

# IMPACT OF SILVICULTURAL PRACTICES ON THE GROWTH OF *EUCALYPTUS* PLANTATIONS: A META-ANALYSIS

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*Eucalyptus* plantations play a crucial role in meeting global timber demand, yet the effects of management practices on their growth remain poorly understood. This meta-analysis assesses the impact of eight silvicultural practices on crucial growth indicators in *Eucalyptus* plantations based on 856 cases. The results show that fertilisation, weeding, land preparation, and irrigation generally boost eucalyptus growth, with mixed planting and intercropping providing moderate benefits. These practices impact diameter growth more than height. Ripping at 0.8 m increased growth by 452.9%, while 0.3 m had no effect. *Eucalyptus*-specific fertilizer at 1 kg tree<sup>-1</sup> increases growth by 4.0%. However, thinning reduces stand volume by 36.2% while enhancing individual growth. Management has a greater impact on seedling-regenerated and younger stands than on coppice-regenerated or mature ones. In plantation forests, growth was 32.3%, far higher than the 6.2% in first-generation coppice forests and 2.0% in second-generation ones. As forests age, the effects of weeding and irrigation diminish, and burning turns negative, while mixed planting and fertilisation continue to promote growth, showing a decreasing trend. This study emphasizes the importance of adaptive management strategies tailored to specific forest conditions to maximize growth and ensure sustainable plantation management.

Keywords: *Eucalyptus* plantations, silvicultural practices, meta-analysis, forest management, growth indicator

## INTRODUCTION

With the global demand for timber rising, the over-exploitation of natural forests has led to severe ecological crises (Shono & Jonsson 2022). Plantation forests provide a sustainable solution by reducing the pressure on natural forests while ensuring a steady timber supply. *Eucalyptus*, predominantly found in Australia and nearby regions, has become the species of choice for plantation forests in many countries due to its fast growth, high adaptability, and economic value (Bayle 2019). *Eucalyptus* plantations are economically viable and offer environmental benefits such as soil improvement and carbon sequestration (Zhang et al. 2018). As a result, the global area of *Eucalyptus* plantations now exceeds 25 million hectares, concentrated in countries like Australia, Brazil, and China (Lan et al. 2007, Eyles et al. 2009, Florêncio et al. 2022).

In managing *Eucalyptus* plantations, various silvicultural practices are applied throughout the growth cycle, starting with pre-planting operations such as controlled burning and land

preparation (Bird et al. 2000, Águas 2019), followed by planting strategies like mixed-species plantations and intercropping (Wu 2017, De Oliveira 2020). Post-planting practices such as fertilisation, weeding, irrigation, and thinning are critical for maintaining growth and optimizing timber yields (Little 2003, Stape et al. 2010, Do et al. 2017, Resquin et al. 2024). While these practices are essential for enhancing yield, their specific effects on growth indicators—including tree height, diameter, volume per tree, and stand volume—remain unclear and, at times, controversial. For example, thinning, which reduces tree density, minimizes competition for light and nutrients, thereby promoting diameter growth in the remaining trees (Del Campo et al. 2022). However, its impact on height growth tends to be limited, as the increased light primarily encourages lateral rather than vertical growth (Kim et al. 2016). The overall growth benefits of thinning depend mainly on its intensity. Generally, moderate thinning can stimulate

growth, and excessive thinning may inhibit production by making trees more susceptible to wind damage and pest infestations (Gadgil & Bain 1999). At the stand level, the effects of thinning on overall growth remain debated. Some studies suggest that thinning does not significantly affect stand volume, as retained carbon and nutrients in the litter and soil compensate for the reduced density (Erkan et al. 2023). Conversely, other studies report that thinning can decrease stand volume (Wang et al. 2022, Resquin et al. 2024). Similarly, the effects of controlled burning are subject to ongoing debate. Some research shows that it leads to significant losses of organic matter and nutrients, which can deplete soil resources in the long term (Bai et al. 2020). Other studies, however, suggest that burning can enhance nutrient availability and stimulate growth (Chungu et al. 2020). The impact of mixed-species planting on growth largely depends on species selection. While some combinations can improve growth, inappropriate pairings may hinder tree development (Debell et al. 1997, Lei 2017). Fertilisation is considered one of the critical technologies for managing *Eucalyptus* plantations (Stape et al. 2010), and many studies have demonstrated its positive effects on growth (Do et al. 2017, Eyles et al. 2009, Liang 2023, Stape 2002, Smethurst et al. 2004). However, while some research has explored the effects of different fertilisation types (Tan 2014, Cen et al. 2023), there still needs to be more in-depth analyses on the subject. For example, excessive fertilisation can lead to soil salinization, which ultimately inhibits growth. Therefore, determining the appropriate fertilisation amount is also essential. Overall, there is a notable absence of systematic comparisons of how different silvicultural practices—including controlled burning, land preparation, mixed-species planting, intercropping, fertilisation, weeding, irrigation, and thinning—affect *Eucalyptus* plantations.

Moreover, the effectiveness of these silvicultural practices can vary significantly depending on stand age and the regeneration method employed (e.g., seedling regeneration versus coppice regeneration). Research suggests that younger stands typically exhibit higher nutrient absorption rates, particularly for nitrogen and phosphorus (Song et al. 2022). As they mature, they develop more extensive root systems and adopt more efficient resource-

use strategies, which may reduce their reliance on external fertilisation (Zhang et al. 2024). Additionally, the response to fertilisation can differ based on the regeneration method. Seedling regeneration, which relies more heavily on external nutrient sources, tends to show more significant benefits from fertilisation. In contrast, coppice regeneration, which utilizes stored carbohydrates and established root systems, may exhibit a more muted response to fertilisation (Han et al. 2021, Sloan & Jacobs 2013). However, for coppiced trees and mature *Eucalyptus* plantations with well-developed root systems, it remains unclear whether other silvicultural practices—such as controlled burning, land preparation, mixed-species planting, intercropping, weeding, irrigation, and thinning—exhibit similar patterns of diminishing returns as fertilisation. This area requires further systematic study.

Given the conflicting results and the need for a unified understanding of how different silvicultural practices affect eucalyptus growth, this study aims to address this knowledge gap. Specifically, we seek to quantify the impact of management practices on various growth indicators—such as diameter, height, volume per tree, and stand volume—while considering factors like stand age, regeneration methods, land preparation methods, mixed-species, thinning intensity, and fertilisation types and amount. Our hypotheses are: (1) Different management practices and their varying approaches and intensities have distinct effects on the growth of various indicators in *Eucalyptus* plantations. (2) Thinning enhances individual tree growth but reduces overall stand productivity. (3) Due to root systems and resource-use efficiency differences, management practices have a more substantial effect on seedling-regenerated or younger stands than coppice-regenerated or mature ones. This meta-analysis aims to comprehensively evaluate these practices' effectiveness, offering insights to optimize *Eucalyptus* plantation management.

