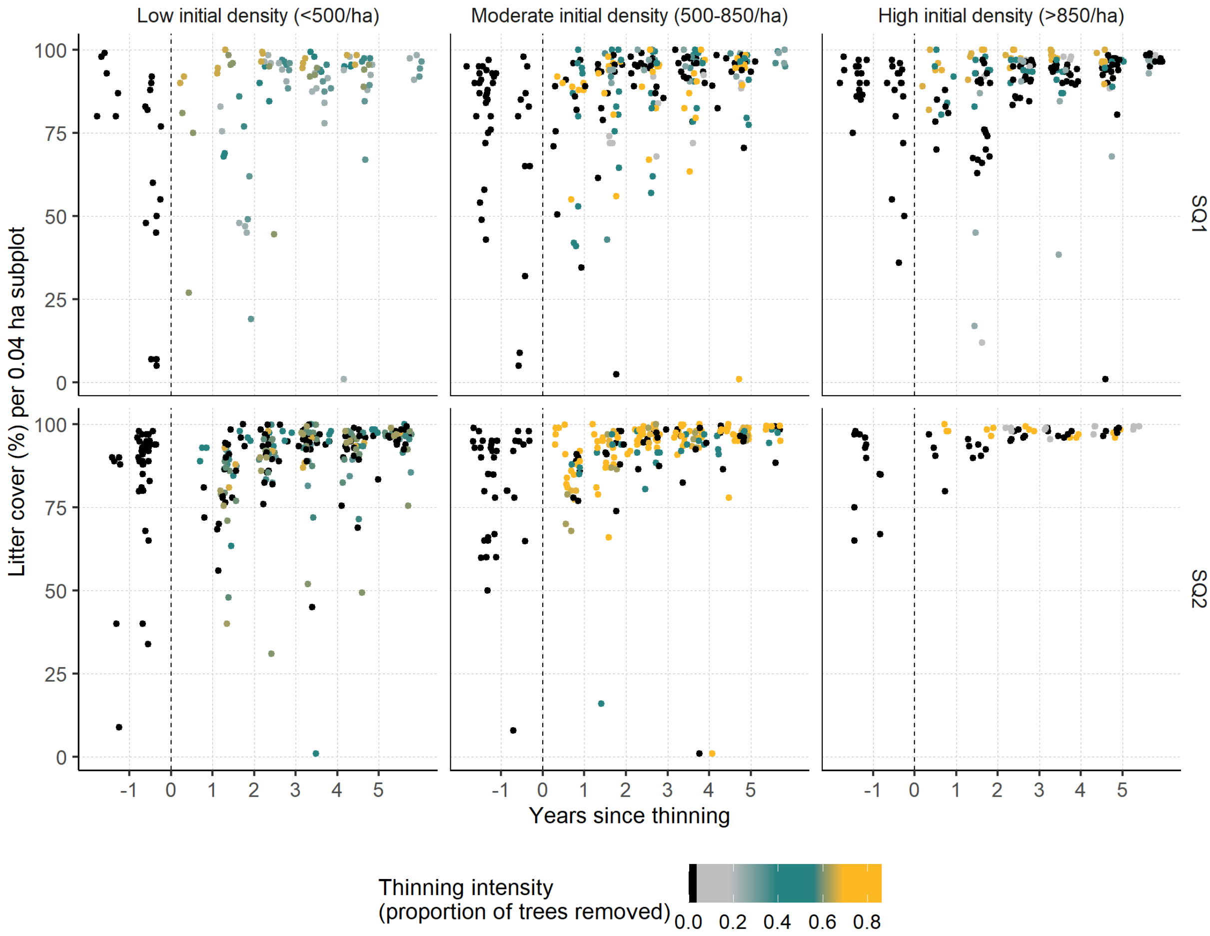

Figure 69 Data for percentage of litter cover in each 0.04-hectare subplot

Model summary

It is difficult to fit regression models to data for which the majority of values are above 90% (and therefore close to the maximum of 100%). However, it is possible to fit regression models to data for which the majority of values are close to a minimum of zero. Therefore, we calculated the percentage of each subplot that was *not* litter (by subtracting the litter cover value from 100) as the response variable to model.

The model for litter cover was analysed as the inverse (that is, the percentage of subplot that was not litter cover) using a gamma distribution with a log link (see Appendices). The model did not include four-way interaction between Site Quality, initial tree density, time since thinning and thinning intensity, but included all two-way and three-way interactions. A random effect for subplot was included, but random effects for survey year, site and 9-hectare subplot were not.

Modelled values of the area that was not litter cover decreased over time (that is, litter cover increased over time) (Figure 70), and this change was statistically significant (Table 50). Refinement of the assessment method of litter cover may have contributed to this change. There was a significant effect of initial tree density on modelled values, with subplots with very low initial tree density having a greater percentage of area that was not litter cover (Figure 70, Table 50). Site Quality 1 had higher values of area that were not litter cover than Site Quality 2 subplots (Figure 70, Table 50).

There was a statistically significant effect of ecological thinning which varied with initial tree density and over time (Table 50). In Site Quality 1, thinning initially caused a slight decrease in the average percentage that was not litter cover where initial tree density was moderate to very high (that is, increased litter cover) (Figure 70). In Site Quality 2 where initial tree density was very low to moderate, the opposite pattern occurred, with thinning initially increasing the average percentage that was not litter cover (that is, decreased litter cover) (Figure 70). Five years post-thinning all of these effects had become non-significant (Table 51).

In Site Quality 1 plots with very high initial tree density, the percentage of area not litter cover increased in the most recent 2 years relative to control plots (that is, litter cover decreased) (Figure 70). Five years post-thinning, litter cover was up to 5% lower on these thinned plots relative to control plots (Table 51).

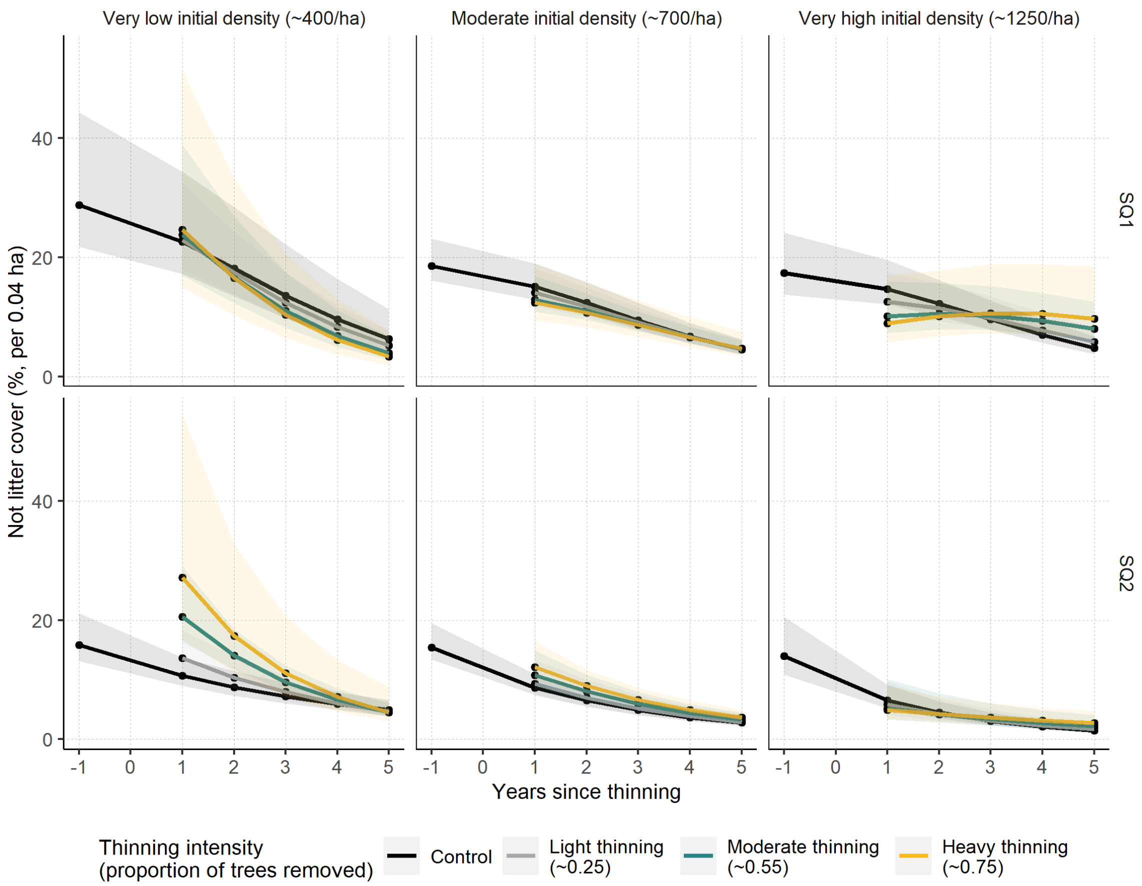

Figure 70 Modelled values and 95% confidence intervals for area that was not litter cover per 0.04-hectare subplot

Table 50 Statistical significance of explanatory variables on area that was not litter cover

	Bootstrapped likelihood ratio test significance	Description
Site Quality	0.01	The area that was not litter cover differed among Site Qualities
Initial tree density	0.01	The area that was not litter cover depended on initial tree density
Time since thinning	0.01	The area that was not litter cover changed over time
Thinning intensity	0.01	Ecological thinning significantly affected the area that was not litter cover
Does the effect of thinning intensity vary depending on:		
• Site Quality	0.42	The effect of thinning on the area that was not litter cover did not depend on Site Quality
• Initial tree density	0.01	The effect of thinning on the area that was not litter cover depended on initial tree density
• Time since thinning	0.01	The effect of thinning on the area that was not litter cover changed over time
• Site Quality **and** initial tree density **and** time since thinning	NA	Four-way interaction was not included in the model

Table 51 Estimated effect sizes for area that was not litter cover 5 years post-thinning, showing difference between fitted values and 95% confidence intervals in thinned plots relative to control plots

Site Quality		Site Quality 1			Site Quality 2		
Thinning intensity		Low intensity	Mod intensity	High intensity	Low intensity	Mod intensity	High intensity
Initial tree density	Very low (400/ha)	–1.1 –2.4 to +1.4	–2.4 –3.6 to +0.5	–2.9 –4.4 to +1.3	–0.2 –1.1 to +1.4	–0.4 –1.2 to +1.1	–0.3 –1.9 to +3.9
	Moderate (700/ha)	0.0 –0.7 to +1.3	+0.1 –0.7 to +1.6	+0.2 –1.1 to +3.0	+0.2 –0.5 to +1.4	+0.5 –0.1 to +1.7	+0.9 +0.2 to +2.2
	Very high (1250/ha)	+1.0 –0.1 to +3.3	+3.2 +1.0 to +7.7	+4.9 +1.6 to +13.8	+0.2 –0.2 to +1.4	+0.8 +0.1 to +2.7	+1.3 +0.4 to +3.3

Hypothesis evaluation

Explicit inclusion of all litter material (no minimum size) and visual estimates of percentage cover are likely to have contributed to uncertainty in this variable. Ecological thinning may have initially increased litter cover in wetter (SQ1) sites and decreased litter cover in drier (SQ2) sites. These effects were not sustained over time for most plot types. However, there was also some evidence to suggest that the hypothesis was not supported in some circumstances, with extremely high tree density thinned plots having decreased litter cover 5 years post-thinning.

13.4 Surface fuel hazard assessment

Hypothesis	1g. Ecological thinning will increase fuel and fire risk.
Key result	**No evidence of a statistically significant effect of ecological thinning.**

Data collection

Surface fuel hazard category is determined based on litter depth and litter cover data. Data collection was described above.

Only some categories for assessing surface fuel hazard by combining litter depth and litter cover are defined by Hines et al. (2010) (grey cells in Table 52). For instance, Hines et al. (2010) define surface fuel hazard as low when litter depth is <10 millimetres and litter cover <60%, and moderate when litter depth is 10–20 millimetres and litter cover is 60–80%. However, many other categories are not defined, for example, when litter depth is <10 millimetres but litter cover is >80%. Additional categories were therefore defined for all categories of litter depth and litter cover to enable objective classification of all data (clear cells in Table 52).

Table 52 Surface fuel hazard assessment categories

Grey cells are defined by Hines et al. (2010), white cells are additionally defined to enable classification of all data.

Litter height (mm)	Litter cover (%)				
	<60	60–80	80–90	>90	>95
<10	L	L	M	M	M
10–20	L	M	M	H	H
20–25	M	M	H	H	VH
25–30	M	H	H	VH	VH
30–35	H	H	VH	VH	VH
35–45	H	VH	VH	VH	E
>45	VH	VH	E	E	E

Data summary

The most common category for surface fuel hazard was high, with moderate and very high also frequently recorded (Figure 63, Figure 64, Figure 71). There were no apparent differences among Site Qualities or initial tree densities. Extreme values were recorded in 21 subplots over the 6 survey seasons, and 17 of those records were in thinned subplots (Figure 71).

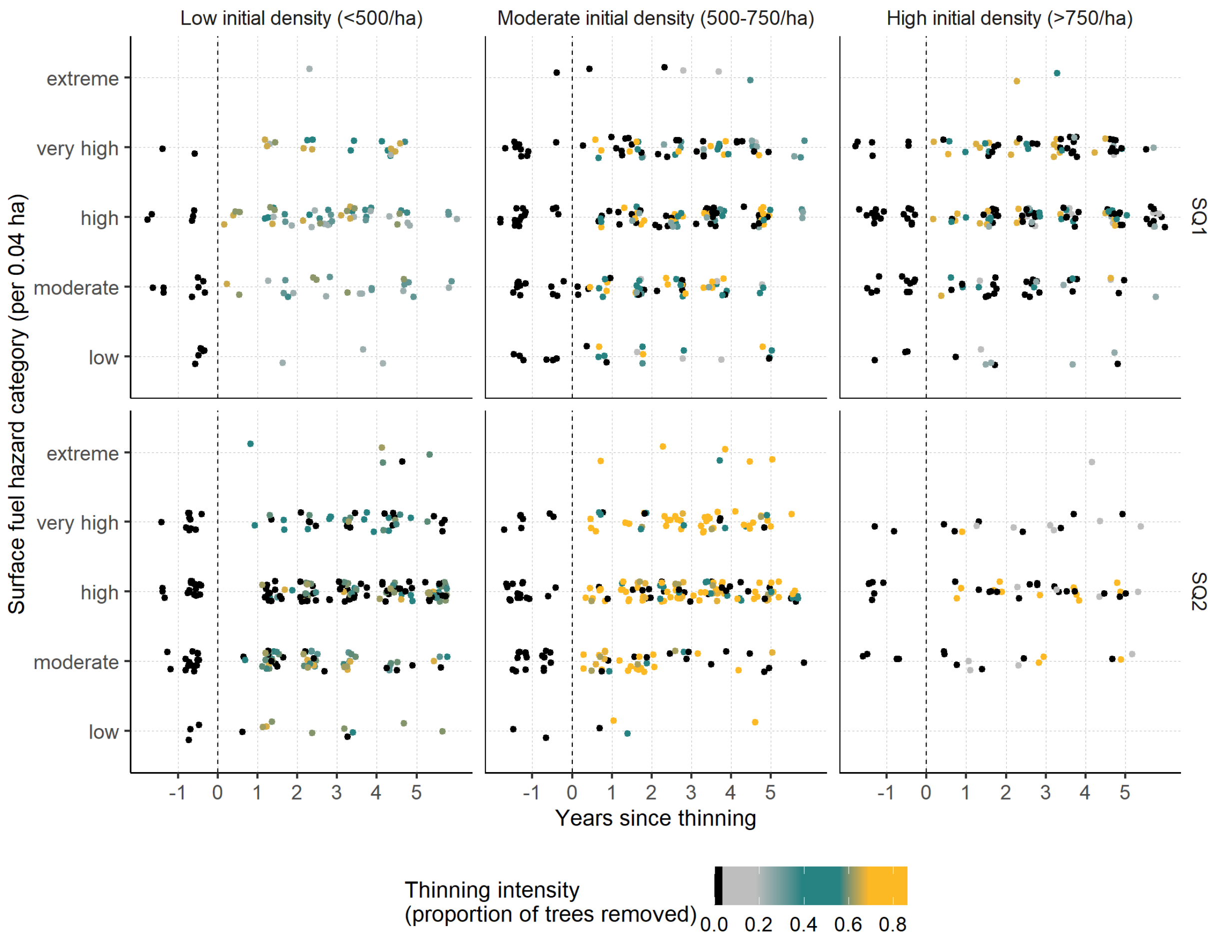

Figure 71 Data summary for surface fuel hazard category

Model results

Surface fuel hazard category was modelled using a Bayesian cumulative ordinal model, a type of regression that calculates the probability of data belonging to a set of ordered categories (see Appendices). The model for surface fuel hazard category included all interactions between Site Quality, initial tree density, thinning intensity and time since thinning. The model also included 4 random effects: site, 9-hectare plot, 0.04-hectare subplot and survey year.

The modelled probability of a subplot being in the high surface fuel hazard category was generally lower in wetter (SQ1) sites than drier (SQ2) sites, but this effect was not statistically significant (Figure 72, Table 53). There were some differences among years, for instance the probability of a subplot being in the very high category was greater in the 2020–21 survey year than other years, but this difference was not statistically significant.

Heavy thinning temporarily reduced the probability of a subplot being in the high category in the first year post-thinning, but this effect was not sustained over time and was not statistically significant (Figure 72, Table 53).

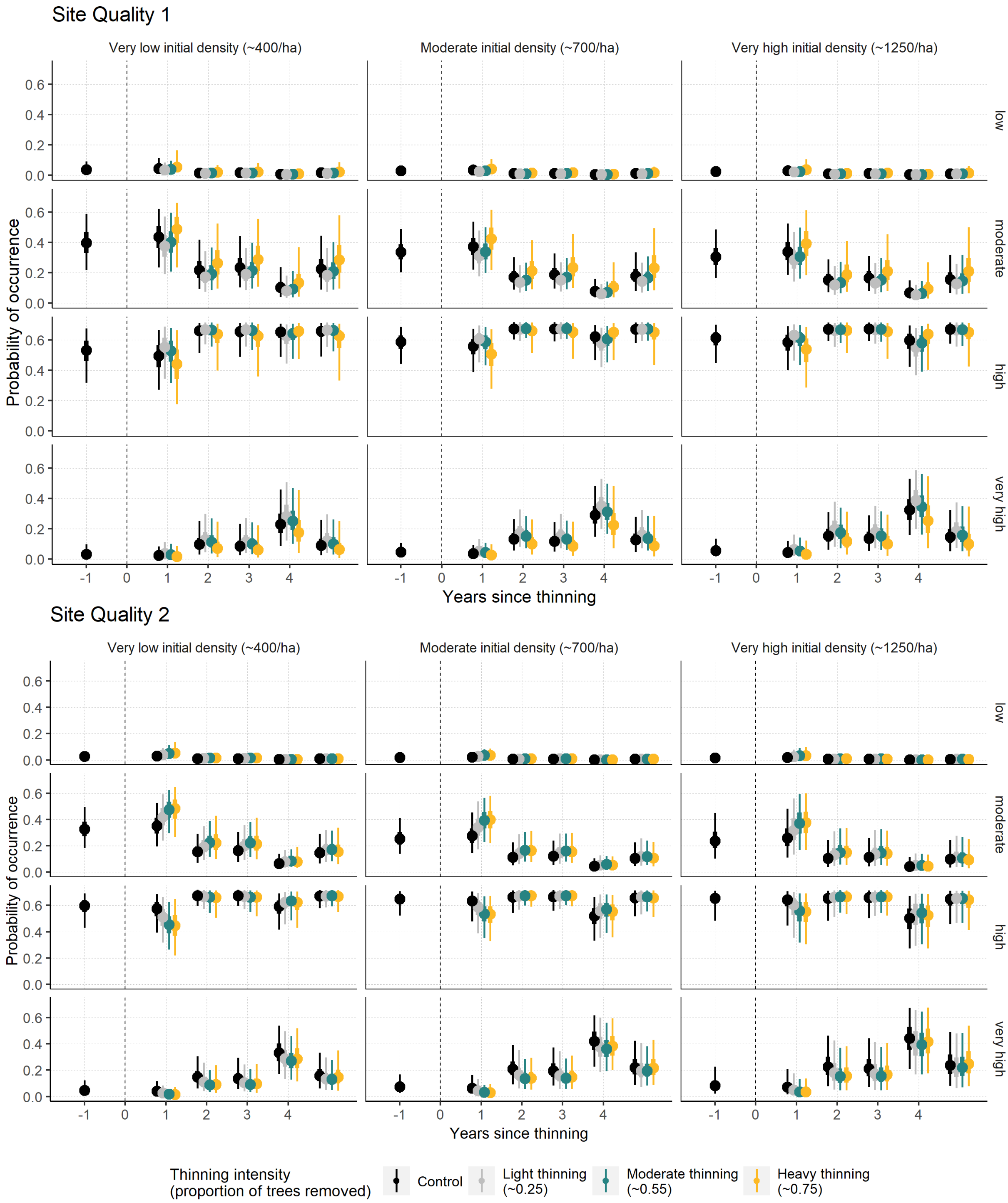

Figure 72 **Modelled probability of being in each of the surface fuel hazard categories ± 50% and 95% bootstrapped confidence intervals for ecological thinning treatment, survey year and Site Quality**

Table 53 Statistical significance of explanatory variables on surface fuel hazard ratings

Evidence of statistical significance for ELPD ratio >4

Model term	ELPD ratio	Comment
Site Quality	0.45	Surface fuel hazard rating did not vary by Site Quality
Initial tree density	0.33	Surface fuel hazard rating did not depend on initial tree density
Time since thinning	0.36	Surface fuel hazard rating did not change over time
Thinning intensity	0.48	There was no effect of ecological thinning on surface fuel hazard rating
Does the effect of thinning intensity vary depending on:		
• Site Quality	1.08	The effect of thinning on surface fuel hazard rating did not vary by Site Quality
• Initial tree density	0.43	The effect of thinning on surface fuel hazard rating did not vary with initial tree density
• Time since thinning	0.21	The effect of thinning on surface fuel hazard rating did not change over time
• Site Quality **and** initial tree density **and** time since thinning	0.25	The effect of thinning on surface fuel hazard rating did not vary for all combinations of Site Quality, initial tree density and time since thinning

Hypothesis evaluation

Ecological thinning was unlikely to have increased surface fuel hazard.

13.5 Near surface fuel hazard: live near surface vegetation cover

Hypothesis	1g. Ecological thinning will increase fuel and fire risk. Live near surface vegetation cover contributes to near surface fire risk, thus the hypothesis was that ecological thinning would increase near surface vegetation cover.
Key result	Ecological thinning initially **decreased** live near surface vegetation cover, and subsequently **increased** live near surface vegetation cover by 1–12% (per 0.04-hectare subplot) in wetter Site Quality 1 plots. Ecological thinning **increased** live near surface vegetation cover in drier Site Quality 2 plots with very high initial tree density plots by 1–6% (per 0.04-hectare subplot).

Data collection

Near surface vegetation is vegetation that is generally between 0 and 1.5 metres in height (Figure 62). Near surface vegetation includes all native and exotic plant cover.

Live near surface vegetation cover was visually estimated in each 0.04-hectare subplot (see 20 x 20 metre subplots in Figure 5). Two observers estimated independently and then conferred to record one estimate as a percentage of the subplot. Surveys were conducted annually, over 6 survey years. In 2021–22, 15% of 0.04-hectare subplots were not able to be surveyed due to flooding.

Data summary

Near surface vegetation cover was most often below 15% but was spatially variable (vertical spread of points in Figure 73). Higher values were recorded in wetter (SQ1) plots than drier (SQ2) plots and variability was higher in SQ1. Sites that were in SQ2 and had very high initial tree density tended to have low cover estimates, but there were relatively few subplots in this plot type.

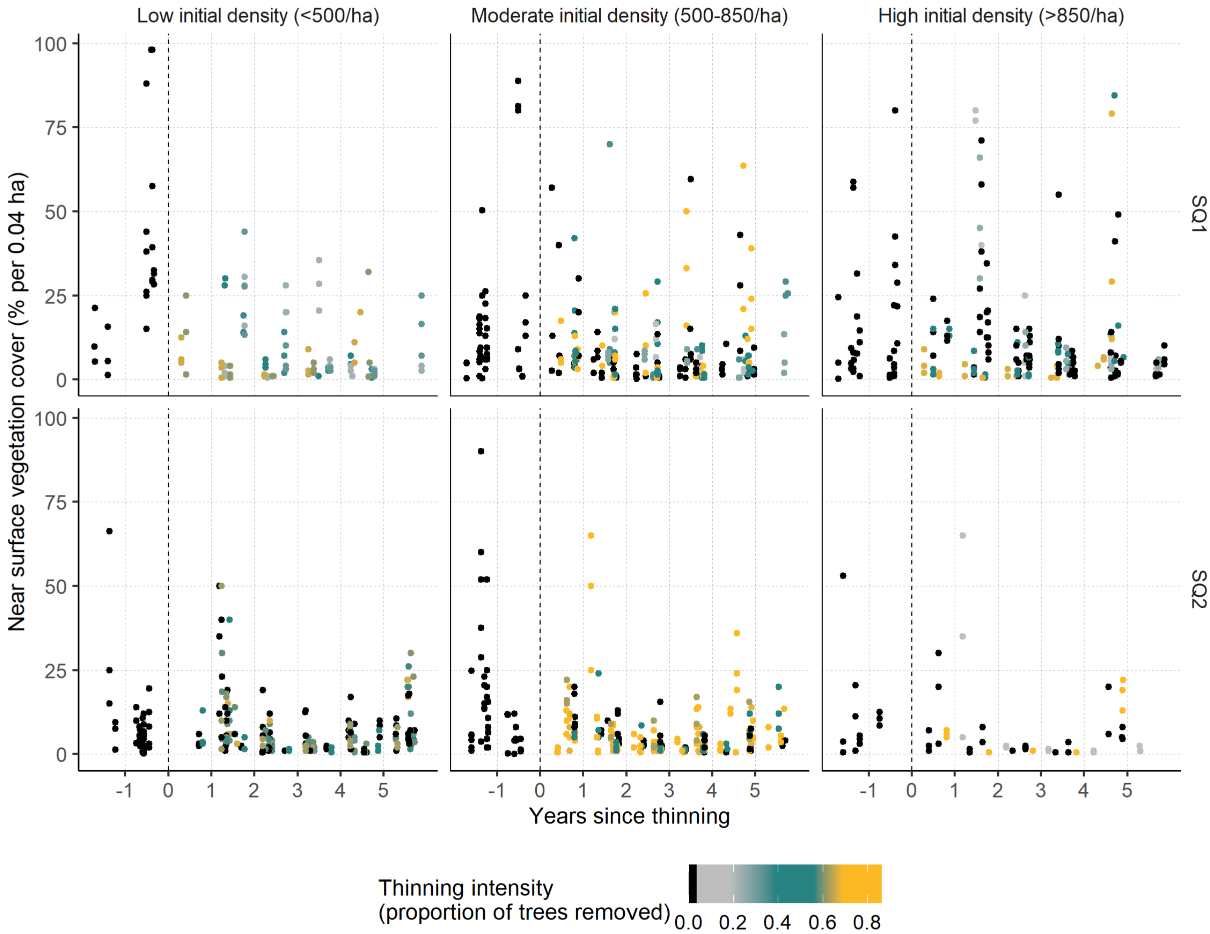

Figure 73 Data for live near surface vegetation cover (%) per 0.04-hectare subplot

Model results

Near surface vegetation cover was modelled using a gamma distribution with a log link (see Appendices). The model included all two- and three-way interactions between predictors but did not include four-way interaction. Random effects for 9-hectare plots and subplots were included, but random effects for survey year and site were not.

Modelled live near surface vegetation cover was variable, with significant variation among Site Quality classes and initial tree densities as well as significant change over time (Figure 74, Table 54). Live near surface vegetation cover was highest in wetter (SQ1) plots with very low initial tree density, and declined over time in all plot types (Figure 74).

There was a statistically significant effect of thinning which differed among Site Qualities (Figure 74, Table 54). In wetter (SQ1) plots, ecological thinning initially caused a decline in live near surface vegetation cover. The magnitude of decline was approximately 2–9% (however the confidence intervals included the fitted control value, making the significance of this initial decline uncertain). After the initial decline, near surface cover increased in plots that had been thinned, but continued to decline in control plots (Figure 74). In the most recent survey period, near surface cover was 1–22% higher in thinned plots than control plots in SQ1 (Table 55).

In drier (SQ2) plots, ecological thinning caused an initial and sustained increase in near surface vegetation cover, however the magnitude of this increase was much smaller (1–10%) (Table 55).

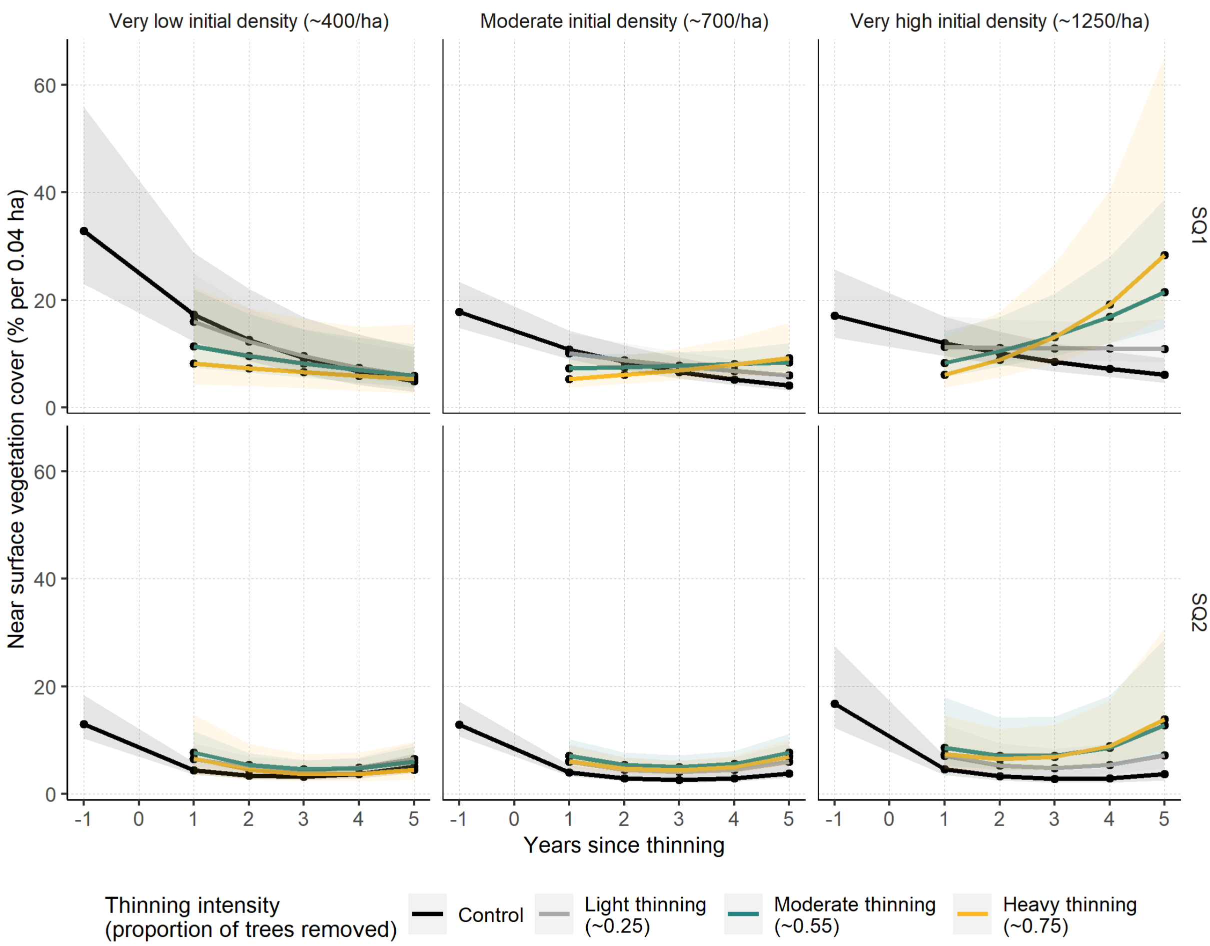

Figure 74 Modelled values and 95% confidence intervals for live near surface vegetation cover per 0.04-hectare subplot

Table 54 Statistical significance of explanatory variables on live near surface vegetation cover per 0.04-hectare subplot

	Bootstrapped likelihood ratio test significance	Description
Site Quality	0.01	Near surface vegetation cover differed among Site Qualities
Initial tree density	0.04	Near surface vegetation cover depended on initial tree density
Time since thinning	0.01	Near surface vegetation cover changed over time
Thinning intensity	0.01	Ecological thinning had a significant effect on near surface vegetation cover
Does the effect of thinning intensity vary depending on:		
• Site Quality	0.01	The effect of ecological thinning differed among Site Qualities
• Initial tree density	0.16	The effect of ecological thinning did not depend on initial tree density
• Time since thinning	0.01	The effect of ecological thinning changed over time
• Site Quality **and** initial tree density **and** time since thinning	NA	Four-way interaction was not included in the model

Table 55 Estimated effect sizes for live near surface vegetation cover (%) 5 years post-thinning, showing difference between fitted values and 95% confidence intervals in thinned plots relative to control plots

<table>
<tr><th colspan="2">Site Quality</th><th colspan="3">Site Quality 1</th><th colspan="3">Site Quality 2</th></tr>
<tr><th colspan="2">Thinning intensity</th><th>Low intensity</th><th>Mod intensity</th><th>High intensity</th><th>Low intensity</th><th>Mod intensity</th><th>High intensity</th></tr>
<tr><th rowspan="3">Initial tree density</th><td>Very low (400/ha)</td><td>+1.0
–0.9 to +5.4</td><td>+1.0
–1.3 to +6.8</td><td>0.0
–2.4 to +10.5</td><td>+1.0
+0.01 to +4.5</td><td>+1.0
–0.2 to +3.8</td><td>–1.0
–2.4 to +4.7</td></tr>
<tr><td>Moderate (700/ha)</td><td>+2.0
+0.8 to +4.0</td><td>+4.0
+2.7 to +8.0</td><td>+5.0
+2.3 to +11.8</td><td>+2.0
+0.4 to +5.3</td><td>+4.0
+2.0 to +7.2</td><td>+3.0
+1.3 to +6.1</td></tr>
<tr><td>Very high (1250/ha)</td><td>+5.0
+2.4 to +10.5</td><td>+15.0
+8.6 to +32.8</td><td>+22.0
+10.7 to +59.4</td><td>+3.0
+0.7 to +9.5</td><td>+9.0
+3.5 to +24.8</td><td>+10.0
+4.2 +26.8</td></tr>
</table>

Hypothesis evaluation

The data and modelling results suggested that the hypothesis that ecological thinning would increase near surface vegetation cover may be supported in wetter (SQ1) sites in the long term, but only after an initial decline in live near surface vegetation cover. The data and modelling also suggested that the hypothesis may be supported in drier (SQ2) sites, but the increase in cover was of a small magnitude. Note that live near surface cover includes cover of exotic (weed) plant species. Also note that, in terms of fuel hazard, live near surface vegetation cover was generally low.

13.6 Near surface fuel hazard: dead near surface vegetation cover

	1g. Ecological thinning will increase fuel and fire risk. Dead near surface vegetation cover contributes to near surface fuel hazard, thus the hypothesis was that ecological thinning would increase dead near surface vegetation cover.
Key result	Ecological thinning had an effect on dead near surface vegetation cover that depended on thinning intensity, Site Quality and initial tree density. One year post-thinning, ecological thinning **increased or decreased** dead near surface vegetation cover up to 4% (per 0.04-hectare subplot) relative to controls in different circumstances, but these effects diminished over time and were a maximum of 1.2% difference 5 years post-thinning.

Data collection

Near surface vegetation is vegetation that is generally between 0 and 1.5 metres in height (Figure 62). Near surface vegetation includes all native and exotic plant cover. Dead near surface vegetation is defined as dead material that is attached to a live plant. It includes both native and exotic plant material. Often, this is high when an aquatic plant is in the process of dying off after flood waters have receded.

Dead near surface vegetation cover was visually estimated in each 0.04-hectare subplot (see 20 x 20 metre subplots in Figure 5). Two observers estimated independently and then conferred to record one estimate as a percentage of the subplot. Surveys were conducted annually, over 6 survey years. In 2021–22, 15% of 0.04-hectare subplots were not able to be surveyed due to flooding.

Data summary

Dead near surface vegetation cover was most often less than 10%, with occasional values of 30% or more (Figure 75). In the most recent survey year, no values more than 10% were recorded.

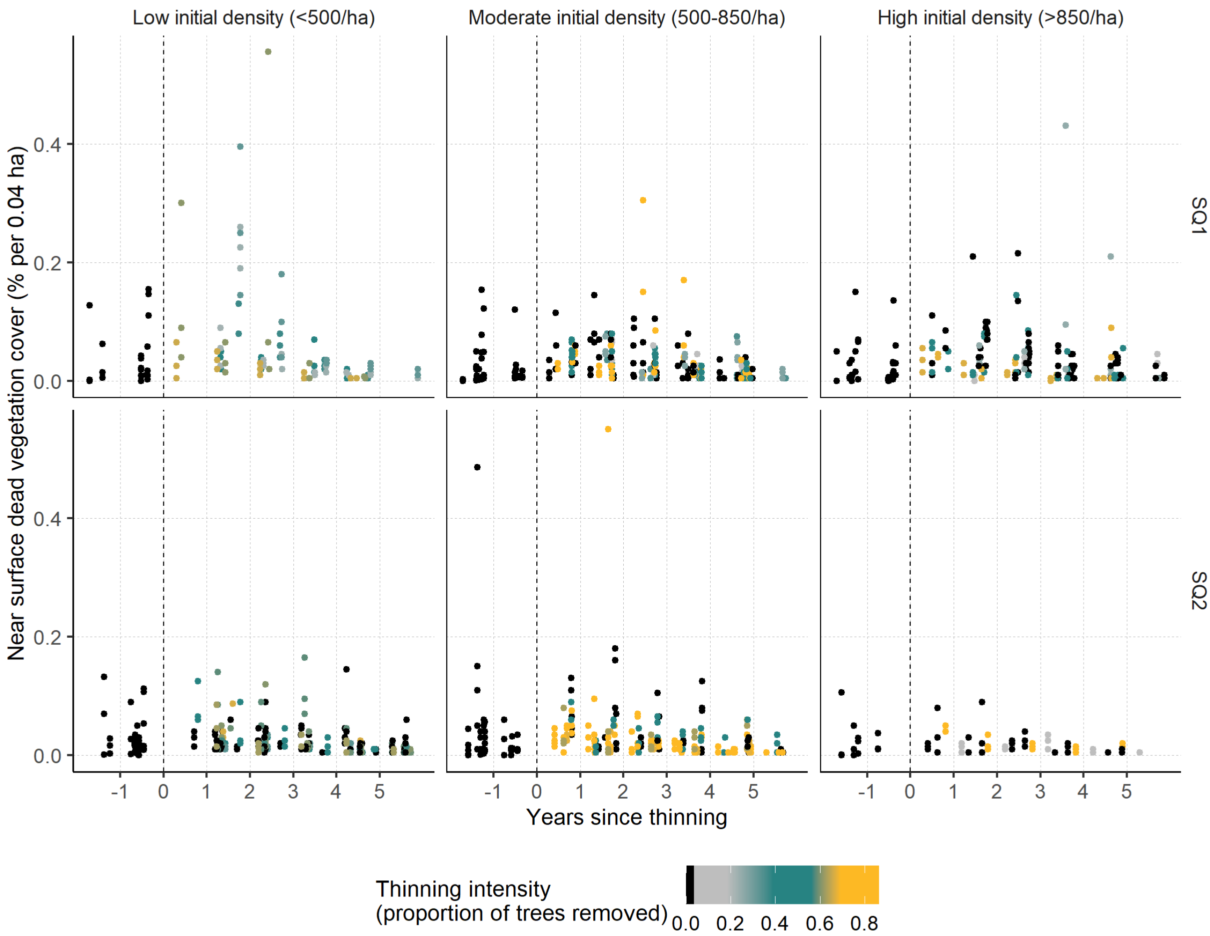

Figure 75 Data for dead near surface vegetation cover (dead vegetation attached to a live plant) (%) per 0.04-hectare subplot

Model results

Dead near surface vegetation was modelled as a proportion of the 0.04-hectare subplot using a binomial distribution (see Appendices). The model included all two- and three-way interactions but did not include four-way interaction between predictors. Random effects of 9-hectare sites and subplots were included, but survey year and site were not.

