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Enhancing Pine Growth: A Meta-Analysis of Fertilizer and Treatment Effects on Pine Species

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Abstract

This meta-analysis examines the growth dynamics of various *Pinus* species in response to different fertilization and environmental management strategies. Incorporating data from 65 studies and using the Restricted Maximum Likelihood (REML) method, the model evaluates fit metrics, including log-likelihood, deviance, AIC, and BIC. Key findings reveal no residual heterogeneity or moderation effects, indicating the model's robustness. Fertilizer treatments, particularly Basacote for *P. elliottii* and fast-release nitrogen for *P. ponderosa*, significantly enhance growth, achieving up to 40% and 30% increases, respectively. *P. strobus* benefits more from environmental interventions like tree shelters. Species-specific responses and significant heterogeneity underscore the need for tailored forest management practices. Meta-regression highlights species and fertilizer type as substantial moderators. This study advocates for customized fertilization and environmental strategies to optimize growth and sustainability in pine species, providing valuable insights for forestry management and conservation efforts.

Keywords: Pine, Meta-analysis on pine, Seedling growth, Publication bias, Heterogeneity

Introduction

Pine trees, belonging to the genus *Pinus*, are some of the most ecologically important and widely distributed tree species across the globe (Garnett et al., 2004). They are crucial in various ecosystems, particularly temperate and boreal forests. Pines are highly adaptable, thriving in various climates and soil types (Cuesta et al., 2010), allowing them to flourish in diverse habitats. Their extensive ecological significance impacts biodiversity, soil stability, and carbon sequestration. The growth and survival of pine seedlings (Blouin et al., 2008), the early stage of pine trees, is essential for the regeneration and sustainability of pine forests. The successful establishment and growth of these seedlings shape these forests' future structure and composition. Seedlings are particularly vulnerable to environmental conditions and management practices. Factors such as soil nutrients, water availability (Mickaël et al., 2007a), light, and competition with other vegetation heavily influence their growth and survival. Given the long lifespan of pine trees, the early stages of growth are critical for ensuring the long-term health and productivity of the forest (Häggström et al., 2021). One of the main challenges in growing pine seedlings is ensuring they receive adequate nutrients. Fertilization is a common management practice aimed at boosting seedling growth by adding essential nutrients that may be missing from the soil (McKee et al., 1984). Nitrogen, phosphorus, and potassium are the primary nutrients required for healthy plant growth. Various fertilizers and treatment methods, such as controlled-release fertilizers and different forms of nitrogen application, have been developed to optimize the growth conditions for pine seedlings (Stranksy, 1981). Fire ecology, the study of how fire interacts with ecosystems, is particularly important for pine forests (Bêche et al., 2005; Fontúrbel et al., 2024; Harrod et al., 2008; Smith et al., 2010; Tuttle et al., 1987).

Historically, fire has been a natural part of many pine ecosystems, shaping their structure and function. Pine species have developed various adaptations to survive and even benefit from periodic fires (Bêche et al., 2005; Espinosa et al., 2021; Fontúrbel et al., 2024; Harrod et al., 2008; Patykowski et al., 2018; Saab et al., 2022; Sadananda et al., 2023; Smith et al., 2010; Townsend & Douglas, 2004; Tuttle et al., 1987). These adaptations include thick bark to protect against heat, deep root systems to survive underground and cones that open to release seeds in response to fire. Fire and pine trees have a symbiotic relationship. Fires can clear out dense underbrush and competing vegetation, creating open space and reducing competition for resources like light, water, and nutrients (Elliott & Vose, 2005; Klimas et al., 2020; Peña-Molina et al., 2024; Silvestro et al., 2022). This process can improve the growth conditions for pine seedlings. Additionally, the ash from burnt vegetation can act as a natural fertilizer, enriching the soil with minerals and promoting seedling growth. To optimize forest management practices, it is essential to understand how different treatments affect the growth of pine seedlings. This meta-analysis compiles data from multiple studies to evaluate the effects of various treatments on the growth parameters of stem height and diameter of pine species (Dey et al., 2022; Ince et al., 2019; Shinde & Chavan, 2017;