## MATERIALS AND METHODS

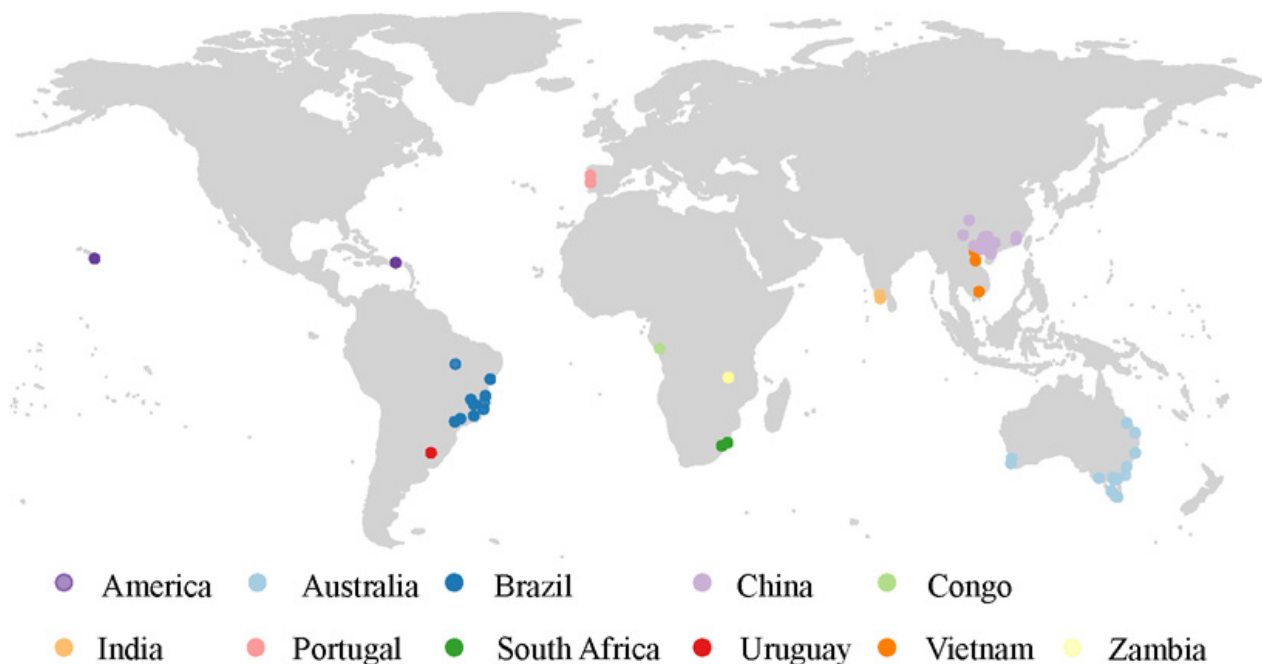
### *Research methodology*

Relevant studies published between 1990 and August 2024 were identified through literature searches in the ISI Web of Science, Google Scholar, and China National Knowledge

Infrastructure. The search used the following terms: (Burning OR Controlled Burning OR Forest land clearing OR Wood-land clearing OR Land preparation OR Site preparation OR Mixed-species plantations OR Mixed forests OR Intercrop\* OR Fertilisation OR Weeding OR Cultivation OR Tending OR Irrigation OR Thinning OR Silviculture) AND ('*Eucalyptus* plantations' OR '*Eucalyptus* artificial forests') AND (Diameter OR Tree height OR Volume per tree OR Stand volume). To be included, studies needed a comparison group without forest management measures, with both groups providing data on mean, standard deviation (or standard error), and sample size. Data extracted included mean, standard deviation (SD) (or standard error, calculated as  $\sqrt{\text{sample size}} \times \text{standard error}$ ), sample size, author, year of publication, regeneration methods, types of forest management, management details (such as mixed tree species, type of fertilizer, amount of fertilizer applied, and thinning intensity, etc.), growth indicators (diameter, tree height, volume per tree, stand volume per hectare), stand age, eucalyptus species, and the country, specific location, and latitude and longitude of study sites.

We unified all diameter measurements to “cm,” tree height to “m,” and the volume per tree and stand volume to “m<sup>3</sup>.”

WebPlotDigitizer was utilized to extract data from graphs presented in several articles. A small subset of the data lacked standard deviations; to address this, we applied the Bracken method, implemented via the *R* package *metagear*, imputing these values using the coefficient of variation derived from all complete cases (Lajeunesse 2016). The proportion of missing values for diameter, tree height, volume per tree, and stand volume per hectare was less than 20% for each variable. A total of 57 studies (see the Appendix: References for Meta-Analysis) were selected, comprising 856 cases, which included 340 cases of individual tree diameters, 338 cases of tree heights, 152 cases of volume per tree, and 26 cases of stand volume per hectare. Figure 1 shows the geographic distribution of the studies. The forest management practices represented include burning (106 cases), land preparation (48 cases), mixed planting (138 cases), intercropping (21 cases), fertilisation (335 cases), weeding (41 cases), irrigation (63 cases), and thinning (104 cases). The stand ages range from 0.1 to 85 years.



**Figure 1** Geographic locations of the 57 studies included in the meta-analysis. Each dot may represent multiple effect sizes

## Data analysis

We calculated the log response ratio (RR, hereafter referred to as response ratios) as a measure of effect size using the *R* package *metafore* (Lajeunesse 2011, Viechtbauer 2010, Benitez-Lopez et al. 2017). The formula used for the calculation is as follows:

$$RR_i = Ln(y_{ti} / y_{ci}) \quad (1)$$

where  $y_{ti}$  and  $y_{ci}$  are the average value of the treatment and control in comparison  $i$ . The within-study sampling variance of  $RR_i$  was computed as (Lajeunesse 2011):

$$v_i = \frac{s_{ti}^2}{n_{ti}y_{ti}^2} + \frac{s_{ci}^2}{n_{ci}y_{ci}^2} \quad (2)$$

where  $s$  is the group SD and  $n$  the sample size

Due to tiered treatments where multiple treatments share a common control, leading to non-independence of effect sizes, we computed the variance-covariance matrix ( $V$ ) based on  $v_i$  using the *blddiag* function (Viechtbauer 2010). We conducted multilevel mixed-effects meta-analyses to account for non-independence in the data arising from multiple effect sizes per study and eucalyptus species (Benitez-Lopez et al. 2017, Rossetti et al. 2017). For diameter, tree height, volume per tree, and stand volume per hectare, we employed random effects models to calculate cumulative effect sizes using the *rma* function (Viechtbauer 2010). Specifically, our model incorporated random effects at both the study and eucalyptus species levels: `rma(RR, V, data=data, method="REM", random = list(~1|Study/ID, ~1|EucalyptusSpecies/ID))`, where *EucalyptusSpecies* represents the species of eucalyptus being studied. The pooled mean on the log scale is the inverse-variance weighted average

$$\mu = \frac{\sum_i w_i RR_i}{\sum_i w_i}, \quad w_i = \frac{1}{V + \sum} \quad (3)$$

where  $V$  is the diagonal matrix of within-study sampling variances, and  $\sum$  is the variance-covariance matrix induced by the random effects, estimated by the model.