Dead near surface vegetation was variable across plot types and also over time (Figure 76), and these differences were statistically significant (Table 57).

Ecological thinning had a statistically significant effect on dead near surface vegetation cover, but this effect depended on thinning intensity, Site Quality and initial tree density (Figure 76, Table 57). The greatest magnitude of effect occurred in the first year post-thinning.

In wetter (SQ1) plots the direction of change in dead near surface vegetation changed with thinning intensity, such that light thinning caused an increase in dead cover but heavy thinning caused a decrease in dead cover. The magnitude of this effect varied with initial tree density, with a maximum of 3–4% difference from controls in both directions. These impacts declined in magnitude over time, and 5 years post-thinning the maximum difference from controls was 0.8% (Table 57).

In drier (SQ2) plots ecological thinning caused an increase in dead cover and the magnitude of the impact increased with increasing intensity of thinning and initial tree density. In the first year post-thinning, the maximum magnitude of the effect was 2.3%. This effect diminished over time and the maximum difference from controls 5 years post-thinning was 1.2% (Table 57).

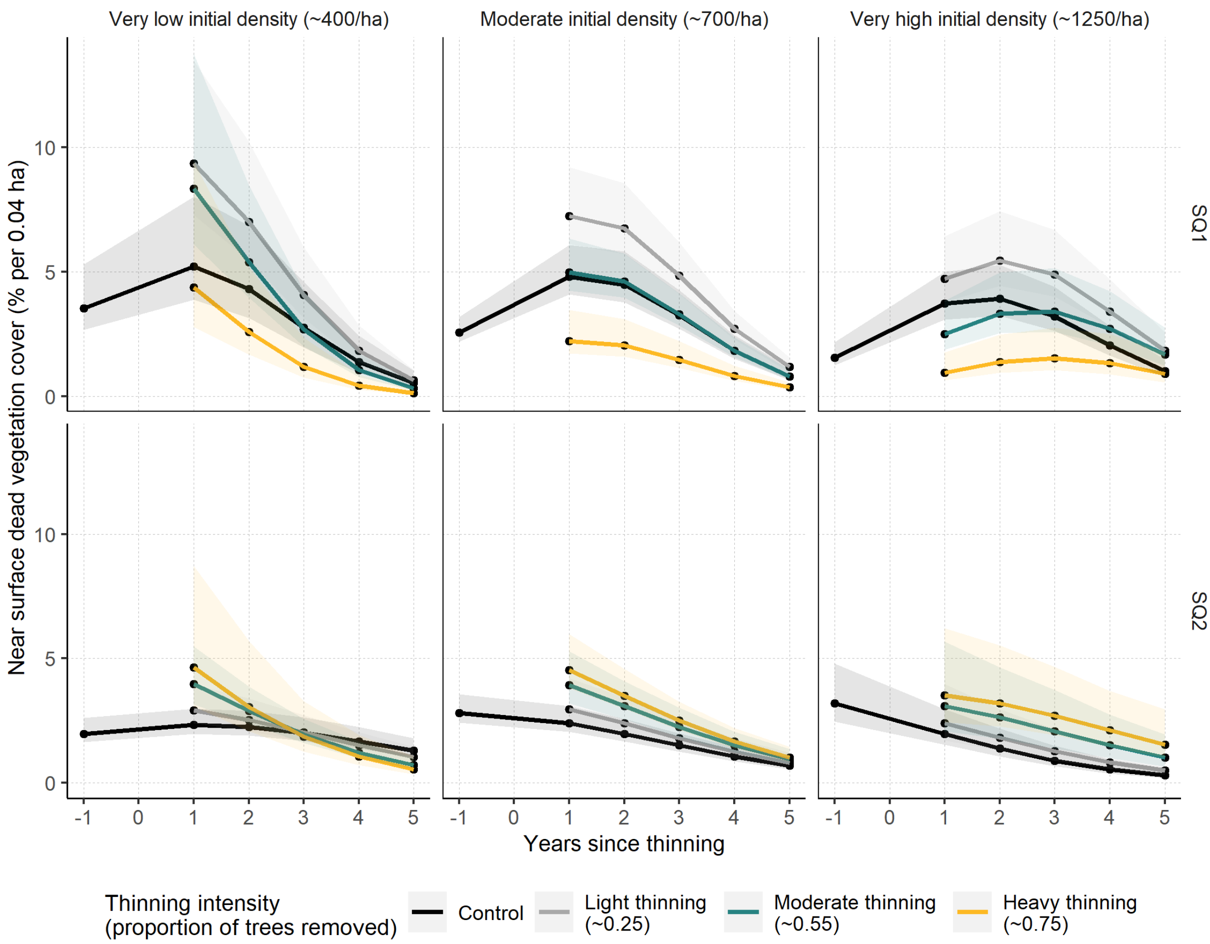

Figure 76 Modelled values and 95% confidence intervals for dead near surface vegetation cover per 0.04-hectare subplot

Table 56 Statistical significance of explanatory variables on dead near surface vegetation cover per 0.04-hectare subplot

	Bootstrapped likelihood ratio test significance	Description
Site Quality	0.01	Dead near surface vegetation cover differed among Site Qualities
Initial tree density	0.01	Dead near surface vegetation cover depended on initial tree density
Time since thinning	0.01	Dead near surface vegetation cover changed over time
Thinning intensity	0.01	Ecological thinning had a significant effect on dead near surface vegetation cover
Does the effect of thinning intensity vary depending on:		

	Bootstrapped likelihood ratio test significance	Description
• Site Quality	0.01	The effect of ecological thinning differed among Site Qualities
• Initial tree density	0.01	The effect of ecological thinning did not depend on initial tree density
• Time since thinning	0.01	The effect of ecological thinning changed over time
• Site Quality **and** initial tree density **and** time since thinning	NA	Four-way interaction was not included in the model

Table 57 Estimated effect sizes for dead near surface vegetation cover (%) 5 years post-thinning, showing difference between fitted values and 95% confidence intervals in thinned plots relative to control plots

Site Quality		Site Quality 1			Site Quality 2		
Thinning intensity		Low intensity	Mod intensity	High intensity	Low intensity	Mod intensity	High intensity
Initial tree density	Very low (400/ha)	+0.1 –0.1 to +0.5	–0.2 –0.3 to +0.03	–0.4 –0.5 to –0.3	–0.3 –0.5 to +0.2	–0.6 –0.7 to –0.3	–0.7 –0.9 to –0.2
	Moderate (700/ha)	+0.4 +0.2 to +0.8	0.0 –0.1 to +0.3	–0.4 –0.5 to –0.2	+0.1 –0.1 to +0.5	+0.3 +0.1 to +0.7	+0.3 +0.1 to +0.7
	Very high (1250/ha)	+0.8 +0.5 to +1.6	+0.7 +0.2 to +1.8	–0.1 –0.4 to +0.8	+0.2 +0.02 to +0.6	+0.7 +0.3 to +1.6	+1.2 +0.7 to +2.6

Hypothesis evaluation

There was some evidence to support the hypothesis that ecological thinning increased dead cover of near surface vegetation in drier (SQ2) plots, but this effect was temporary. Further, in some circumstances the hypothesis was not supported as ecological thinning decreased dead near surface vegetation.

13.7 Near surface fuel hazard assessment

Hypothesis	1g. Ecological thinning will increase fuel and fire risk.
Key result	**No statistically significant effect of ecological thinning.**

Data collection

As described for surface fuel assessment, the near surface fuel assessment categories defined by Hines et al. (2010) are incomplete. Additional categories were defined to objectively allocate all data to a near surface fuel hazard category (clear cells in Table 58).

Near surface fuel assessment is based on total near surface vegetation cover (that is, live + dead cover described in the previous 2 sections), and the proportion of total cover that is dead (that is, dead cover divided by total cover).

Table 58 Near surface fuel assessment categories (adapted from Hines et al. 2010)

Grey cells are defined by Hines et al. (2010), clear cells were defined by the authors to enable classification of all data.

Proportion dead cover	Total near surface plant cover (%)				
	<10	10–20	20–40	40–60	>60
<10	L	M	M	M	M
10–20	L	M	M	H	H
20–30	L	H	H	H	VH
30–50	M	H	H	VH	VH
>50	M	H	H	VH	E

Data summary

Near surface fuel hazard scores for 0.04-hectare subplots were most commonly in the moderate and high categories (Figure 63, Figure 64, Figure 77). There were no apparent differences between the Site Qualities. In the most recent 2 survey seasons (3–5 years post-thinning), fewer high category scores were recorded.

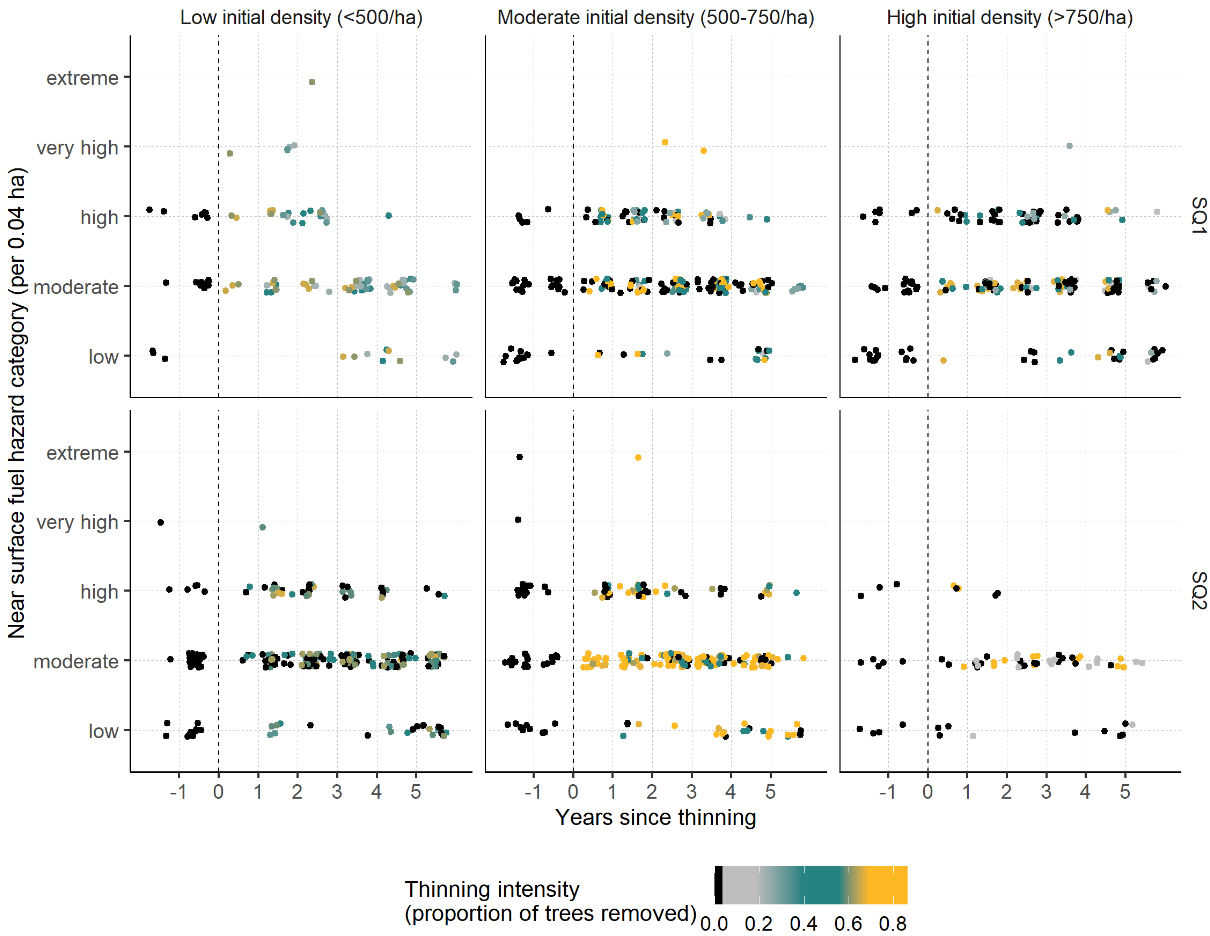

Figure 77 Data for near surface fuel hazard category

Model results

Near surface fuel hazard category was modelled using a Bayesian cumulative ordinal model, a type of regression that calculates the probability of data belonging to a set of ordered categories (see Appendices). The model for near surface fuel hazard category included all interactions between Site Quality, initial tree density, thinning intensity and time since thinning. The model also included 4 random effects: site, 9-hectare plot, 0.04-hectare subplot and survey year.

Near surface fuel hazard scores initially increased between the pre-thinning surveys and the first year post-thinning surveys; subsequently, scores decreased over time (Figure 78, Table 56). Scores were higher in wetter (SQ1) sites than drier (SQ2) sites, with a higher probability of a 0.04-hectare subplot being in the high category.

In wetter (SQ1) thinned plots, ecological thinning caused a slight decrease in the near surface fuel hazard score (decreased probability of being in the high category; increased probability of being in the moderate category), although this effect was not apparent in drier (SQ2) plots and was not statistically significant (Figure 78, Table 56).

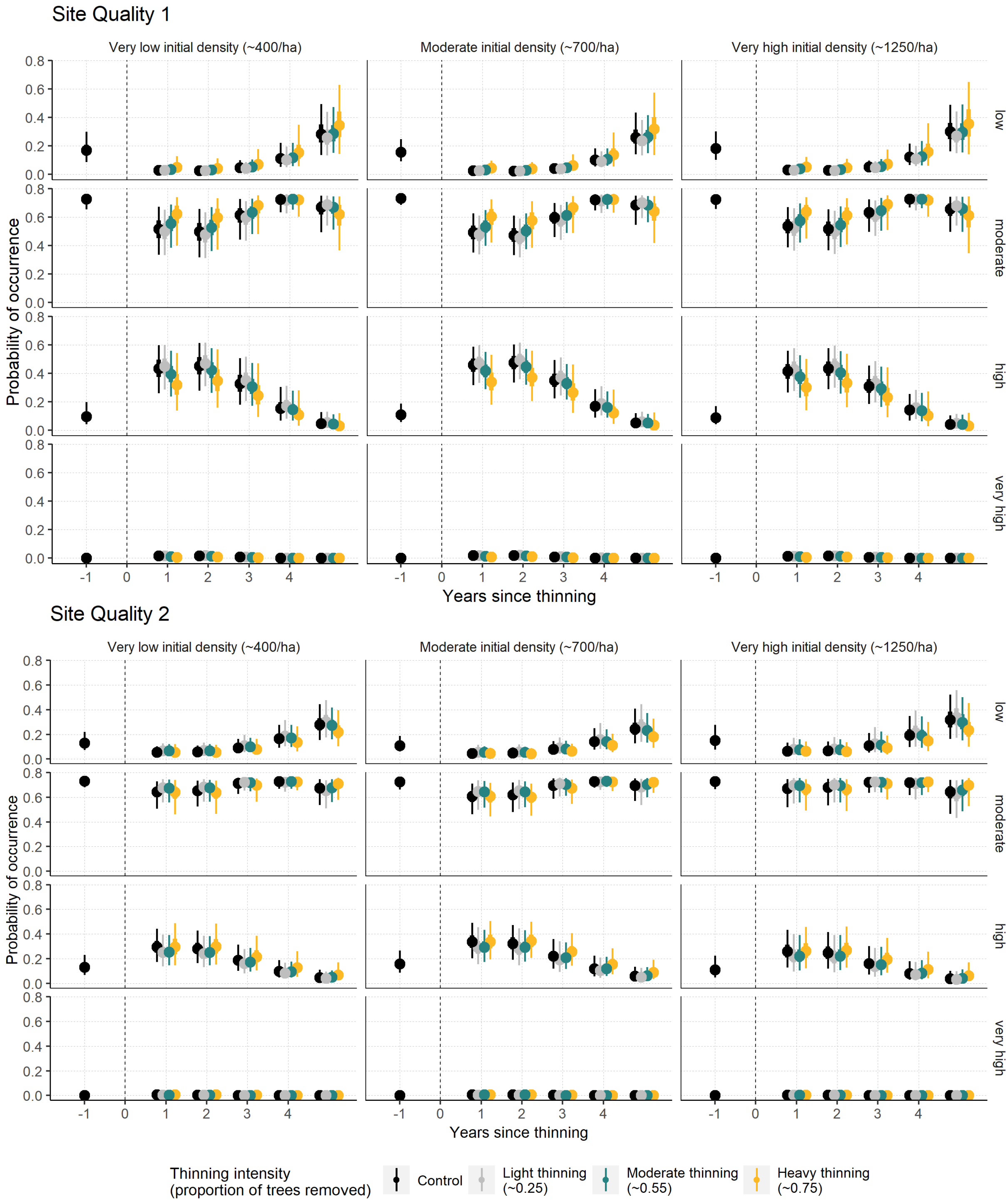

Figure 78 Modelled probability of being in each of the near surface fuel hazard categories ± 50% and 95% bootstrapped confidence intervals for ecological thinning treatment, survey year and Site Quality.

Table 59 Statistical significance of explanatory variables on near surface fuel hazard ratings

Evidence of statistical significance for ELPD ratio >4

Model term	ELPD ratio	Comment
Site Quality	1.97	Near surface fuel hazard rating did not vary by Site Quality
Initial tree density	1.39	Near surface fuel hazard rating did not depend on initial tree density
Time since thinning	2.01	Near surface fuel hazard rating did not change over time
Thinning intensity	0.65	There was no effect of ecological thinning on near surface fuel hazard rating
Does the effect of thinning intensity vary depending on:		
• Site Quality	0.58	The effect of thinning on near surface fuel hazard rating did not vary by Site Quality
• Initial tree density	0.82	The effect of thinning on near surface fuel hazard rating did not vary with initial tree density
• Time since thinning	0.62	The effect of thinning on near surface fuel hazard rating did not change over time
• Site Quality **and** initial tree density **and** initial tree diameter	2.26	The effect of thinning on near surface fuel hazard rating did not vary for all combinations of Site Quality, initial tree density and time since thinning

Hypothesis evaluation

No evidence that thinning altered near surface fuel hazard.

13.8 Combined surface and near surface fuel hazard assessment

Hypothesis	1g. Ecological thinning will increase fuel and fire risk.
Key result	**No statistically significant effect of ecological thinning.**

Data collection

The surface and near surface fuel hazard categories are combined to determine a combined surface hazard category. All categories are defined by Hines et al. (2010) (Table 60).

Table 60 Combined surface and near surface fuel hazard assessment categories (from Hines et al. 2010)

Surface risk	Near surface risk				
	L	**M**	**H**	**VH**	**E**
L	L	L	M	H	VH
M	M	M	H	VH	E
H	H	VH	VH	VH	E
VH	VH	VH	E	E	E
E	E	E	E	E	E

Data summary

Scores for combined surface and near surface fuel hazard were variable among plot types and over time (Figure 79). The most commonly recorded score was very high in both Site Qualities.

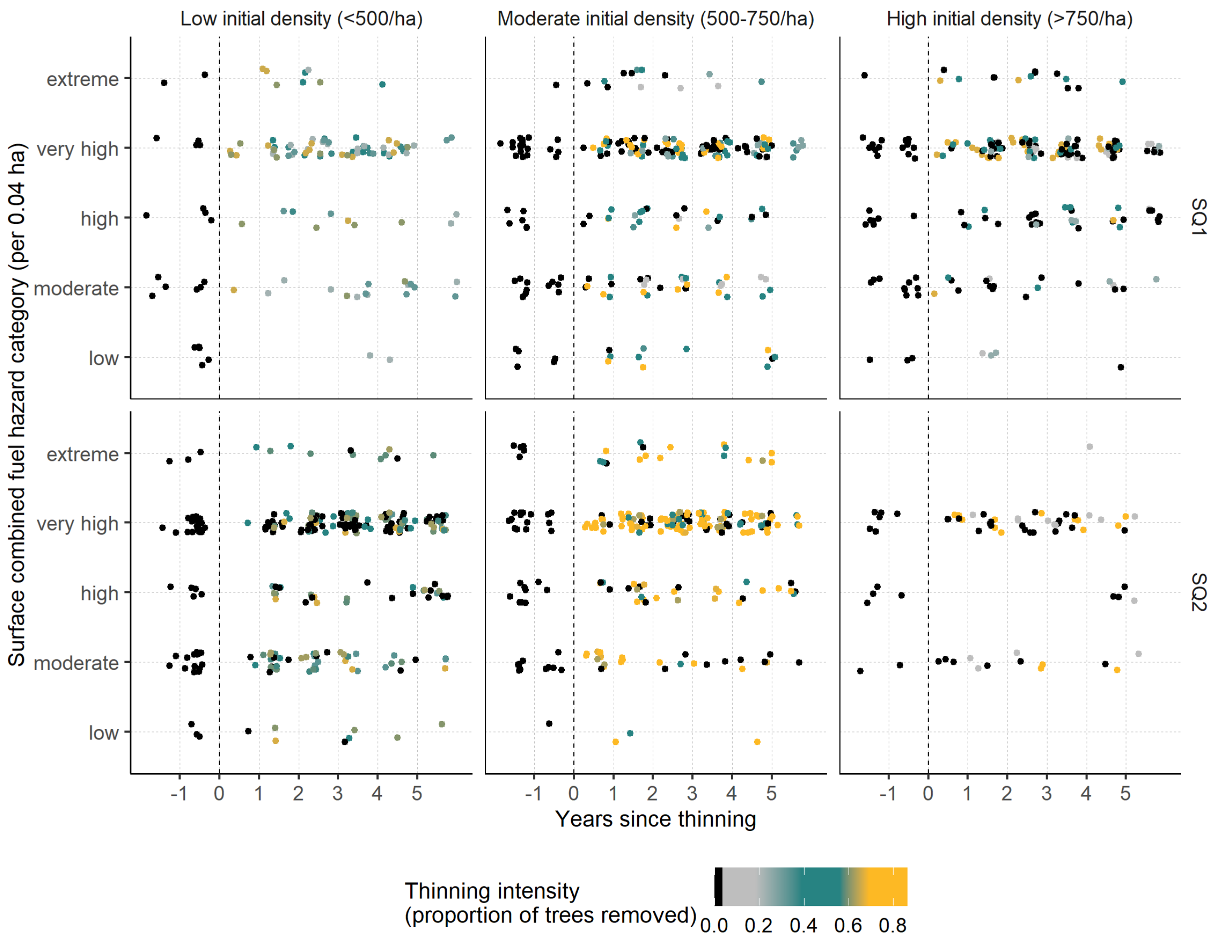

Figure 79 Data for combined surface and near surface fuel hazard categories

Model results

Surface fuel hazard category was modelled using a Bayesian cumulative ordinal model, a type of regression that calculates the probability of data belonging to a set of ordered categories (see Appendices). The model for surface fuel hazard category included all interactions between Site Quality, initial tree density, thinning intensity and time since thinning. The model also included 4 random effects: site, 9-hectare plot, 0.04-hectare subplot and survey year.

In the absence of ecological thinning, combined surface and near surface fuel hazard scores were similar among Site Qualities, initial tree densities and over time (Figure 80). There were no statistically significant differences (Table 58).

Ecological thinning caused an initial decrease in combined score, with a decreased probability of being in the very high category than control subplots (Figure 80). This effect was apparent for all thinning intensities in drier (SQ2) plots but only heavy intensity thinning in wetter (SQ1) plots. This effect was temporary, and in the most recent survey year (5 years post-thinning) thinned subplots had a slightly higher probability of being in the very high category than control plots. None of these differences were statistically significant (Table 58).

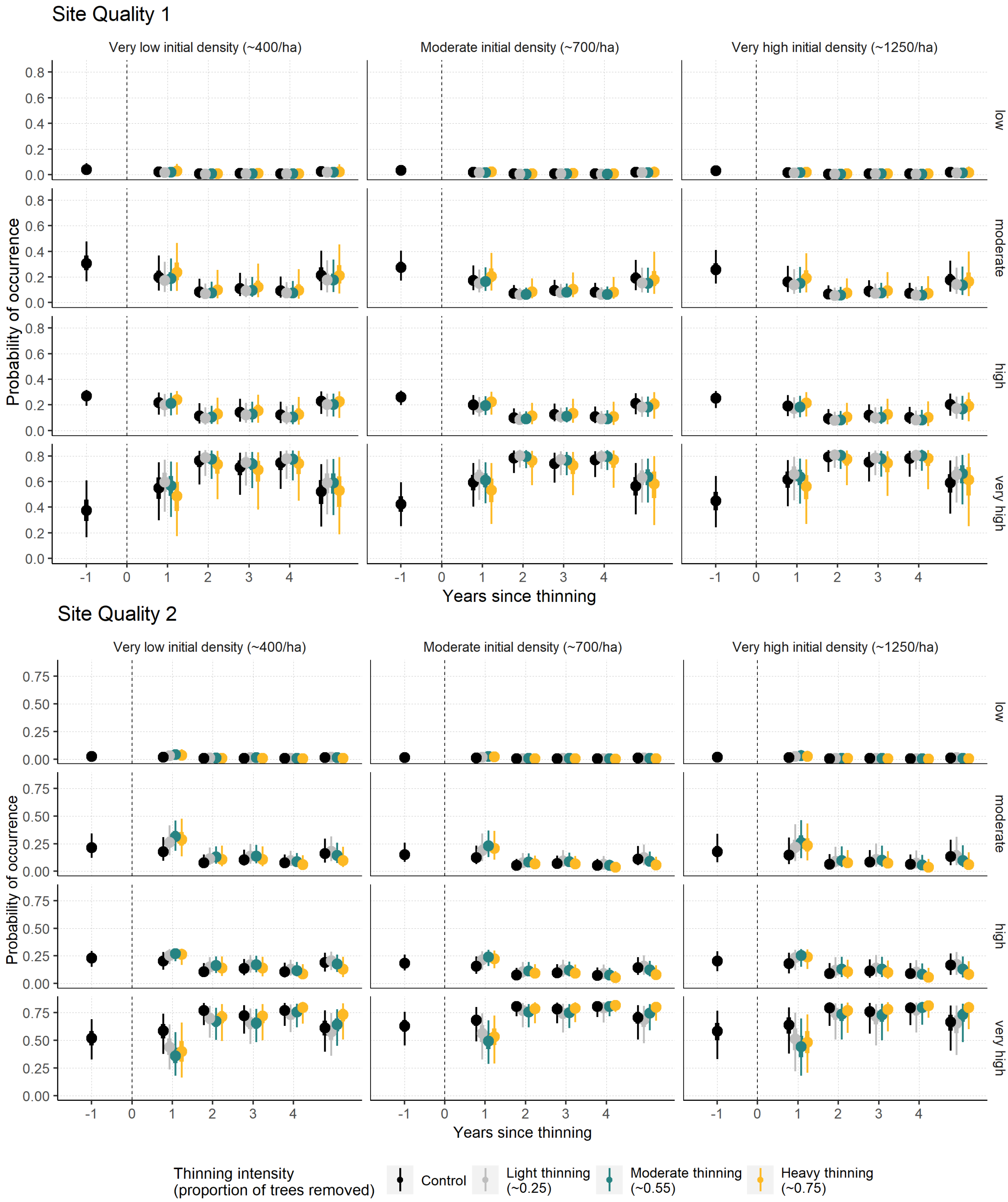

Figure 80 Modelled probability of being in each of the combined surface and near surface fuel hazard categories ±50% and 95% bootstrapped confidence intervals for ecological thinning treatment, survey year and Site Quality

Table 61 Statistical significance of explanatory variables on combined surface and near surface fuel hazard ratings

Evidence of statistical significance for ELPD ratio >4

Model term	ELPD ratio	Comment
Site Quality	1.29	Combined surface and near surface fuel hazard rating did not vary by Site Quality
Initial tree density	1.11	Combined surface and near surface fuel hazard rating did not depend on initial tree density
Time since thinning	1.17	Combined surface and near surface fuel hazard rating did not change over time
Thinning intensity	0.91	There was no effect of ecological thinning on combined surface and near surface fuel hazard rating
Does the effect of thinning intensity vary depending on:		
• Site Quality	1.06	The effect of thinning on combined surface and near surface fuel hazard rating did not vary by Site Quality
• Initial tree density	0.97	The effect of thinning on combined surface and near surface fuel hazard rating did not vary with initial tree density
• Time since thinning	0.83	The effect of thinning on combined surface and near surface fuel hazard rating did not change over time
• Site Quality **and** initial tree density **and** initial tree diameter	0.2	The effect of thinning on combined surface and near surface fuel hazard rating did not vary for all combinations of Site Quality, initial tree density and time since thinning

Hypothesis evaluation

Evidence for combined surface and near surface fuel hazard suggested that the hypothesis may not be supported in the first post-thinning year, with weak evidence of a temporary reduction in this component of fuel hazard. However, there was also weak support for the hypothesis in the most recent survey year. None of the effects of thinning were statistically significant.

13.9 Elevated fuel hazard: live elevated cover

Hypothesis	1g. Ecological thinning will increase fuel and fire risk. Live vegetation cover of the elevated stratum contributes to the assessment of fuel hazard, therefore the hypothesis was that ecological thinning would increase live elevated cover.
Key result	Ecological thinning likely temporarily reduced live vegetation cover in the elevated stratum by 3–5% (per 0.04-hectare subplot), however a statistical model was not able to be fitted to these data.

Data collection

The elevated stratum is defined as being clearly separated from the near surface stratum and consisting predominantly of woody plants (Figure 62). In river red gum forest the elevated stratum consists almost exclusively of *Eucalyptus camaldulensis* saplings and small trees.

Live elevated vegetation cover was assessed by visual estimation in three 0.04-hectare plots within each 9-hectare plot (see the 20 x 20 metre subplots in Figure 5). Surveys were conducted annually, over 6 survey years. In 2021–22, 15% of 0.04-hectare subplots were not able to be surveyed due to flooding.

Data summary

Elevated vegetation cover most commonly ranged between 0 and 10% (Figure 81). The elevated stratum was absent from approximately 10% of subplots, often reflecting the absence of saplings from minor topographic depressions in which floodwaters pool and limit sapling recruitment.

Average cover was slightly higher in wetter (SQ1) plots (3.7%) than it was in drier (SQ2) plots (2.5%) (Figure 81, Figure 82). Highest values were recorded 2–4 years post-thinning in the 2018–19 to 2020–21 surveys.

Without considering the influence of initial tree density on ecological thinning outcomes, the raw data suggest that ecological thinning reduced live elevated cover for at least 3 years post-thinning (until 2019–20 surveys) (Figure 82). The maximum difference in elevated cover between heavily thinned and control plots was approximately 4–5% in wetter (SQ1) and 3% in drier (SQ2) plots.

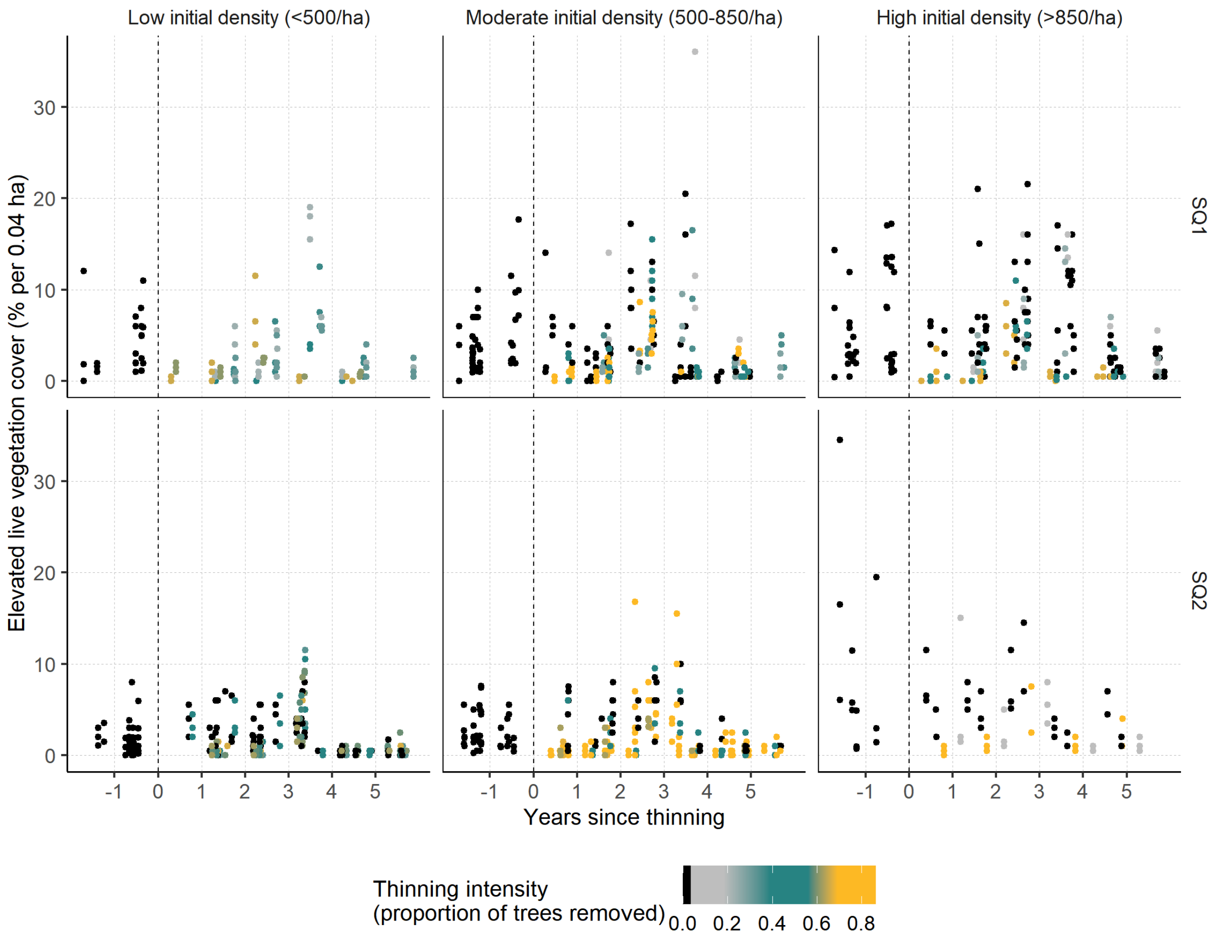

Figure 81 Data for live elevated vegetation cover (%) visually estimated per 0.04-hectare subplot

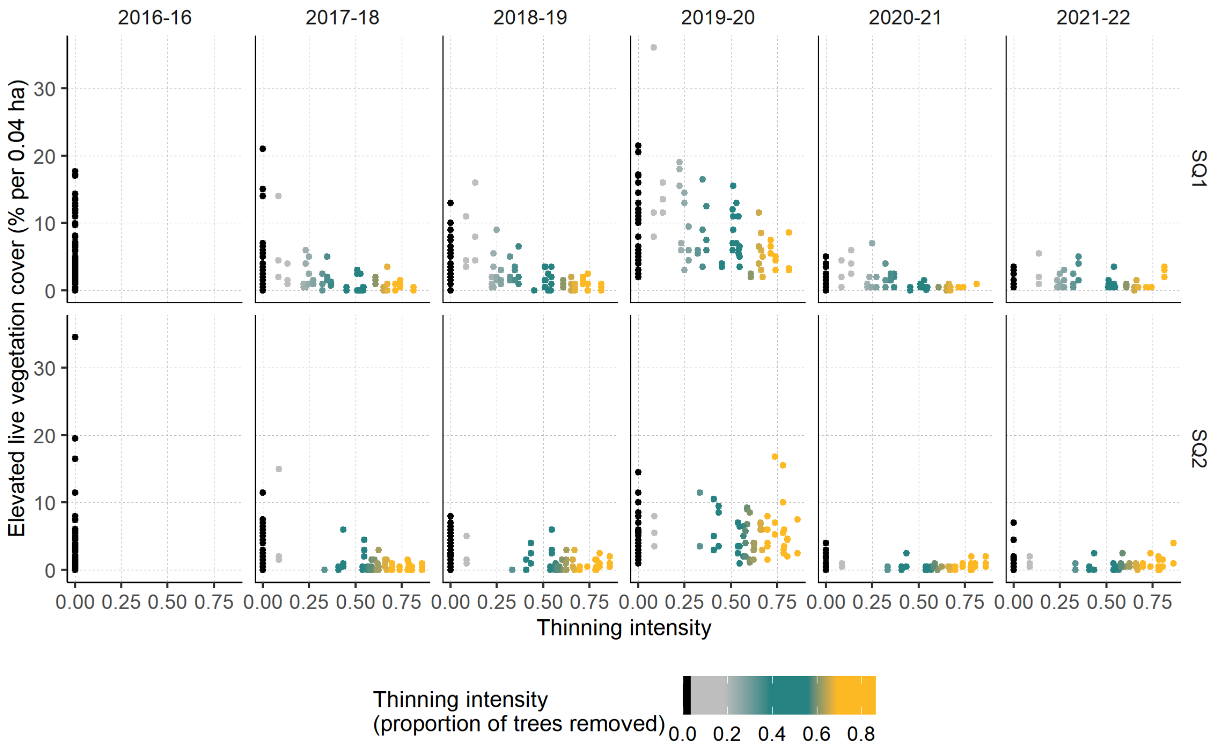

Figure 82 Data for live elevated cover by survey year, Site Quality and thinning intensity

Note that this figure does not include initial tree density.

Model results

A model could not be fitted for live elevated vegetation cover (see Appendices).

Hypothesis evaluation

Statistical analyses were not undertaken for live vegetation cover in the elevated stratum; however, the data do not support the hypothesis. Ecological thinning reduced cover for at least 3 years post-thinning.

13.10 Elevated fuel hazard: dead elevated cover

Hypothesis	1g. Ecological thinning will increase fuel and fire risk. Dead vegetation cover of the elevated stratum contributes to the assessment of fuel hazard, therefore the hypothesis was that ecological thinning would increase dead elevated cover.
Key result	No evidence in the data that ecological thinning affected dead elevated vegetation cover (per 0.04-hectare subplot), however a statistical model was not able to be fitted to these data.

Data collection

The elevated stratum is defined as being clearly separated from the near surface stratum and consisting predominantly of woody plants (Figure 62). In river red gum forest the elevated stratum consists almost exclusively of dead foliage in *Eucalyptus camaldulensis* saplings and small trees.

Dead elevated vegetation cover was assessed by visual estimation in three 0.04-hectare subplots within each 9-hectare plot (see the 20 x 20 metre subplots in Figure 5). Surveys were conducted annually, over 6 survey years. In 2021–22, 15% of 0.04-hectare subplots were not able to be surveyed due to flooding.

Prior to thinning (2015–16 surveys), observers estimated dead elevated cover as a proportion of total elevated cover, which were converted into estimates of the cover of dead vegetation per 0.04-hectare subplot in these analyses. In subsequent years, observers estimated actual dead elevated vegetation cover. Where dead foliage was present but not able to be measured, observers ascribed a value of 0.5%.

Data summary

Dead elevated vegetation cover was most often less than 1%, across all plot types and over time (Figure 83). A handful of higher values of dead elevated cover were recorded across all plot types 3 years post-thinning (2019–20 surveys). There was no evidence in the data that ecological thinning affected dead elevated vegetation cover.