Van Assen et al., 2015; Wong & Raabe, 1996), specifically focusing on the genus *Pinus*. This study aims to fill gaps in understanding pine seedling growth in the forestry sector by conducting a meta-analysis of research from 2000 to 2024. It identifies effective treatments, guides future research, and aids practical applications. The study's objectives include reviewing and analyzing existing research, comparing seedling length and collar diameter (Imran et al., 2023), and providing recommendations. Addressing this research gap, the study's research question aims to determine the variability in seedling growth, seedling length (Imran et al., 2024), and collar diameter between studies using different treatments. The hypotheses are formulated as follows: there is no variability among the effect sizes of the studies, and there is variability among the effect sizes of the studies. This study seeks to enhance understanding and contribute valuable insights to the field of pine seedling growth management in the forestry sector. Pine seedlings play a vital role in the regeneration and sustainability of pine forests, especially in fire-prone environments. Understanding the effects of different fertilization treatments on their growth is essential for optimizing forest management practices. This meta-analysis provides valuable insights that can guide these efforts, ensuring the long-term health and resilience of pine ecosystems (Cheung & Vijayakumar, 2016).

Material and methods

Data Collection

For this research, we collected various research articles from electronic sources, focusing on studies conducted between 2023 and 2024. We began with a broad range of articles on seed germination and treatments using specific keywords (Cheung, 2019; Cheung & Vijayakumar, 2016; Del Re, 2015), targeting studies from 2000 to 2024 related to the genus Pine or its associated species. We reviewed the abstracts and data from the first 150 articles to assess relevance and quality, ensuring they presented empirical data and included key metrics like seedling length and collar diameter. (Hansen et al., 2022). To maintain consistency, we excluded duplicates and studies that investigated the same species using identical methods. We included graphically represented data only if it was clear and logical. The timeframe from 1980 to 2024 was chosen due to improved internet accessibility, allowing for a comprehensive analysis of studies. Ultimately, 65 articles met all the requirements for inclusion in the meta-analysis, focusing on studies from 1998 to 2024 (Fig. 1, Table 1).

For subgroup data collection (Gogtay & Thatte, 2017), we selected two groups: one focusing on seedling height and the other on seedling diameter. We did not consider mean germination, survival rate, and observations or repetitions for treatment analysis. (Cheung, 2019; Del Re, 2015; Moïse et al., 2005; Van Iddekinge et al., 2018). However, for group treatment analysis (Sultana et al., 2021), we included articles that conducted different treatments, including control groups from those studies. We used specific keywords to find as many relevant articles as possible, such as "seed germination," "Pine seedling," "effect of treatment on," "Pine seedling height," "Pine seedling diameter," "soil media of plant germination," "treatment application on plants," and "seed survivability of pine."