Its standard error and 95% confidence interval are

$$SE = \frac{1}{\sum_i w_i}, \quad 95\%CI = \mu \pm 1.96SE \quad (4)$$

To facilitate model selection, we employed the *glmulti* function from the *glmulti* package (Calcagno & De Mazancourt 2010), using the following model specification: `glmulti(RR ~ types_of_forest_management * log_age * Regeneration_method, V = "V", random = random_effect, data = data, level = 1, method = "h", fitfunction = rma.glmulti, crit = "aicc", confsetsize = 32)`. In this model, the random effect is defined as: `list(~1|Study/ID, ~1|EucalyptusSpecies/ID)`, where *types\_of\_forest\_management* represents different forest management categories, *log\_age* refers to the natural logarithm of stand age, and *Regeneration\_method* refers to the regeneration method. Through model selection, the optimal model for diameter includes only stand age, while the best models for tree height and individual tree volume do not incorporate these variables. Stand age is the most critical factor for individual tree volume. For stand volume, the optimal model includes only management type. Furthermore, we examined the effect of stand age on diameter and individual tree volume across different management practices.

For each indicator (diameter, tree height, individual tree volume, and stand volume per hectare) under different management practices (burning, land preparation, mixed planting, intercropping, fertilisation, weeding, irrigation, and thinning), a multivariate meta-analysis model using the *rma.mv* function was applied to estimate effect sizes and their variances (Viechtbauer 2010). Specifically, RR and V were used to fit random-effects models, with "Study/ID" and "EucalyptusSpecies/ID" included as random effects. These models were fitted using the restricted maximum likelihood estimation method. Effect sizes and standard errors for each forest management practice were derived from model coefficients. After obtaining the effect sizes and their standard errors for all treatment types, Tukey's Honest Significant Difference post-hoc test was performed to evaluate the significance of differences between treatments. We also analyzed the effects of different land preparation methods, mixed tree species, and fertilisation types on eucalyptus growth using the same method.

Additionally, using the same methods, we assessed the effect sizes of various management practices under different regeneration methods at the individual tree and stand scales. For fertilisation, we focused on the effect of varying fertilisation amounts per tree using eucalyptus-specific fertilizer. Due to the sufficient sample size (a total of 96) and accurate individual tree fertilisation amounts, this analysis provided insights into the growth of eucalyptus trees. In the constructed model, fertilisation amount per tree, stand age, and regeneration methods were included in the full model. Through model selection, the optimal model encompassed these three factors (fertilisation amount per tree + stand age + regeneration methods). The model selection method followed the same approach as described above. Similarly, we examined the effect of land preparation depth on growth, and no significant effect was found. We also examined the impact of thinning intensity at both the stand and individual tree scales. The figures were plotted using the *metafor* package and *R*'s *plot* function (Viechtbauer 2010), and all analyses were conducted in *R* software (version 4.3.1).

## RESULTS

Overall, forest management increased volume per tree by 37.4% (95% confidence interval [CI]: 28.9% to 46.4%), diameter by 22.0% (95% CI: 17.8% to 26.3%), and tree height by 10.6% (95% CI: 8.4% to 12.6%) ( $P < 0.01$ ). However, stand volume per hectare decreased by 9.6% (95% CI: -20.6% to 3.0%) ( $P > 0.05$ ) (Figure 2).

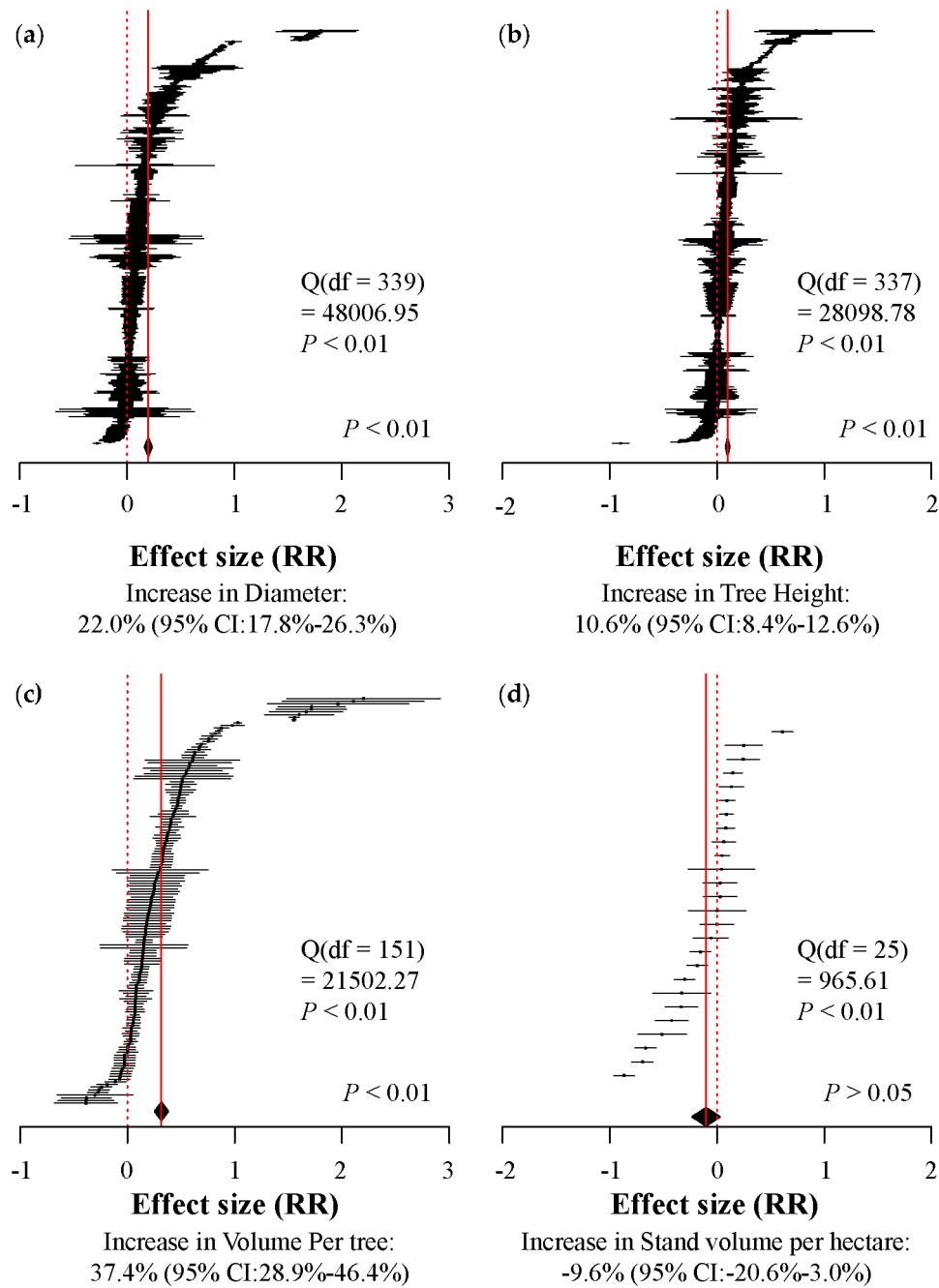
Mixed planting, intercropping, fertilisation, weeding, and thinning significantly promoted tree diameter growth, increasing it by 12.7% (95% CI: 6.2% to 19.7%), 6.2% (95% CI: 2.0% to 9.4%), 24.6% (95% CI: 8.3% to 43.3%), 60.0% (95% CI: 22.1% to 111.7%), and 23.4% (95% CI: 9.4% to 37.7%), respectively ( $P < 0.05$ ). In contrast, burning, land preparation, and irrigation did not significantly affect tree diameter growth ( $P > 0.05$ ). Land preparation outperformed all other management practices except weeding ( $P < 0.05$ ). Weeding also had significantly higher effects than other treatments except irrigation ( $P < 0.05$ ) (Figure 3a). No significant differences were observed among burning, mixed planting, intercropping, fertilisation, irrigation, and thinning ( $P > 0.05$ ) (Figure 3a). Fertilisation and thinning significantly promoted tree height