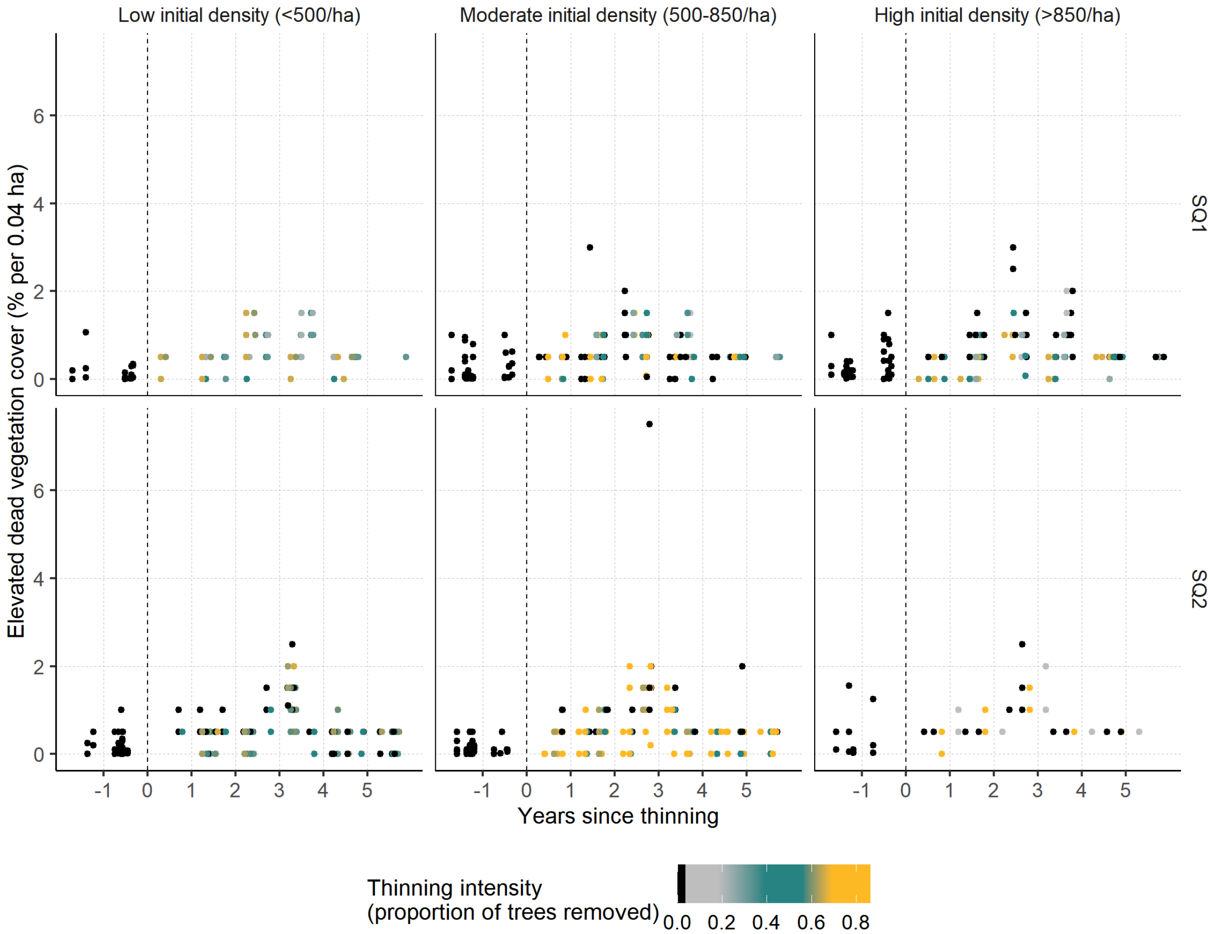

Figure 83 Data for visual estimates of dead elevated vegetation cover (%) per 0.04-hectare subplot

Model results

No model was able to be fitted for dead elevated vegetation.

Hypothesis evaluation

There was no support for the hypothesis in the raw data, although no statistical analyses were able to be undertaken for this variable.

13.11 Elevated fuel hazard assessment

Hypothesis	1g. Ecological thinning will increase fuel and fire risk.
Key result	**No statistically significant effect of ecological thinning.**

Data collection

Elevated fuel assessment is based on total elevated vegetation cover (that is, live + dead cover), and the proportion of total elevated cover that is dead (that is, dead cover divided by total cover). Some category definitions by Hines et al. (2010) are incomplete, therefore additional categories were defined by the authors to objectively allocate all data to a near surface fuel hazard category (clear cells in Table 59).

Table 62 Elevated fuel hazard assessment categories (adapted from Hines et al. 2010)

Grey cells are defined by Hines et al. (2010), clear cells are additionally defined by the authors to enable classification of all data.

Proportion dead cover	Total elevated plant cover (%)		
	<5	<20	20–30
<20	L	L	M
20–30	M	M	M
30–50	M	M	H
>50	M	H	VH

Data summary

Elevated fuel hazard scores in 0.04-hectare subplots were most commonly low or moderate, with only 2 scores in the high category in all surveys (Figure 63, Figure 64, Figure 84). The distribution of scores across low and moderate elevated fuel hazard categories was similar across all plot types and over time.

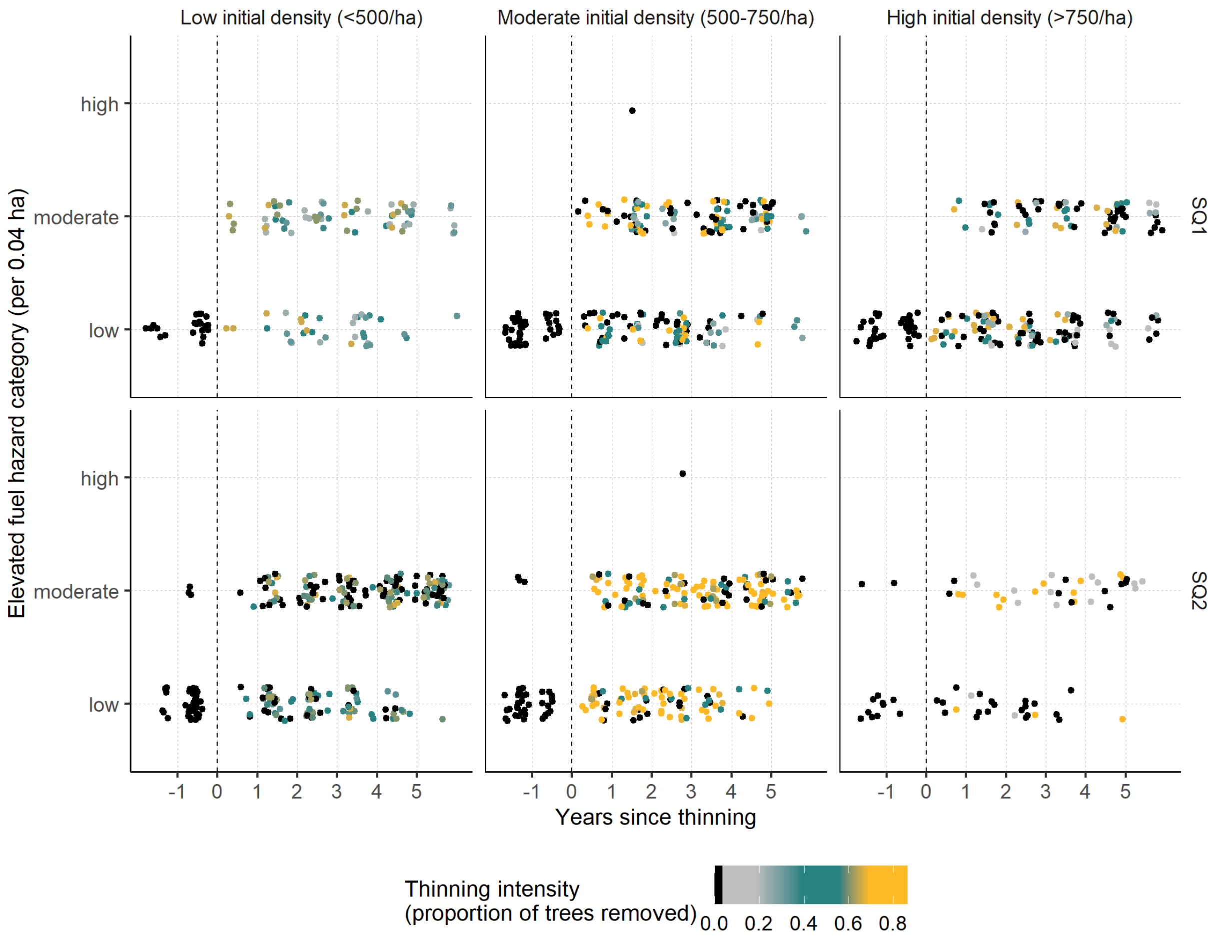

Figure 84 Data for elevated fuel hazard scores

Model results

Elevated fuel hazard category was modelled using a Bayesian cumulative ordinal model, a type of regression that calculates the probability of data belonging to a set of ordered categories (see Appendices). The model for elevated fuel hazard category included all interactions between Site Quality, initial tree density, thinning intensity and time since thinning. The model also included 4 random effects: site, 9-hectare plot, 0.04-hectare subplot and survey year.

In the absence of thinning, there was little difference among Site Qualities or initial tree densities in the most likely fuel hazard category for the elevated stratum (Figure 85). Scores changed over time, with an increased likelihood of being in the moderate category. None of these effects were statistically significant (Table 60).

The effect of heavy intensity ecological thinning was to increase the probability of being in the moderate category (and decrease the probability of being in the low category) (Figure 85). This effect diminished over time. None of these effects were statistically significant (Table 60).

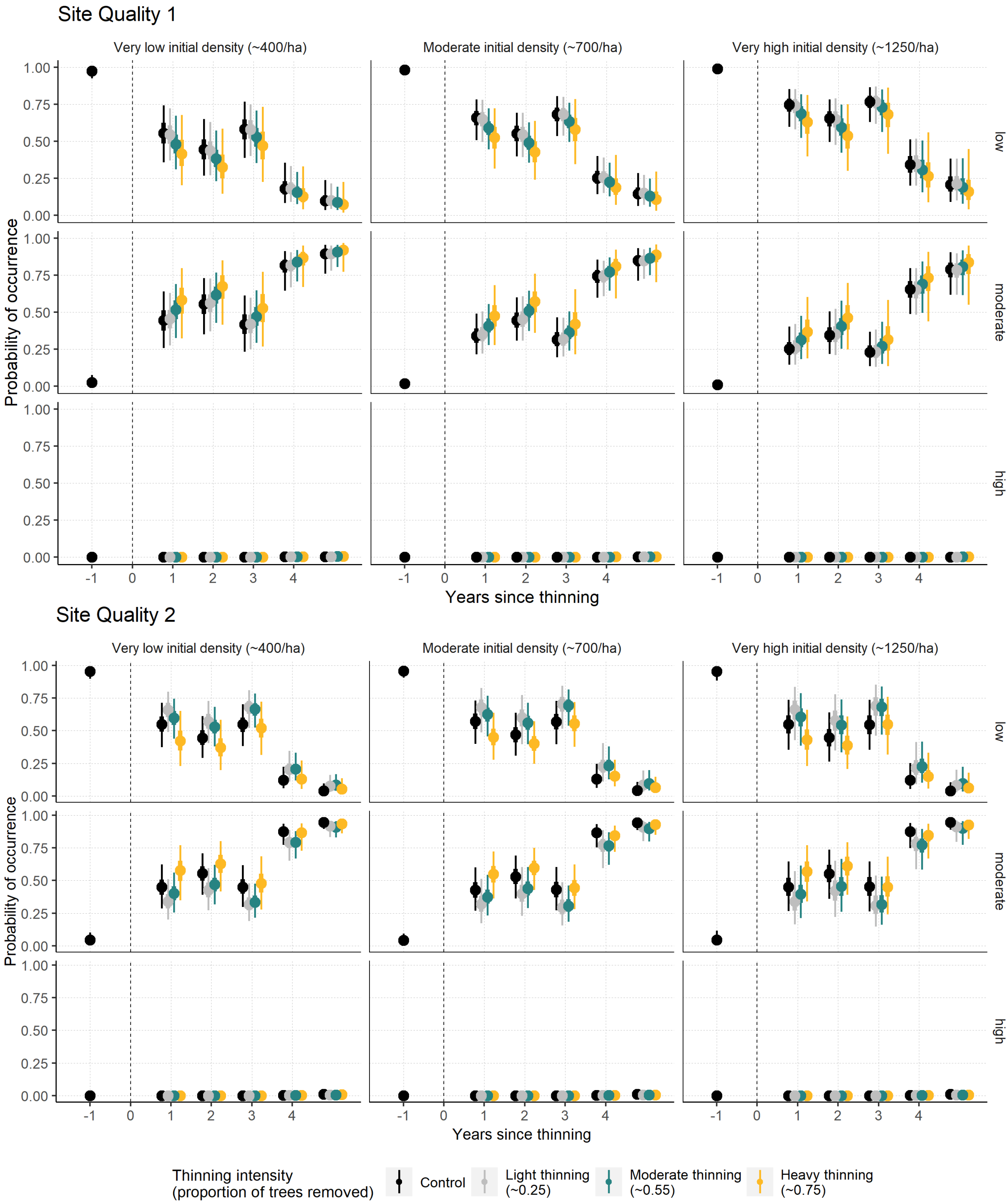

Figure 85 Modelled probability of being in each of the elevated fuel hazard assessment categories ± 50% and 95% bootstrapped confidence intervals for ecological thinning treatment, survey year and Site Quality

Table 63 Statistical significance of explanatory variables on elevated fuel hazard ratings

Evidence of statistical significance for ELPD ratio >4

Model term	ELPD ratio	Comment
Site Quality	1.51	Elevated fuel hazard rating did not vary by Site Quality
Initial tree density	0.08	Elevated fuel hazard rating did not depend on initial tree density
Time since thinning	1.13	Elevated fuel hazard rating did not change over time
Thinning intensity	0.19	There was no effect of ecological thinning on elevated fuel hazard rating
Does the effect of thinning intensity vary depending on:		
• Site Quality	0.82	The effect of thinning on elevated fuel hazard rating did not vary by Site Quality
• Initial tree density	0.79	The effect of thinning on elevated fuel hazard rating did not vary with initial tree density
• Time since thinning	0.40	The effect of thinning on elevated fuel hazard rating did not change over time
• Site Quality **and** initial tree density **and** initial tree diameter	1.51	The effect of thinning on elevated fuel hazard rating did not vary for all combinations of Site Quality, initial tree density and time since thinning

Hypothesis evaluation

The modelled probability of thinned 0.04-hectare subplots being in the moderate fuel hazard category for the elevated stratum was temporarily slightly higher than control plots. However, the hypothesis that ecological thinning increased elevated fuel hazard was not well supported, as the effect diminished over time and was not statistically significant.

14. Results: Bats

14.1 Bat species richness

Hypothesis	2a. Ecological thinning will increase diversity of bat species. Species diversity is an index that combines data about species richness (the count of bat species) and the abundance of each species. As differences in species diversity can be difficult to interpret, the hypothesis is also evaluated for species richness.
Key result	No evidence of an effect of ecological thinning, although statistical analyses were not undertaken as most bat species were recorded on most plots and a model was not able to be fitted to these data.

Data collection

An Anabat detector (Titley Electronics, Ballina, NSW, Australia) was mounted on a tree facing towards a flyway in the centre of each 9-hectare treatment plot (see Figure 5). Ultrasonic observations were recorded in each subplot for 3 nights around the time of a new moon. The recordings were processed through Anascheme to separate recordings that only contained noise from those containing bat calls, with tentative identifications being provided for the calls. Sonograms of the calls were visually inspected to validate species identification. Observations where species identification was uncertain were excluded.

Data from 7 successive summers was analysed: December 2015 immediately before the commencement of thinning; February 2017 during the thinning phase but excluding plots where thinning was in progress; and annually after thinning between February 2018 and February 2022. In 2022, 42% out of 66 plots were not surveyed for bats due to restricted access around the time of the full moon.

Data summary

A total of 11 bat species were recorded across all surveys. Most species were recorded on at least two-thirds of the 9-hectare plots in each year (Table 61). The least frequently recorded species was *Scotorepens greyii* (little broad-nosed bat), which was not detected in either of the 2 most recent surveys.

Table 64 Proportion of surveyed 9-hectare plots that each bat species was recorded in by survey year

Species	2015–16	2016–17	2017–18	2018–19	2019–20	2020–21	2021–22
Chalinolobus gouldii	94	71	95	92	88	100	100
Chalinolobus morio	62	32	68	71	59	89	78
Mormopterus spp	82	71	100	100	95	100	100
Nyctophilus spp	97	79	100	100	100	100	98
Saccolaimus flaviventris	21	50	59	62	76	76	61
Scotorepens balstoni	79	68	92	89	83	94	93

Species	2015–16	2016–17	2017–18	2018–19	2019–20	2020–21	2021–22
Scotorepens greyii	18	26	48	3	30	-	-
Tadarida australis	83	64	91	97	100	100	95
Vespadelus darlingtoni	97	73	98	97	98	98	100
Vespadelus regulus	94	73	98	94	88	97	95
Vespadelus vulturnus	97	77	100	100	100	100	100

The number of species recorded in each 9-hectare plot (over 3 nights of sampling per survey) was most commonly 9 or 10 (Figure 86). There was no apparent variation in species richness with Site Quality or initial tree density. Control plots appear to have had more records with fewer than 9 species than thinned plots.

In the absence of information about initial tree density, there were no strongly apparent effects of ecological thinning on bat richness (Figure 87).

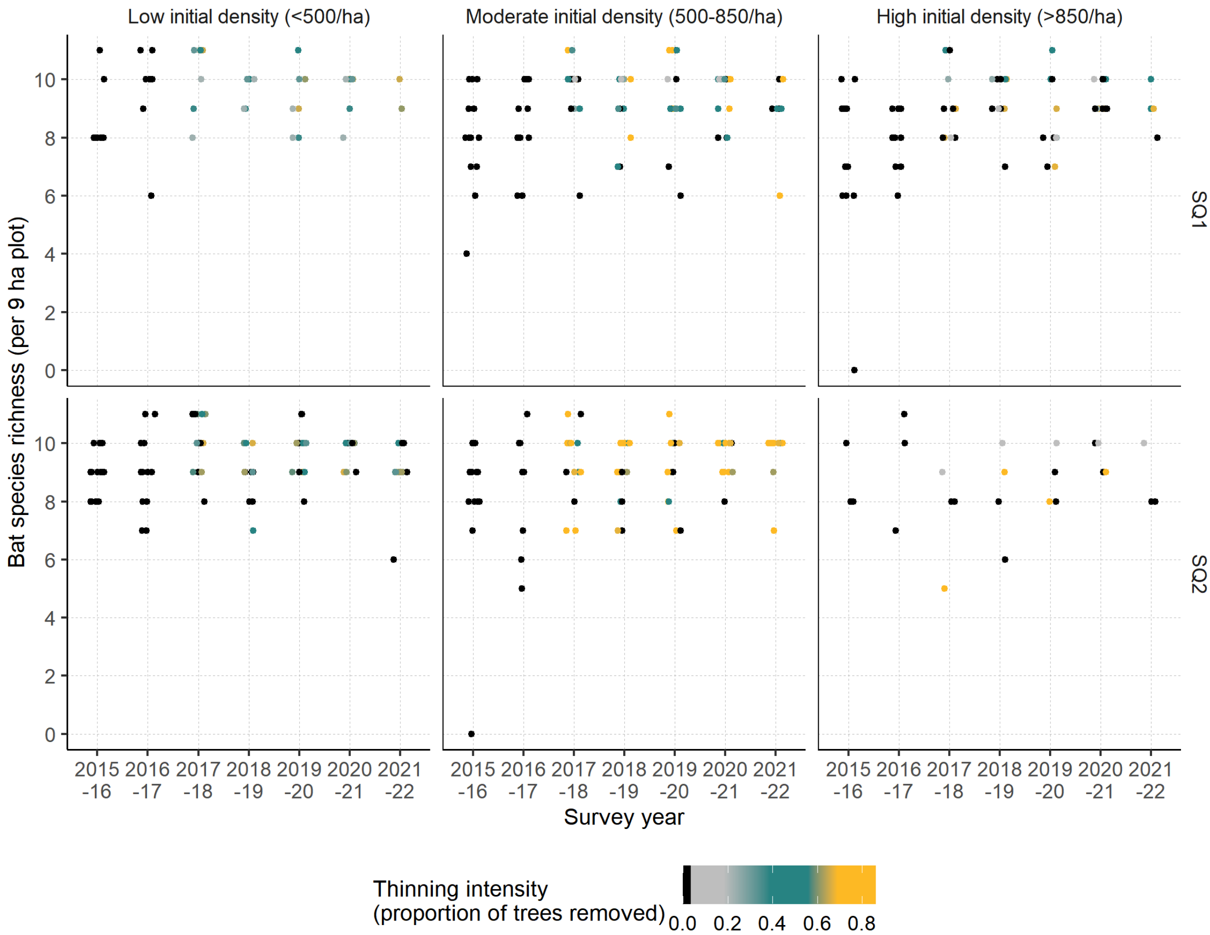

Figure 86 Data for bat species richness (number of unique species recorded in 3 overnight surveys per 9-hectare plot)

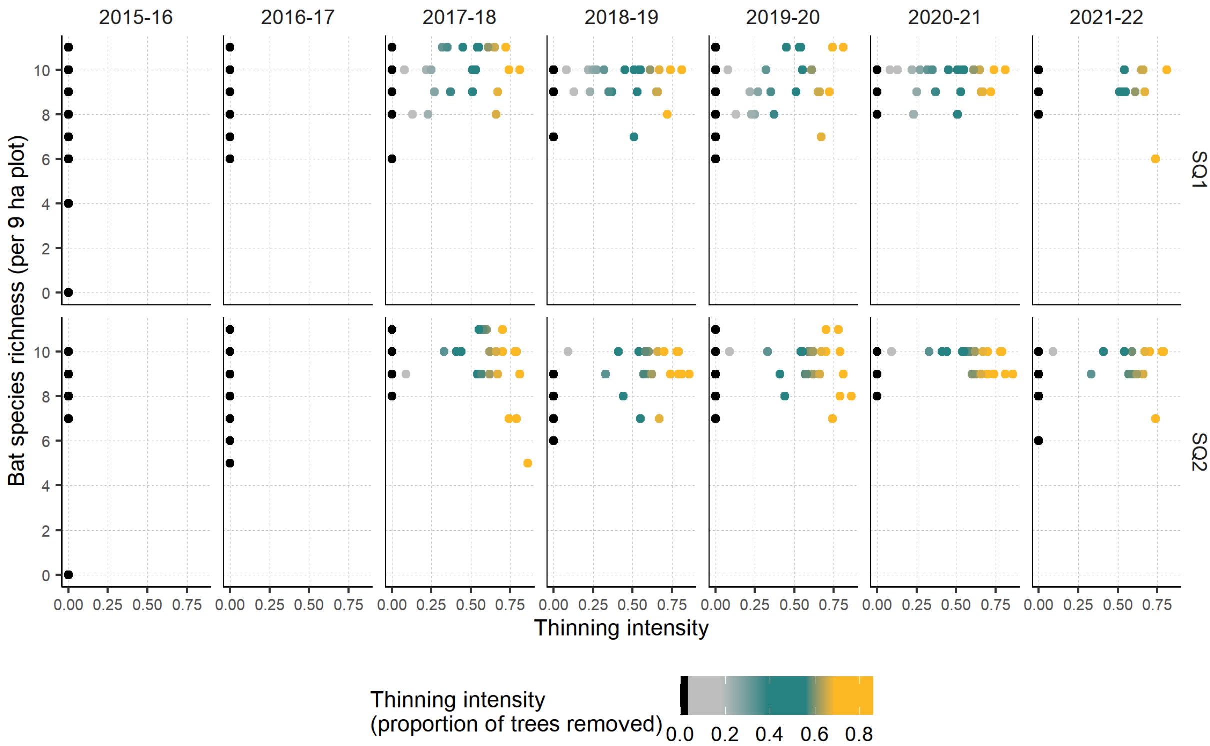

Figure 87 Bat species richness per 9-hectare plot (unique number of species over 3 nights of recording)

Model results

Model could not be fitted to the data for bat species richness.

Hypothesis evaluation

Bat species richness was not highly variable across plots. Although there were no statistical analyses undertaken, the data did not provide evidence to support the hypothesis.

14.2 Bat species diversity

Hypothesis	2a. Ecological thinning will increase diversity of bat species.
Key result	Heavy intensity ecological thinning (~75% of trees removed) **increased** Hill-Shannon bat diversity by the equivalent of 1–1.8 equally abundant species per night in Site Quality 1 plots with very high initial tree density. Moderate intensity thinning (~50% of trees removed) temporarily increased bat diversity in some Site Quality 2 plots 3 years post-thinning.

Data collection

An Anabat detector (Titley Electronics, Ballina, NSW, Australia) was mounted on a tree facing towards a flyway in the centre of each 9-hectare treatment plot (see Figure 5). Ultrasonic observations were recorded in each subplot for 3 nights around the time of a new moon. The recordings were processed through Anascheme to separate recordings that only contained noise from those containing bat calls, with tentative identifications being provided for the calls. Sonograms of the calls were visually inspected to validate species identification. Observations, where species identification was uncertain, were excluded.

Data from 7 successive summers was analysed: December 2015 immediately before the commencement of thinning; February 2017 during the thinning phase but excluding plots where thinning was in progress; and post-thinning operations between February 2018 and February 2022. In 2022, 42% out of 66 plots were not surveyed for bats due to restricted access around the time of the full moon.

Hill-Shannon diversity is an index that combines information about both the number of bat species (richness) and the abundance of each species (that is, how many individual bats of each species were present). We calculated Hill-Shannon diversity for each of the 3 overnight surveys undertaken in each 9-hectare plot in each survey season. This index places equal importance on common and rare species (Roswell et al. 2021). The index has a value of zero when only one species is present, and higher values represent higher numbers of species with greater abundance. A Hill-Shannon value of 3 is equivalent to 3 equally abundant bat species; a Hill-Shannon value of 6 is equivalent to 6 equally abundant bat species.

Data summary

Hill-Shannon values were commonly between 2 and 6 (Figure 88). Values of 1 were recorded on 10 nights, 7 of which were prior to thinning. Values above 7 were recorded on 8 nights in a range of site types.

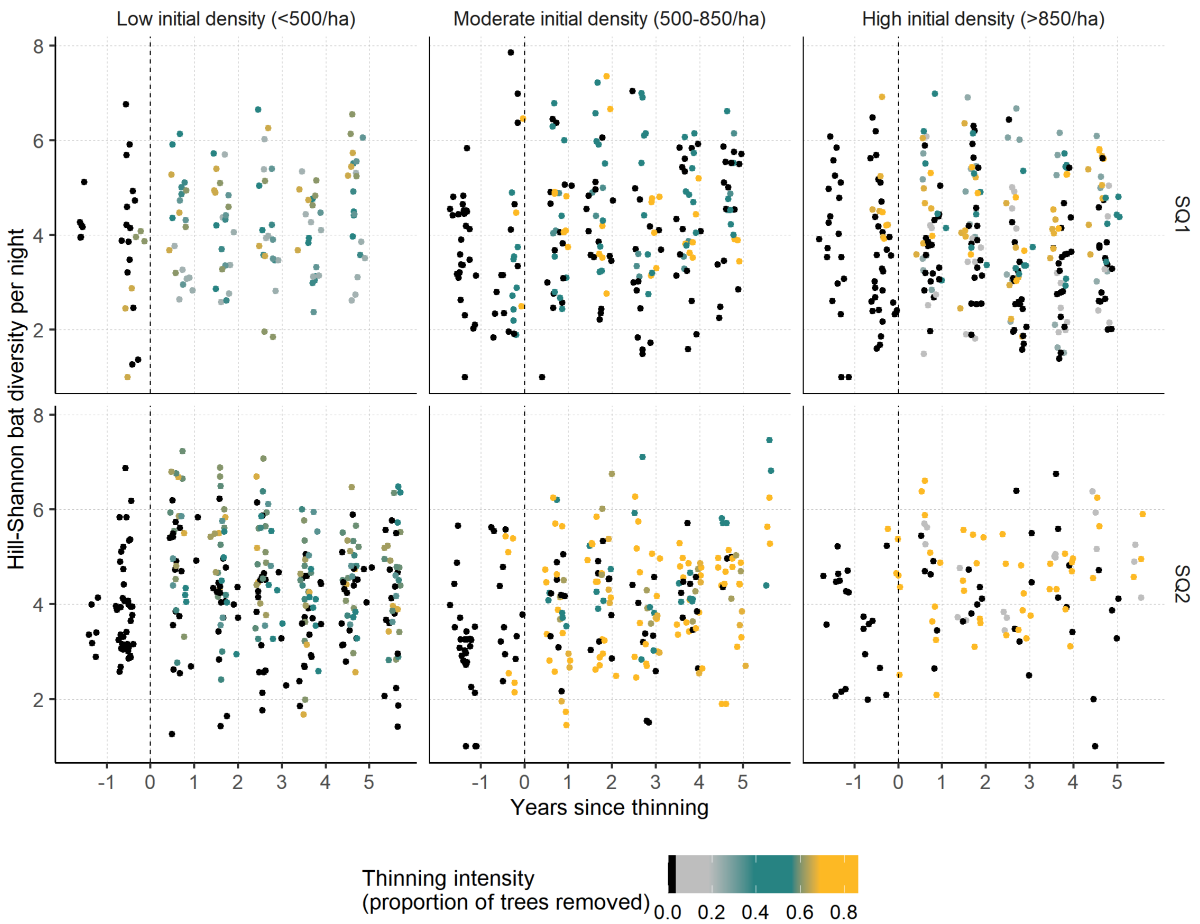

Figure 88 Data for bat species Hill-Shannon diversity (per overnight survey on a 2-hectare subplot within each 9-hectare plot)

Model results

Bat Hill-Shannon diversity was analysed as a continuous positive variable, using a Gaussian distribution (see Appendices). All explanatory variables were included, with all combinations of initial tree density, thinning intensity and Site Quality. Random effects for site, 9-hectare plot and survey year were also included.

Bat diversity differed significantly between Site Qualities, with slightly higher diversities recorded in wetter (SQ1) plots (Table 65). Bat diversity was also significantly affected by pre-thinning tree density, with higher diversities recorded in lower density plots.

The effect of ecological thinning on bat species diversity was statistically significant, and the effect varied significantly among Site Qualities,initial tree densities and changed over time (Table 65).

In drier plots (SQ2) the effect of moderate intensity thinning was greater than the effect of heavy intensity thinning (Figure 89). In these plots, moderate intensity thinning increased bat diversity when pre-thinning tree density had been moderate or high density.

In wetter plots (SQ1) with very high pre-thinning tree density, moderate and heavy intensity thinning also increased bat diversity. The increase was significantly different from the controls 4 years post-thinning. In all other Site Quality, initial tree density and thinning intensities, overlapping confidence intervals with control plots indicated uncertainty about the nature and magnitude of the effect.

Five years post-thinning, increases in mean bat diversity were between 1.1 and 1.8 relative to controls in Site Quality 2 plots that had either very high initial tree density or moderate initial tree density and moderate intensity thinning (Table 66).

Table 65 Statistical significance of explanatory variables on Hill-Shannon bat diversity

	Bootstrapped likelihood ratio test significance	Description
Site Quality	0.01	Significant difference in bat diversity between Site Qualities
Initial tree density	0.01	Significant difference in bat diversity with initial tree density
Survey year	0.01	Some evidence that bat diversity varied with survey year
Thinning intensity	0.01	Significant effect of ecological thinning on bat diversity
Does the effect of thinning intensity vary depending on:		
• Site Quality	0.01	The effect of ecological thinning on bat diversity differed between Site Qualities
• Initial tree density	0.03	The effect of ecological thinning on bat diversity varied with initial tree density
• Survey year	0.06	Marginally significant effect of ecological thinning on bat diversity changed over time
• Site Quality **and** initial tree density **and** time since thinning	0.05	The effect of ecological thinning varied for all combinations of Site Quality, initial tree density and time

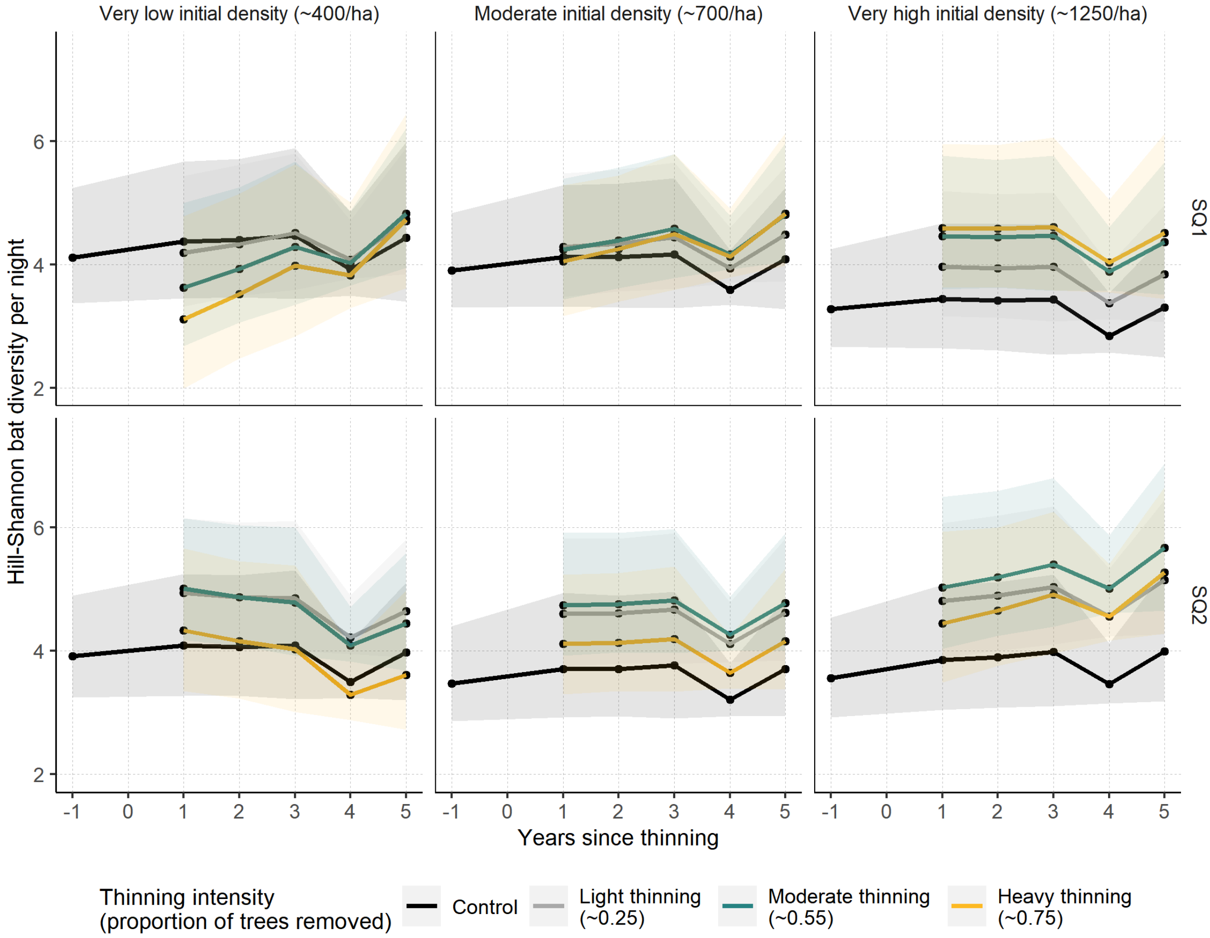

Figure 89 Modelled values and confidence intervals for Hill-Shannon bat diversity

Table 66 Estimates of effect sizes for Hill-Shannon bat diversity 5 years post-thinning, showing difference between fitted values and 95% confidence intervals in thinned plots relative to control plots

Site Quality		Site Quality 1			Site Quality 2		
Thinning intensity		Low intensity	Mod intensity	High intensity	Low intensity	Mod intensity	High intensity
Initial tree density	Very low (400/ha)	+0.4 –0.6 to +1.8	+0.7 –0.4 to +2.3	+0.7 –0.6 to +2.6	+0.6 –0.3 to +1.9	+0.4 –0.5 to +1.6	–0.5 –1.6 to +1.0
	Moderate (700/ha)	+0.5 –0.4 to +1.7	+0.9 +0.01 to +2.2	+1.0 –0.1 to +2.4	+0.9 –0.02 to +2.2	+1.1 +0.2 to +2.3	+0.5 –0.5 to +1.8
	Very high (1250/ha)	+0.5 –0.3 to +1.8	+1.1 0.0 to +2.6	+1.2 –0.1 to +3.1	+1.2 +0.2 to +2.6	+1.8 +0.7 to +3.4	+1.5 +0.3 to +3.01

Hypothesis evaluation

There was evidence to support the hypothesis that ecological thinning increased diversity of bat species, but only for heavy thinning in wetter (SQ1) plots with very high initial tree density. The data and modelling results also indicated that bat diversity in thinned plots may be higher than control plots in some years more than others, and this was likely due to the influence of hydro-climatic conditions on bat activity.

14.3 Total bat activity

Hypothesis	2a. Ecological thinning will increase levels of site utilisation by bat species.
Key result	Ecological thinning increased total bat activity by a maximum of approximately 300 calls per night relative to control plots. However, this increase was only statistically different from controls in some years due to annual fluctuations.

Data collection

An Anabat detector (Titley Electronics, Ballina, NSW, Australia) was mounted on a tree facing towards a flyway in the centre of each 9-hectare treatment plot (see Figure 5). Ultrasonic observations were recorded in each subplot for 3 nights around the time of a new moon. The recordings were processed through Anascheme to separate recordings that only contained noise from those containing bat calls, with tentative identifications being provided for the calls. Sonograms of the calls were visually inspected to validate species identification.

Total bat activity was determined by summing all bat calls per 9-hectare plot per night.

Data from 7 successive summers was analysed: December 2015 immediately before the commencement of thinning; February 2017 during the thinning phase but excluding plots where thinning was in progress and post-thinning operations between February 2018 and February 2022. In 2022, 42% out of 66 plots were not surveyed for bats due to restricted access around the time of the full moon.

Data summary

Total bat activity was most commonly fewer than 1,000 calls per night (Figure 90). There were a handful of values up to 3263 calls per night recorded, most of which were recorded in the 2 most recent surveys (4 and 5 years post-thinning). The high values were recorded in both thinned and control plots.