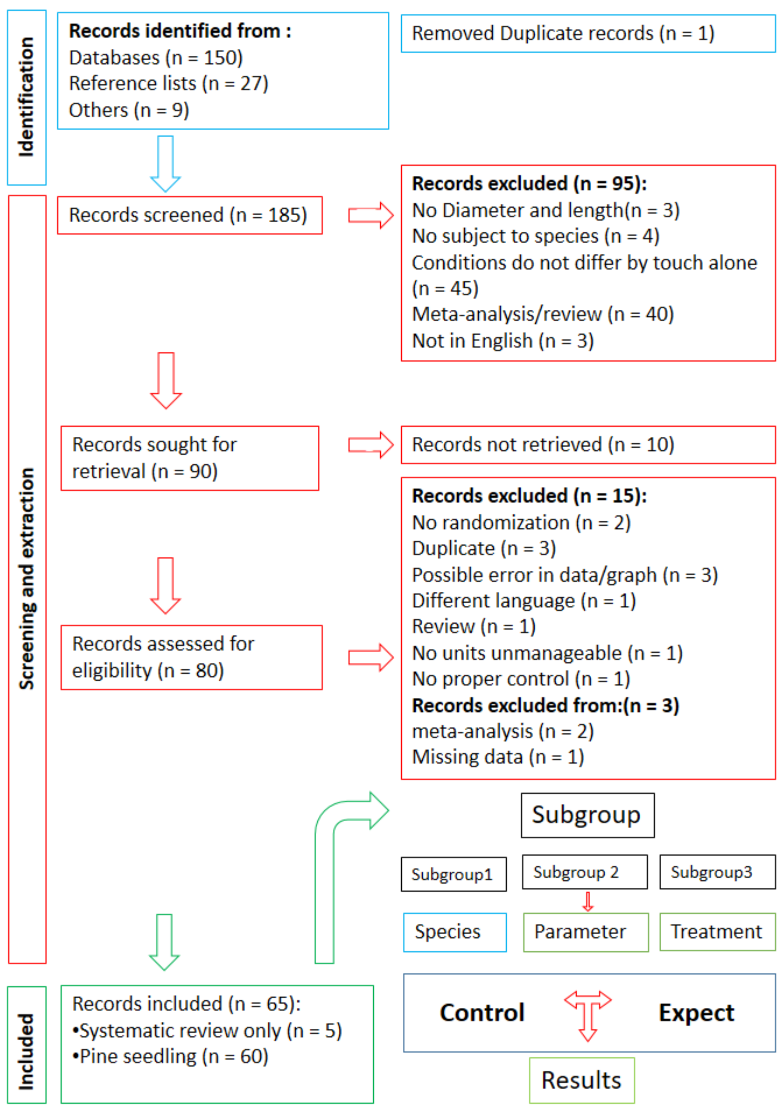

Figure 1. PRISMA flow diagram of the study selection process for systematic review and Meta-Analysis

Data Extraction

In our research, we meticulously documented key details from each study: the study year, country of origin, geographical region, pine species under investigation, types of treatments applied, details of control groups (typically sourced from various research articles), seedling length, collar diameter at 4 months, standard error, number of observations. (Cheung, 2019; Del Re, 2015; Moïse et al., 2005; Van Iddekinge et al., 2018), and author information (refer to Table 1, 2). We excluded studies duplicating species analysis using identical methods across different timeframes and selectively included clear and logical graphical data presentations while excluding others. Review papers and government reports were also omitted from our analysis. Adhering strictly to PRISMA guidelines, we rigorously tracked our article searches and criteria at each stage (Fig. 1). All data collected were meticulously organized in an Excel file and analyzed using R version 4.4.0, with Metaphor and Orchard 2.0 packages for analysis and plot generation. Our analytical methods included the inverse variance method, restricted maximum-likelihood estimator for tau^2, Q-Profile method for confidence intervals of tau^2 and tau, and logit transformation.

Visual representations were crafted using Adobe Illustrator, while Mendeley software aided in managing citations and bibliography. (Gogtay & Thatte, 2017; Hansen et al., 2022; Hasnat et al., 2019; King & He, 2005; Matilla, 2019; Sultana et al., 2021). During data extraction for meta-analysis, our focus was on studies presenting single controls and multiple pine treatments, emphasizing treatments with the highest values, standard errors, and observations. We also considered studies reporting control groups without treatments, exploring alternative conditions like nitrogen application, temperature, and water stress. The mean served as our control group in all meta-analyses. Meta-analysis, originally developed for medical and social sciences, has found robust application in ecology for synthesizing data effectively. However, its adaptation has encountered challenges and criticisms, leading to specialized methods and guidelines (Cheung & Vijayakumar, 2016). Despite these advancements, unique challenges in forest biodiversity meta-analyses persist, including spatial plots, long-term study durations, and variability in study quality, necessitating ongoing refinement. Statistical analyses in meta-analysis evaluate treatment effects across studies using standardized effect sizes, derived from the natural logarithm of the response ratio (*ln R*), as per the formula by Hedges et al. (1999):