growth, increasing it by 13.9% (95% CI: 3.0% to 24.6%) and 9.4% (95% CI: 3.0% to 15.0%), respectively ( $P < 0.01$ ). Weeding significantly outperformed all other management practices except irrigation ( $P < 0.01$ ). Irrigation had a significantly greater effect than mixed planting ( $P < 0.05$ ) (Figure 3b). For volume per tree, land preparation, mixed planting, and thinning significantly promoted growth, increasing it by 52.2% (95% CI: 24.6% to 85.9%), 10.5% (95% CI: 7.3% to 12.7%), and 63.2% (95% CI: 13.9% to 134.0%), respectively ( $P < 0.01$ ). Burning significantly reduced the volume per tree by 12.2% (95% CI: -18.1% to -4.9%) ( $P < 0.01$ ) (Figure 3c). Irrigation significantly promoted stand volume per hectare by 12.7% (95% CI: 4.1% to 22.1%) ( $P < 0.01$ ), while thinning reduced it by 36.2% (95% CI: -44.6% to -25.9%) ( $P < 0.01$ ). Fertilisation and irrigation also had significantly higher effects than thinning ( $P < 0.01$ ) (Figure 3d).

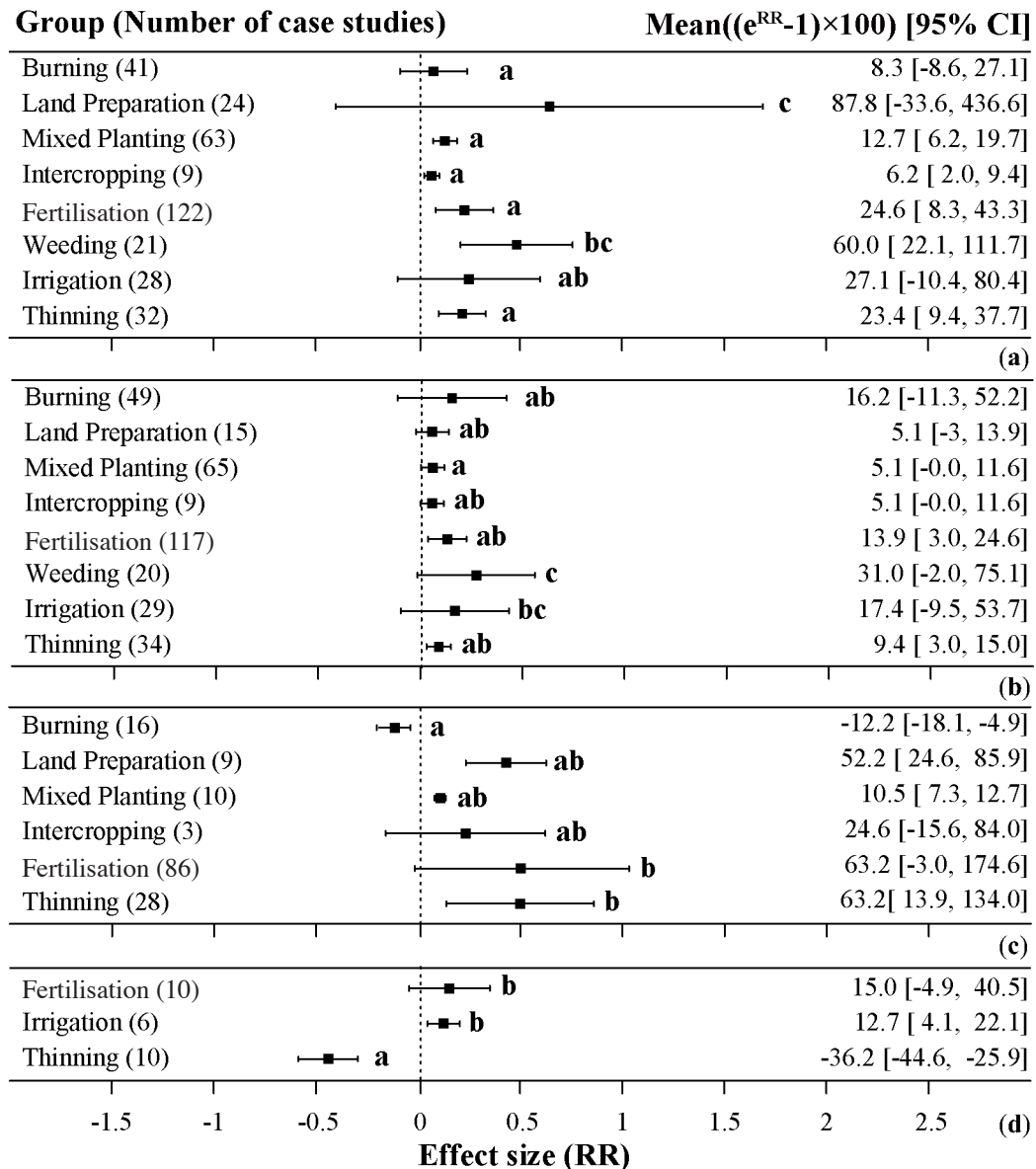
All ripping depths from 0.6 to 0.8 m in land preparation treatments significantly promoted Eucalyptus growth ( $P < 0.05$ ). Strip ripping at 0.8 m and strip ripping at 0.6 m had the most pronounced effects on growth, promoting eucalyptus growth by 452.9% (95% CI: 405.3% to 498.9%,  $P < 0.01$ ) and 436.6% (95% CI: 415.5% to 464.1%,  $P < 0.01$ ), respectively. No significant differences were found between strip ripping with the same depth, small mound and large mound, or between strip and full ripping (Figure 4a).

Among the tree species types, Evergreen broadleaf showed the highest increase at 9.4% (95% CI: 4.1% to 13.9%,  $P < 0.0001$ ). Coniferous trees and Deciduous broadleaf did not significantly affect eucalyptus growth. No significant differences were found between the tree species types (Figure 4b). In terms of fertilizer types, both Single-nutrient mineral fertilizer, Multi-nutrient mineral Fertiliser, and Organo-mineral fertilizer significantly enhanced eucalyptus growth by 20.9% (95% CI: 5.1% to 40.5%), 28.4% (95% CI: 1.0% to 63.2%) and 20.9% (95% CI: 5.1% to 39.1%) respectively ( $P < 0.05$ ). In comparison, Biofertiliser showed no significant effect on eucalyptus growth. The Single-nutrient mineral fertilizer and Multi-nutrient mineral fertiliser treatments were significantly higher than the Biofertiliser ( $P < 0.05$ ) (Figure 4c).