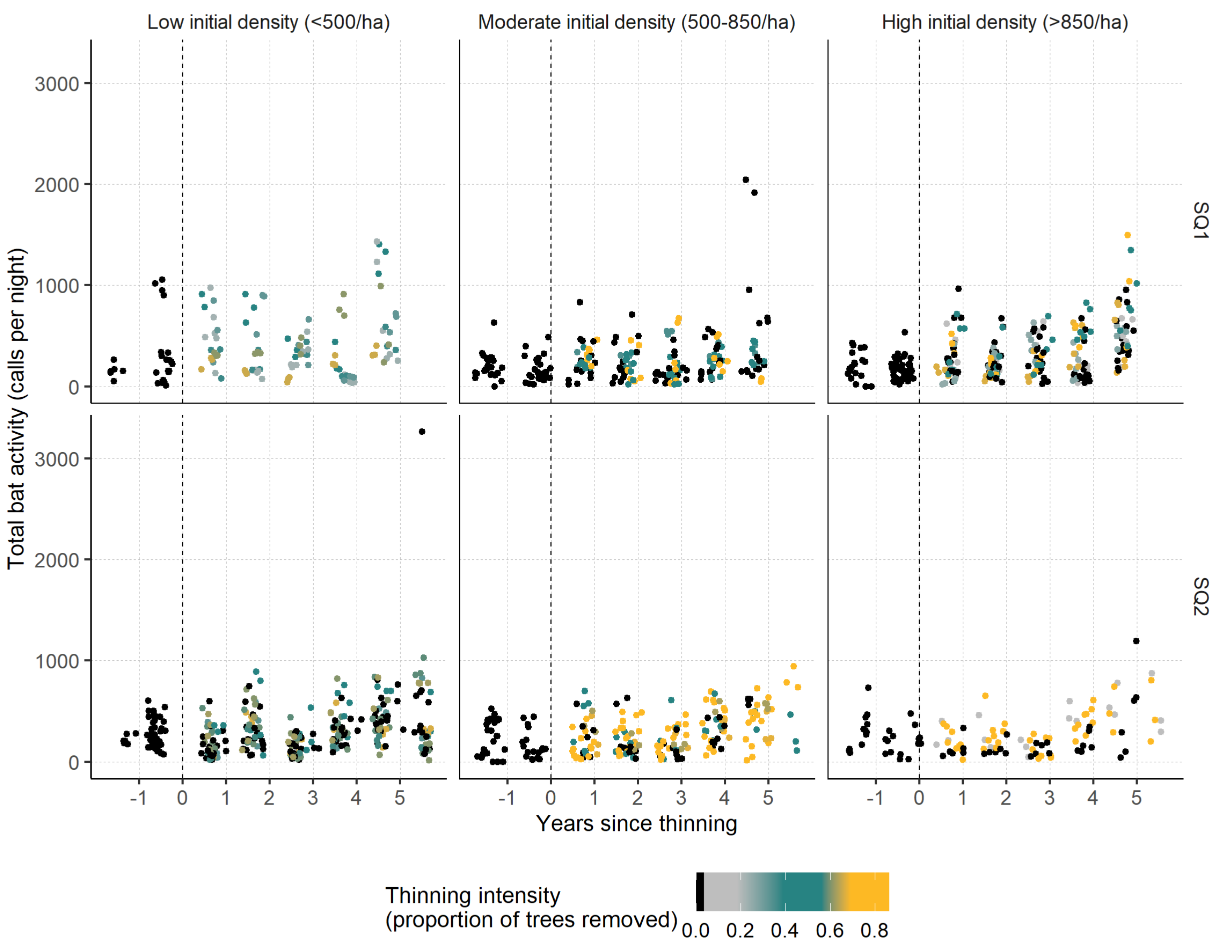

Figure 90 Data for bat species overall bat activity (per overnight survey within each 9-hectare plot)

When the influence of initial tree density was not considered, it was apparent that total bat activity was variable over time, as was the effect of thinning (Figure 91). Note the variation in the range of values recoded in control plots each year. The variable effect of thinning was apparent, for example, in drier (SQ2) plots: in 2017–18 bat activity declined with increasing thinning intensity; the opposite effect was apparent in the same plot type in the subsequent year (2018–19).

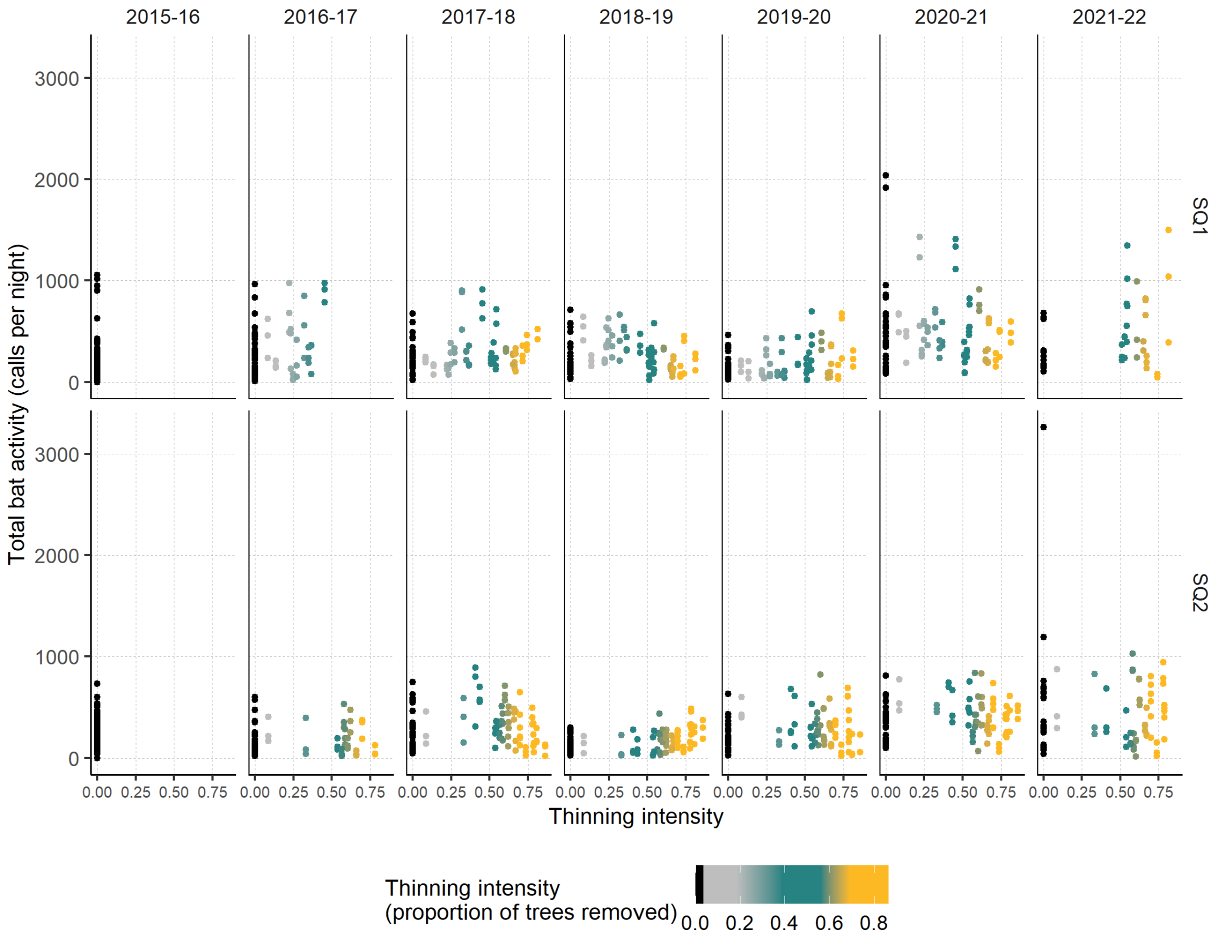

Figure 91 Data for overall bat activity (calls per overnight survey per 9-hectare plot), not including information on initial tree density

Model results

Total bat activity was modelled using a negative binomial distribution (see Appendices). The model included all two- and three-way interactions between predictors but did not include four-way interaction. The model included random effects for survey year, site and 9-hectare plot.

Model predictions can be generated, including or excluding year-to-year variation (the survey year random effect). When the predictions included year-to-year variation (Figure 92), the modelled confidence interval was unrealistically small for 3 years since thinning (survey year 2019–20). When the predictions did not include year-to-year variation, but instead plotted the trend for an average year (Figure 94), important information about the effect of ecological thinning over time was not apparent. Both sets of predictions were used to evaluate total bat activity.

In the absence of ecological thinning, total bat activity was slightly higher in drier (SQ2) plots than wetter (SQ1) than plots (Figure 92, Figure 94). There was a slight positive relationship with increasing initial tree density. Total bat activity changed substantially between years, for control and thinned plots.

Heavy intensity ecological thinning significantly increased total bat activity (Figure 94, Table 68), but the significant difference from controls varied over time. For moderate initial tree density, the initial effect of thinning was to increase bat activity by approximately 160 calls per night and this effect was sustained over time (Table 69). However, when year-to-year variation was considered, this increase in bat activity in thinned plots was only significantly different from control plots 3 and 5 years post-thinning (in the 2019–20 and 2021–22 survey years) (Figure 94). In plots with very low initial density, the effect of thinning diminished over time. In plots with very high initial density, the effect increased in magnitude over time, and were significantly higher than controls in wetter (SQ1) plots 5 years post-thinning by approximately 300 calls per night.

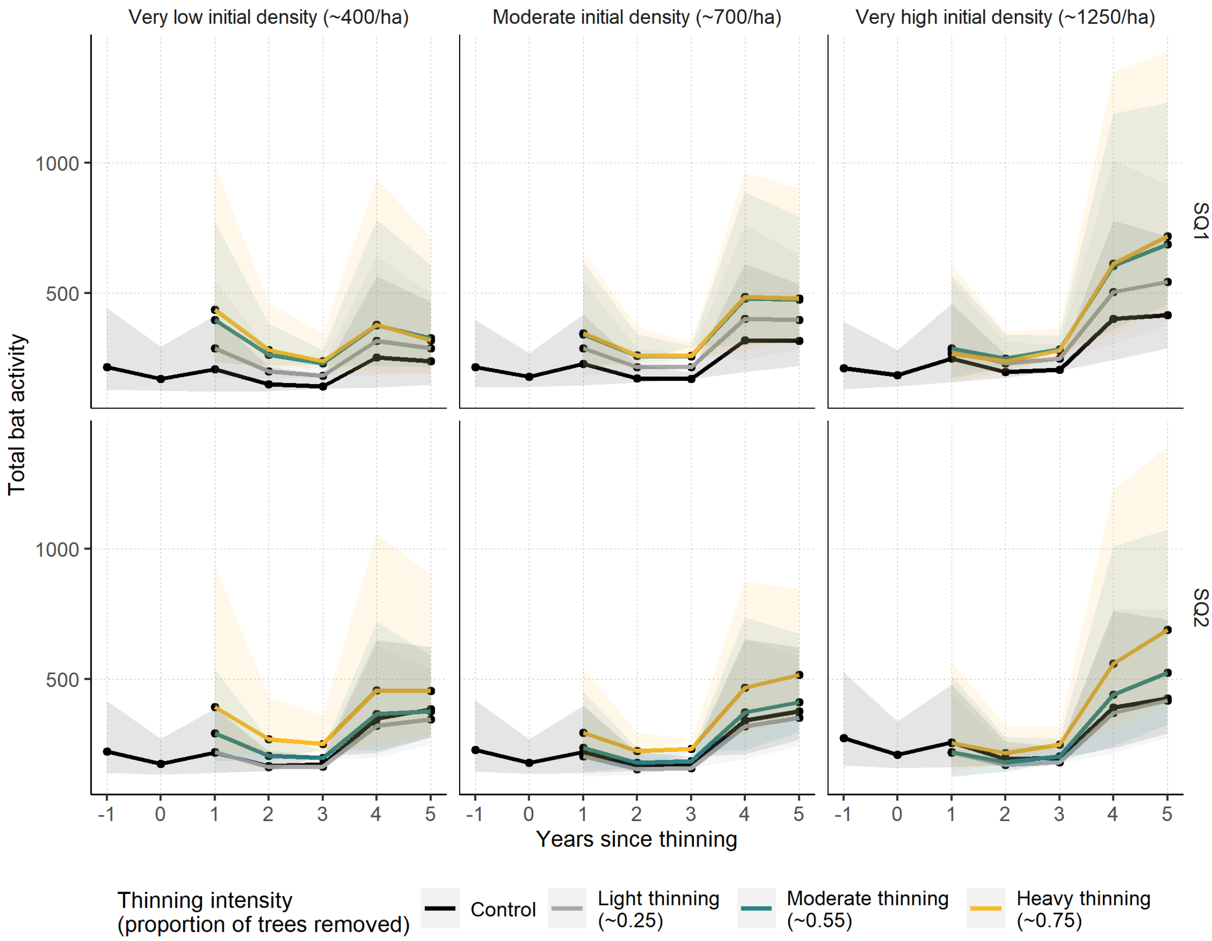

Figure 92 Modelled values and confidence intervals for overall bat activity (per overnight survey per 9-hectare plot) – including year-to-year variation

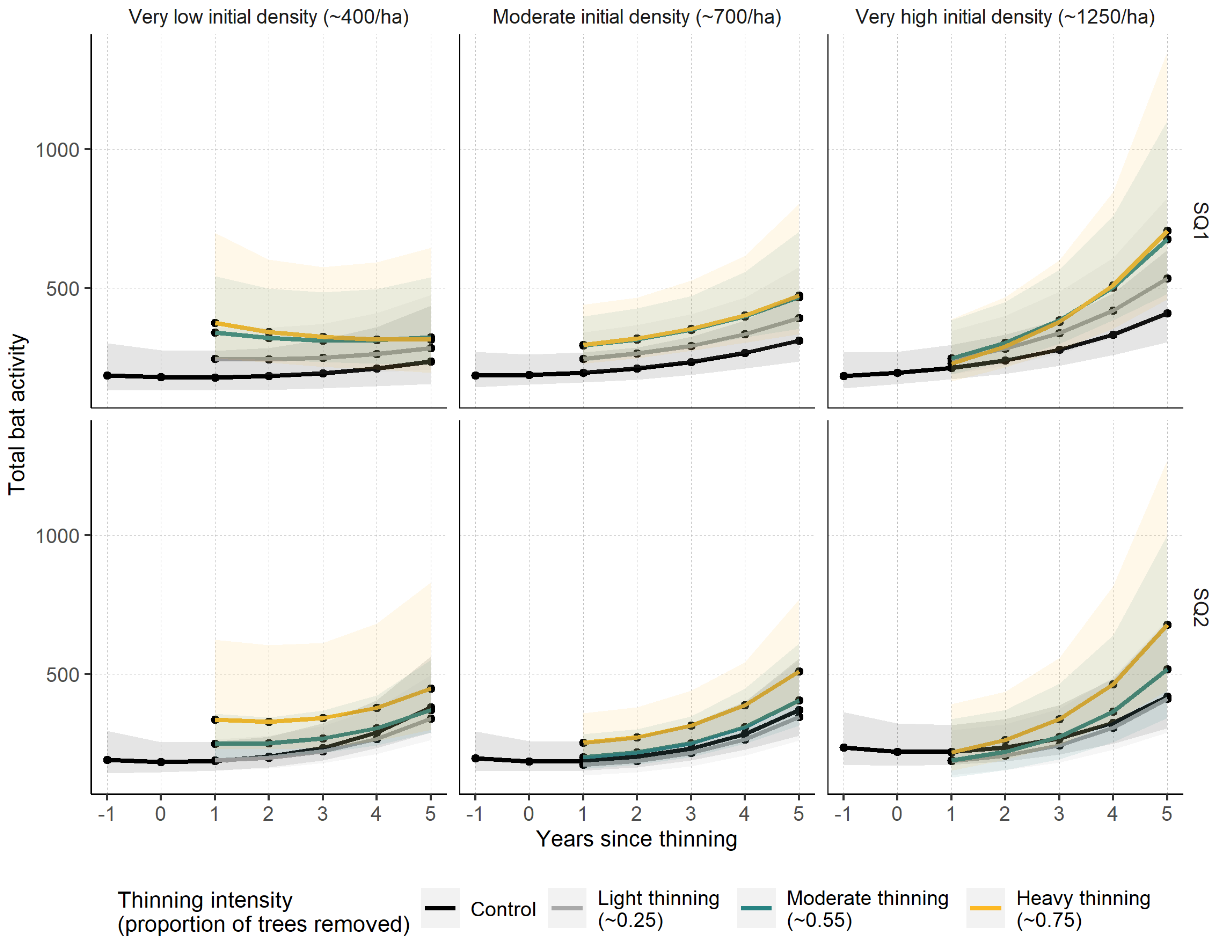

Figure 93 Modelled values and confidence intervals for overall bat activity (per overnight survey per 9-hectare plot) – excluding year-to-year variation

Table 67 Statistical significance of explanatory variables on overall bat activity (per overnight survey per 9-hectare plot)

	Bootstrapped likelihood ratio test significance	Description
Site Quality	0.28	Total bat activity did not significantly differ between Site Qualities
Initial tree density	0.15	Total bat activity did not depend on initial tree density
Survey year	0.01	Total bat activity significantly changed over time
Thinning intensity	0.02	Ecological thinning had a significant effect of total bat activity
Does the effect of thinning intensity vary depending on:		
• Site Quality	0.09	The effect of ecological thinning on total bat activity was not dependent on Site Quality

	Bootstrapped likelihood ratio test significance	Description
• Initial tree density	0.15	The effect of ecological thinning on total bat activity did not vary by initial tree density
• Survey year	0.20	The effect of ecological thinning on total bat activity did not change over time
• Site Quality **and** initial tree density **and** time since thinning	NA	Four-way interaction not modelled

Table 68 Estimates of effect sizes for overall bat activity (number of calls per night) 5 years post-thinning (including year-to-year variation), showing difference between fitted values and 95% confidence intervals in thinned plots relative to control plots

Site Quality		Site Quality 1			Site Quality 2		
Thinning intensity		Low intensity	Mod intensity	High intensity	Low intensity	Mod intensity	High intensity
Initial tree density	Very low (400/ha)	+87.8 –19.6 to +261	+87.8 –19.6 to +370.7	+81.1 –48.4 to +475.6	–41 –134.3 to +153.6	–9.7 –111 to +205.3	+68.7 –97.5 to +513
	Moderate (700/ha)	+80.8 –30 to +80.8	+158.3 +18 to +478.5	+163.6 +4.9 to +584.4	–24.1 –130.7 to +210.7	+35.7 –79.2 to +298.4	+141.8 –8.6 to +469
	Very high (1250/ha)	+126.2 –40.4 to +497.2	+270.3 +43.3 to +814.4	+301.1 +24.5 to +1009.9	–7.9 –149.5 to +338.8	–99.7 –100.6 to +647.5	+263 –13.9 to +967.8

Hypothesis evaluation

The hypothesis that ecological thinning would increase total bat activity was supported, but total bat activity was only higher in thinned plots than control plots in some years. Year-to-year variation was due to fluctuations of resource availability triggered by variability in environmental conditions such as flooding and rainfall.

14.4 Bat guild activity: clutter specialists

Hypothesis	2a. Ecological thinning will increase levels of site utilisation by bat species.
Key result	Ecological thinning initially **decreased** clutter specialist activity by 3–11 calls per night in some plot types relative to controls. Five years post-thinning, there were no significant differences from controls.

Data collection

The hypothesis was assessed for activity of bat species in the *Nyctophilus* genus that forage around patches of trees (clutter specialists). All species in this genus have indistinguishable calls and were grouped and analysed as clutter specialists.

Data for identified *Nyctophilus* calls per night were extracted from the total bat activity data described above. Only positively identified ultrasonic calls were included in analysis.

Data summary

Activity of clutter specialists ranged predominantly from 0 to 59 calls per night (Figure 94). The data was positively skewed, with a handful of outliers between 100 and 819 calls per night and few low or zero values. High total call records were most frequent in wetter (SQ1) control plots up to 3 years post-thinning (2019–20 surveys). No strong trends with initial tree density were apparent.

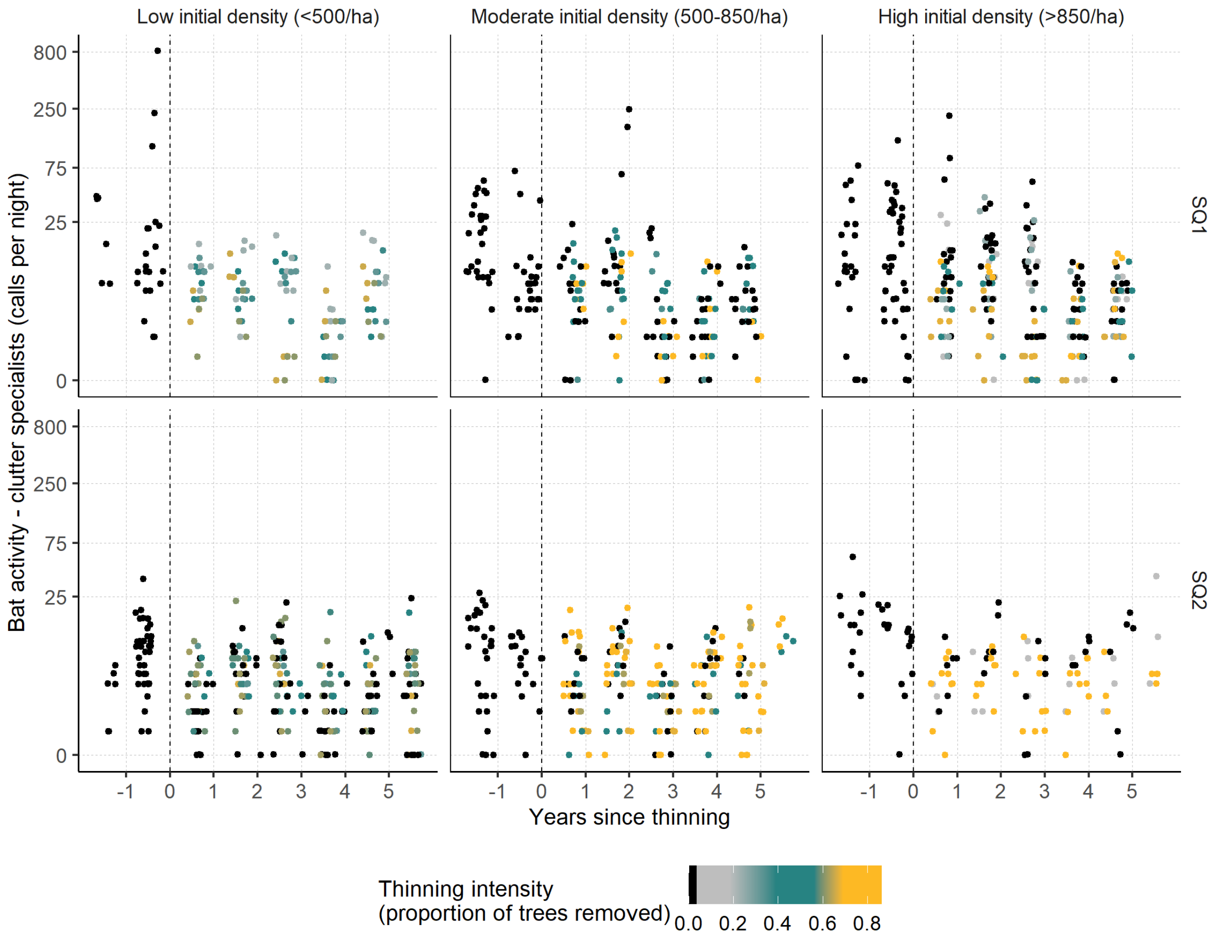

Figure 94 Data summary for activity of bat clutter specialists (per overnight survey per 9-hectare plot)
Note the log scale for the response variable.

In the absence of information about initial tree density, a negative correlation between thinning intensity and clutter specialist activity was apparent in wetter (SQ1) plots, particularly in 2018–19 and 2020–21 surveys (Figure 95). A weaker trend was apparent in drier (SQ2) plots in some years.

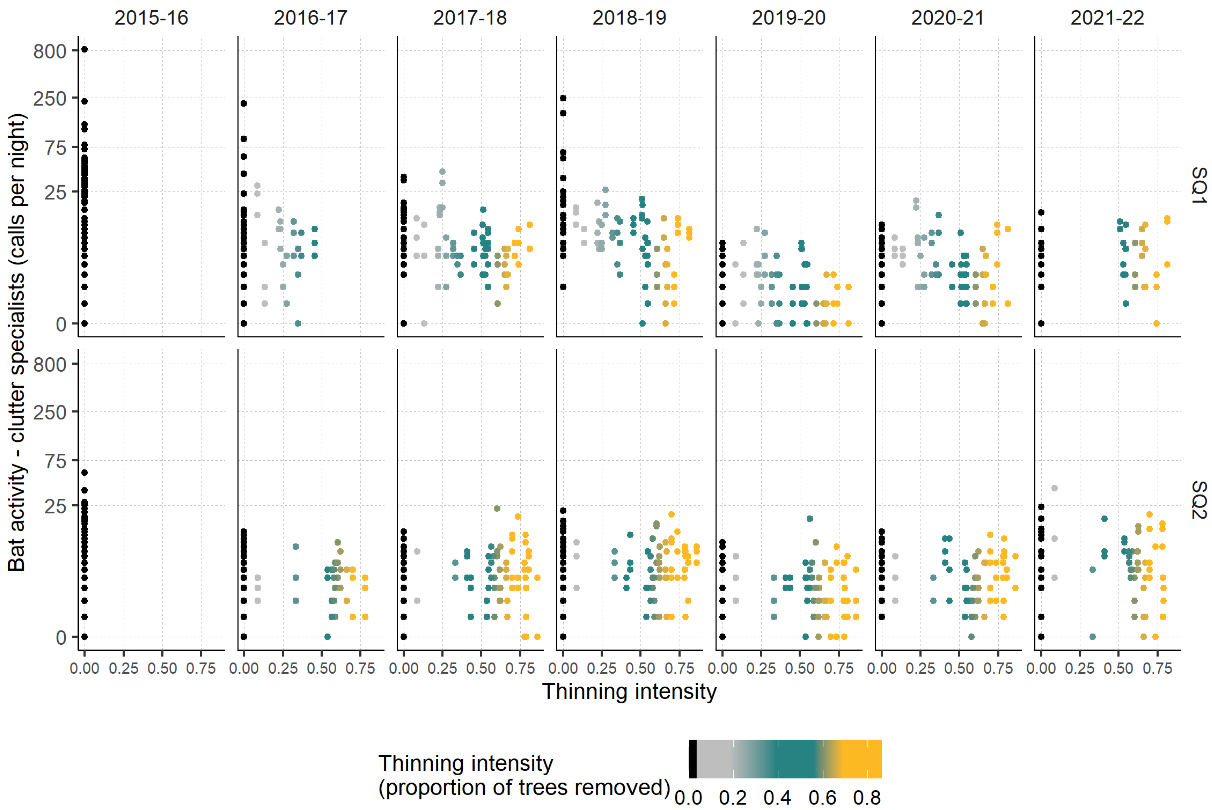

Figure 95 Data for activity of clutter specialist bats (calls per night), not including initial tree density information
Note the log scale for the response variable.

Model results

Clutter specialist activity was analysed as a discrete positive variable, using a negative binomial distribution (see Appendices). All outliers were retained in analyses. All two- and three-way interactions between explanatory variables were included, but four-way interaction was not included. Random effects for survey year, site and 9-hectare plot were included. As for total bat activity above, there was difficulty obtaining model fit that adequately captured year-to-year variation.

Model predictions can be generated, including or excluding year-to-year variation (the survey year random effect). When the predictions included year-to-year variation (Figure 96), the modelled confidence interval was unrealistically small for 3 years since thinning (survey year 2019–20). When the predictions did not include year-to-year variation, but instead plotted the trend for an average year (Figure 97), important information about the effect of ecological thinning over time was not apparent. Both sets of predictions were used to evaluate clutter specialist bat activity.

In the absence of ecological thinning, activity of clutter specialist bats was significantly higher in wetter (SQ1) plots than drier (SQ2) plots (Figure 96, Table 71). Clutter specialist calls per night changed significantly over time, with a peak in 2018–19 (approximately 2 years post-thinning) (note that these fluctuations are not represented in Figure 97). There was no statistically significant effect of initial tree density.

Ecological thinning had a significant effect on clutter specialist activity, but the nature and magnitude of this effect depended on both Site Quality and time (Table 71). The effects that were significantly different from controls were immediate reductions of 3–11 calls per night in wetter (SQ1) plots and very high initial tree density drier plots (SQ2). Over time, the number of calls in thinned plots remained relatively stable, in contrast to the controls, particularly in

Site Quality 1. No significant effects of thinning occurred on very low or moderate initial tree density in drier (SQ2) plots. There were no significant differences between control and thinned plots 5 years post-thinning (Table 72).

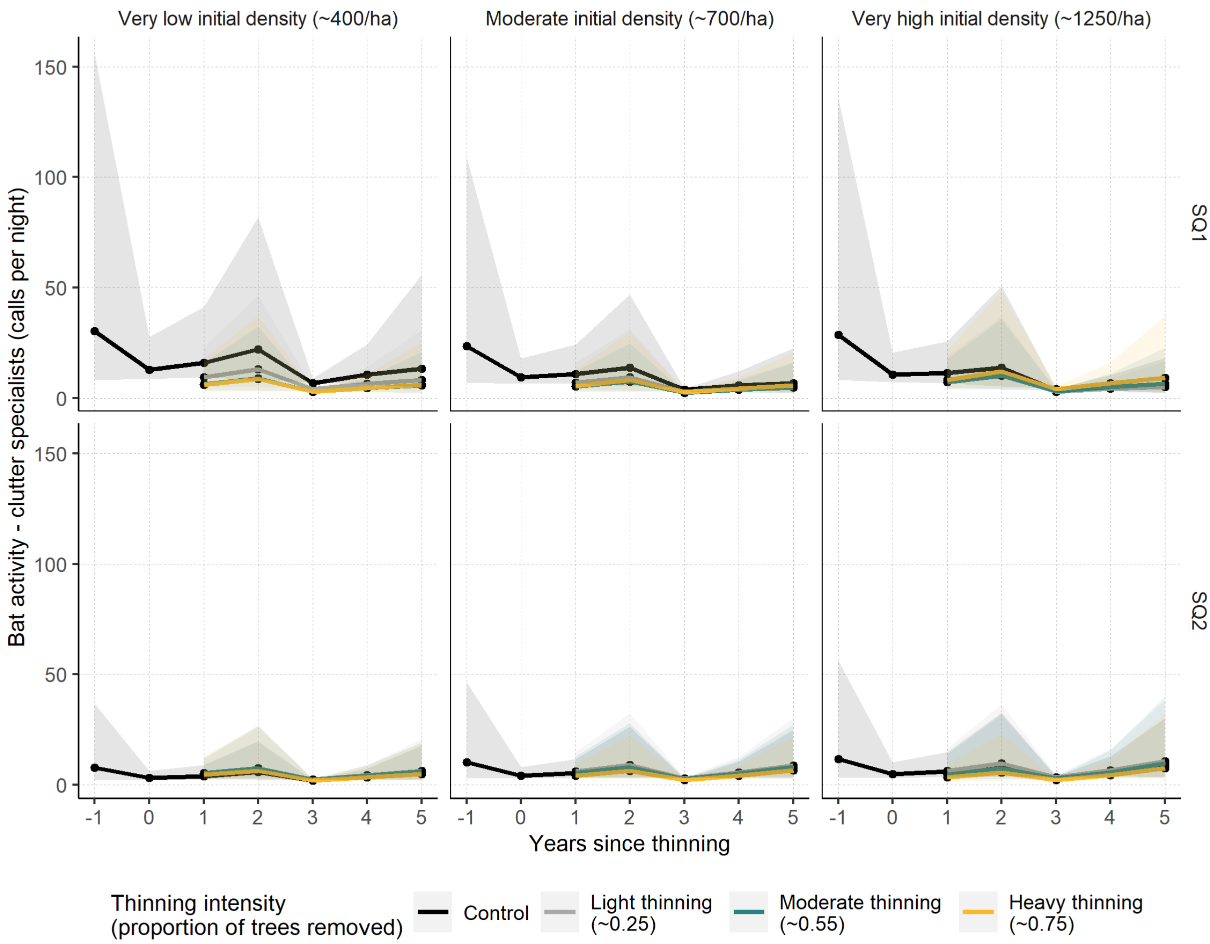

Figure 96 Modelled values and confidence intervals for bat clutter specialists (per overnight survey on a 2-hectare subplot within each 9-hectare plot) – including year-to-year variation

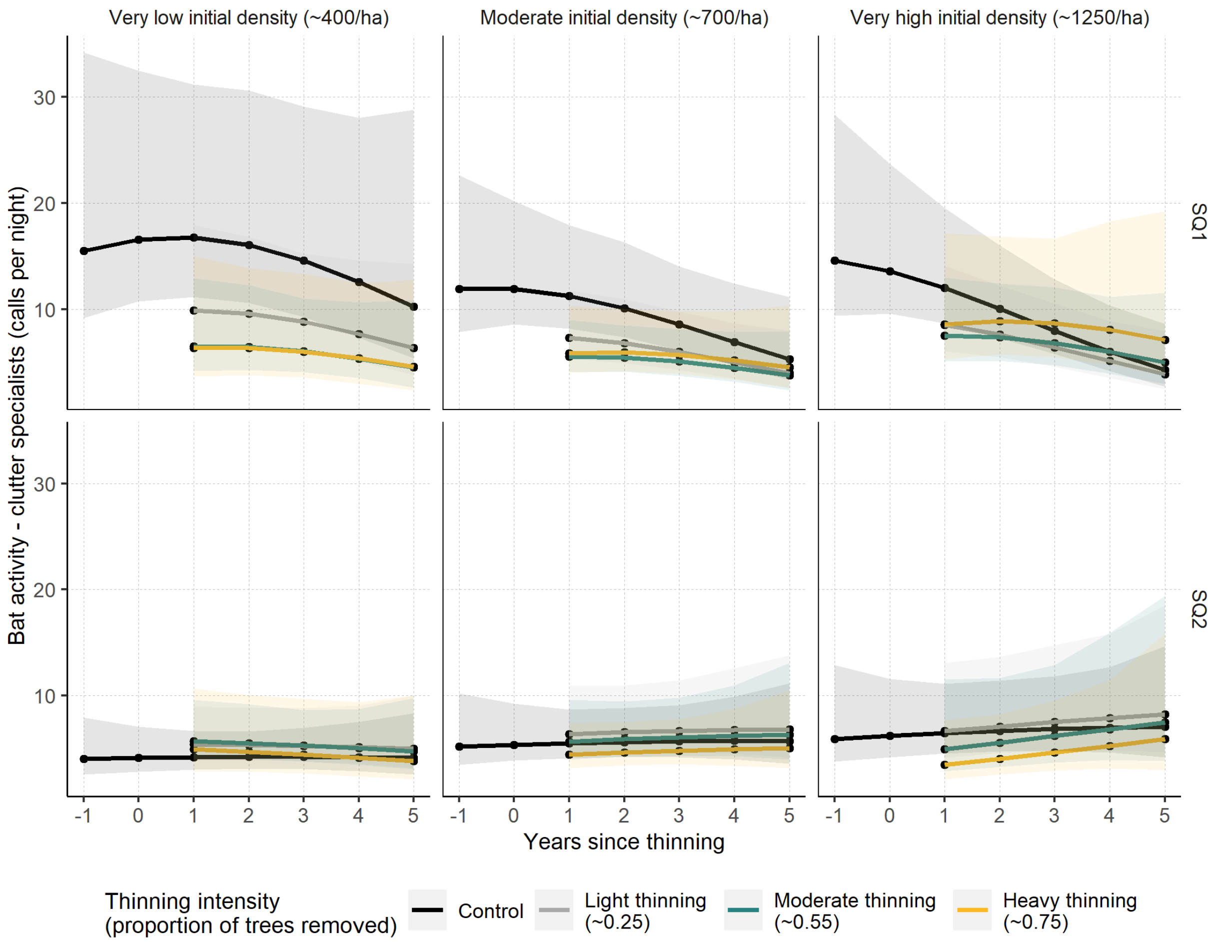

Figure 97 Modelled values and confidence intervals for overall bat activity (per overnight survey per 9-hectare plot) – excluding year-to-year variation

Table 69 Statistical significance of explanatory variables for bat clutter specialist activity

	Bootstrapped likelihood ratio test significance	Description
Site Quality	0.01	Significant difference in bat clutter specialist activity between Site Qualities
Initial tree density	0.27	No significant difference in bat clutter specialist activity with initial tree density
Time since thinning	0.02	Significant difference in bat clutter specialist activity with survey year
Thinning intensity	0.01	Significant effect of ecological thinning on bat clutter specialist activity
Does the effect of thinning intensity vary depending on:		
• Site Quality	0.01	The effect of ecological thinning on bat clutter species varied with Site Quality
• Initial tree density	0.33	The effect of ecological thinning on bat clutter species did not vary with initial tree density

	Bootstrapped likelihood ratio test significance	Description
• Survey year	0.02	The effect of ecological thinning on bat clutter species varied over time
• Site Quality **and** initial tree density **and** time since thinning		The effect of ecological thinning did not vary for all combinations of Site Quality, initial tree density and time

Table 70 Estimates of effect sizes for *Nyctophilus* species activity 5 years post-thinning (including year-to-year variation), showing difference between fitted values and 95% confidence intervals in thinned plots relative to control plots

Site Quality		Site Quality 1			Site Quality 2		
Thinning intensity		Low intensity	Mod intensity	High intensity	Low intensity	Mod intensity	High intensity
Initial tree density	Very low (400/ha)	–5 –10 to +17	–7 –11 to +8	–7 –11 to +12	+1 –3 to +15	+1 –3 to +14	0 –3 to +14
	Moderate (700/ha)	–2 –5 to +9	–2 –5 to +9	–1 –5 to +14	+1 –4 to +23	+1 –4 to +20	–1 –5 to +14
	Very high (1250/ha)	0 –3 to +11	+1 –3 to +17	+4 –2 to +32	+2 –5 to +29	+1 6 to +31	–1 –6 to +23

Hypothesis evaluation

There was evidence that the hypothesis was not supported for bats who prefer higher tree canopy cover, as ecological thinning reduced activity of clutter specialist bats. In most wetter plots, the reduction was substantial but became more similar to controls over time. In drier very high tree density plots, the reduction was of a smaller magnitude but sustained.

14.5 Bat guild activity: clutter avoiders

Hypothesis	2a. Ecological thinning will increase levels of site utilisation by bat species.
Key result	Ecological thinning **increased** clutter avoider activity. The magnitude of the effect changed over time and was highest in the most recent year with a modelled average of 38–149 additional calls per night relative to controls.

Data collection

The hypothesis was assessed for activity of bat species that forage between trees within the canopy and tend to avoid areas with dense canopy cover (clutter avoiders) included all positively identified bat calls, excluding those identified as *Nyctophilus* genus.

Data excluding *Nyctophilus* calls and calls that could not be attributed to a bat species with confidence were extracted from the total bat activity data described above.

Data summary

Activity of clutter avoiders ranged predominantly from 1 to 500 calls per overnight survey (Figure 99). There were 8 instances where no bat calls were recorded and 31 instances where bat calls were greater than 500, with one survey detecting 1,471 calls. Call totals for clutter avoiders tended to increase over time.