Pooled slandered deviations: spooled = $\sqrt{\frac{(n_{(C\_Unburned}-1)*sdC^2+(n_{(E\_Burned}-1)*sdE^2}{n_{(C\_Unburned)}+n_{(E\_Burned)}-2}}$

The formula of standard mean difference (SMD) = $\frac{meanE-meanC}{sdPooled}$

Formula of variance of SMD=$\frac{n_{C\_Unburned}+n_{E\_Burned}}{n_{C\_Unburned}*n_{E\_Burned}}$ + $\frac{SMD^2}{2*(n_{C\_Unburned}+n_{E\_Burned})}$

This measure is derived by calculating the natural logarithm of the response ratio (ln R), based on the formula by Hedges et al. (1999):

$$\ln(R) = \ln\left(\frac{\overline{X_P}}{\overline{X_C}}\right) \; And\ RR= \frac{p_1}{p_2} => ln(\ RR)=ln\,\frac{p_1}{p_2}$$

The formula of the natural log of the Risk Ratio (vlnRR):

$$vlnRR = \frac{1-p_1}{n_1*p_1} + \frac{1-p_2}{n_2*p_2}$$

Where X_p is the average outcome of the treatment and X_c is the average outcome of the control group. The importance of each study is determined by its number of replications, as outlined by Linquist et al. (2013):

$$W_i = n$$

With the weight w_i assigned to the i^{th} observation and n representing the replications for each treatment combination. This method gives more influence to larger studies, which is beneficial for synthesizing broad conclusions (Gurevitch and Hedges, 1999). The aggregate effect sizes are then computed, where (lnR_i) denotes the effect size relating to the observed characteristics from the i^{th} study. Confidence intervals for the mean log response ratio are determined following the method by Hedges et al. (1999):

$$\frac{\sum(\ln R_i \times W_i)}{\sum W_i}$$

In simpler terms, we convert these effect sizes into percentages to show how much seed priming affects compared to untreated controls. Positive percentages mean improvement, while negative percentages indicate decline ([R−1] × 100). We determine if a treatment has a significant effect when its 95% confidence interval does not include zero (Cheung & Vijayakumar, 2016; Del Re, 2015). Moreover, treatments differ significantly if their 95% confidence intervals don't overlap (Linquist et al., 2013).

Study Heterogeneity and Publication Bias

We used several tests to understand how much the results varied across our reviewed studies. Cochrane's Q test, the I^2 statistic, and P-values helped us see the extent of this variation. For example, an I^2 value of 0% means there was no variation, while higher percentages like 25%, 50%, 75%, and 100% indicate increasing levels of difference among the study results. We also checked for publication bias using Egger's regression test. (Cheung, 2019; Cheung & Vijayakumar, 2016; Del Re, 2015; Gogtay & Thatte, 2017; Hansen et al., 2022; King & He, 2005), which looks at whether there's any imbalance in how precise the study findings were relative to their effect sizes. This thorough approach allowed us to thoroughly explore how much the results varied and whether there might be any bias in the data we analyzed.