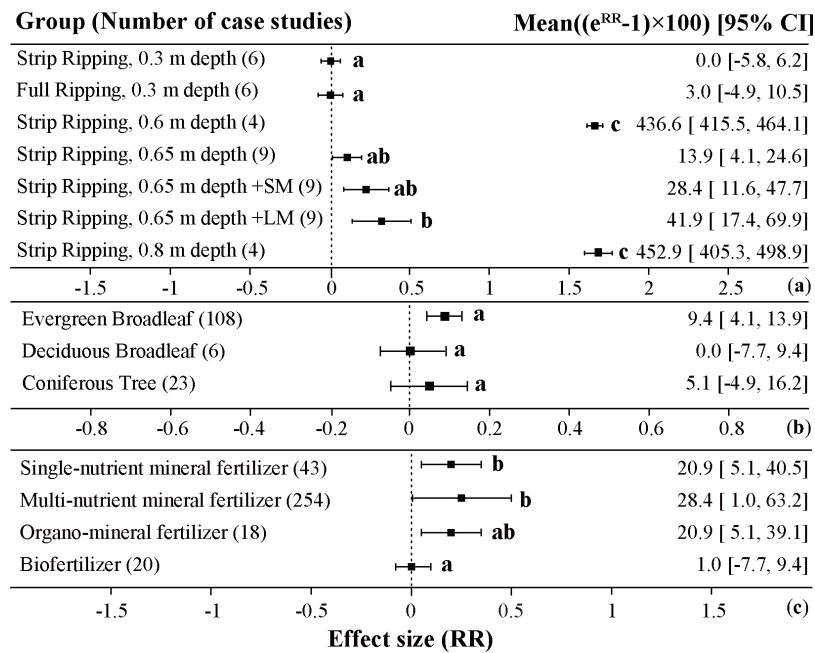
At the single tree scale, a 0.1 increase in thinning intensity results in a 4.4% growth



**Figure 2** Forest plots show the effect of forest management on diameter (a), tree height (b), volume per tree (c), and stand volume per hectare (d). Black dots represent effect sizes (RR), with gray lines indicating 95% confidence intervals. The black diamonds represent the overall weighted mean effect size, with the width indicating the 95% CI. RR = 0 is indicated by the dashed red line. For readability, percent changes are  $(e^{RR}-1) \times 100\%$  back-transforms of pooled RR; the x-axis remains RR



**Figure 3** Effects of forest management practices on (a) diameter, (b) tree height, (c) volume per tree, and (d) stand volume per hectare. Effect sizes are shown as log response ratios (RR) with 95% CIs; numbers in parentheses indicate the number of effect-size cases. The black dashed line represents no effect (RR = 0). Percent values in the right column are back-transformed from RR using  $(e^{RR}-1) \times 100\%$ ; the x-axis remains on the RR scale. Different lowercase letters denote significant differences among practices



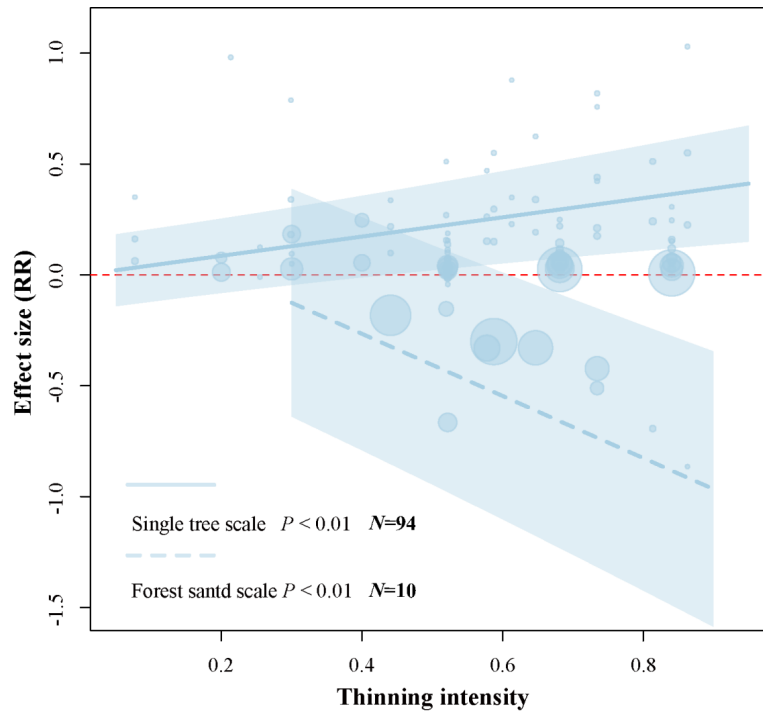
**Figure 4** Effects of land preparation methods, mixed tree species, and fertilizer types on growth, with panels (a), (b), and (c) showing results for each respectively. Effect sizes are shown as log response ratios (RR) with 95% CIs; numbers in parentheses indicate the number of effect-size cases. The black dashed line represents no effect (RR = 0). Percent values in the right column are back-transformed from RR using  $(e^{RR}-1) \times 100\%$ ; the x-axis remains on the RR scale. Different lowercase letters denote significant differences among practices

increase (95% CI: 2.2% to 6.7%,  $P < 0.0001$ ), based on  $RR = 0.4338$  (95% CI: 0.2173 to 0.6504,  $P < 0.0001$ ) ( $QM = 15.4190$ ,  $P < 0.0001$ ), calculated using the formula  $(e^{RR \times 0.1} - 1) \times 100\%$ . At the forest stand scale, a 0.1 increase in thinning intensity results in a 14.0% growth decrease (95% CI: 9.9% to 18.1%,  $P < 0.0001$ ), based on  $RR = -1.5000$  (95% CI: -1.9312 to -1.0688,  $P < 0.0001$ ) ( $QM = 44.5409$ ,  $P < 0.0001$ ), calculated using the same formula (Figure 5).

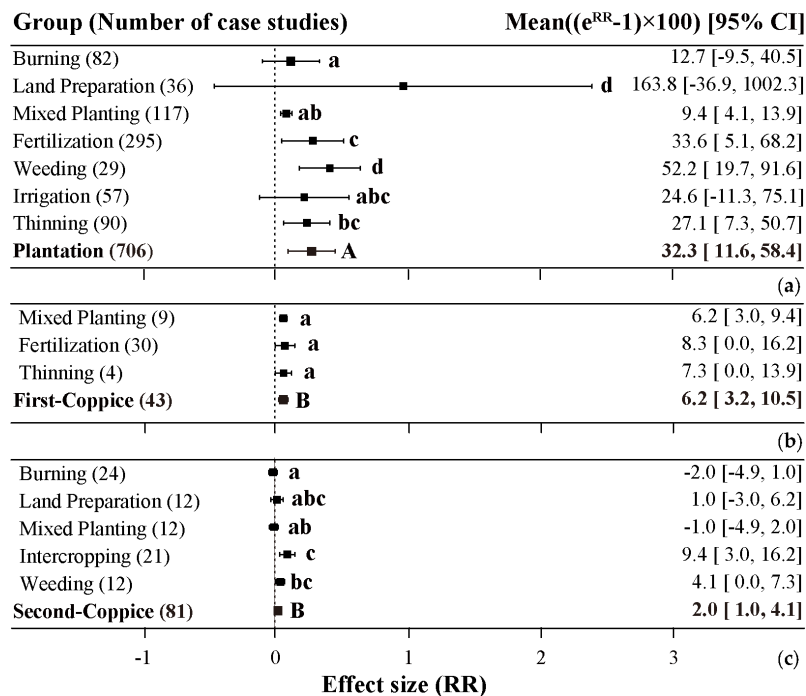
At the individual tree scale in plantation forests, mixed planting, fertilisation, weeding, and thinning significantly promoted growth by 9.4% (95% CI: 4.1% to 13.9%), 33.6% (95% CI: 5.1% to 68.2%), 52.2% (95% CI: 19.7% to 91.6%), and 27.1% (95% CI: 7.3% to 50.7%), respectively ( $P < 0.05$ ). Land preparation and weeding outperformed all other practices ( $P < 0.01$ ), fertilisation significantly outperformed mixed planting and burning ( $P < 0.01$ ), and thinning significantly outperformed burning ( $P < 0.05$ ) (Figure 6a). For first-coppice forests, mixed planting, fertilisation, and thinning promoted growth by 6.2% (95% CI: 3.0% to 9.4%), 8.3% (95% CI: 0.0% to 16.2%), and 7.3% (95% CI: 0.0% to