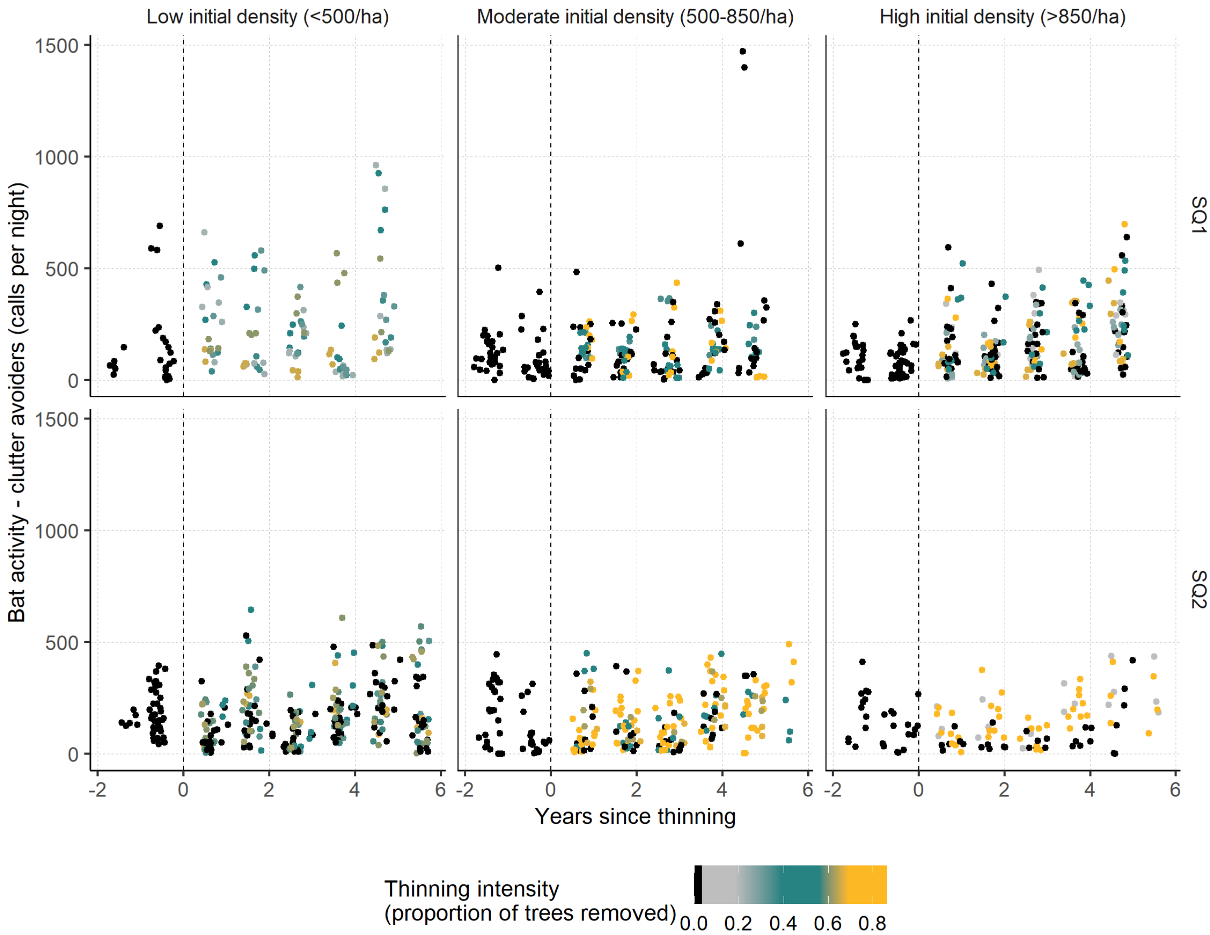

Figure 98 Data summary for activity of bat clutter avoiders (per overnight survey on a 2-hectare subplot within each 9-hectare plot)

Model results

Bat activity of clutter avoiders was analysed using a negative binomial distribution (see Appendices). All outliers were retained in analyses. All two- and three-way interactions between explanatory variables were included, but four-way interaction was not included. Random effects for 9-hectare plot and survey year were included but site was removed.

Irrespective of thinning, bat activity of clutter avoiders significantly increased over time (Table 71). There was no statistically significant effect of initial tree density. There was a marginally significant ($p = 0.06$) difference between Site Qualities, with slightly higher clutter avoider activity in drier (SQ2) plots.

Ecological thinning increased activity of clutter avoiding bats, but the year-to-year variation caused the difference from controls to change over time (Figure 99, Table 71). In wetter (SQ1) plots, the greatest magnitude of effect 5 years post-thinning was caused by moderate intensity thinning with the effect of thinning estimated to increase activity by 149 calls per night (Table 72). The apparent influence of initial tree density on the effect of thinning in SQ1 was not statistically significant.

In drier (SQ2) plots, ecological thinning also caused an increase in clutter avoider activity. The greatest magnitude of change was due to heavy intensity thinning in the most recent year, with 73 more calls per night 5 years post-thinning (Figure 99, Table 72).

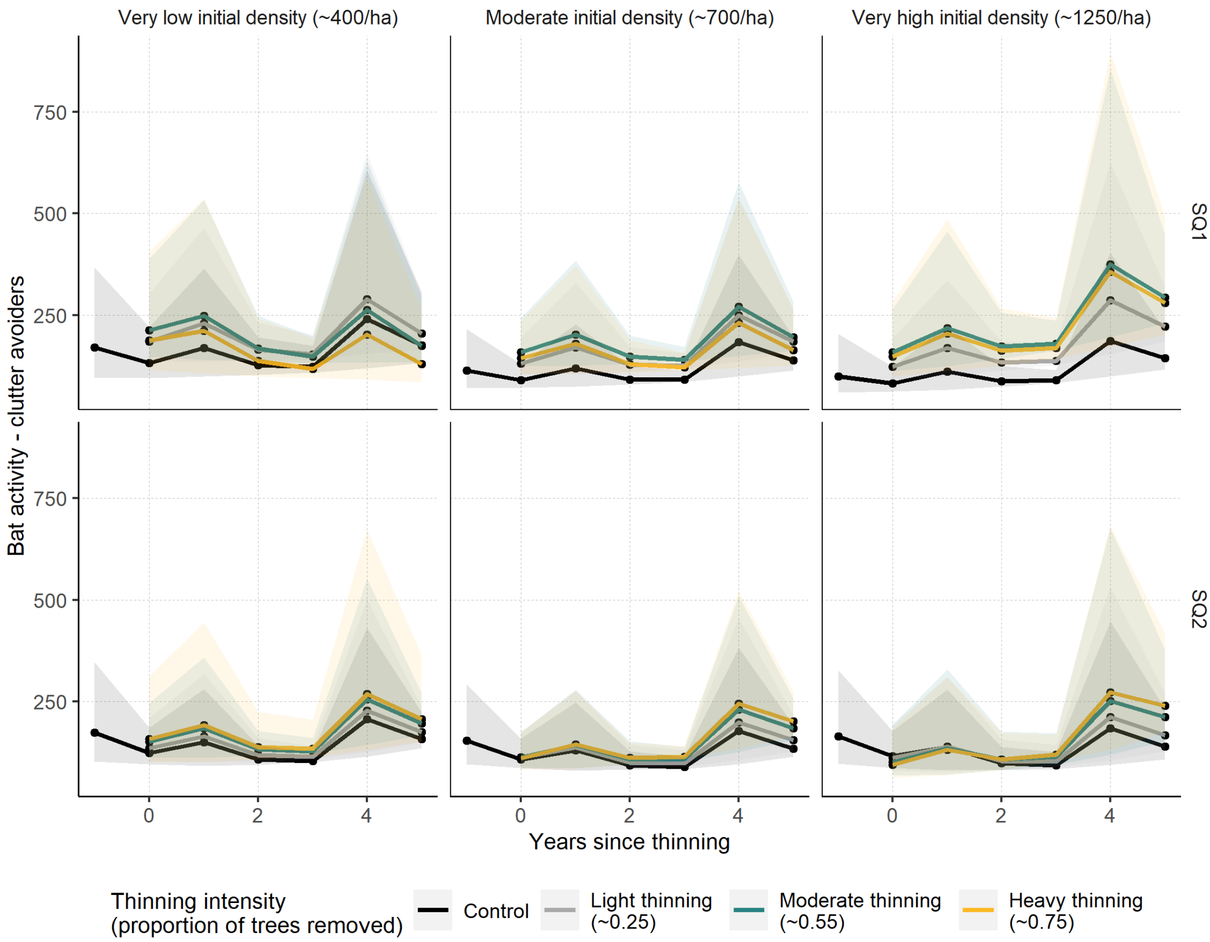

Figure 99 Modelled values and confidence intervals for bat activity of clutter avoiders' diversity per overnight survey

Table 71 Statistical significance of explanatory variables on bat activity of clutter avoiders

	Bootstrapped likelihood ratio test significance	Description
Site Quality	0.07	Some evidence of a difference in bat activity for clutter avoiders between Site Qualities

	Bootstrapped likelihood ratio test significance	Description
Initial tree density	0.26	There was no significant difference in bat activity for clutter avoiders with initial tree density
Survey year	0.04	There was a significant change in bat activity for clutter avoiders over time
Thinning intensity	0.01	Ecological thinning had a significant effect on the bat activity of clutter avoiders
Does the effect of thinning intensity vary depending on:		
• Site Quality	0.15	The effect of ecological thinning did not differ among Site Qualities
• Initial tree density	0.37	The effect of ecological thinning on clutter avoider activity did not depend on initial tree density
• Survey year	0.04	The effect of ecological thinning on clutter avoider activity changed over time
• Site Quality **and** initial tree density **and** time since thinning	Not modelled	

Table 72 Estimates of effect sizes for bat activity of clutter avoiders 5 years post-thinning, showing difference between fitted values and 95% confidence intervals in thinned plots relative to control plots

Site Quality		Site Quality 1			Site Quality 2		
Thinning intensity		Low intensity	Mod intensity	High intensity	Low intensity	Mod intensity	High intensity
Initial tree density	Very low (400/ha)	+28.0 –10.6 to +129.2	–1.8 –42.4 to +116.4	–46.7 –91.3 to +85.9	+16.4 –7.0 to +77.3	+37.9 +9.0 to +111.4	+47.6 –6.6 to +203.7
	Moderate (700/ha)	+46.2 +19.1 to +124.4	+56.9 +24.6 to +144.6	+25.6 –13.0 to +129.0	+20.0 –6.8 to +80.7	+50.1 +20.8 to +122.6	+66.1 +29.5 to +139.8
	Very high (1250/ha)	+78.3 +40.4 to +175.3	+149.3 +85.8 to +301.2	+135.3 +57.4 to +350.0	+27.5 –11.9 to +131.0	+72.9 +13.5 to +236.7	+99.8 +35.1 to +277.8

Hypothesis evaluation

There was evidence to support the hypothesis that thinning caused an increase in activity of bats that prefer wider canopy gaps in which to forage. The effect of thinning was affected by considerable fluctuations in bat activity over time, likely in response to hydro-climatic conditions.

15. Results: Birds

15.1 Bird abundance

Hypothesis	2b. Ecological thinning will increase abundance of birds.
Key result	Ecological thinning **increased** bird abundance between 3 and 5 years post-thinning. Five years post-thinning the only statistically significant difference relative to controls was an additional 13 birds (per 20-minute survey of 2 hectares) in wetter Site Quality 1 plots with very high initial tree density.

Data collection

Birds were surveyed in a 2-hectare subplot within each 9-hectare treatment plot (see Figure 5), with visual and auditory observations recorded for 20 minutes on 4 occasions (2 pre-9 am and 2 post-9 am) during each survey period. Surveys were conducted annually in spring-summer over 6 survey years. The total number of birds per 20-minute survey on each plot were analysed as bird abundance for that survey year.

Data summary

The abundance of birds ranged from 1 to 118 birds per 20 minute visit, though most plots had fewer than 60 birds, and the average was 22 birds. There appeared to be similar numbers of birds in the different initial tree density treatments, but slightly more birds in Site Quality 1 plots than Site Quality 2 plots (Figure 100). Bird abundance seemed to increase slightly over time (Figure 100).

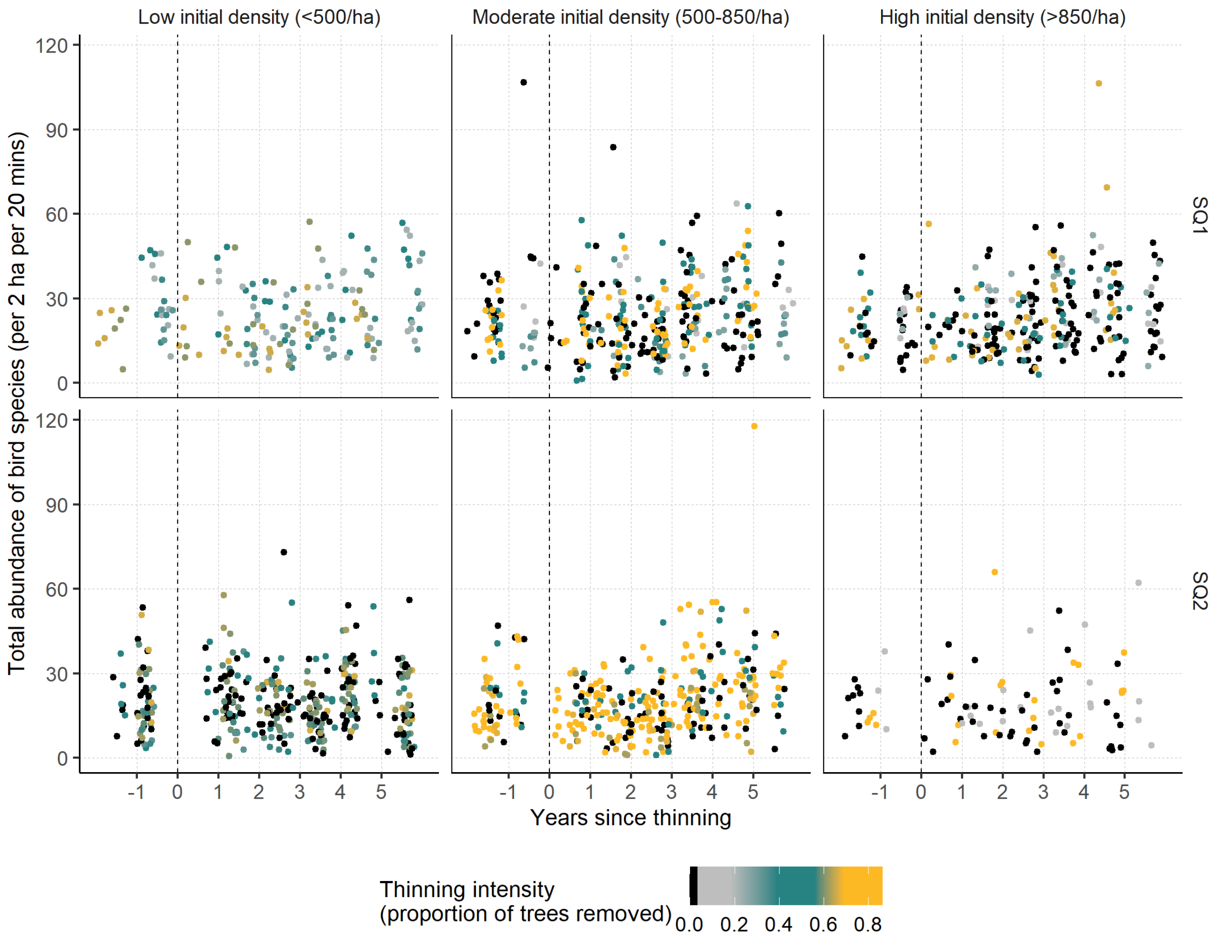

Figure 100 Data for bird abundance (total count of individuals per 20-minute survey on a 2-hectare subplot within each 9-hectare plot)

Model results

The model for bird abundance was analysed using a negative binomial (linear parameterisation) distribution with a log link (see Appendices). The model did not include four-way interaction between Site Quality, initial tree density, time since thinning and thinning intensity, but included all two-way and three-way interactions. Random effects for 9-hectare plot and survey year were included, but a random effect for site was not.

Modelled values of bird abundance were greater in Site Quality 1 plots than Site Quality 2 plots (Figure 101), and this difference was statistically significant (Table 73). There was no significant effect of initial tree density on modelled values (Figure 101, Table 73). Independent of ecological thinning, fluctuations over time were also significant.

The effect of thinning on bird abundance was significant but changed over time (Table 73). For most plot types, ecological thinning caused an initial decline in bird abundance (Figure 101). However, the declines were not significantly different from controls. Between 3 and 5 years post-thinning, abundance of birds increased in both control and thinned plots.

In the most recent surveys, abundance was higher in all thinned plots than control plots. However, the only plot type for which abundance became significantly higher by year 5 was wetter (SQ1) plots with very high initial tree density (14 more birds compared to control plots) (Figure 101, Table 74).

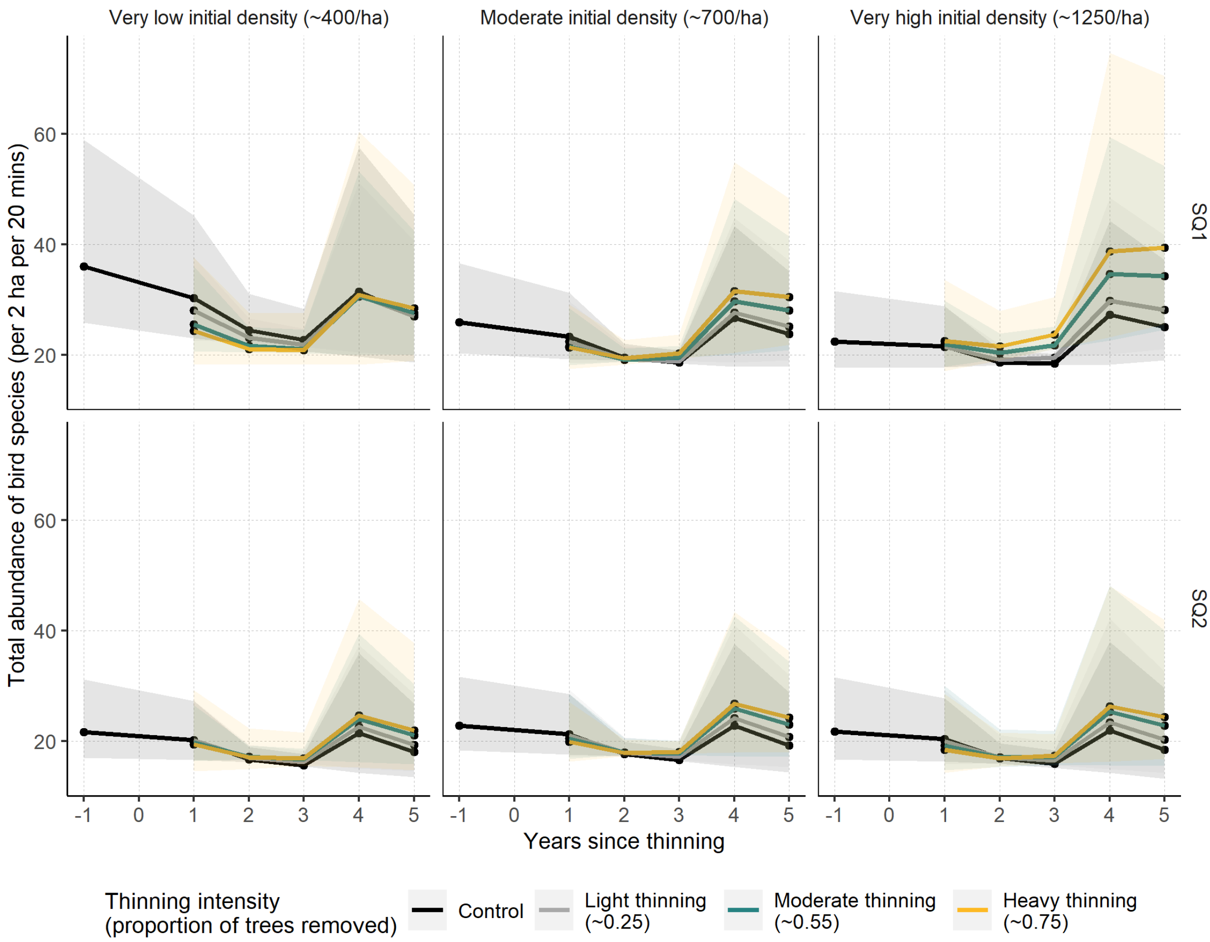

Figure 101 Modelled values and 95% bootstrapped confidence intervals for bird abundance (total count of individuals per 20-minute survey on a 2-hectare subplot within each 9-hectare plot)

Table 73 Statistical significance of explanatory variables on bird abundance (total count of individuals per 20-minute survey on a 2-hectare subplot within each 9-hectare plot)

	Bootstrapped likelihood ratio test significance	Description
Site Quality	0.02	Bird abundance differed among Site Qualities
Initial tree density	0.20	Bird abundance did not depend on initial tree density
Time since thinning	0.01	Bird abundance changed over time
Thinning intensity	0.01	Bird abundance was affected by thinning intensity
Does the effect of thinning intensity vary depending on:		
• Site Quality	0.98	The effect of thinning on bird abundance did not depend on Site Quality

	Bootstrapped likelihood ratio test significance	Description
• Initial tree density	0.81	The effect of thinning on bird abundance did not depend on initial tree density
• Time since thinning	0.01	The effect of thinning on bird abundance changed over time
• Site Quality **and** initial tree density **and** time since thinning	NA	Four-way interaction was not included in the model

Table 74 Estimates of effect sizes for bird abundance 5 years post-thinning, showing difference between fitted values and 95% confidence intervals in thinned plots relative to control plots

Site Quality		Site Quality 1			Site Quality 2		
Thinning intensity		Low intensity	Mod intensity	High intensity	Low intensity	Mod intensity	High intensity
Initial tree density	Very low (400/ha)	0.0 –7.1 to +13.6	+0.6 –7.0 to +15.4	+1.4 –8.1 to +23.7	+1.3 –3.5 to +10.5	+3.0 –2.2 to +12.3	+3.9 –3.3 to +19.8
	Moderate (700/ha)	+1.4 –4.7 to +13.3	+4.3 –2.8 to +17.7	+6.8 –1.9 to +24.6	+1.6 –3.8 to +12.8	+3.8 –2.0 to +15.2	+5.2 –1.3 to +17.2
	Very high (1250/ha)	+3.1 –4.0 to +16.6	+9.2 –0.5 to +29.2	+14.4 +0.5 to +45.5	+1.8 –4.2 to +14.2	+4.4 –3.0 to +21.5	+5.9 –1.7 to +23.5

Hypothesis evaluation

There was evidence that ecological thinning initially decreased bird abundance. In the 2 most recent survey years, bird abundance increased on all plot types, but it increased at a faster rate in thinned plots, suggesting that birds may have responded to favourable conditions in thinned plots. The only instance in which bird abundance was significantly different from controls was on wetter (SQ1) very high initial density sites in the most recent year.

15.2 Bird species richness

Hypothesis	2b. Ecological thinning will increase the abundance of bird species. Bird species richness (count of bird species) is relevant to understanding whether total abundance changes are due to changes in the number of individuals or number of species present.
Key result	Marginally significant ($p = 0.06$) effect of ecological thinning on bird species richness. For most plot types, thinning caused an **increase** in richness with a maximum of 5 additional species (per 20-minute survey of 2 hectares) relative to controls in the most recent survey year. However, prior to the most recent year, thinning caused a **decrease** of 2 species in wetter Site Quality 1 plots with very high initial tree density.

Data collection

Birds were surveyed in a 2-hectare subplot within each 9-hectare treatment plot (see Figure 5), with visual and auditory observations recorded for 20 minutes on 4 occasions (2 pre-9 am and 2 post-9 am) per survey period. Surveys were conducted annually in spring-summer for 6 survey years. The number of bird species recorded during each 20-minute survey was analysed as species richness.

Data summary

Bird species richness ranged between 1 and 25 species per 20-minute survey, with an average of 9 species in wetter (SQ1) plots and 8 species in drier (SQ2) plots (Figure 102). Bird richness fluctuated slightly with the lowest averages occurring in 2018–2019 (approximately 2 years post-thinning) and the highest averages occurring in 2020–21. Averge bird species richness tended to be slightly lower in very high initial tree density sites.

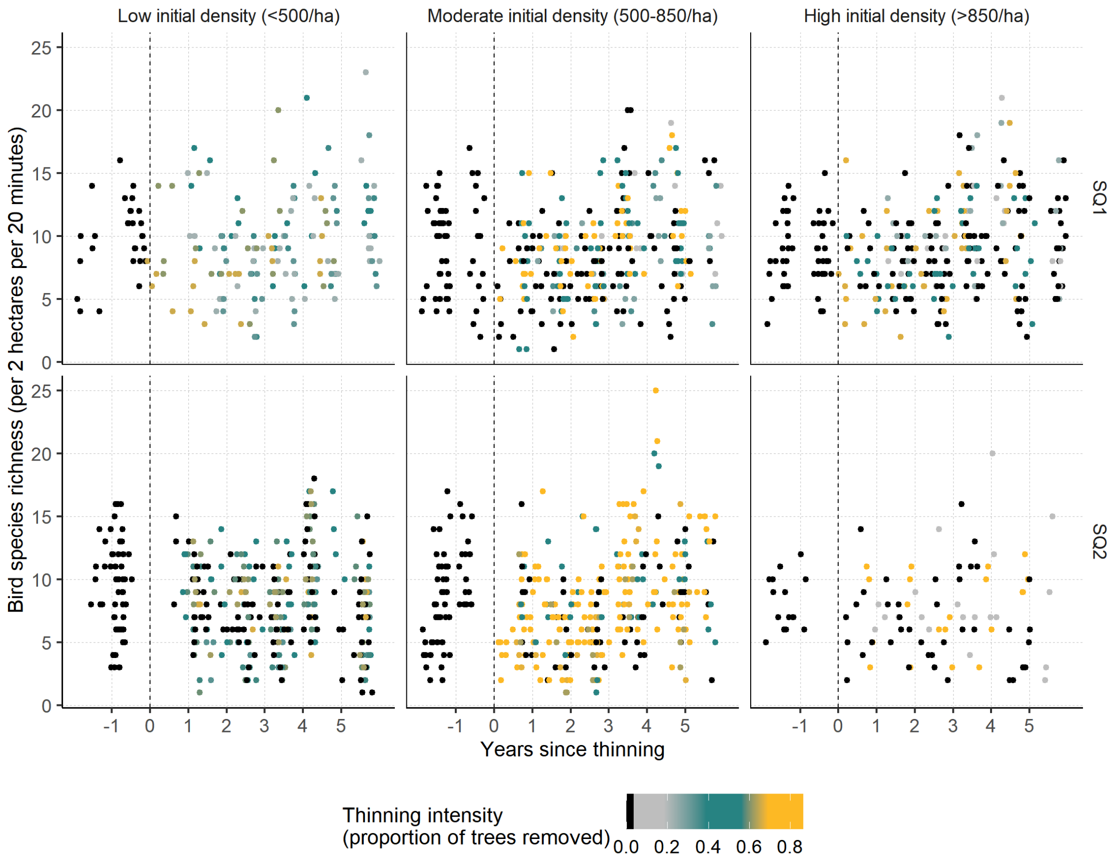

Figure 102 Data for bird species richness (number of different species recorded in 4 20-minute surveys to a 2-hectare subplot within each 9-hectare plot)

Model results

Bird species richness was analysed as a continuous positive variable, using a Gaussian distribution (see Appendices). Time was included in this model as a fixed factor of survey year. Years elapsed was not included, and year was not included as a random factor. All other explanatory variables were included, with all combinations of initial tree density, time since thinning, thinning intensity and Site Quality. Random effects for site and 9-hectare plot were also included.

In the absence of ecological thinning, bird species richness was highly variable over time (Figure 103) and these fluctuations were statistically significant (Table 75). There was also some evidence that bird richness varied with Site Quality ($p = 0.08$), with different maximums and minimums apparent among these plot types.

There was some evidence ($p = 0.08$) of a statistically significant effect of ecological thinning on bird richness (Table 75). The main impact of ecological thinning on bird richness per visit was on year-to-year change, with maximums in heavily thinned plots occurring in different years to maximums in control plots, particularly in wetter (SQ1) plots (Figure 103).

Heavy thinning in very low initial tree density plots caused an increase in richness per visit, but the increase was significantly different from controls for only one or 2 years post-thinning (Figure 103).

Heavy thinning in very high initial tree density plots in Site Quality 1 caused a decrease in bird richness (of magnitude 2 species) which was significantly lower than controls 3 and 4 years post-thinning, but then in year 5 richness was 5 species higher than controls (Table 76).

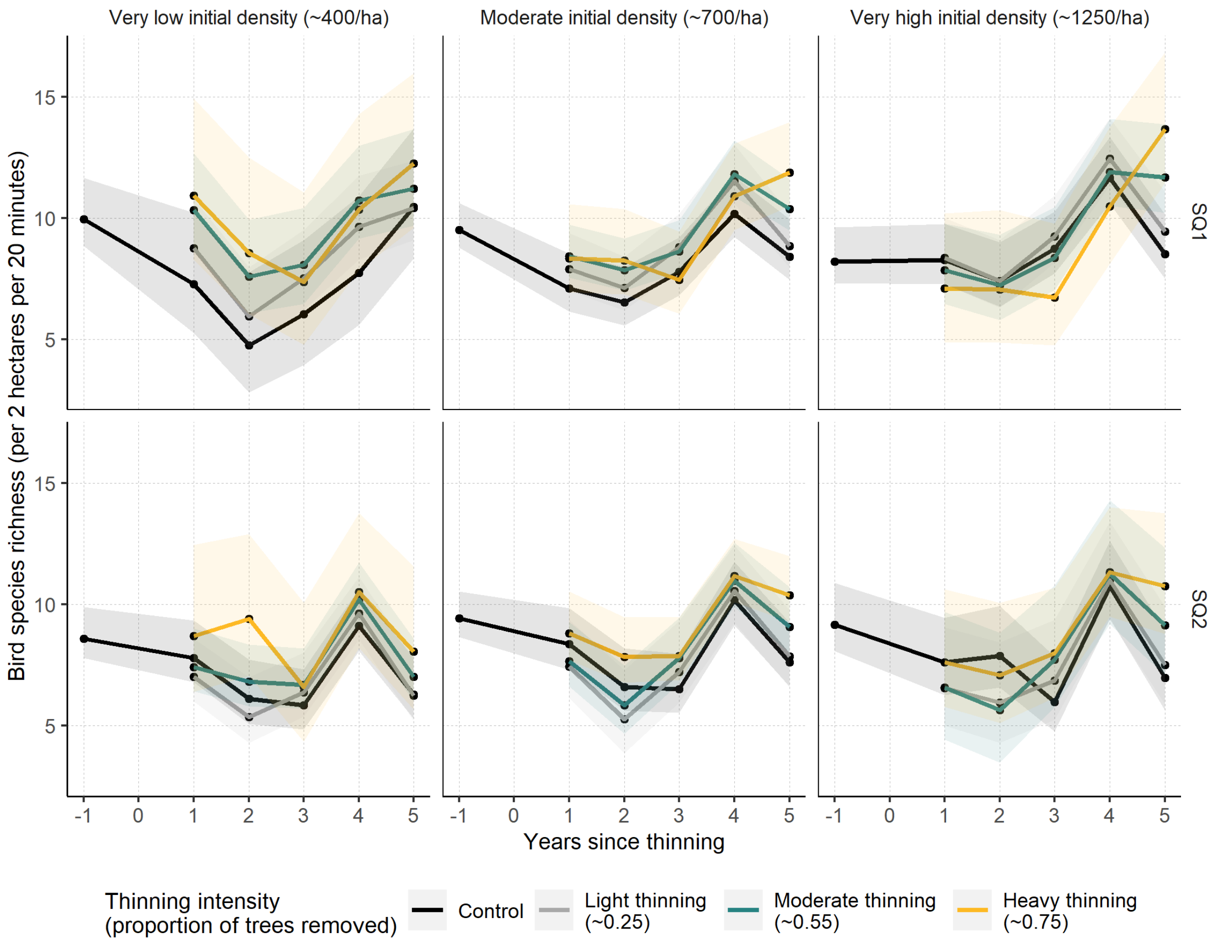

Figure 103 Modelled values and 95% confidence intervals for bird species richness per 2 hectares from four 20-minute surveys

Table 75 Statistical significance of explanatory variables on bird species richness

	Bootstrapped likelihood ratio test significance	Description
Site Quality	0.08	Marginally significant effect of Site Quality on bird species richness
Initial tree density	0.13	No significant effect of initial tree density on bird species richness
Survey year	0.01	Bird species richness changed over time
Thinning intensity	0.08	The effect of ecological thinning on bird species richness was marginally significant
Does the effect of thinning intensity vary depending on:		
• Site Quality	0.77	The effect of thinning on bird species richness was not dependent on Site Quality, initial tree density or survey year
• Initial tree density	0.58	
• Survey year	0.13	

	Bootstrapped likelihood ratio test significance	Description
• Site Quality **and** initial tree density **and** time since thinning	0.86	The effect of ecological thinning on bird species richness did not vary for all combinations of Site Quality, initial tree density and time

Table 76 Estimates of effect sizes for bird species richness per 20-minute visit 5 years post-thinning, showing difference between fitted values and 95% confidence intervals in thinned plots relative to control plots

Site Quality		Site Quality 1			Site Quality 2		
Thinning intensity		Low intensity	Mod intensity	High intensity	Low intensity	Mod intensity	High intensity
Initial tree density	Very low (400/ha)	–0.1 –1.4 to +1.9	+0.7 –0.8 to +3.2	+1.8 –0.9 to +5.5	0.0 –1.1 to +1.5	+0.7 –0.3 to +2.3	+1.8 –0.6 to +5.3
	Moderate (700/ha)	+0.4 –0.4 to +1.8	+1.9 +1.1 to +3.2	+3.5 +2.1 to +5.5	+0.2 –1.0 to +2.1	+1.5 +0.4 to +3.1	+2.8 +1.7 to +4.4
	Very high (1250/ha)	+0.9 –0.2 to +2.6	+3.2 +1.7 to +5.4	+5.2 +3.0 to +8.3	+0.5 –1.1 to +2.9	+2.2 +0.1 to +5.4	+3.8 +1.8 to +6.8

Hypothesis evaluation

Bird richness per 20-minute survey fluctuated over time. It is likely that fluctuations were related to different hydro-climatic conditions. There was some evidence to support the hypothesis that ecological thinning increased bird species richness, particularly in the most recent survey years with favourable hydro-climatic conditions. However, there was also evidence that ecological thinning was associated with at least temporary decreases in bird species richness in some plot types.

15.3 Bird species diversity

Hypothesis	2b. Ecological thinning will increase abundance of bird species. Bird species diversity combines information about the number of species and the abundance of each species.
Key result	Ecological thinning initially **decreased** bird Hill-Shannon diversity in drier Site Quality 2 plots with moderate to very high initial tree density by the equivalent of 2 equally abundant species (per 20-minute survey of 2 hectares) relative to controls. Subsequently, moderate and heavy intensity ecological thinning **increased** bird diversity in all site types and the magnitude of change increased over time to a maximum of 3.3 more than controls.

Data collection

Birds were surveyed in a 2-hectare subplot within each 9-hectare treatment plot (see Figure 5), with visual and auditory observations recorded for 20 minutes on 4 occasions (2 pre-9 am and 2 post-9 am) per survey period. Surveys were conducted annually in spring-summer for 6 survey years.

Hill-Shannon diversity is an index that combines information about both the number of bird species (richness) and the abundance of each species (that is, how many individual birds of each species were present). We calculated Hill-Shannon diversity for each 20-minute survey. This index places equal importance on common and rare species (Roswell et al. 2021). The index has a value of zero when only one species is present, and higher values represent higher numbers of species with greater abundance. A Hill-Shannon value of 5 is equivalent to 5 equally abundant species; a Hill-Shannon value of 25 is equivalent to 25 equally abundant species.

Data summary

Hill-Shannon diversity values commonly ranged from 2 to 15 equally abundant species (Figure 104). Across all surveys, there were 10 occasions where a Hill-Shannon value of 1 was recorded. Values tended to be higher in more recent years and all occurrences of values greater than 15 were all recorded in either 2020–21 or 2021–22.

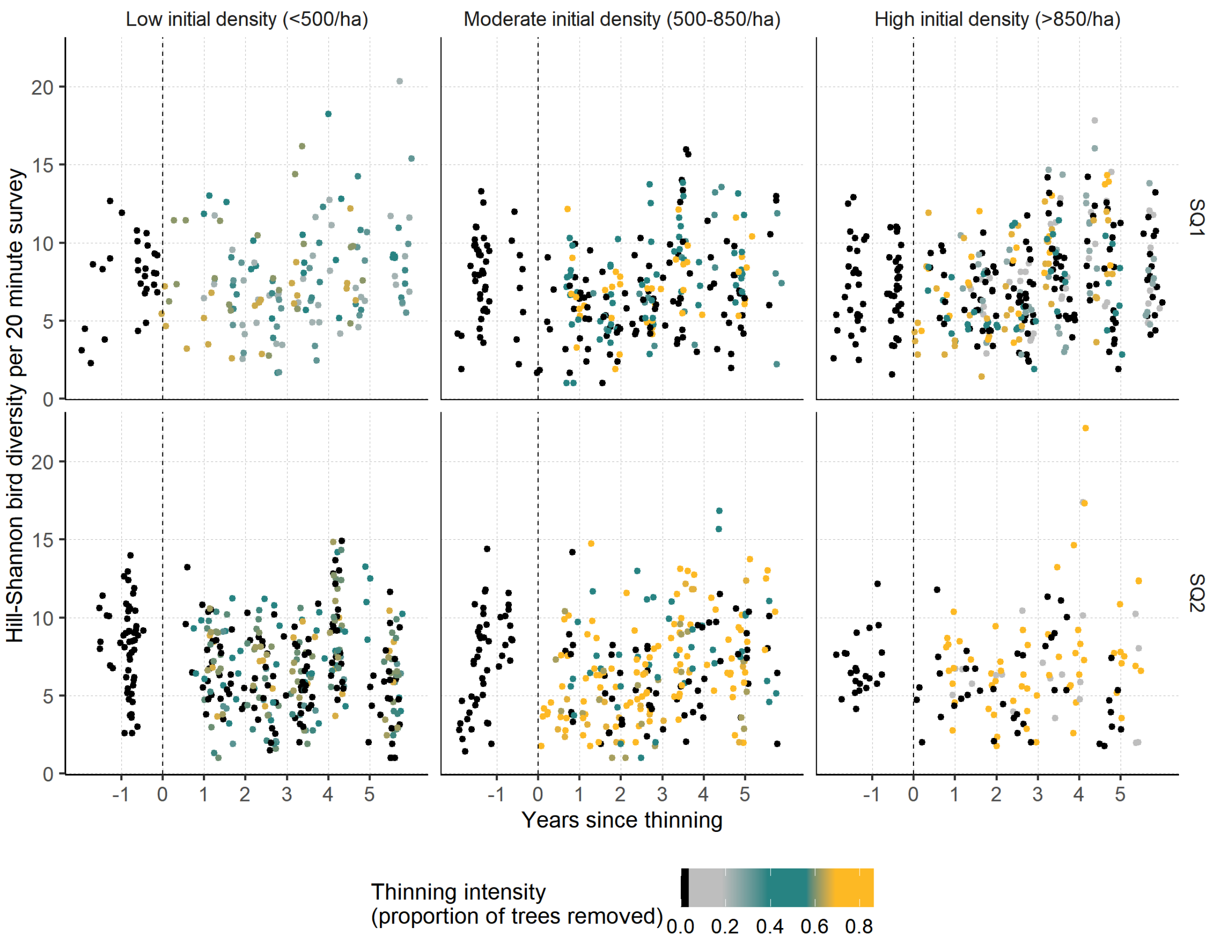

Figure 104 Data for bird species Hill-Shannon diversity (per 20-minute survey on a 2-hectare subplot within each 9-hectare plot)

Model results

Bird species diversity was analysed as a continuous positive variable, using a Gaussian distribution (see Appendices). Time was included in this model as a fixed factor of survey year. Years elapsed was not included, and year was not included as a random factor. All other explanatory variables were included, with all combinations of initial tree density, thinning intensity and Site Quality. Random effects for site and 9-hectare plot were also included.

Bird species diversity results were very similar to bird species richness results.

Bird species diversity was significantly different between Site Qualities, with slightly higher Hill-Shannon values of bird diversity observed in wetter (SQ1) plots (Table 78, Figure 105). Bird species diversity also changed significantly over time, regardless of ecological thinning, but did not vary among plots with differing initial tree densities.

Ecological thinning had a marginally significant (p = 0.05) effect on bird species diversity, but the effect changed over time (Figure 105, Table 77). Initially, ecological thinning reduced bird diversity in Site Quality 2 plots with moderate and very high pre-thinning tree density. The magnitude of this reduction was the equivalent of 2.2–2.7 equally abundant species. Subsequently, moderate and heavy intensity thinning increased bird species diversity on all site types relative to controls, with the magnitude of the effect increasing over time. Five years post-thinning, the largest effect recorded was a maximum increase of 3.3 equally abundant species in plots that had either moderate or high initial tree density and were moderate or heavily thinned (Table 78).