13.9%), respectively ( $P < 0.05$ ), with no significant differences among these practices (Figure 6b). In second-coppice forests, intercropping and weeding significantly promoted growth by 9.4% (95% CI: 3.0% to 16.2%) and 4.1% (95% CI: 0.0% to 7.3%), respectively ( $P < 0.05$ ). Intercropping significantly outperformed burning and mixed planting ( $P < 0.01$ ), while weeding significantly outperformed burning ( $P < 0.01$ ) (Figure 6c). At the individual tree level, forest management practices were more effective in promoting growth in plantation forests, with a 32.3% increase (95% CI: 11.6% to 58.4%), compared to a 6.2% increase (95% CI: 3.2% to 10.5%) in first-generation coppice forests and a 2.0% increase (95% CI: 1.0% to 4.1%) in second-generation coppice forests ( $P < 0.01$ ) (Figure 6a-c). Figure 3d illustrates the effects of fertilisation, irrigation, and thinning on growth at the stand level in plantation forests.

Forest management practices significantly reduced tree diameter by 4.2% (95% CI: -7.4% to -0.9%,  $P < 0.05$ ) ( $QM = 6.0066$ ,  $P = 0.0143$ ) as log-transformed forest age increased. Percent changes were derived from log response ratios (RR) using  $(e^{RR} - 1) \times 100\%$ ;



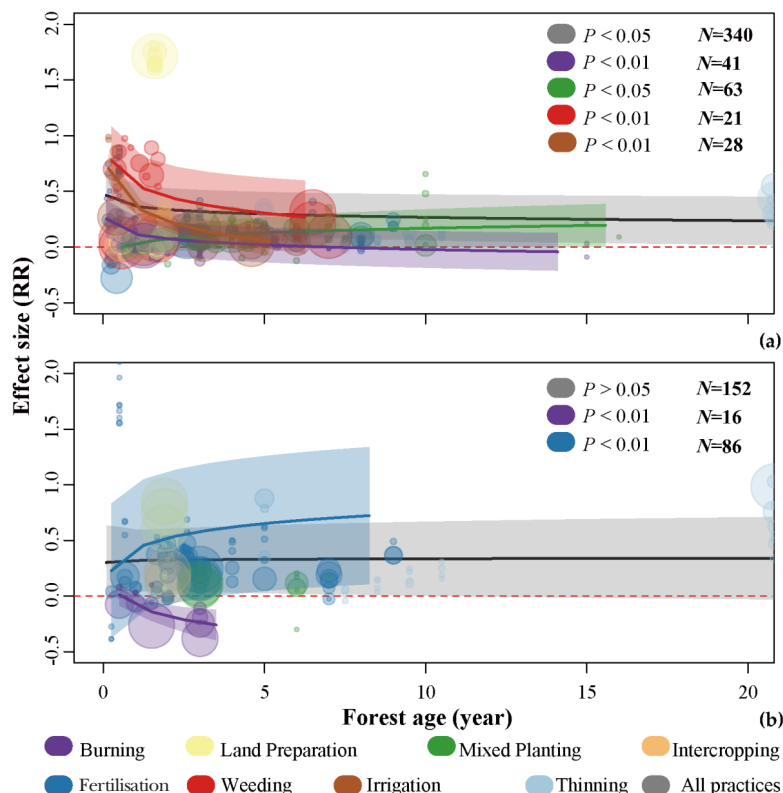
**Figure 5** Effect of thinning intensity on growth response (RR) at the single tree and forest stand scales. The response ratios (RR) represent the effect size, with RR = 0 indicated by the dashed red line, representing no effect. The solid light blue line shows the predicted effect size for the single tree scale, while the dashed light blue line represents the forest stand scale. Shaded areas indicate the 95% confidence intervals. Light blue circles are proportional to the sampling variance



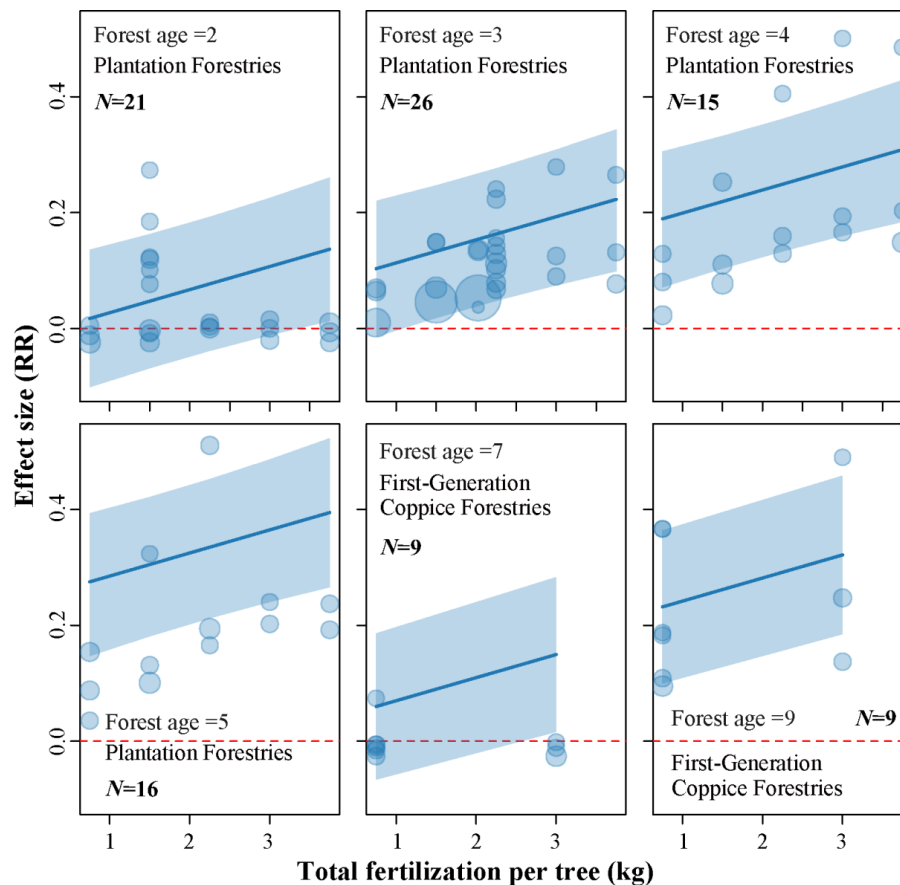
**Figure 6** Effects of different regeneration methods on growth at individual trees. Panel (a) shows results for plantation forests, panel (b) for first-generation coppice forests, and panel (c) for second-generation coppice forests. Percent values in the right column are back-transformed from RR using (e<sup>RR</sup>-1)×100%; the x-axis remains on the RR scale. Different lowercase letters denote significant differences among practices, and different uppercase letters indicate statistically significant differences among regeneration methods