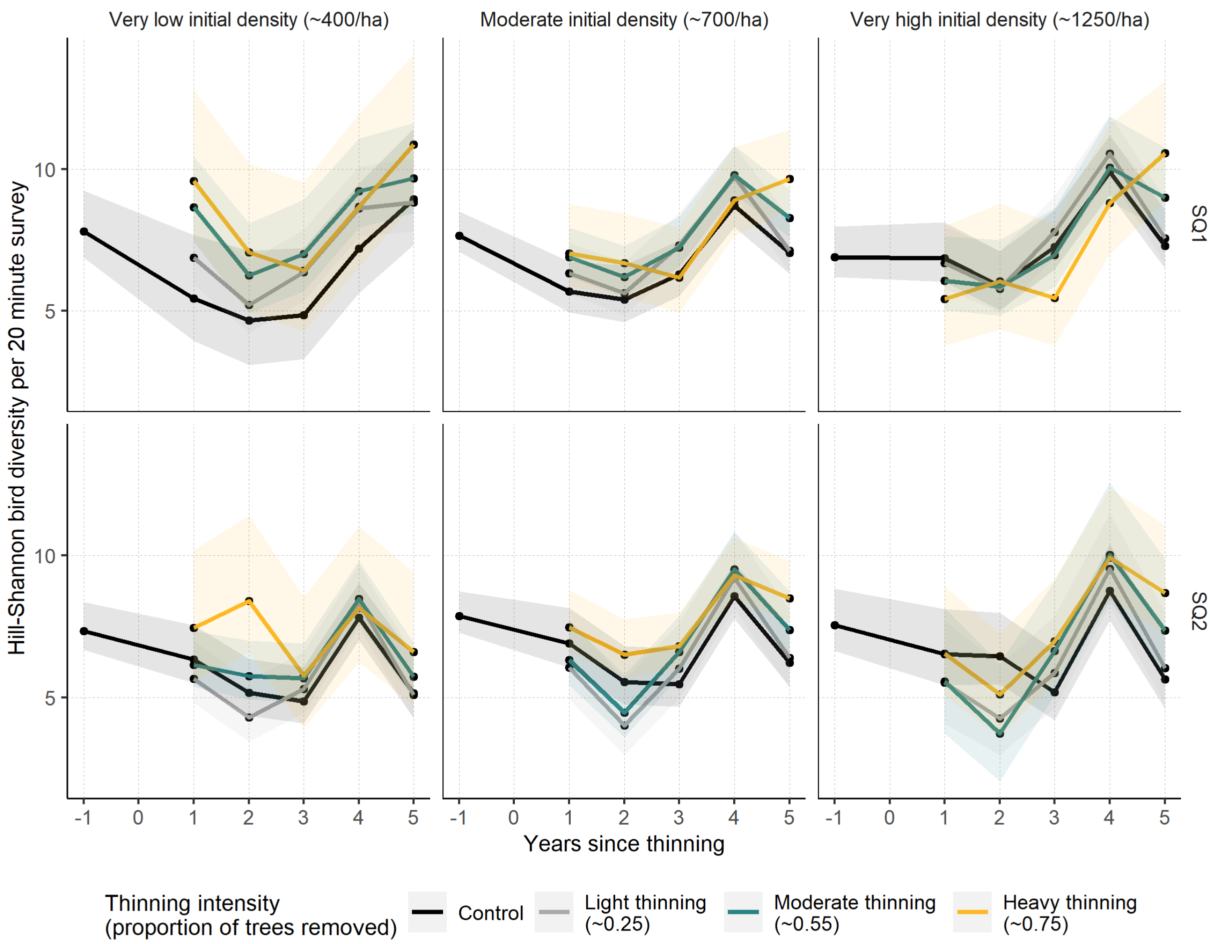

Figure 105 Modelled values and 95% bootstrapped confidence intervals for bird species Hill-Shannon bird diversity per 20-minute survey

Table 77 Statistical significance of explanatory variables on Hill-Shannon bird diversity

	Bootstrapped likelihood ratio test significance	Description
Site Quality	0.02	Significant difference in bird diversity between Site Qualities
Initial tree density	0.32	No significant difference in bird diversity with initial tree density
Survey year	0.01	Significant change in bird diversity over time
Thinning intensity	0.05	Marginally significant effect of ecological thinning on bird diversity
Does the effect of thinning intensity vary depending on:		
• Site Quality	0.54	The effect of thinning on bird diversity did not depend on Site Quality
• Initial tree density	0.38	The effect of thinning on bird diversity did not depend on initial tree density
• Survey year	0.20	The effect of thinning on bird diversity did not change over time
• Site Quality **and** initial tree density **and** survey year	0.67	The effect of ecological thinning on bird diversity did not vary for all combinations of Site Quality, initial tree density and time

Table 78 Estimates of effect sizes for Hill-Shannon bird diversity 5 years post-thinning, showing difference between fitted values and 95% confidence intervals in thinned plots relative to control plots

Site Quality		Site Quality 1			Site Quality 2		
Thinning intensity		Low intensity	Mod intensity	High intensity	Low intensity	Mod intensity	High intensity
Initial tree density	Very low (400/ha)	–0.1 –1.1 to +1.4	+0.7 –0.5 to +2.7	+1.9 –0.2 to +5.1	–0.1 –0.9 to +1.3	+0.6 –0.2 to +1.8	+1.5 –0.4 to +4.3
	Moderate (700/ha)	+0.1 –0.7 to +1.2	+1.2 +0.6 to +2.3	+2.6 +1.5 to +4.3	+0.2 –0.9 to +1.9	+1.2 +0.3 to +2.5	+2.3 +1.4 to +3.6
	Very high (1250/ha)	+0.3 –0.6 to +1.7	+1.7 +0.5 to +3.5	+3.3 +1.6 to +5.8	+0.4 –0.9 to +2.4	+1.7 +0.1 to +4.2	+3 +1.6 to +5.4

Hypothesis evaluation

Data and modelling results provided mixed evidence for the hypothesis that thinning increased bird activity. However, the similarity in results for bird species richness and bird diversity suggest that changes in bird abundance due to thinning are predominantly driven by changes in the number of species recorded in thinned plots.

Plate 4 White-throated tree creeper on a tree. Nicholas Chu

15.4 Bird foraging activity

Hypotheses	2b. Ecological thinning will increase frequency of foraging activity by woodland bird species.
Key result	Raw data provide evidence that bird activity increased in most microhabitat locations in thinned plots relative to control plots but statistical analyses were not undertaken.

Data collection

Birds were surveyed in a 2-hectare subplot within each 9-hectare treatment plot (see Figure 5), with visual and auditory observations recorded for 20 minutes on 4 occasions (2 pre-9 am and 2 post-9 am). Surveys were conducted annually in spring-summer for 6 survey seasons. The microhabitat in which each bird species was observed was recorded.

Data summary

Raw data suggest that ecological thinning increased the number of birds observed in most microhabitat locations, particularly in trees and the upper tree canopy (Figure 106). In wetter (SQ1) plots, the effect of thinning was more pronounced for moderate thinning. In drier (SQ2) plots, the effect was more pronounced for heavy thinning.

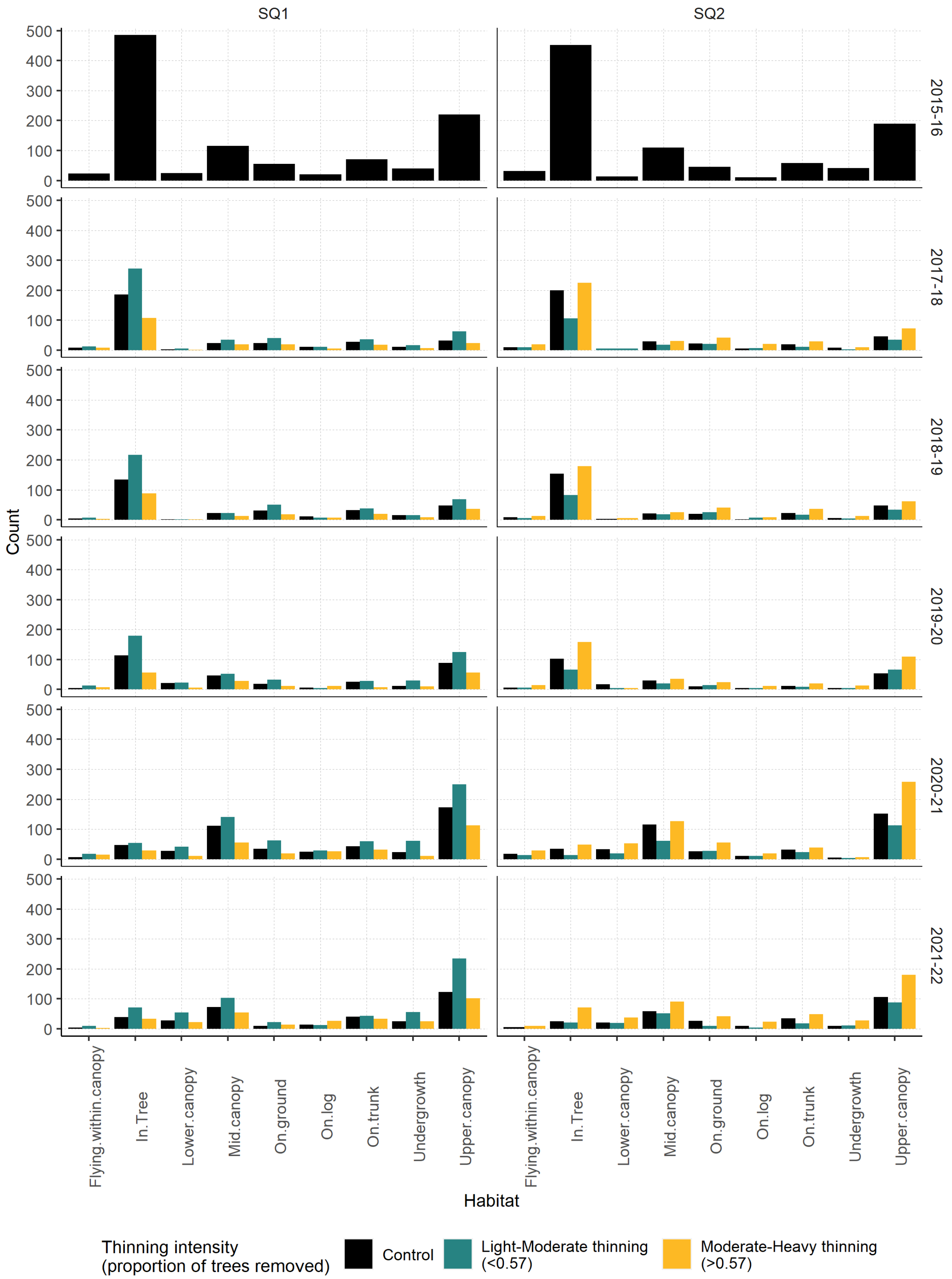

Figure 106 Data for the number of records of bird species in each microhabitat during each survey season. Thinned sites have been allocated to 2 thinning categories so that the number of 9-hectare plots that were sampled in each bar was equal

Model results

Statistical analyses were not conducted on these data.

Hypothesis evaluation

Raw data provided evidence for increased foraging activity in most microhabitat locations, particularly trees, in thinned plots.

15.5 Threatened bird species

Hypothesis	The ecological thinning trial was designed to minimise impacts on threatened species and no hypothesis was specified.
Key result	Twelve threatened bird species were recorded. These opportunistic data were sparse and not appropriate for statistical analyses.

Data collection

Birds were surveyed in a 2-hectare subplot within each 9-hectare treatment plot (see Figure 5), with visual and auditory observations recorded for 20 minutes on 4 occasions (2 pre-9 am and 2 post-9 am). Surveys were conducted annually in spring-summer for 6 survey seasons. No targeted surveys were undertaken for threatened bird species.

Data summary

Twelve bird species that are listed as vulnerable under the NSW Biodiversity Conservation Act were recorded in the study area – 9 of those species were recorded in 2 or more survey years and 3 species were recorded in one survey year (Table 73). One species previously observed in 2020–21 (square-tailed kite) has since been relisted as endangered. Five species were recorded in the most recent 2021–22 surveys.

Table 79 Threatened bird species recorded

Name	Habitat	Number of 9-hectare plots					
		2015	2017	2018	2019	2020	2021
Black-chinned honeyeater	Found in drier open forests and woodlands. Large feeding territories; species locally nomadic. Forages in upper branches, trunks and canopy; feeds on insects and nectar. Nests high in the crown of a tree.	1	-	-	1	-	-
Dusky woodswallow	Forest with open or sparse understorey and groundcover of grasses, sedges or fallen woody debris. Forages primarily over leaf litter and dead timber.	9	7	9	12	8	9
Flame robin	Migrates between tall eucalypts at higher altitude in	-	-	-	-	1	-

Name	Habitat	Number of 9-hectare plots					
		2015	2017	2018	2019	2020	2021
	warmer months to open habitats in the lowlands in winter. Forages from low perches on invertebrates on tree trunks, logs and other coarse woody debris.						
Hooded robin	Prefers lightly wooded vegetation. Requires structurally diverse habitats. Perches on low stumps and branches to forage. Nests in tree fork or crevice.	1	2	-	2	1	1
Little eagle	Found in eucalypt forest and riparian woodlands. Nests in tall living trees. Soars above trees or swoops from trees to take prey from the ground, trees or bushes.	1	1	-	-	1	1
Painted honeyeater	Occurs in box-gum woodlands and other inland slopes vegetation. Nomadic. Specialist feeder on the fruits of mistletoes. Nests in the outer canopy of drooping tree foliage.	-	-	1	1	-	-
Scarlet robin	Abundant logs and fallen timber. Forages from low perches or the ground; sometimes the shrub or canopy layer. Nests are often found in a dead branch in a live tree, or a dead tree or shrub.	29	22	29	19	18	29
Superb parrot	Abundant logs and fallen timber. Forages from low perches or the ground; sometimes the shrub or canopy layer. Nests are often found in a dead branch in a live tree, or a dead tree or shrub.	3	1	2	3	7	-
Swift parrot	Migrate from Tasmania to the Australian mainland where they are nomadic and mainly occur where eucalypts are profusely flowering or there are abundant lerp infestations.	-	-	-	-	1	-
Square-tailed kite	Timbered watercourses and open forests. Nest sites generally located near watercourses in a fork or on large horizontal limbs.	-	-	-	-	2	-

Name	Habitat	Number of 9-hectare plots					
		2015	2017	2018	2019	2020	2021
Varied sittella	Eucalypt forests with mature smooth-barked gums with dead branches. Forages in crevices in bark, dead branches and dead trees. Nests in an upright tree fork high in the canopy.	5	4	11	11	13	15
White-bellied sea eagle	Large areas of open water. Breeds in mature tall open forest close to foraging habitat. Nests in large emergent eucalypts often with emergent dead branches or large dead trees nearby.	2	-	2	1	-	-

When the data for thinned plots were divided into thirds based on thinning intensity, there were no apparent effects of ecological thinning on threatened bird species recorded in the study area (Figure 107). However, these opportunistic data for threatened birds were sparse and statistical analyses were not possible.

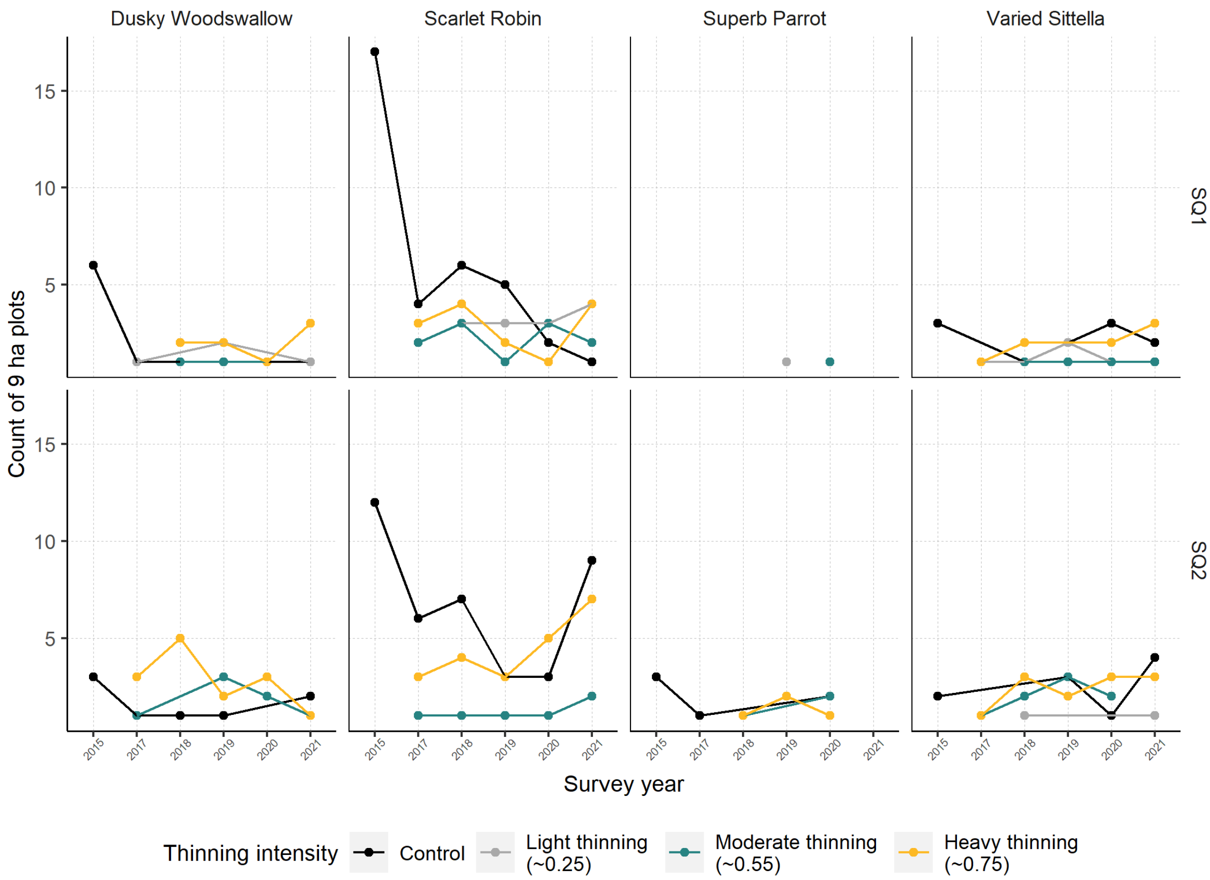

Figure 107 Number of 9-hectare plots that each threatened bird species was recorded in during each survey year

Excluding 8 threatened bird species that were recorded a maximum of twice in any survey.

Hypothesis evaluation

The ecological thinning trial was designed to minimise impacts on threatened species and no hypothesis was specified. Data were too sparse to draw conclusions.

16. Results: Gliders

16.1 Count of glider feed trees

Hypothesis	2c. Ecological thinning will increase abundance of gliders.
Key result	**No statistically significant effect of ecological thinning.**

Data collection

Glider feed trees were defined as any tree with a glider notch, which are distinct V shaped notches left on trees when gliders collect sap. All glider feed trees were counted in each 9-hectare plot, and were categorised as either recent or old, based on presence of wet sap on glider notches. Surveys were conducted one year post-thinning in 2017–18 and 5 years post-thinning in 2021–22.

We analysed the number of trees with recent glider notches only.

Data summary

The number of glider feed trees within a 9-hectare plot ranged from 0 to 11, and generally there appeared to be more in Site Quality 2 plots than Site Quality 1 plots (Figure 108). There was a decrease in the number of glider feed trees between one year after thinning and the final year of monitoring, except for Site Quality 1 low initial tree density plots (Figure 108). There were no obvious effects of thinning on the number of glider feed trees (Figure 108).

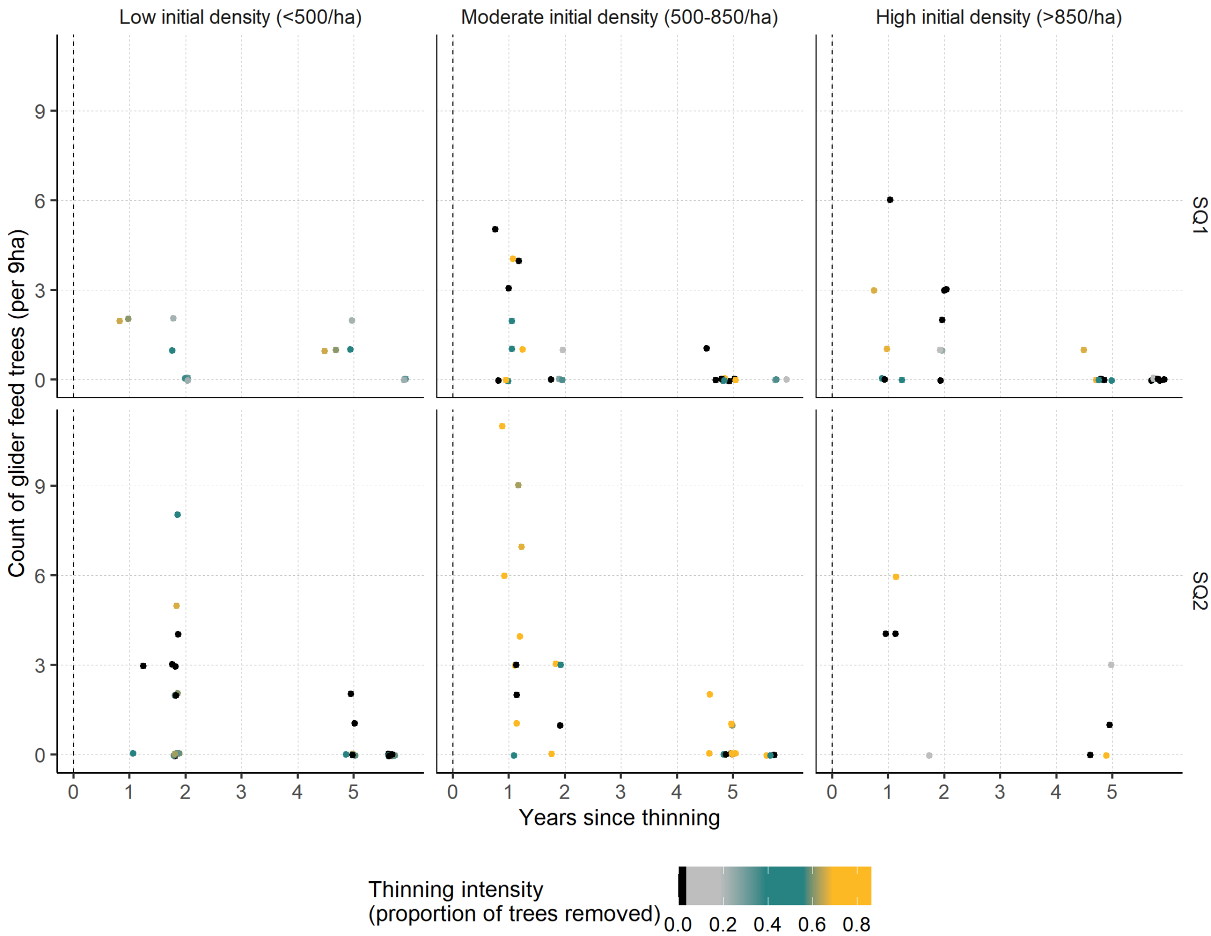

Figure 108 Data for count of glider feed trees per 9-hectare plot

Model results

The number of glider feed trees was analysed using a Poisson error distribution (see Appendices). The model for count of glider feed trees did not include four-way interaction between Site Quality, initial tree density, time since thinning and thinning intensity, but included all two-way and three-way interactions. A random effect of plot was included. The results of the model are presented on a log scale for count of glider feed tree (Figure 109), as the confidence interval bounds on the original scale were very wide making it difficult to visualise differences among treatments. However, the modelled results are presented on the count scale in Table 81 and Table 33.

The modelled data suggested no significant difference in number of glider feed trees based on Site Quality (Figure 109, Table 80). The number of glider feed trees was similar across all initial tree density types. There was a significant change in the number of glider feed trees over time, with the number generally decreasing between the first year following thinning and the final year of monitoring, although this effect was less pronounced in some treatment categories in Site Quality 1.

There was no significant effect of thinning on the number of glider feed trees (Figure 109, Table 80, Table 81).

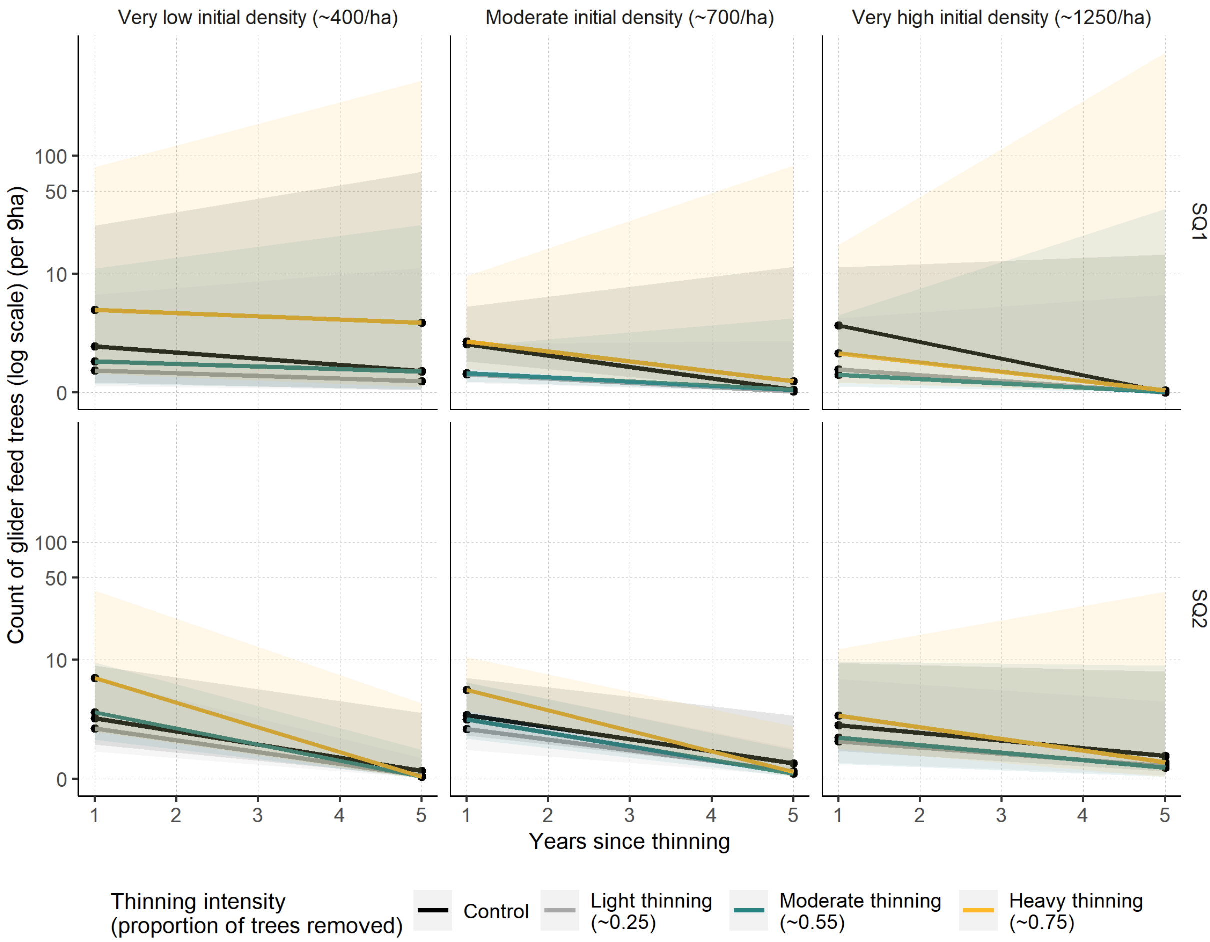

Figure 109 Modelled values and 95% confidence intervals for count of glider feed trees per 9-hectare plot, on a log scale

Table 80 Statistical significance of explanatory variables on count of glider feed trees per 9-hectare subplot

	Bootstrapped likelihood ratio test significance	Description
Site Quality	0.13	Number of glider feed trees did not differ among Site Qualities
Initial tree density	0.30	Number of glider feed trees did not depend on initial tree density
Time since thinning	0.01	Number of glider feed trees changed over time
Thinning intensity	0.37	Number of glider feed trees did not depend on thinning intensity
Does the effect of thinning intensity vary depending on:		
• Site Quality	0.48	The effect of thinning on number of glider feed trees did not depend on Site Quality

	Bootstrapped likelihood ratio test significance	Description
• Initial tree density	0.91	The effect of thinning on number of glider feed trees did not depend on initial tree density
• Time since thinning	0.33	The effect of thinning on number of glider feed trees did not change over time
• Site Quality **and** initial tree density **and** time since thinning	NA	Four-way interaction was not included in the model

Table 81 Estimated effect sizes for count of glider feed trees per 9-hectare subplot 5 years post-thinning, showing difference between fitted values and 95% confidence intervals in thinned plots relative to control plots

Site Quality		Site Quality 1			Site Quality 2		
Thinning intensity		Low intensity	Mod intensity	High intensity	Low intensity	Mod intensity	High intensity
Initial tree density	Very low (400/ha)	–0.4 –0.8 to +10.3	0.0 –0.7 to +25.1	+2.8 –0.7 to +432.4	–0.2 –0.3 to +0.6	–0.2 –0.3 to +0.9	–0.2 –0.3 to +3.9
	Moderate (700/ha)	–0.1 –0.1 to +2.2	0.0 –0.1 to +3.9	+0.3 –0.1 to +83.0	–0.3 –0.5 to +0.7	–0.4 –0.5 to +0.6	–0.3 –0.5 to +1.8
	Very high (1250/ha)	–0.01 –0.02 to +6.5	0.0 –0.02 to +35.6	+0.1 –0.02 to +745.4	–0.4 –0.8 to +3.3	–0.5 –0.9 to +8.0	–0.3 –0.8 to +37.1

Hypothesis evaluation

There was no evidence to support the hypothesis that ecological thinning would increase glider feed tree abundance.

17. Results: Predators

17.1 Foxes

Hypothesis	2d. Ecological thinning will increase abundance of predators, in particular foxes.
Key result	Insufficient fox scats were recorded to enable statistical analyses.

Data collection

Fox scat surveys were conducted annually in each of 6 survey years, by searching each 0.04-hectare subplot (see 20 x 20 metre subplots in Figure 5) and sending any uncertain specimens to a scat analysis expert. In 2021–22, 15% of 0.04-hectare subplots were not able to be surveyed due to flooding.

Data summary

In total, 100 scats were recorded on 57 subplots in all survey years (Figure 110). More fox scats were observed in moderately thinned sites (45 scats), when compared to heavily thinned (26 scats) and control (29 scats) sites. Of these observations, the majority of records were in more recent survey years with 46 scats observed in 2020–21 and 38 scats in 2021–22.

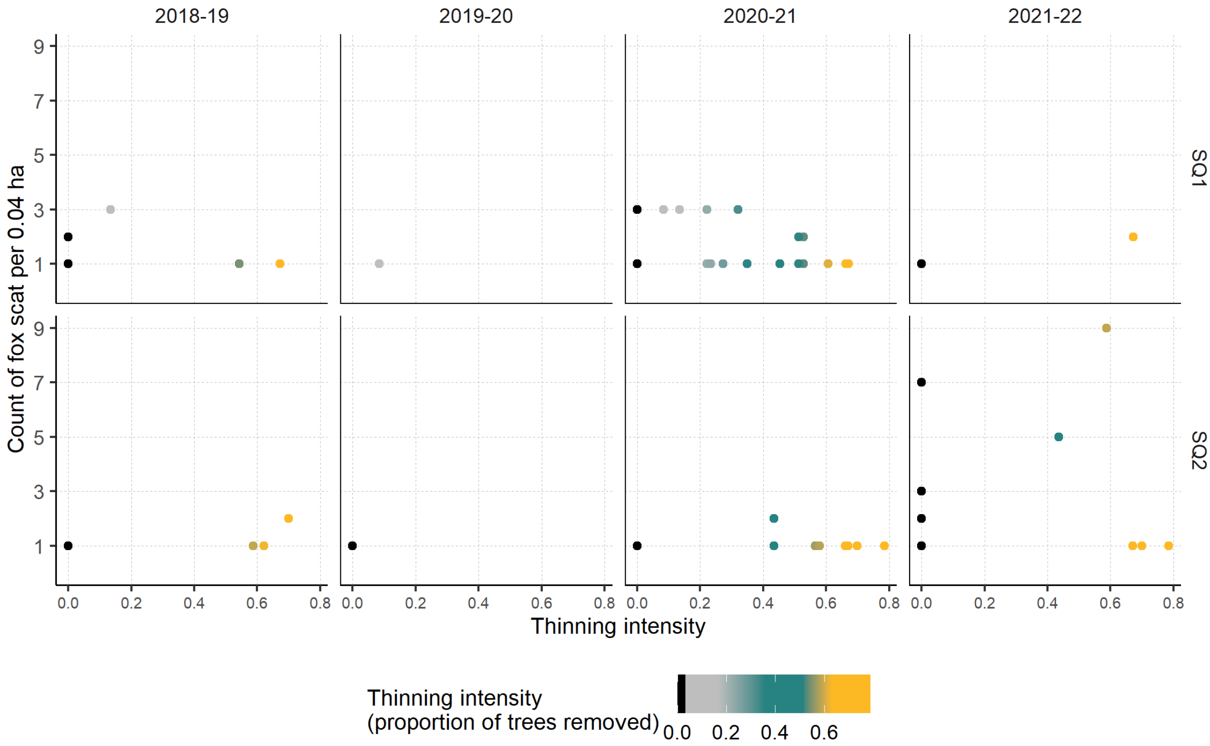

Figure 110 Data summary of fox scats per 0.04-hectare subplot

Model summary

A model was not able to be fitted to this data due to the prevalence of zeros.

Hypothesis evaluation

Data was insufficient to evaluate this hypothesis.

18. Results: Floristics

18.1 Exotic plant diversity

Hypothesis	3a. Ecological thinning will increase diversity of exotic plant species.
Key result	Heavy and moderate intensity ecological thinning (>50% of trees removed) caused an initial **increase** in exotic plant Hill-Shannon diversity by the equivalent of up to 6.6 equally abundant species (per 0.04-hectare subplot) in drier Site Quality 2 plots. The increase was maintained for very low to moderate initial tree density plots but declined over time for high initial tree density plots.

Data collection

Floristic composition was surveyed in three 0.04-hectare subplots on each 9-hectare plot (see 20 x 20 metre subplots in Figure 5). Floristic subplots were placed in the 9-hectare plots to sample the range of variation in understorey vegetation. Surveys involved recording all native and exotic plant species present. A total of 198 subplots were surveyed annually, excluding the most recent survey year (2021–22, 5 years post-thinning) where 29 subplots were not surveyed due to flood conditions.

Within each 0.04-hectare subplot, 10 quadrats (1 x 1 metre) were placed along the western boundary. In each quadrat, the presence of all exotic plant species was recorded.

Hill-Shannon diversity is an index that combines information about both the number of plant species (richness) and the abundance of each species (that is, how many of the 1 metre x 1 metre quadrats each species was present in). We calculated Hill-Shannon diversity for each subplot. This index places equal importance on common and rare species (Roswell et al. 2021). The index has a value of zero when only one species is present, and higher values represent higher numbers of species with greater abundance. A Hill-Shannon value of 2 is equivalent to 2 equally abundant exotic plant species; a Hill-Shannon value of 15 is equivalent to 15 equally abundant exotic plant species.

Data summary

Exotic plant diversity ranged from 0 to 15 equally abundant species, with values greater than 5 more frequently recorded in drier (SQ2) sites than wetter (SQ1) sites (Figure 111). In wetter (SQ1) sites there was an apparent increase in exotic diversity with increasing initial tree density. Exotic diversity values appeared relatively consistent over time.

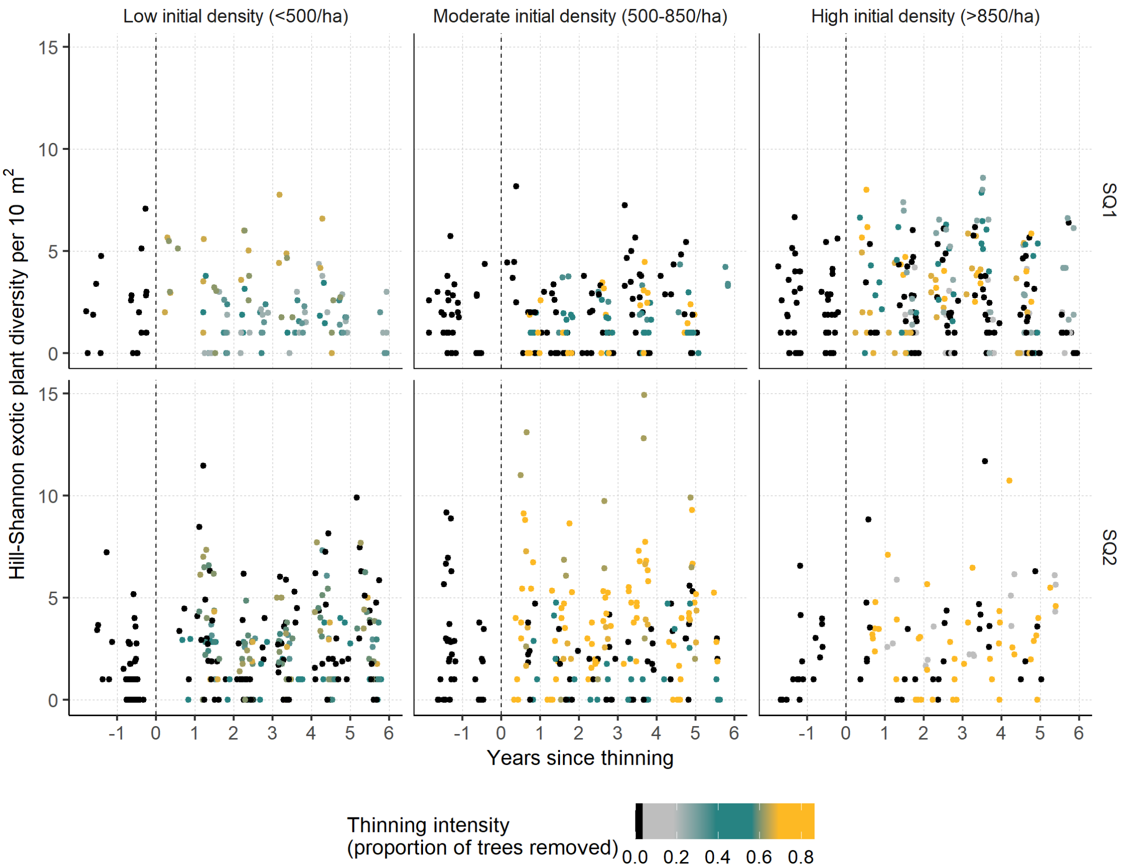

Figure 111 Data summary for exotic plant Hill-Shannon diversity (per 10 m^2 sampling quadrat within each 0.04-hectare subplot)

Model results

Exotic plant diversity was modelled as a positive integer variable using a Poisson distribution by rounding each value to the nearest whole number (see Appendices). All two- and three-way interactions between initial tree density, thinning intensity, time since thinning and Site Quality were included in the model, but the four-way interaction was not. Random effects for 9-hectare plot and 0.04-hectare subplot were included, but random effects of survey year or site could not be included.

Exotic plant diversity differed among Site Qualities and over time (Table 82). Exotic diversity was marginally higher in drier (SQ2) sites (Figure 112). There were slight trends with initial tree density, which differed between Site Qualities, but were not statistically significant.

Ecological thinning had a significant effect on exotic plant diversity, but the magnitude of difference from controls varied with time since thinning and there was also a marginally significant difference between Site Qualities ($p = 0.07$) (Table 82). The effect of thinning was to increase exotic species diversity for most plot types (Figure 112). Note that the modelled effect of thinning did not include year-to-year variation.

In wetter (SQ1) plots, the increase was only significantly different from controls in very high initial density plots, in which the magnitude increased slightly over time. In drier (SQ2) plots, heavy thinning caused an initial increase in exotic diversity, with a maximum increase equivalent to 6.6 equally abundant exotic species more than controls in plots with very low initial density. The difference from controls declined slightly over time to a maximum increase equivalent to 3.2 equally abundant exotic species more than controls 5 years post-thinning (Figure 112; Table 83). In plots with very high initial density in SQ2, the increase in thinned plots was not significantly different to controls.

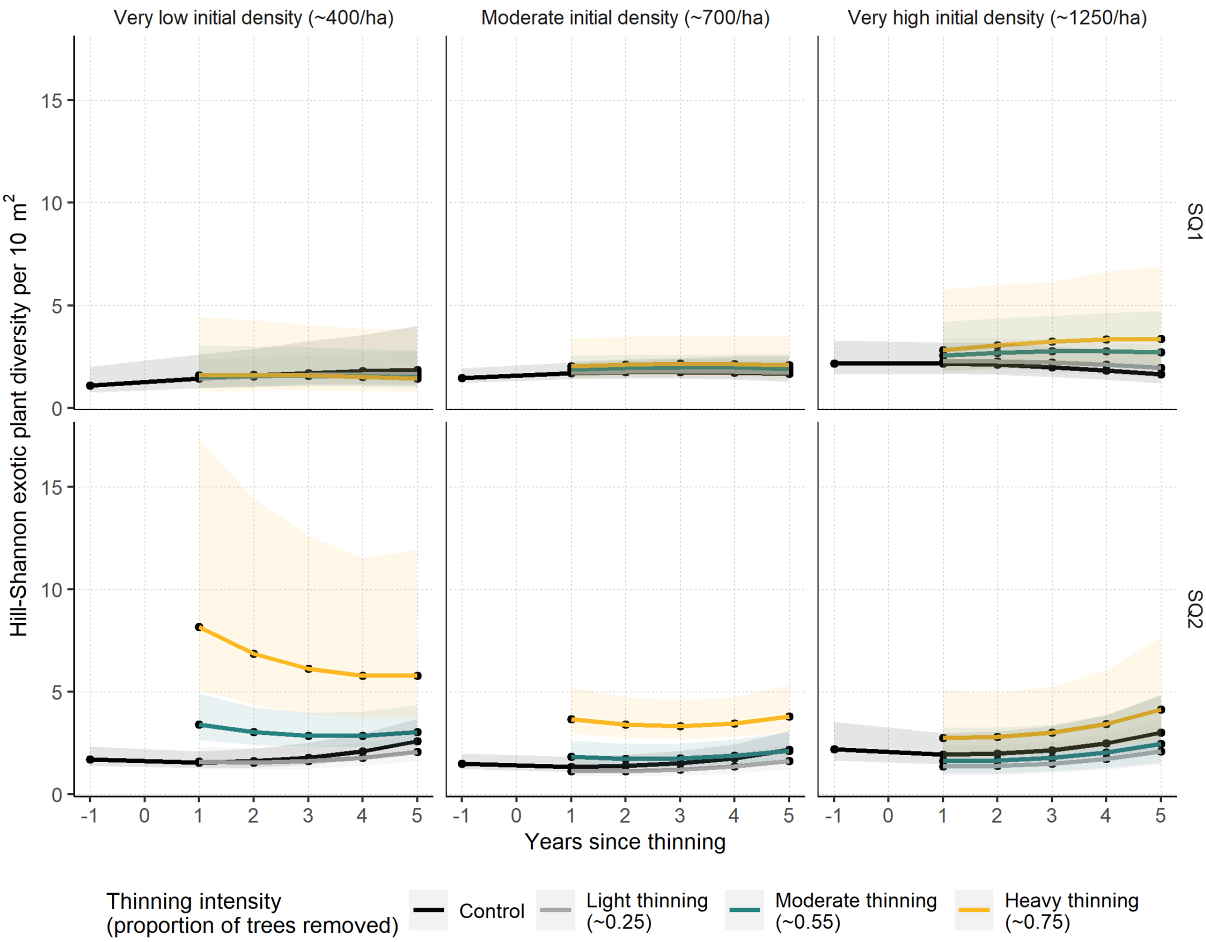

Figure 112 Modelled values and confidence intervals for exotic plant diversity (per 10 m^2 sampling quadrat within each 0.04-hectare subplot)

Table 82 Statistical significance of explanatory variables on exotic plant diversity per 0.01 hectare

	Bootstrapped likelihood ratio test significance	Description
Site Quality	0.03	Exotic plant diversity significantly differed by Site Quality
Initial tree density	0.16	Exotic plant diversity did not significantly differ by initial tree density
Time since thinning	0.01	Exotic plant diversity significantly changed over time
Thinning intensity	0.01	Exotic plant diversity significantly changed with thinning intensity
Does the effect of thinning intensity vary depending on:		
• Site Quality	0.07	Marginally significant difference between the effect of thinning between Site Quality categories

	Bootstrapped likelihood ratio test significance	Description
• Initial tree density	0.10	The effect of thinning intensity did not depend on initial tree density
• Time since thinning	0.02	The effect of thinning intensity changed over time
• Site Quality **and** initial tree density **and** time since thinning	NA	Not modelled

Table 83 Estimates of effect sizes for exotic plant diversity per 0.01 hectare 5 years post-thinning, showing difference between fitted values and 95% confidence intervals in thinned plots relative to control plots

Site Quality		Site Quality 1			Site Quality 2		
Thinning intensity		Low intensity	Mod intensity	High intensity	Low intensity	Mod intensity	High intensity
Initial tree density	Very low (400/ha)	–0.2 –0.7 to +0.9	–0.4 –0.9 to +1.0	–0.4 –1.1 to +2.0	–0.5 –1.0 to +0.4	+0.4 –0.2 to +1.8	+3.2 +1.2 to +9.3
	Moderate (700/ha)	+0.1 –0.3 to +0.7	+0.2 –0.1 to +0.9	+0.4 –0.2 to +1.8	–0.6 –0.9 to +0.3	+0.04 –0.5 to +0.9	+1.6 +0.9 to +3.2
	Very high (1250/ha)	+0.3 –0.2 to +1.4	+1.1 +0.3 to +3.1	+1.7 +0.5 to +5.2	–0.9 –1.6 to +0.6	–0.6 –1.5 to +1.8	+1.1 –0.3 to +4.6

Hypothesis evaluation

As a random effect for survey year could not be included in this model, any year-to-year fluctuations in exotic diversity are not included in the results. The data and model provided support for the hypothesis that ecological thinning would increase exotic plant diversity, particularly in drier (SQ2) plots.

18.2 Exotic plant species richness

Hypothesis	3a. Ecological thinning will increase diversity of exotic plant species. Exotic plant species richness (count of exotic plant species) is relevant to understanding whether diversity changes are due to changes in the number of individuals or number of species present.
Key result	Ecological thinning **increased** exotic plant species richness on most plot types in most years by up to 11 additional species (per 0.04-hectare subplot) relative to controls, with the exception of wetter Site Quality 1 plots with very low initial tree density 4 years post-thinning that had up to 6 **fewer** exotic plant species. Results were highly variable over time.

Data collection

Floristic composition was surveyed in three 0.04-hectare subplots on each 9-hectare plot (see Figure 5), with a total of 198 subplots. Floristic subplots were placed in the 9-hectare plots to sample the range of variation in understorey vegetation. Surveys involved recording all native and exotic plant species present. A total of 198 subplots were surveyed annually, excluding the most recent survey year (2021–22, 5 years post-thinning) where 29 subplots were not surveyed due to flood conditions.

Exotic species richness is the count of exotic species present in each 0.04-hectare subplot. Richness calculations include species that were identified to genus level, but do not include species that were identified to family level (see Appendices). A full species list is in the Appendices document.

Data summary

The number of exotic plant species present per 0.04-hectare subplot was commonly between 1 and 15 species. Across all survey years, the average number of exotic species present in Site Quality 1 subplots was 6.8 and the average number present in Site Quality 2 subplots was 7.8. The minimum number of exotic species recorded was zero and the maximum was 28.

Table 84 Average number of exotic plant species recorded per 0.04-hectare subplot, by Site Quality and survey year

Survey year	Site Quality 1	Site Quality 2
2015	6.3	5.5
2017	6.4	9.0
2018	6.3	6.5
2019	7.4	6.6
2020	9.6	10.8
2021	6.6	9.0

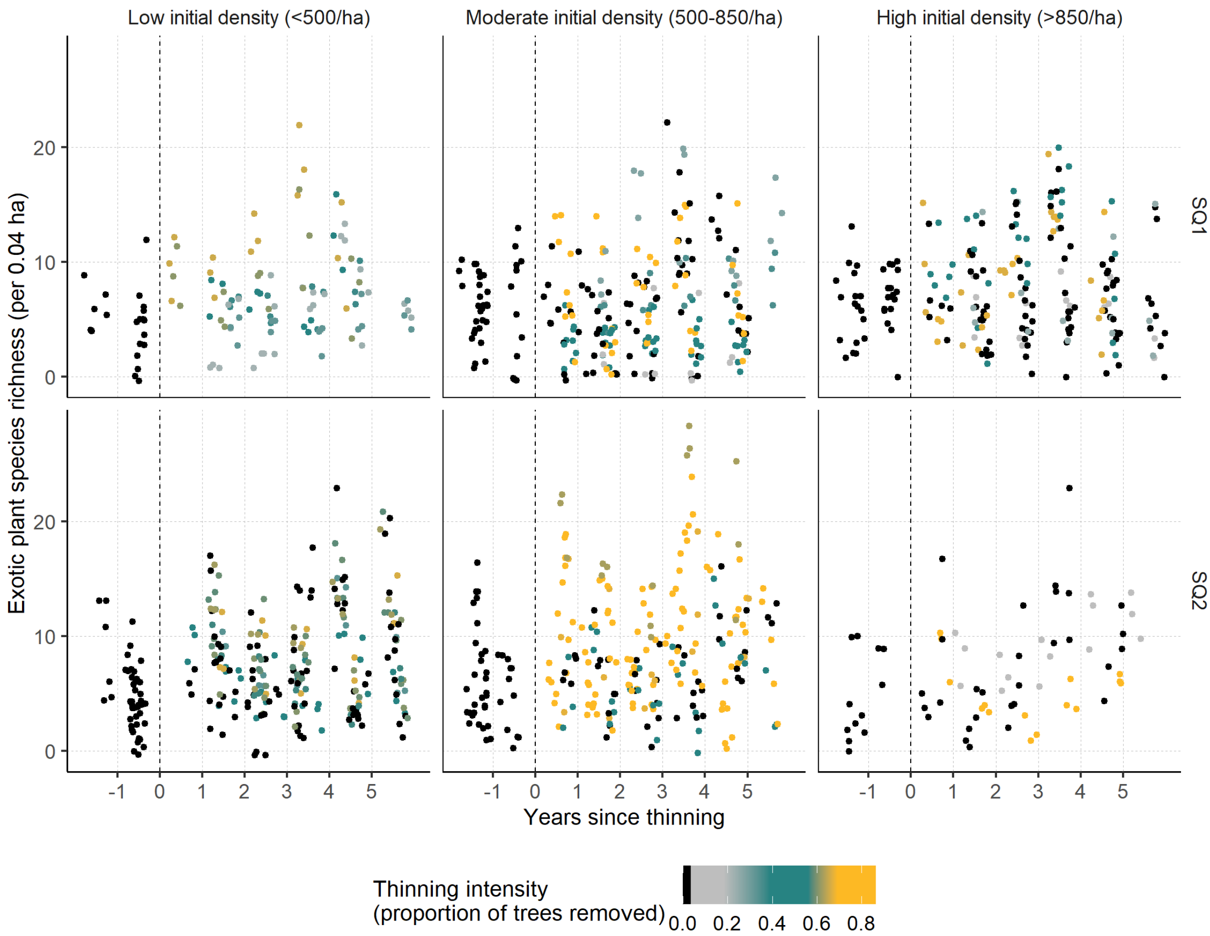

Figure 113 Data for exotic plant species richness per 0.04-hectare subplot

Model results

Exotic plant species richness was modelled as a positive count variable using a Gaussian distribution (see Appendices). The model for exotic plant species richness included a four-way interaction between Site Quality, initial tree density, time since thinning and thinning intensity, as well as all two-way and three-way interactions. Time was included in this model as a fixed factor of survey year. Years elapsed was not included, and year was not included as a random factor. Random effects of site, 9-hectare plot and subplot were included.

Exotic plant richness differed among Site Qualities, by initial tree density and over time (Figure 114, Table 85). Ecological thinning significantly affected exotic plant species richness, but the effect was highly variable with significant differences in the effect of thinning among Site Qualities, initial tree densities and over time (Figure 114, Table 85).

In all plot types, ecological thinning initially caused an increase in exotic plot species richness (Figure 114). The maximum magnitude of increase one year post-thinning was 5 additional species.

In heavily thinned plots, exotic plant species richness remained higher than control plots in almost all circumstances, with a peak 4 years post-thinning (2020–21 survey year) (Figure 114). The maximum increase was 11 additional exotic plant species in wetter (SQ1) plots with very high initial tree density. The exception was in wetter (SQ1) plots with very low initial tree density, for which exotic plant species richness was up to 6 species lower than control plots 4 years post-thinning.

Five years post-thinning the only thinned plot type with significantly higher exotic plant species richness was drier (SQ2) plots with moderate initial tree density, which had 1.6 more exotic plant species than control plots (Table 86).

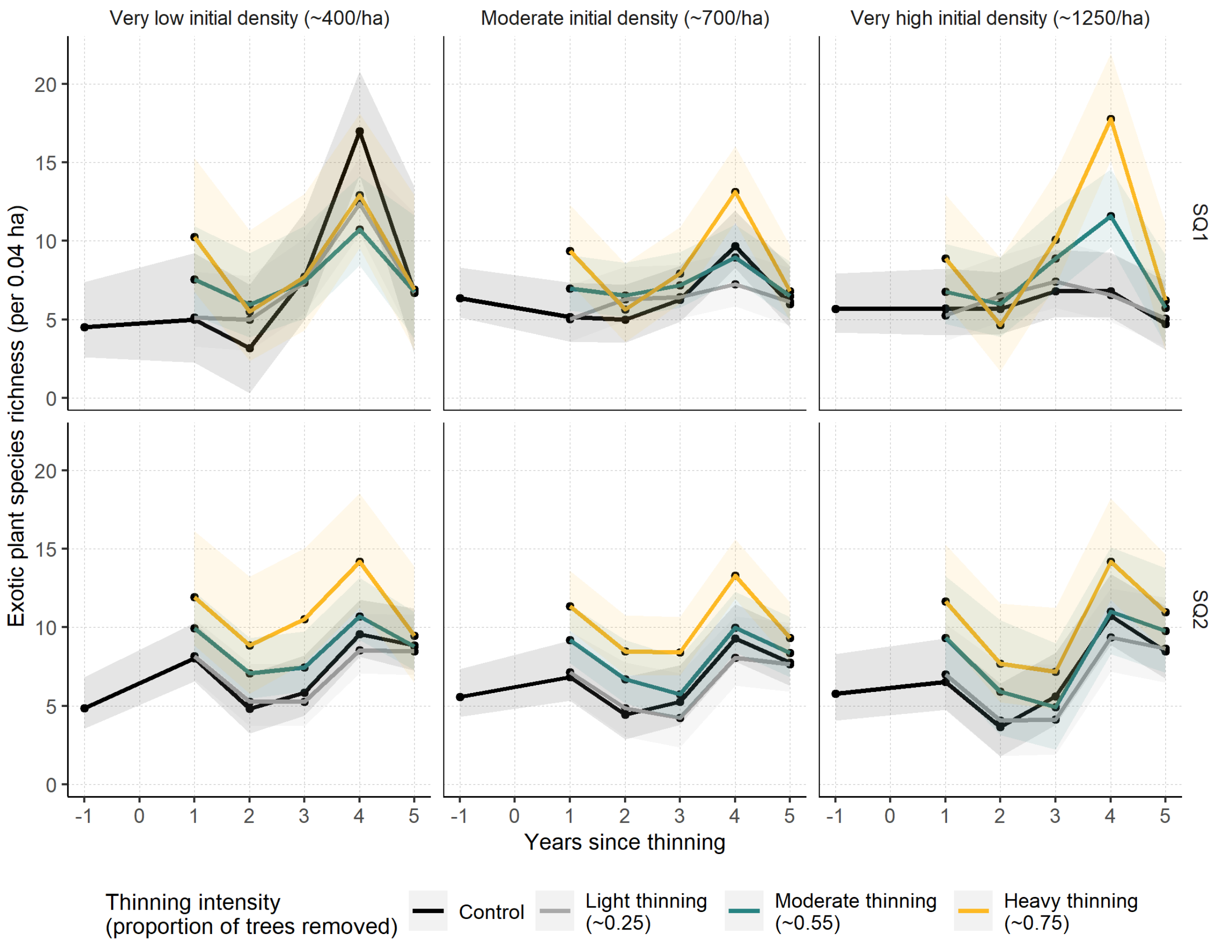

Figure 114 Modelled values and 95% confidence intervals for exotic plant species richness (per 0.04 hectare)

Table 85 Statistical significance of explanatory variables on exotic plant species richness

	Bootstrapped likelihood ratio test significance	Description
Site Quality	0.01	Exotic plant species richness differed by Site Quality
Initial tree density	0.01	Exotic plant species richness varied with initial tree density
Time since thinning	0.01	Exotic plant species richness changed over time
Thinning intensity	0.01	Exotic plant richness changed with thinning intensity
Does the effect of thinning intensity vary depending on:		

	Bootstrapped likelihood ratio test significance	Description
• Site Quality	0.12	The effect of thinning intensity did not vary with Site Quality
• Initial tree density	0.03	The effect of thinning intensity did not depend on initial tree density
• Time since thinning	0.01	The effect of thinning intensity changed over time
• Site Quality **and** initial tree density **and** time since thinning	0.01	The effect of thinning on exotic plant species richness significantly differed for all combinations of predictors

Table 86 Estimates of effect sizes for exotic plant species richness 5 years post-thinning, showing difference between fitted values and 95% confidence intervals in thinned plots relative to control plots

Site Quality		Site Quality 1			Site Quality 2		
Thinning intensity		Low intensity	Mod intensity	High intensity	Low intensity	Mod intensity	High intensity
Initial tree density	Very low (400/ha)	−0.1 −3.2 to +5.0	0.0 −3.0 to +4.9	+0.2 −3.7 to +6.1	−0.4 −1.9 to +1.9	−0.1 −1.6 to +2.1	+0.6 −2.4 to +5.0
	Moderate (700/ha)	+0.1 −1.4 to +2.3	+0.5 −0.9 to +2.7	+0.8 −1.1 to +3.7	−0.1 −1.9 to +2.5	+0.6 −0.9 to +2.9	+1.6 +0.03 to +3.8
	Very high (1250/ha)	+0.3 −1.5 to +3.1	+1.0 −1.4 to +4.4	+1.5 −1.8 to +6.3	−0.2 −2.0 to +3.4	+1.3 −1.4 to +5.3	+2.5 −0.04 to +6.2

Hypothesis evaluation

There was some evidence to support the hypothesis for drier (SQ2) plots.

18.3 Exotic plant cover

Hypothesis	3a. Ecological thinning will increase diversity of exotic plant species. Exotic plant vegetation cover is relevant to understanding whether diversity changes are due to changes in the number of individuals or cover of species present.
Key result	Ecological thinning caused a significant **increase** in exotic vegetation cover on most plot types. The greatest magnitude of increase was 2.1% (per 0.04-hectare subplot) in wetter Site Quality 1 plots 3 years post-thinning, but the difference from controls diminished over time.

Data collection

In the 2019–20, 2020–21 and 2021–22 survey seasons, total live exotic vegetation cover was visually estimated as a percentage of each 0.04-hectare subplot (see 20 x 20 metre subplots in Figure 5). In 2021–22, 15% of 0.04-hectare subplots were not able to be surveyed due to flooding. Exotic plant cover had not been estimated in previous years. In each plot, 2 observers independently estimated the area occupied by live exotic vegetation. They then conferred to agree on an area estimate and converted it to a percentage.

Data summary

Exotic plant cover values were most commonly less than 5% in both Site Qualities and initial tree density categories. Higher cover values were recorded approximately 4 years post-thinning in the 2020–21 surveys. Paterson's Curse (*Echium plantagineum*) was particularly abundant that year.

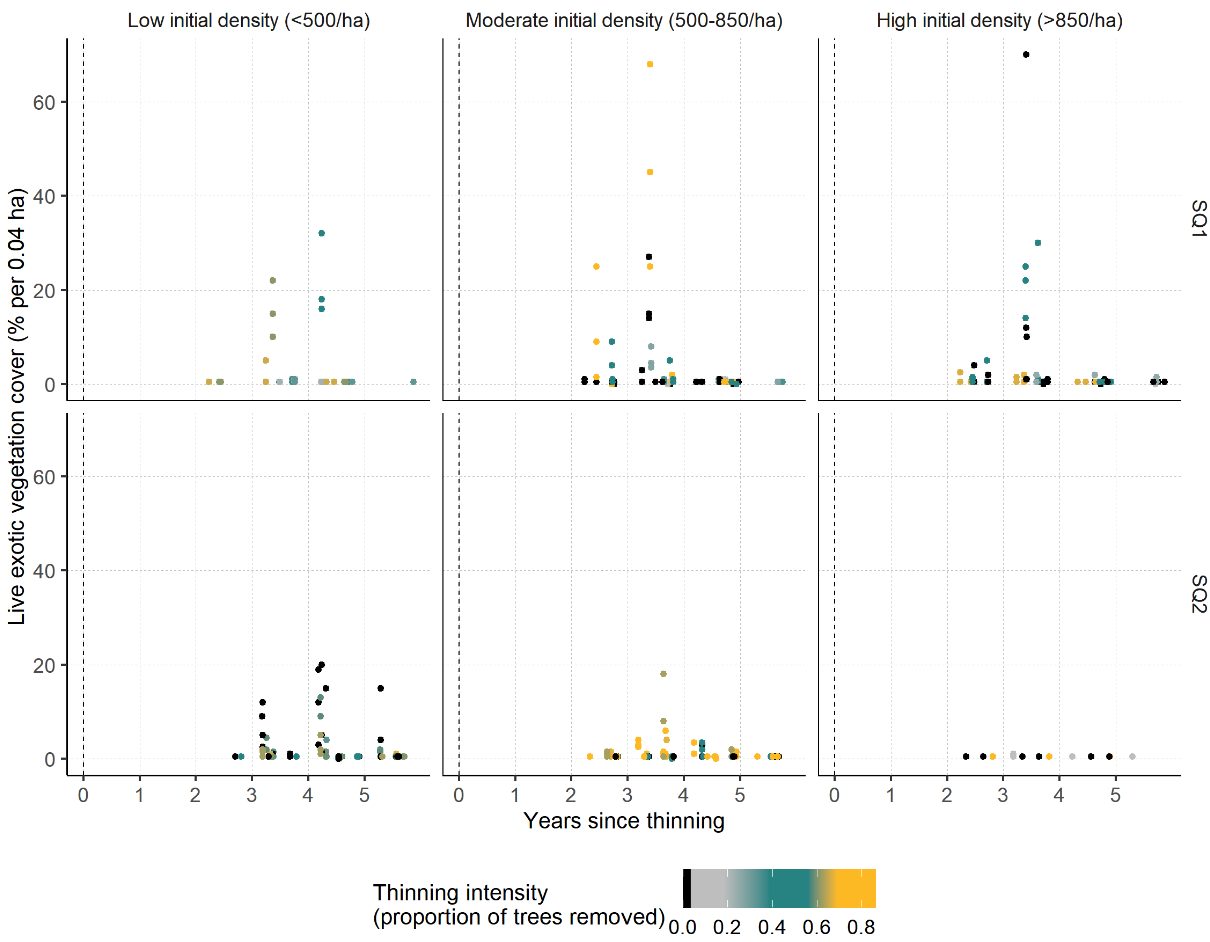

Figure 115 Data for exotic plant cover (%) per 0.04-hectare subplot

Ecological thinning may have increased exotic plant cover in 2020–21, particularly in wetter (SQ1) plots (Figure 116, Table 87). There was no evidence in the raw data that exotic cover was higher in thinned than control plots in the most recent survey year (2021–22).

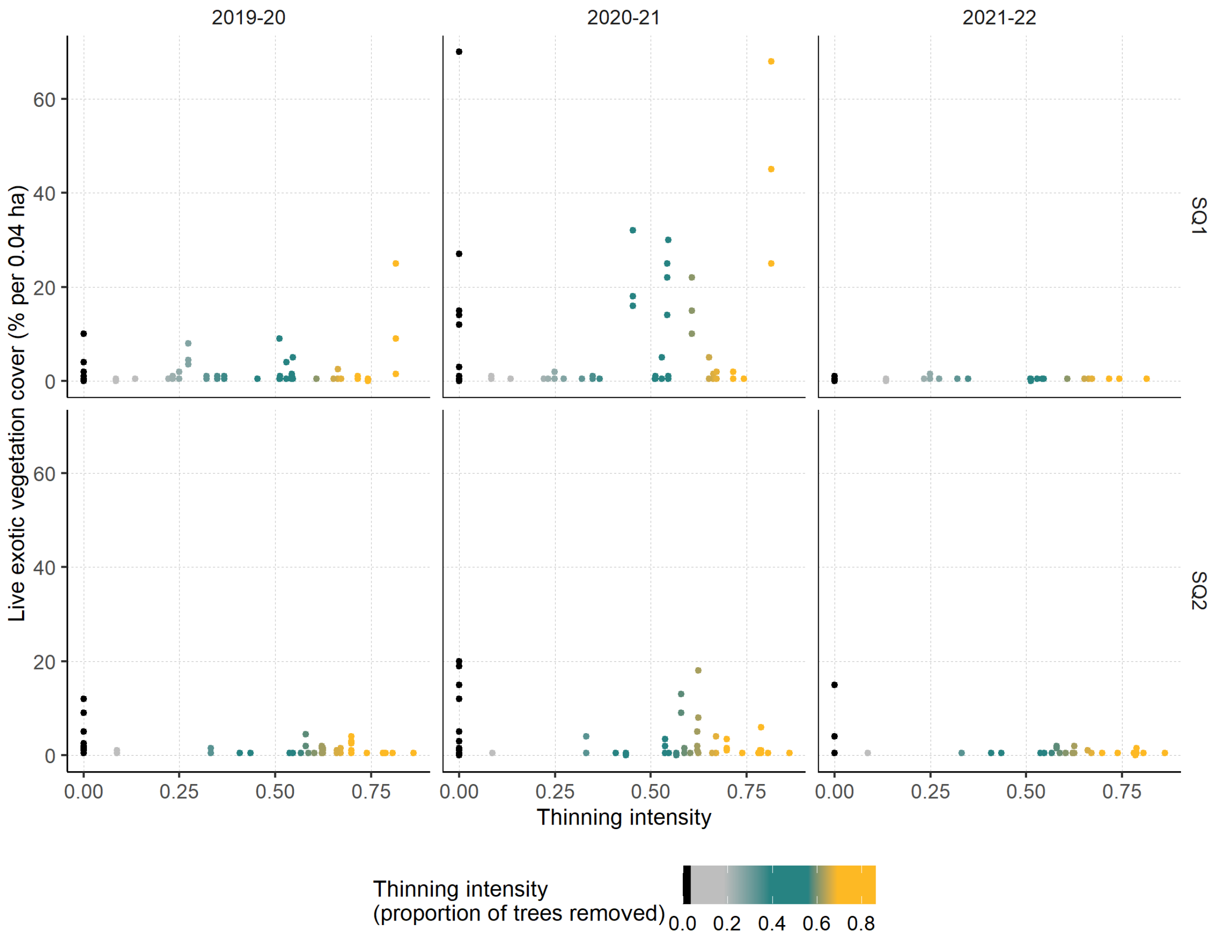

Figure 116 Data for live exotic plant cover (%) per 0.04-hectare subplot, not including initial tree density information

Table 87 Average live exotic plant cover (%) in the 3 most recent survey seasons

Values are rounded to the nearest whole percentage point

	Thinning intensity	Average cover			Proportion of 0.04-hectare plots with >1% exotic cover		
		2019	2020	2021	2019	2020	2021
SQ1	Control	1%	5%	1%	9%	18%	0%
	Light thinning	1%	1%	1%	15%	4%	6%
	Moderate thinning	2%	9%	1%	22%	44%	0%
	Heavy thinning	2%	10%	1%	19%	50%	0%
SQ2	Control	1%	3%	1%	18%	24%	6%
	Light thinning	1%	2%	1%	17%	33%	0%
	Moderate thinning	1%	2%	1%	14%	29%	15%
	Heavy thinning	1%	2%	1%	18%	21%	6%

Model results

Exotic plant cover was analysed as the proportion of the subplot that was exotic plant cover using a binomial distribution (see Appendices). This type of variable (continuous percentage) would generally be analysed using a beta distribution, however residuals tests indicated this distribution was not appropriate. The model for exotic plant cover did not include four-way interaction between Site Quality, initial tree density, time since thinning and thinning intensity, or the three-way interaction between initial tree density, time since thinning and thinning intensity. All other two-way and three-way interactions were included. Random effects of 9-hectare plot and subplot were included, but year and site were not included as random factors. Note that the results are presented on the modelled (logit) scale (Figure 117), but the magnitudes of change are presented on the percentage scale (Table 89, Table 90 and text).

In the absence of ecological thinning, live exotic vegetation cover varied significantly with Site Quality, initial tree density and over time (Table 87).

Three years post-thinning, ecological thinning caused a significant increase in exotic vegetation cover for all plot types except drier (SQ2) plots with very low initial tree density. The highest magnitude of increase was 2.1% for SQ1 plots with moderate initial tree density (Table 89). In wetter (SQ1) plots, the magnitude of difference relative to controls declined and was not significantly different from controls 5 years post-thinning (Table 90). In drier (SQ2) plots, the magnitude of increase was sustained over time but was not significantly different from controls.

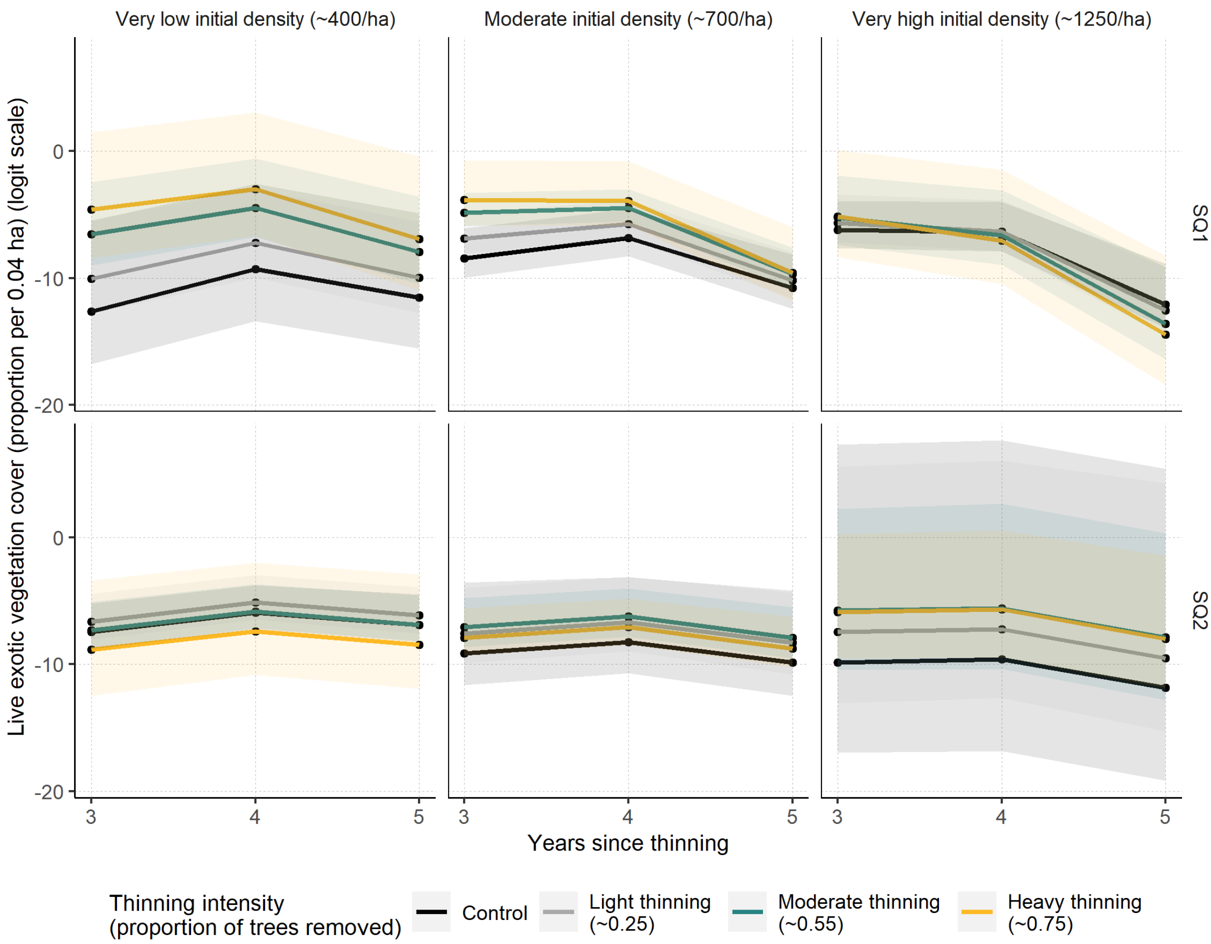

Figure 117 Modelled values and 95% confidence intervals for exotic plant cover

Results are presented on the modelled (logit) scale.

Table 88 Statistical significance of explanatory variables on exotic plant cover

	Bootstrapped likelihood ratio test significance	Description
Site Quality	0.01	Exotic plant cover differed by Site Quality
Initial tree density	0.01	Exotic plant cover varied with initial tree density
Time since thinning	0.01	Exotic plant cover changed over time
Thinning intensity	0.01	Exotic plant cover changed with thinning intensity
Does the effect of thinning intensity vary depending on:		
• Site Quality	0.02	The effect of thinning intensity on exotic plant cover varied with Site Quality
• Initial tree density	0.31	The effect of thinning intensity on exotic plant cover did not depend on initial tree density
• Time since thinning	0.01	The effect of thinning intensity on exotic plant cover changed over time
• Site Quality **and** initial tree density **and** time since thinning	NA	

Table 89 Estimates of effect sizes for exotic plant cover (%) 3 years post-thinning, showing difference between fitted values and 95% confidence intervals in thinned plots relative to control plots

Effect sizes are on the percentage scale.

Site Quality		Site Quality 1			Site Quality 2		
Thinning intensity		Low intensity	Mod intensity	High intensity	Low intensity	Mod intensity	High intensity
Initial tree density	Very low (400/ha)	0.0 0.0 to +0.4	+0.1 +0.01 to +7.8	+1.0 +0.02 to +81.4	+0.1 0.0 to +1.1	0.0 0.0 to +0.6	0.0 –0.1 to +3.2
	Moderate (700/ha)	+0.1 +0.01 to +0.7	+0.8 +0.2 to +3.5	+2.1 +0.3 to +32.6	0.0 0.0 to +1.8	+0.1 +0.01 to +0.8	0.0 0.0 to +0.4
	Very high (1250/ha)	+0.1 –0.1 to +3.0	+0.3 –0.1 to +12.0	+0.4 –0.2 to +51.8	+0.1 0.0 to +99.6	+0.3 0.0 to +90.4	+0.3 0.0 to +56.2

Table 90 Estimates of effect sizes for exotic plant cover (%) 5 years post-thinning, showing difference between fitted values and 95% confidence intervals in thinned plots relative to control plots

Effect sizes are on the percentage scale.

Site Quality		Site Quality 1			Site Quality 2		
Thinning intensity		Low intensity	Mod intensity	High intensity	Low intensity	Mod intensity	High intensity
Initial tree density	Very low (400/ha)	0.0 0.0 to +0.4	0.0 0.0 to +2.6	+0.1 0.0 to +39.4	+0.1 –0.1 to +1.8	0.0 –0.1 to +0.9	–0.1 –0.1 to +4.9
	Moderate (700/ha)	0.0 0.0 to 0.0	0.0 0.0 to +0.1	0.0 0.0 to +0.3	0.0 0.0 to +1.3	0.0 0.0 to +0.4	0.0 0.0 to +0.2
	Very high (1250/ha)	0.0 0.0 to 0.0	0.0 0.0 to 0.0	0.0 0.0 to 0.0	0.0 0.0 to +98.6	0.0 0.0 to +57.5	0.0 0.0 to +18.8

Hypothesis evaluation

There was evidence to support the hypothesis that ecological thinning increased exotic vegetation cover. The magnitude of this effect likely depended on rainfall and flooding, as differences from controls changed with Site Quality and over time.

18.4 Native plant diversity

Hypothesis	3b. Ecological thinning will increase diversity of native plant species
Key result	Ecological thinning **increased** native plant Hill-Shannon diversity in some plot types by a maximum of the equivalent of 4.4 equally abundant species (per 0.04-hectare subplot). However, the significant differences from controls changed over time and by plot type. In addition, thinning **decreased** native plant diversity in wetter Site Quality 1 plots with very high initial density by the equivalent of one species for 3 years.

Data collection

Floristic composition was surveyed in three 0.04-hectare subplots on each 9-hectare plot (see 20 x 20 metre subplots in Figure 5). Floristic subplots were placed in the 9-hectare plots to sample the range of variation in understorey vegetation. Surveys involved recording all native and exotic plant species present. A total of 198 subplots were surveyed annually, excluding the most recent survey year (2021–22, 5 years post-thinning) where 29 subplots were not surveyed due to flood conditions.

Within each 0.04-hectare subplot, 10 quadrats (1 x 1 metre) were placed along the western boundary. In each quadrat, the presence of all native plant species was recorded.

Hill-Shannon diversity is an index that combines information about both the number of plant species (richness) and the abundance of each species (that is, how many of the 1 metre x 1 metre quadrats each species was present in). We calculated Hill-Shannon diversity for each subplot. This index places equal importance on common and rare species (Roswell et al. 2021). The index has a value of zero when only one species is present, and higher values represent higher numbers of species with greater abundance. A Hill-Shannon value of 2 is equivalent to 2 equally abundant native plant species; a Hill-Shannon value of 15 is equivalent to 15 equally abundant native plant species.

Data summary

Hill-Shannon values for native plant diversity commonly ranged from 2 to 15 equally abundant species. Across all surveys, there were 2 occasions where a Hill-Shannon value of 1 was recorded. Values tended to be higher in more recent years.