the same transformation was applied throughout. Specific management practices, such as burning, weeding, and irrigation, further reduced tree diameter by 5.9% (95% CI: -9.1% to -2.6%), 14.7% (95% CI: -22.3% to -6.3%), and 17.4% (95% CI: -21.5% to -13.2%) as log-transformed forest age increased ( $P < 0.01$  for all) (Burning:  $QM = 14.4261$ ,  $P < 0.0001$ ; Weeding:  $QM = 10.8670$ ,  $P < 0.0001$ ; Irrigation:  $QM = 46.6189$ ,  $P < 0.0001$ ). In contrast, mixed planting increased tree diameter by 6.1% (95% CI: 0.1% to 12.5%) as log-transformed forest age increased ( $P < 0.05$ ) ( $QM = 3.9615$ ,  $P = 0.0466$ ) (Figure 7a). Forest management did not significantly affect volume per tree with increasing log-transformed forest age (CI: -7.0% to 9.0%,  $P = 0.8634$ ) ( $QM = 0.0296$ ,  $P = 0.8634$ ) (Figure 7b). Burning significantly reduced the volume per tree by 12.9% (95% CI: -20.5% to -4.5%) with increasing forest age ( $P < 0.01$ ) ( $QM = 8.6730$ ,  $P = 0.0032$ ), while fertilisation significantly increased the volume per tree by 15.0% (95% CI: 6.0% to 24.8%) ( $P < 0.01$ ) ( $QM = 12.3314$ ,  $P = 0.0004$ ) (Figure 7b).

A multivariate meta-analysis was conducted to evaluate the effects of fertilisation amount per tree, forest age, and regeneration methods on growth response. The results ( $QM = 69.6919$ ,  $P < 0.0001$ ) demonstrate that regeneration methods and fertilisation amount per tree significantly influence growth across forest ages. Among these factors, regeneration methods had the strongest effect, with plantation forests promoting 47.3% more growth (95% CI: 30.0% to 66.9%) compared to first-generation coppice forests ( $RR = 0.3874$ ,  $P < 0.0001$ ). While fertilisation amount per tree also contributed positively, its effect was small ( $RR = 0.0399$ ,  $P = 0.0013$ ), indicating that increasing the fertilisation amount by 1 kg of eucalyptus-specific fertilizer per tree can result in a 4.0% (95% CI: 1.5% to 6.6%) increase in growth. Additionally, forest age ( $RR = 0.0860$ ,  $P < 0.0001$ ) was found to have a significant positive effect, suggesting that each additional year in forest age can lead to a 9.0% (95% CI: 6.0% to 12.1%) increase in growth (Figure 8).



**Figure 7** Effects of forest management on changes in diameter (a) and volume per tree (b) with increasing forest age. The response ratios (RR) represent the effect size, with  $RR = 0$  indicated by the dashed red line. The black line shows the predicted mean effect size (95% CI in grey) across all forest management practices. Colored lines represent the predicted mean effect size (with 95% CI in corresponding colors) for specific management practices. The size of the data points is proportional to sampling variance, and the colors correspond to different forest management practices.



**Figure 8** Relationship between fertilisation amount per tree and effect size (RR) across forest ages and regeneration methods. The response ratios (RR) represent the effect size, with RR = 0 indicated by the dashed red line representing no effect. The blue line represents the fitted regression line, and the shaded areas indicate the 95% confidence intervals for the predictions across different forest ages and regeneration methods. Blue points are proportional to sampling variance.

## DISCUSSION

### *Effects of Forest Management Practices on Growth Indicators*

Overall, this study demonstrates that different management practices have varying effects on various growth indicators in *Eucalyptus* plantations, supporting Hypothesis 1: Different management practices exert distinct influences on the growth of various indicators. Specifically, these practices significantly increased tree diameter (22.0%), height (10.6%), and volume per tree (37.4%) (Figure 2). However, despite the enhanced growth of individual trees, stand volume per hectare decreased by 9.6% (Figure 2). This decline is mainly attributed to thinning, which reduced stand volume by 36.2%, while fertilisation and irrigation increased stand volume by 15.0% and 12.7%, respectively

(Figure 3d). Previous studies have shown that thinning reduces stand density to promote the growth of remaining trees, though it may also decrease overall stand biomass, especially under higher thinning intensities (Resquin et al. 2024). In contrast, fertilisation and irrigation increase stand volume by improving nutrient and water availability, as evidenced by the Brazil *Eucalyptus* Potential Productivity Project (Stape et al. 2010).

Furthermore, as illustrated in Figures 3a-b, fertilisation, thinning, and weeding have a marked effect on increasing tree diameter and height. Previous research has emphasized that fertilisation enhances soil fertility, promoting tree growth (Saarsalmi & Mälkönen 2001), while weeding or thinning reduces competition, improving resource availability and stimulating growth (Del Río Gaztelurrutia et al. 2017, Kang et al. 2014, Mead 2005). Additionally, mixed planting and intercropping have demonstrated

moderate positive effects on plantation growth, likely by improving resource-use efficiency through resource complementarity, whereby different species utilize light, water, and nutrients in a complementary manner (Richards et al. 2010, Wu et al. 2016). Fertilisation, thinning, weeding, mixed planting, and intercropping generally have a more substantial effect on promoting diameter growth than height growth (Figure 3). This is likely because young trees prioritize height growth to compete for light, whereas, after establishing dominance, they shift their focus toward radial expansion (Vanninen & Makela 1999). Other studies have also shown that thinning promotes diameter growth by alleviating competition for light and space but has minimal effect on height growth (Del Campo et al. 2022, Kim et al. 2016). The effects of burning and land preparation further illustrate the variability in management outcomes. Burning reduced individual tree volume by 12.2%, while land preparation significantly promoted growth, increasing individual tree volume by 52.2% (Figure 3c). These contrasting outcomes reflect the impact of these practices on soil quality and resource availability. Burning can negatively affect soil organic matter and nutrient levels, though it may occasionally have neutral or positive effects, ultimately impairing tree growth performance (Alcaniz et al. 2018). Conversely, land preparation improves soil structure, increases nutrient availability, and reduces resource competition, facilitating root establishment and nutrient uptake and significantly enhancing tree volume (Hawkins et al. 2006, Smith et al. 2001).

Moreover, management practices such as burning, land preparation, irrigation, and mixed cropping can positively and negatively affect specific growth indicators, such as diameter and height, depending on environmental conditions. Even fertilisation, a critical management practice for *EUCALPYTUS* plantations, may negatively impact individual tree volume and stand accumulation under certain circumstances (Figure 3). These findings highlight the critical importance of selecting appropriate management practices for plantation growth and underscore the need for further analysis to identify additional influencing factors throughout the management process.