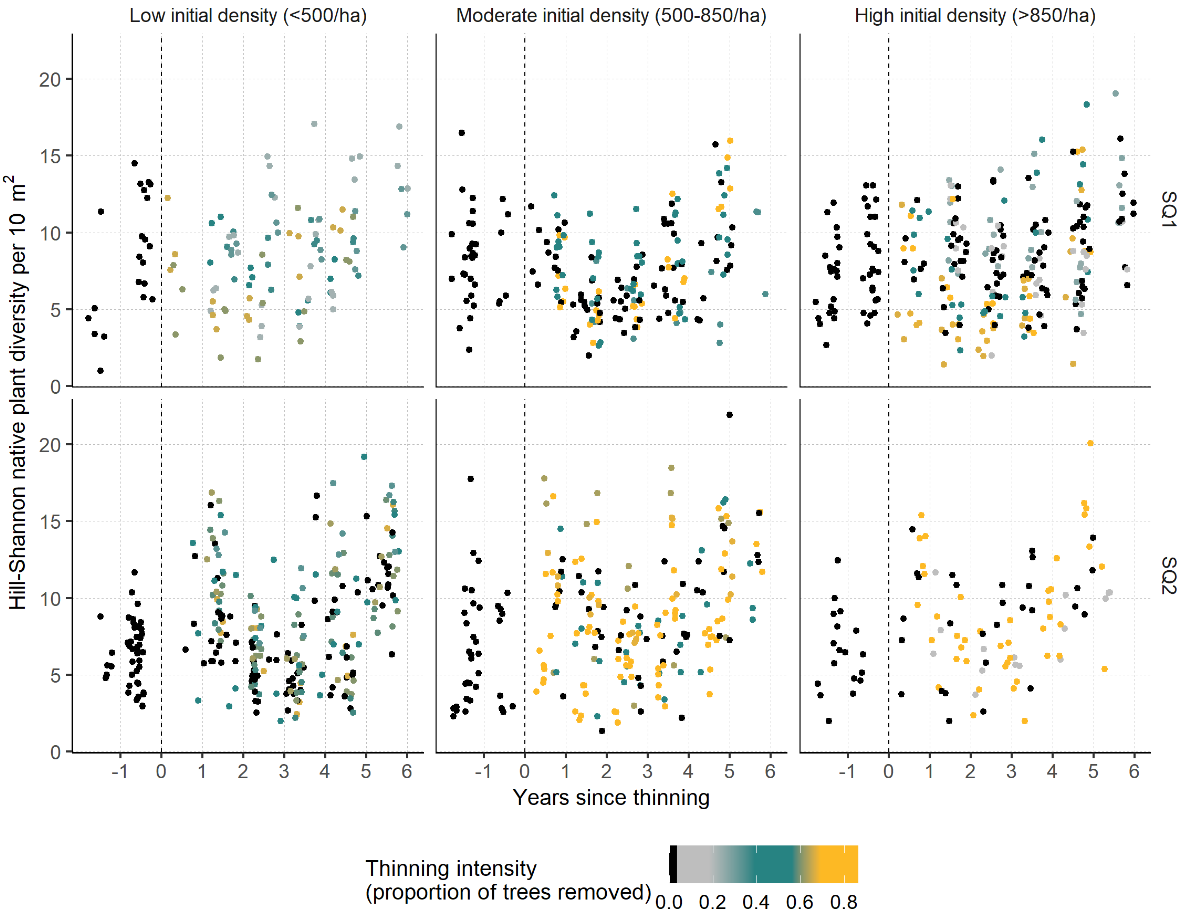

Figure 118 Data summary for native plant Hill-Shannon diversity (per 10 m² sampling quadrat within each 0.04-hectare subplot)

Model results

Native plant diversity was modelled as a continuous positive variable using a Gaussian distribution (see Appendices). All explanatory variables were included, with all combinations of initial tree density, thinning intensity, and Site Quality. Random effects for year of survey, 9-hectare plot and 0.04-hectare subplot were included, but the random effect of site was removed.

Native plant diversity differed significantly with Site Quality, with marginally higher Hill-Shannon values observed in drier sites (SQ2) (Figure 119, Table 91). Native plant diversity also significantly changed over time.

Ecological thinning significantly increased native plant diversity, but the effect was highly variable with significant differences in the effect of thinning among Site Qualities, initial tree densities and over time (Figure 119, Table 91). In wetter (SQ1) plots, native plant diversity initially declined post-thinning. Subsequently, all thinned SQ1 plots increased, but the rate and timing of the increase relative to controls differed depending on initial tree density. Five years post-thinning the maximum increase was equivalent to 4.4 equally abundant plant species relative to controls (Table 92).

In drier (SQ2) plots, ecological thinning caused an increase in native plant diversity which was maintained in very high-density plots; gradually diminished over time in moderate density plots; and decreased to below control values on heavily thinned very low initial density plots.

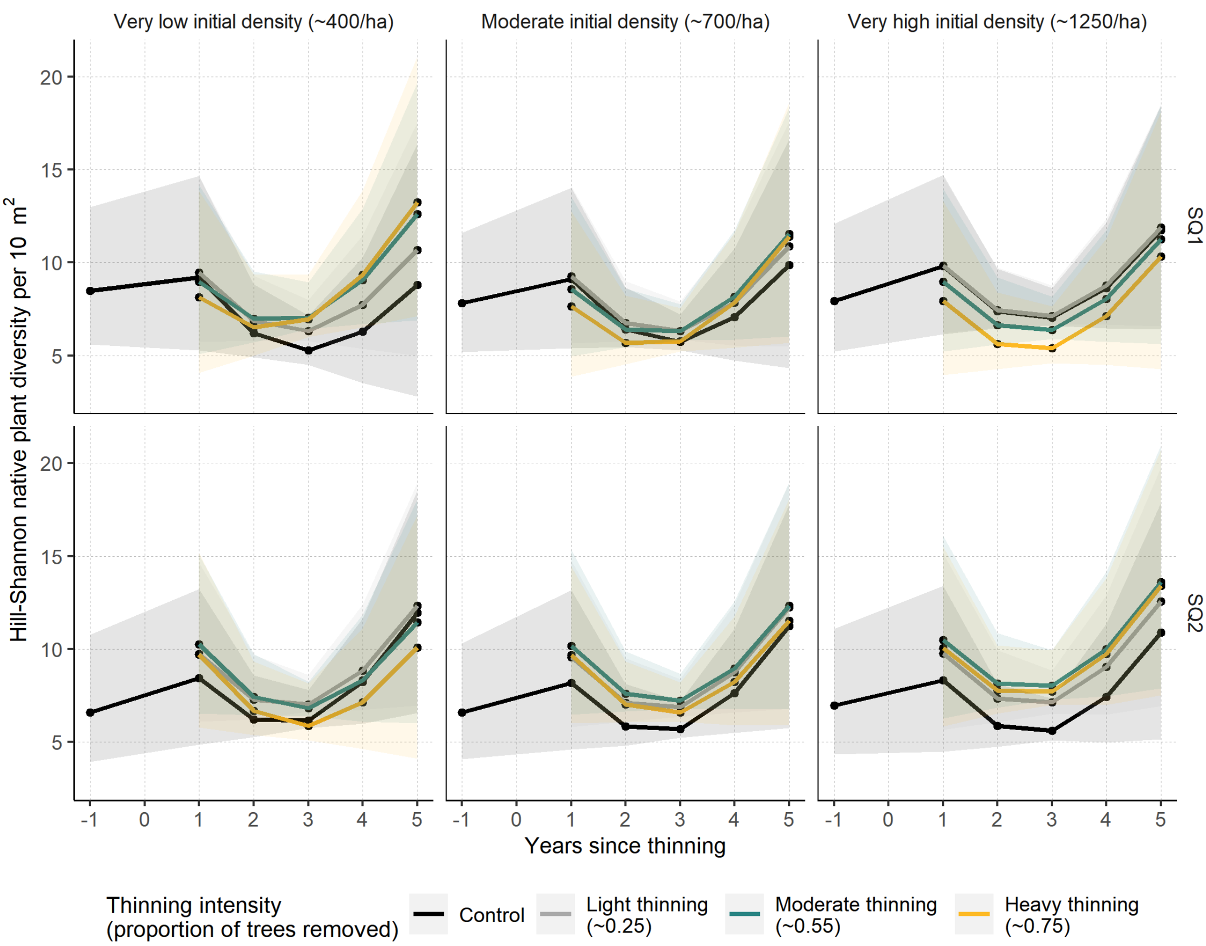

Figure 119 Modelled values and confidence intervals for Hill-Shannon index of native plant diversity

Table 91 Statistical significance of explanatory variables on native plant diversity

	Bootstrapped likelihood ratio test significance	Description
Site Quality	0.01	Significant difference in native plant diversity between Site Qualities
Initial tree density	0.25	Native plant species diversity did not depend on initial tree density
Time since thinning	0.01	Native plant diversity significantly changed over time
Thinning intensity	0.01	Thinning intensity had a significant effect on native plant diversity
Does the effect of thinning intensity vary depending on:		
• Site Quality	0.01	The effect of thinning intensity on native plant diversity differed among Site Qualities
• Initial tree density	0.05	The effect of thinning intensity on native plant diversity was affected by initial tree density
• Time since thinning	0.01	The effect of thinning intensity on native plant diversity changed over time
• Site Quality **and** initial tree density **and** time since thinning	0.02	The effect of thinning significantly differed for all combinations of predictors

Table 92 Estimated effect sizes for native plant diversity 5 years post-thinning, showing difference between fitted values and 95% confidence intervals in thinned plots relative to control plots

Site Quality		Site Quality 1			Site Quality 2		
Thinning intensity		Low intensity	Mod intensity	High intensity	Low intensity	Mod intensity	High intensity
Initial tree density	Very low (400/ha)	+1.9 –3.3 to +8.7	+3.8 –1.5 to +10.9	+4.4 –1.3 to +12.2	+0.4 –4.5 to +7.2	–0.5 –5.6 to +6.1	–1.9 –7.3 to +4.9
	Moderate (700/ha)	+1.0 –3.9 to +8.0	+1.7 –3.4 to +8.7	+1.5 –3.8 to +9.0	+1.0 –4.0 to +7.8	+1.1 –3.9 to +8.0	+0.3 –4.8 to +7.1
	Very high (1250/ha)	+0.2 –4.8 to +7.0	–0.5 –5.6 to +6.7	–1.4 –7.0 to +6.0	+1.7 –3.5 to +8.7	+2.7 –2.6 to +9.9	+2.5 –2.8 to +9.5

Hypothesis evaluation

Native plant diversity was spatially and temporally variable, as was the effect of ecological thinning on this variable. There was some support for the hypothesis that ecological thinning would increase native plant diversity, however there was also evidence that native plant diversity declined with ecological thinning in some circumstances. The effect of thinning was primarily to affect the rate of change of native plant diversity; the magnitudes of change were not significantly different to controls.

18.5 Native plant species richness

Hypothesis	3a. Ecological thinning will increase diversity of native plant species. Native plant species richness is relevant to understanding whether changes in native plant diversity are due to changes in the number of species or the cover of native plants.
Key result	There was a significant effect of ecological thinning on native plant species richness, however there was uncertainty about the nature and magnitude of the effect due to high levels of year-to-year variation related to climate and flooding. - In drier Site Quality 2 plots an initial **increase** relative to controls of approximately 3 species (per 0.04-hectare subplot) diminished over time - In wetter Site Quality 1 plots with very low initial density, the difference from controls increased over time to 6 species (per 0.04-hectare subplot) 5 years post-thinning.

Data collection

Floristic composition was surveyed annually in three 0.04-hectare subplots on each 9-hectare plot (see the 20 x 20 metre subplots in Figure 5). In the most recent survey year (2021–22, 5 years post-thinning) 29 subplots were not surveyed due to flood conditions. Floristic subplots were placed in the 9-hectare plots to sample the range of variation in understorey vegetation.

Native species richness is the total count of native species present in each 0.04-hectare subplot. Richness calculations include species that were identified to genus level, but do not include species that were identified to family level. A full species list is in the Appendices.

Data summary

Native species richness was generally between 10 and 30 species per 0.04-hectare subplot. Average native species richness was higher in the most recent survey year than previous years, for both Site Qualities (Table 93, Figure 120). Average species richness was slightly higher in drier (SQ2) sites in most survey years, and values above 30 species almost all occurred on Site Quality 2.

The minimum native species richness value recorded was 4 species and the maximum was 38.

Table 93 Average number of native plant species recorded per 0.04-hectare subplot, by Site Quality and survey year

Survey year	Site Quality 1	Site Quality 2
2015	17.6	15.5
2017	18.3	20.4
2018	16.0	16.9
2019	16.0	16.0
2020	18.7	21.3
2021	23.8	25.6

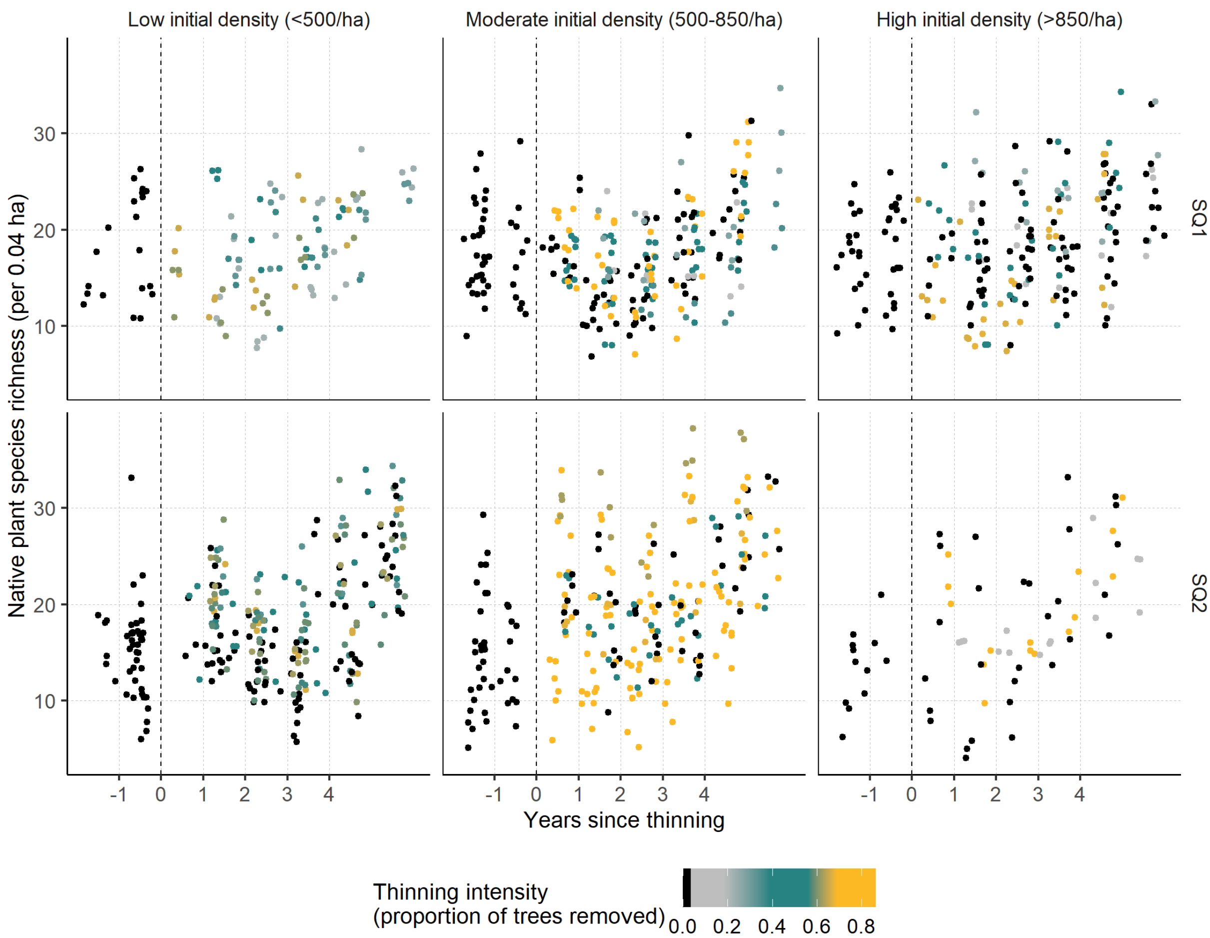

Figure 120 Data summary for native plant species richness

Model results

Native plant species richness per 0.04-hectare subplot was modelled as a continuous positive variable using a Gaussian distribution, which had a superior fit to other distributions often used for count variables (see Appendices). All combinations of interactions between explanatory variables were included in this model. Random effects of survey year, 9-hectare plot and 0.04-hectare subplot were included.

The effect of ecological thinning on native species richness was statistically significant, and the effect differed among Site Qualities and changed over time (Table 94). However, there were no instances where the confidence intervals for thinned plots did not include the fitted values for the control plots (Figure 41), therefore there is uncertainty about the nature and magnitude of the effect of thinning on native plant species richness. This uncertainty is likely due the fact that year-to-year variation caused by flooding and rainfall had a greater magnitude of effect on native plant species richness than ecological thinning.

The most likely effect of thinning was to cause an initial increase in plant species richness in drier (SQ2) plots, which declined over time. In wetter (SQ1) plots, thinning may have caused native plant species richness to initially decrease, but then increased over time relative to the controls.

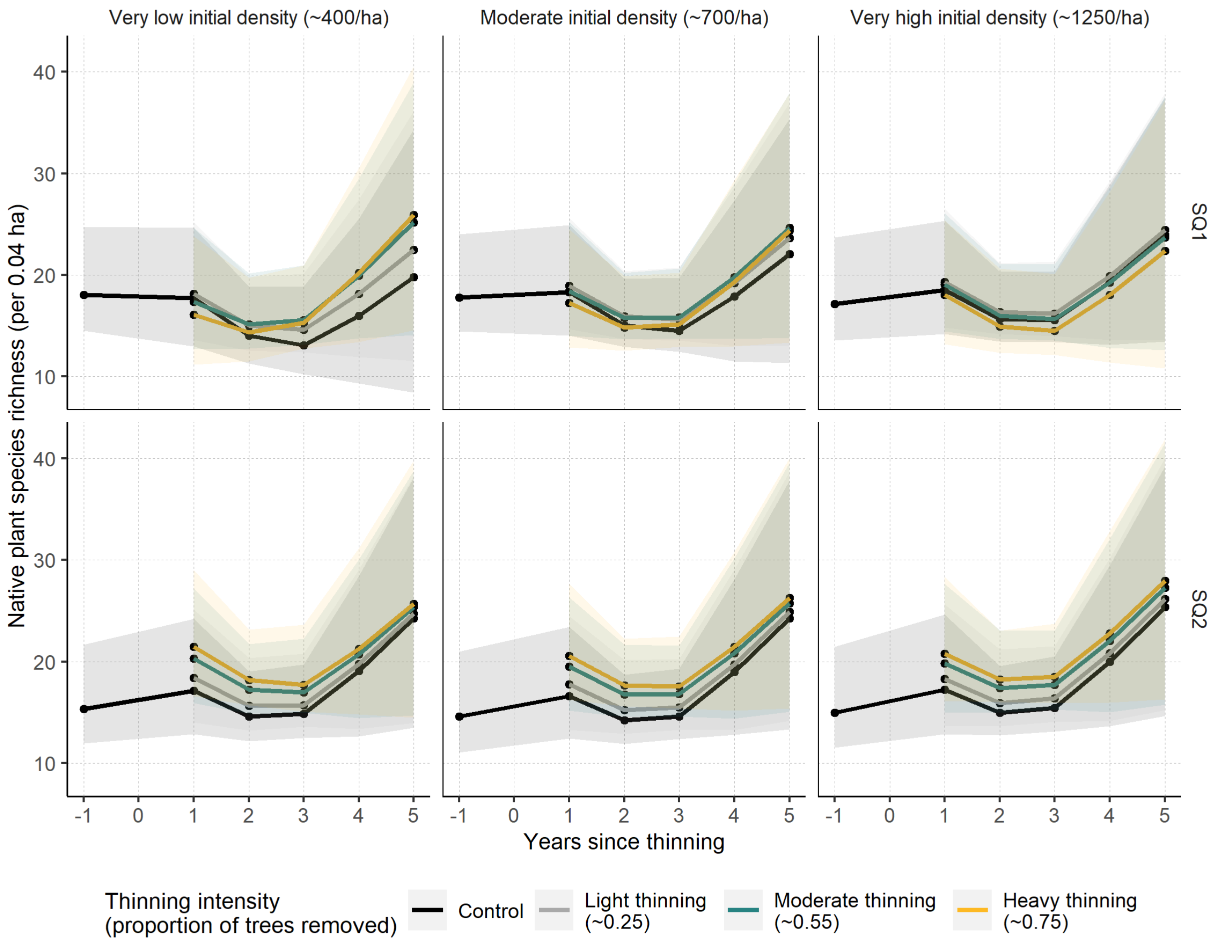

Figure 121 Modelled values and 95% confidence intervals for native plant species richness

Table 94 Statistical significance of explanatory variables on native plant species richness

	Bootstrapped likelihood ratio test significance	Description
Site Quality	0.01	Native plant species richness differed by Site Quality
Initial tree density	0.55	Native plant species richness did not depend on initial tree density
Time since thinning	0.02	Native plant species richness changed over time
Thinning intensity	0.01	Thinning intensity affected native plant species richness
Does the effect of thinning intensity vary depending on:		
• Site Quality	0.03	The effect of thinning intensity on native species richness differed among Site Qualities
• Initial tree density	0.44	The effect of thinning intensity on native species richness was not affected by initial tree density
• Time since thinning	0.04	The effect of thinning intensity on native species richness changed over time
• Site Quality **and** initial tree density **and** time since thinning	0.11	The effect of thinning did not differ for all combinations of predictors

Table 95 Estimated effect sizes for native plant species richness 5 years post-thinning, showing difference between fitted values and 95% confidence intervals in thinned plots relative to control plots

Site Quality		Site Quality 1			Site Quality 2		
Thinning intensity		Low intensity	Mod intensity	High intensity	Low intensity	Mod intensity	High intensity
Initial tree density	Very low (400/ha)	+2.7 –8.2 to +16.3	+5.4 –5.7 to +19.2	+6.1 –5.2 to +20.7	+0.4 –10.3 to +14.0	+1.1 –9.6 to +14.5	+1.4 –9.8 to +15.5
	Moderate (700/ha)	+1.6 –9.0 to +14.9	+2.6 –8.2 to +15.9	+2.3 –8.7 to +15.9	+0.6 –10.1 to +14.4	+1.5 –9.2 to +15.3	+2 –8.9 to +15.8
	Very high (1250/ha)	+0.5 –10.3 to +13.9	–0.3 –11.4 to +13.7	–1.6 –13.1 to +13.2	+0.8 –10.1 to +14.6	+1.9 –9.6 to +16.2	+2.6 –9.1 to +16.5

Hypothesis evaluation

There was some evidence to support the hypothesis that ecological thinning would increase native plant diversity through increasing native plant species richness. However, there was uncertainty about the effect of thinning due to variation in native plant species richness associated with rainfall and flooding.

18.6 Native plant cover

Hypothesis	3b. Ecological thinning will increase diversity of native plant species Exotic plant species vegetation cover is relevant to understanding whether diversity changes are due to changes in the number of individuals or number of species present.
Key result	Ecological thinning initially **decreased** native plant cover in wetter Site Quality 1 plots. Between the 2 most recent survey periods thinning **increased** cover on all plot types, with a maximum of 13–17% higher cover (per 0.04-hectare subplot) than control plots.

Data collection

In the 2019–20, 2020–21 and 2021–22 survey seasons, total live native vegetation cover of the ground stratum (to 2 metres in height) was visually estimated as a percentage of each 0.04-hectare subplot (see 20 x 20 metre subplots in Figure 5). In 2021–22, 15% of 0.04-hectare subplots were not able to be surveyed due to flooding. Live native vegetation cover had not been estimated in previous years. In each plot, 2 observers independently estimated the area occupied by live exotic vegetation. They then conferred to agree on an area estimate and converted it to a percentage.

Data summary

Across all the 0.04-hectare subplots, native plant cover was on average 4.8%, and was generally less than 40%, with a maximum value of 75%. Native plant cover was, on average, greater in Site Quality 1 (6.0%) than Site Quality 2 (3.6%) subplots and seemed to increase over time (Figure 122). There was no obvious effect of thinning on the percentage of native plant cover (Figure 122).

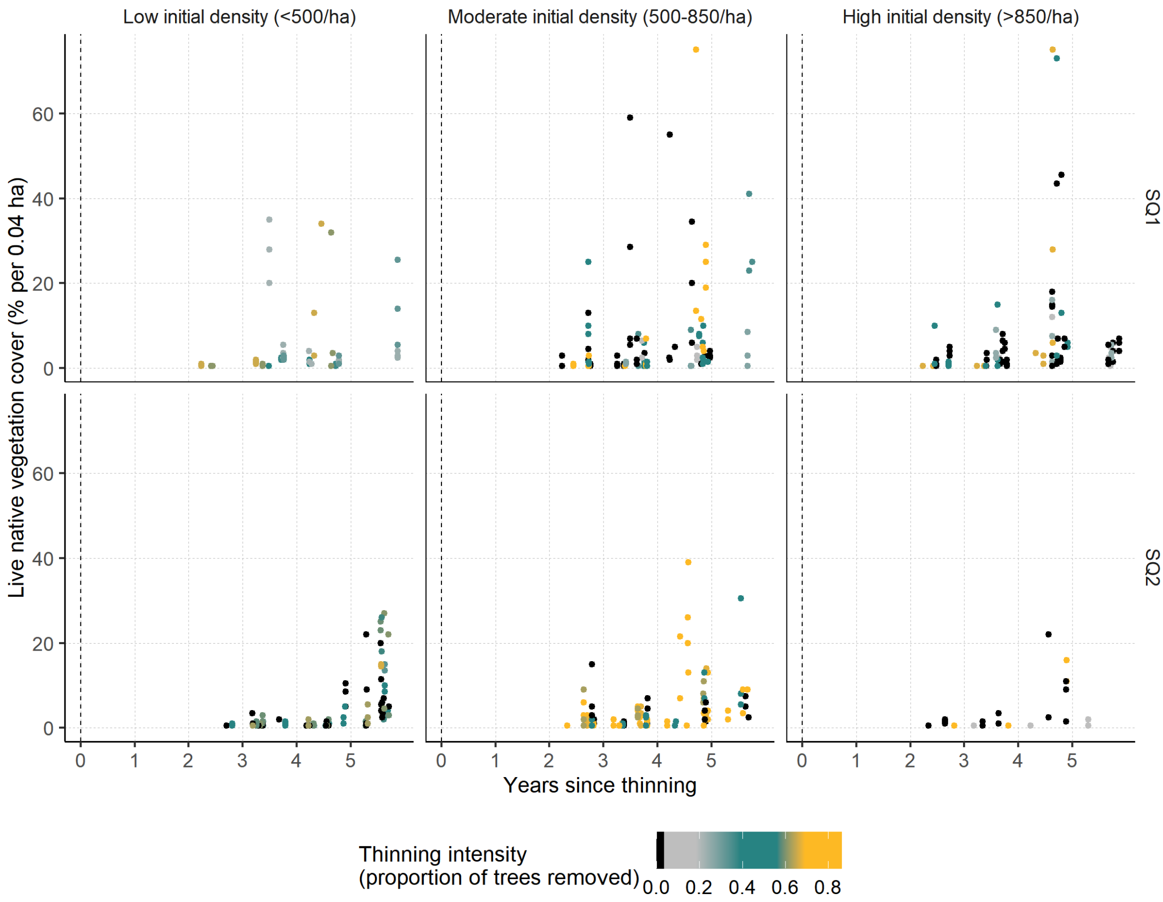

Figure 122 Data for native plant cover (%) per 0.04-hectare subplot

Model results

Native plant cover was analysed as the proportion of the subplot that was native plant cover using a binomial distribution (see Appendices). This type of variable (continuous percentage of native cover) would generally be analysed using a beta distribution, however residuals tests indicated this distribution was not appropriate. The model for native plant cover included a four-way interaction between Site Quality, initial tree density, time since thinning and thinning intensity, as well as all two-way and three-way interactions. Time was included in this model as a fixed factor of survey year. Years elapsed was not included, and year was not included as a random factor. Random effects of 9-hectare plot and subplot were included.

Modelled values of native cover were generally quite low, less than 25% (Figure 123). Native plant cover was significantly different between Site Qualities, though this effect depended on thinning intensity (Table 96). Native plant cover also varied by initial tree density and time since thinning (Table 96).

Native plant cover was similar in all thinning intensities, initial tree densities, and Site Quality in the third and fourth year since thinning (Figure 123). An exception was subplots with very low initial tree density in Site Quality 1, where control and light thinning intensity subplots had greater native plant cover than moderate and heavy thinning subplots (Figure 123). In the fifth year since thinning, native plant cover increased in all thinning intensities in both Site Qualities, however this effect was most pronounced in Site Quality 1 subplots that had moderate and very high initial tree densities (Figure 123). In these treatments, subplots that were heavily thinned had significantly greater native plant cover (13–17%) than control plots (Figure 123, Table 97).

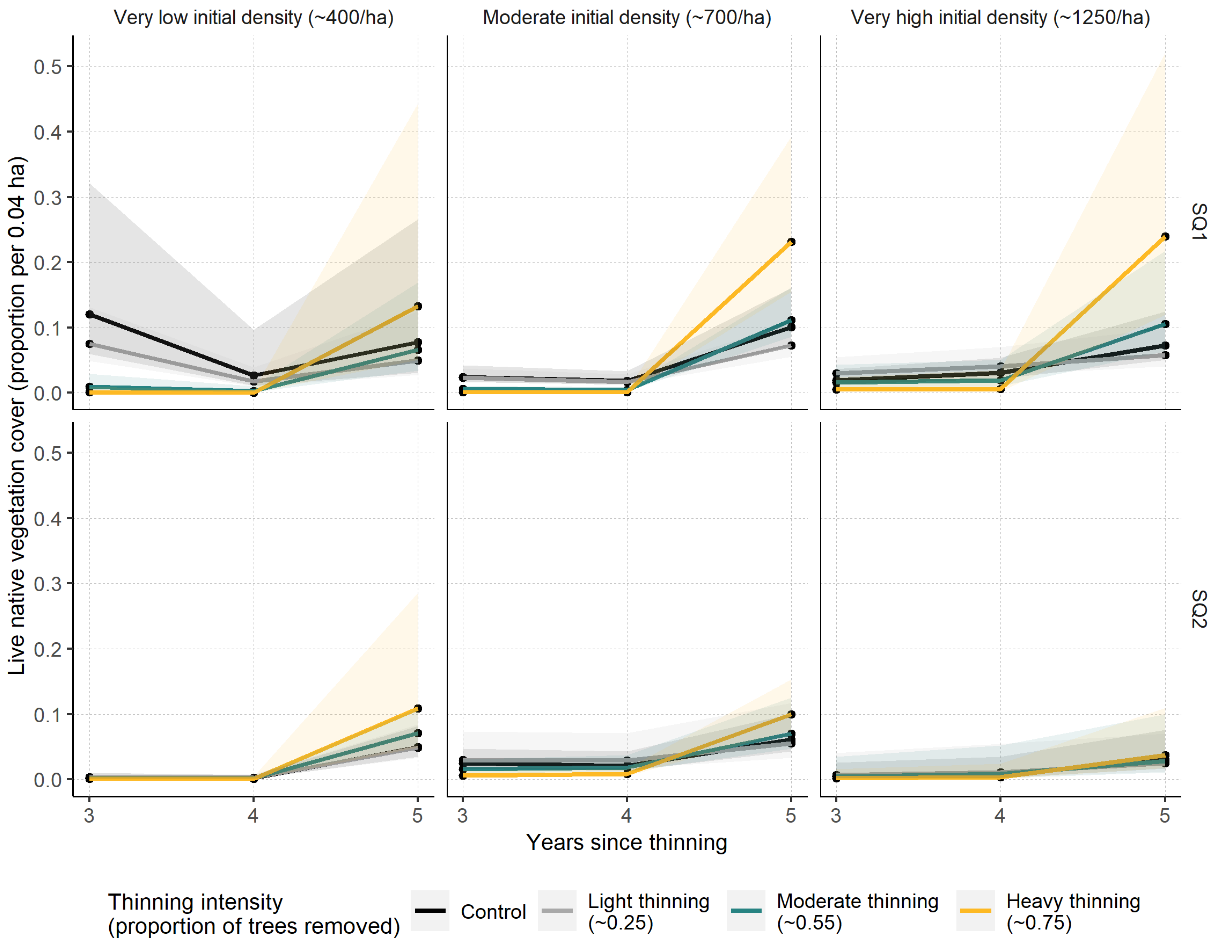

Figure 123 Modelled values and 95% confidence intervals for native plant cover

Table 96 Statistical significance of explanatory variables on native plant cover

	Bootstrapped likelihood ratio test significance	Description
Site Quality	0.01	Native plant cover differed by Site Quality
Initial tree density	0.01	Native plant cover varied with initial tree density
Time since thinning	0.01	Native plant cover changed over time
Thinning intensity	0.01	Native plant cover changed with thinning intensity
Does the effect of thinning intensity vary depending on:		
• Site Quality	0.01	The effect of thinning intensity on native plant cover varied with Site Quality
• Initial tree density	0.33	The effect of thinning intensity on native plant cover did not depend on initial tree density

	Bootstrapped likelihood ratio test significance	Description
• Time since thinning	0.17	The effect of thinning intensity on native plant cover did not change over time
• Site Quality **and** initial tree density **and** time since thinning	0.75	The effect of ecological thinning on native plant cover did not vary for all combinations of Site Quality, initial tree density and time

Table 97 Estimates of effect sizes for native plant cover (%) 5 years post-thinning, showing difference between fitted values and 95% confidence intervals in thinned plots relative to control plots

Site Quality		Site Quality 1			Site Quality 2		
Thinning intensity		Low intensity	Mod intensity	High intensity	Low intensity	Mod intensity	High intensity
Initial tree density	Very low (400/ha)	−3.0 −5.3 to +4.4	−1.0 −4.6 to +8.9	+5.0 −3.0 to +36.3	0.0 −1.7 to +3.4	+2.0 +0.2 to +5.9	+6.0 −0.2 to +23.6%
	Moderate (700/ha)	−3.0 −4.5 to +0.7	+1.0 −1.4 to +6.2	+13.0 +5.5 to +29.3	0.0 −2.7 to +5.7	+1.0 −1.3 to +6.5	+4.0 +1.5 to +9.3
	Very high (1250/ha)	−1.0 −2.9 to +2.8	+4.0 −0.6 to +14.8	+17.0 +5.0 to +45.1	0.0 −1.8 to +4.0	0.0 −1.9 to +7.0	+1.0 −1.2 to +8.0

Hypothesis evaluation

In wetter (SQ1) plots 3- and 4- years post-thinning, the evidence did not support the hypothesis that ecological thinning would increase diversity of native plant species by increasing native plant cover. However, there was evidence that ecological thinning did increase native plant diversity by increasing native plant cover in the most recent survey year. It is likely that these effects depended on rainfall and flooding.

1.6 Threatened plant species

Hypothesis	The ecological thinning trial was designed to minimise impacts on threatened species and no hypothesis was specified.
Key result	Insufficient data were collected for statistical analyses, but raw data suggest it was unlikely that ecological thinning had a negative effect on floating swamp wallaby grass.

Data collection

The plant species floating swamp wallaby grass (*Amphibromus fluitans*) occurs across the study site and is listed as vulnerable in the NSW *Biodiversity Conservation Act 2016* and Commonwealth *Environment Protection and Biodiversity Conservation Act 1999*. The habitat for *A. fluitans* is almost exclusively aquatic with occurrence tending to be temporary and associated with standing floodwaters.

Data were collected annually in three 0.04-hectare subplots per 9-hectare plot.

Data summary

Observations of the species were restricted to Site Quality 1 sites that were more frequently flooded, being present in control (5 plots), light (5 plots) and moderately thinned plots (3 plots) across all survey years. The species was not recorded in any plots that were heavily thinned.

Five years post-thinning, the species was present in only one moderately thinned plot. However, many wetter sites (SQ1), in which *A. fluitans* was most likely to occur, could not be surveyed due to flooding conditions.

Hypothesis evaluation

The ecological thinning trial was designed to minimise impacts on threatened species and no hypothesis was specified. Data were too sparse to draw conclusions.

19. References

Baur G 1984, *Notes on the silviculture of major NSW forest types, No. 5, River red gum types*, Forestry Commission of NSW, Sydney.

Bren LJ 1988, Effects of river regulation on flooding of a riparian river red gum forest on the River Murray, Australia*. Regulated Rivers: Research and Management* 2: 65–77.

Gorrod EJ, Childs P, Keith DA, Bowen S, Pennay M, O'Kelly T, Woodward R, Haywood A, Pigott JP and McCormack C 2017, Can ecological thinning deliver conservation outcomes in high-density river red gum forests? Establishing an adaptive management experiment, *Pacific Conservation Biology*, vol.23, no.3, pp.262–276.

Gorrod E, Travers S, Ellis M, Hope B, McAllister D, Val J, O'Kelly T and Curtis E 2020, *River red gum ecological thinning trial: Monitoring report 2020*, NSW National Parks and Wildlife Service, Hurstville, available at https://www.environment.nsw.gov.au/research-and-publications/publications-search/river-red-gum-ecological-thinning-trial-monitoring-report-2020.

Gorrod E, Travers S, Ellis M, Hope B, McAllister D, Val J and O'Kelly T 2021, *River red gum ecological thinning trial: Monitoring report 2021*, NSW National Parks and Wildlife Service, Hurstville, available at https://www.environment.nsw.gov.au/research-and-publications/publications-search/river-red-gum-ecological-thinning-trial-monitoring-report-2021.

Hines F, Tolhurst KG, Wilson AAG and McCarthy GJ 2010, *Overall fuel hazard assessment guide: Fire and adaptive management*, Report no. 82, 4th edition, July 2010, Victorian Department of Sustainability and Environment, Melbourne.

Murray–Darling Basin Authority, *River Murray data*, accessed 15 June 2022, riverdata.mdba.gov.au/edward-river-offtake.

OEH 2012, *Ecological thinning trial in New South Wales and Victorian River Red Gum forests: Experimental design and monitoring plan*, NSW Office of Environment and Heritage, Sydney, available at www.environment.nsw.gov.au/-/media/OEH/Corporate-Site/Documents/Parks-reserves-and-protected-areas/River-red-gums/ecological-thinning-trial-river-red-gum-forests-public-environment-report-appendices.pdf.

OEH 2014, *Public Environment Report: Ecological thinning trial in New South Wales River Red Gum Forests*, NSW Office of Environment and Heritage, Sydney, available at www.environment.nsw.gov.au/-/media/OEH/Corporate-Site/Documents/Parks-reserves-and-protected-areas/River-red-gums/ecological-thinning-trial-river-red-gum-forests-public-environment-report-140621.pdf.

OEH 2017, *River red gum pre-ecological thinning monitoring report 2017*, NSW Office of Environment and Heritage, Sydney, available at www.environment.nsw.gov.au/research-and-publications/publications-search/river-red-gum-pre-ecological-thinning-monitoring-report-2017.

OEH 2018, *River red gum ecological thinning trial monitoring report 2018*, NSW Office of Environment and Heritage, Sydney, available at www.environment.nsw.gov.au/research-and-publications/publications-search/river-red-gum-ecological-thinning-trial-monitoring-report-2018.

OEH 2019, *River red gum ecological thinning trial monitoring report 2019*, NSW Office of Environment and Heritage, Sydney, available at www.environment.nsw.gov.au/research-and-publications/publications-search/river-red-gum-ecological-thinning-trial-monitoring-report-2019.

R Core Team 2022 *R: A language and environment for statistical computing*, R Foundation for Statistical Computing, Vienna, Austria.

Roswell M, Dushoff J, Winfree R 2021, A conceptual guide to measuring species diversity. Oikos, vol.130, no.3, pp.321–338.

Scarth P, Armston J and Danaher T 2008, ‘On the relationship between crown cover, foliage projective cover and leaf area index’, in R Bartolo and A Edwards (eds), *Proceedings of the 14th Australasian Remote Sensing and Photogrammetry Conference*, *29 September to 3 October 2008*, *Darwin NT,* Spatial Sciences Institute, Australia.

Schonau APG and Coetzee J 1989, Initial spacing, stand density and thinning in eucalypt plantations, *Forest Ecology and Management*, vol.29, pp.245–266.