### *Heterogeneous Effects of Different Silvicultural Practices on the Growth*

Significant differences were observed among the different land preparation methods, among the mixed tree species, and among the fertilizer types (Figure 4), which supports Hypothesis 1, demonstrating that different management approaches have distinct effects on growth outcomes. Strip ripping at 0.8 m and strip ripping at 0.6 m had the most pronounced effects on growth, promoting eucalyptus growth by 452.9% and 436.6% ( $P < 0.01$ ). However, the 0.3 m ripping depth had no significant effect on eucalyptus growth ( $P > 0.05$ ) (Figure 4a). *Eucalyptus* is a species sensitive to soil looseness and root expansion depth. Deep soil preparation methods, such as strip ripping, can significantly promote eucalyptus root growth and biomass, especially in areas where deeper roots can access nutrients and water from lower soil layers, while shallow tillage fails to achieve the same effect (Basílio et al. 2024, Laclau et al. 2013). However, we did not find a clear regression relationship between ripping depth and eucalyptus growth. Further research may still be needed to analyze the differences between full tillage and strip tillage, as well as between large and small mounds.

Among the tree species types, evergreen broadleaf species had the most significant positive impact on eucalyptus growth, increasing diameter by 9.4%, suggesting they create a more favorable growth environment. Coniferous trees and deciduous broadleaf species did not significantly affect eucalyptus growth. As Kelty (2006) noted, mixed-species combinations can induce competition, potentially inhibiting growth depending on species interactions. In terms of fertilizers, Single-nutrient mineral fertilizers, Multi-nutrient mineral fertilizers, and Organo-mineral fertilizers significantly enhanced eucalyptus growth, with increases of 20.9%, 28.4%, and 20.9%, respectively. In contrast, biofertilizers showed no significant effect, and the mineral fertilizers were significantly more effective. These findings align with Liang (2023), which suggests that traditional mineral fertilizers remain more effective in promoting eucalyptus growth, particularly in the early stages.

At the individual tree scale, for every 0.1 increase in thinning intensity, tree growth increases by 4.4% (95% CI: 2.2% to 6.7%,  $P < 0.0001$ ).

However, at the forest stand scale, growth decreases by 14.0% for every 0.1 increase in thinning intensity (95% CI: 9.9% to 18.1%,  $P < 0.0001$ ) (Figure 5). This finding supports both Hypotheses 1 and 2, demonstrating that management intensities, including thinning, have distinct effects on growth outcomes. While higher thinning intensities enhance the growth of individual trees, they also reduce overall stand productivity, emphasizing the need to carefully balance thinning intensity to optimize individual tree growth and stand yield.

#### *Impact of Regeneration Methods, Management Practices, and Forest Age on Growth*

Silvicultural practices promoted growth in plantation forests by 32.3%, which was significantly higher compared to the growth observed in first-generation coppice forests (6.2%) and second-generation coppice forests (2.0%) ( $P < 0.01$ ) (Figure 6). Specifically, compared to plantation forests, the effects of mixed-species planting, fertilisation, weeding, and thinning on growth were relatively lower in first-generation and second-generation coppice forests. This result supports Hypothesis 3, which states that management practices have a more substantial impact on seedling-regenerated stands than coppice-regenerated ones. The diminished response in coppice forests aligns with studies showing that coppice species rely on their well-established root systems, enhancing resource utilization efficiency and reducing dependence on external inputs such as mixed-species planting, fertilisation, and other management practices (Bellingham & Sparrow 2003, Bond & Midgley 2001).

As forests age, management practices such as burning, weeding, and irrigation show diminishing positive effects on growth and can even turn negative such as burning (Figure 7). This decline can be attributed to competition dynamics, root system development, and changes in resource availability. Younger stands rely heavily on external inputs, while older forests with well-developed root systems show reduced dependence on such practices. For example, as forests age, the well-established root systems of older trees may dominate resource uptake, making the elimination of smaller competitors through weeding less impactful (Powers et al. 2005, Zhang et al. 2024). Similarly, irrigation

may have a limited effect in older forests because mature trees typically have deeper roots that can access water from lower soil layers, reducing their reliance on surface water supplementation (Cusack et al. 2021). These results support Hypothesis 3, which posits that management practices have a more substantial effect on younger stands than mature ones, supported by these findings. As forest age increases, burning becomes less effective for growth and even has adverse effects. This could be due not only to the reduced competition from understory vegetation as forests mature (Bond & Midgley 2001), but also to nutrient loss caused by burning, which inhibits growth (Bai et al. 2020).

On the other hand, mixed planting and fertilisation continue to have positive effects even in older forests (Figure 7). Mixed-species plantations tend to increase resource-use efficiency by exploiting complementary traits among species, such as varying rooting depths and nutrient acquisition strategies, that enable sustained growth benefits over time, particularly in older stands where competition among trees of the same species might intensify (Depauw et al. 2024). Fertilisation, especially in nutrient-limited soils, remains influential in increasing growth in older forests by addressing nutrient deficiencies that become more pronounced as stands mature (Stape et al. 2010, Zhu & Wu 2023). However, as shown in Figure 7, although mixed planting and fertilisation promote growth in older forests, their effects noticeably taper off with increasing forest age (Figure 7). This observation supports Hypothesis 3. The diminishing impact over time is consistent with the idea that younger forests rely more heavily on external interventions to facilitate growth, while older forests, with well-developed root systems and more efficient resource-use strategies, exhibit reduced responsiveness (Kuuluvainen & Gauthier 2018).

Figure 8 validates Hypothesis 3 by demonstrating the effects of fertilisation from the perspectives of regeneration methods and forest age. The results show that fertilisation has a more substantial impact on seedling-regenerated or younger stands than on coppice-regenerated or mature stands. Figure 8 reveals that plantation forests exhibit a 47.3% greater growth response compared to coppice forests ( $RR = 0.3874$ ,  $P < 0.0001$ ), suggesting that plantations are generally more responsive to fertilisation inputs

(Bellingham & Sparrow 2003, Bond & Midgley 2001). The results show that in plantation forests aged 2 to 5 years, increasing fertilisation promotes growth; however, the baseline effect size (intercept) decreases as forests mature (Figure 8). This trend suggests that younger stands exhibit a stronger initial response to fertilisation, while mature stands show diminished responsiveness with more developed root systems and improved resource-use efficiency (Zhu & Wu 2023). Figure 8 further validates Hypothesis 1, demonstrating that varying fertilisation levels have a measurable impact on growth. Specifically, increasing eucalyptus-specific fertilizer by 1 kg per tree yields a 4.0% growth increase. As trees age and continue extracting nutrients from the soil, sustained fertilisation becomes essential to mitigate nutrient deficiencies, yielding a 9.0% growth increase per additional year of forest age (RR = 0.0860,  $P < 0.0001$ ). These results align with previous studies that highlight the role of fertilisation in mitigating nutrient deficiencies that accumulate over time, particularly in nutrient-limited soils (Stape et al. 2010, Zhu & Wu 2023). These findings indicate that younger, seedling-regenerated stands benefit most from fertilisation, while older forests require sustained fertilisation to counteract nutrient depletion.

### Declaration of Competing Interest

The authors declare no conflict of interest.

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