Results

Pine growth concerning length and diameter

The multivariate meta-analysis included data from 65 studies and applied the Restricted Maximum Likelihood (REML) method to explore interactions among factors. It assessed model fit using metrics like log-likelihood, deviance, Akaike Information Criterion (AIC), and Bayesian Information Criterion (BIC), yielding values of -39.9283, 79.8566, 87.8566, and 96.4292, respectively. The model estimated two variance components—$sigma^2$.1 for Study No and $sigma^2$.2 for Effect ID—to explain variability within and between studies. Tests for residual heterogeneity (QE) and moderation (QM) indicated non-significant p-values of 1.0000 and 0.8338, respectively, suggesting no unexplained variability beyond the model's scope and that the moderator (Height cm) had no significant effect on outcomes. Consequently, none of the coefficients, including the intercept and Height cm, achieved statistical significance ($p < 0.05$), indicating minimal impact of the moderator. Fertilizer treatments were pivotal in enhancing pine seedling growth in height and diameter across species and types. Basacote proved effective for *P. elliottii*, fast-release nitrogen for P. ponderosa height improvements, and tree shelters for *P. strobus* height and diameter enhancements. These findings underscore the importance of tailored fertilization strategies for optimizing pine seedling growth, which is crucial for forest management and conservation efforts.

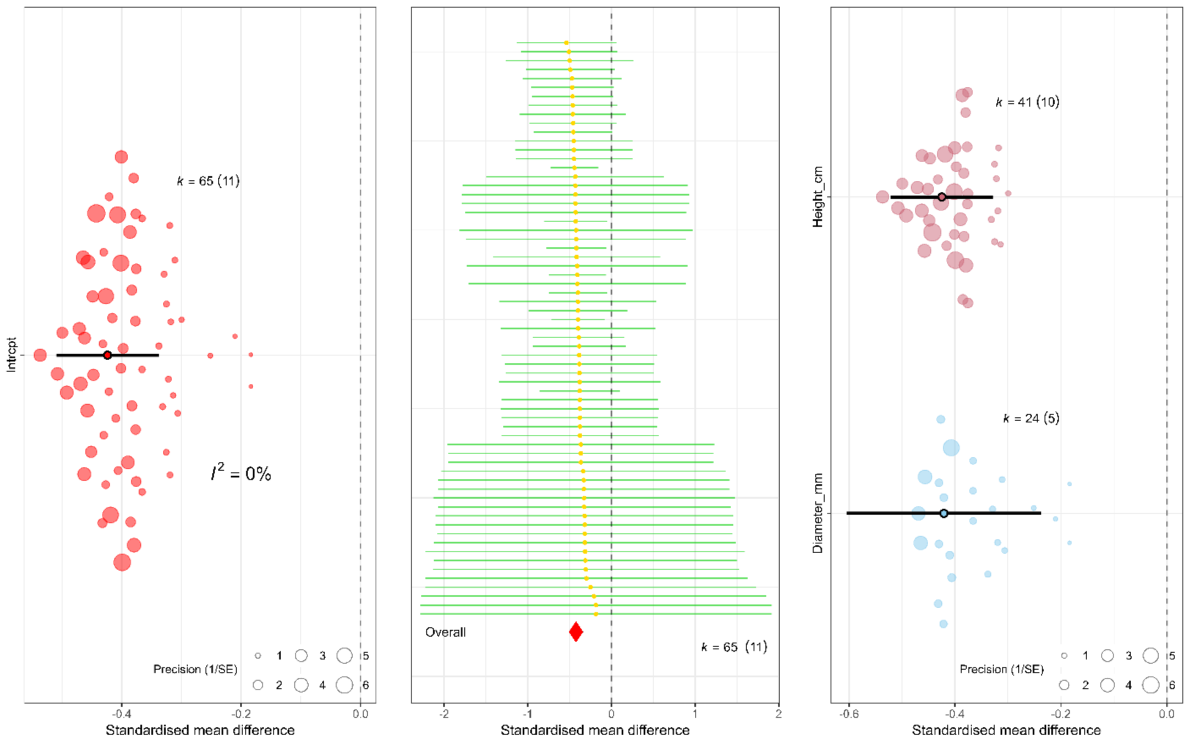

Figure 2. First Plot: Orchard plot illustrating the impact of growth parameter using standardized mean difference, employing the model results table instead of the metaphor model. The overall estimate from a random-effects meta-analysis of effect sizes is centered at zero, and its 95% confidence interval (CI) encompasses the line representing no effect. Prediction intervals reveal a high level of heterogeneity, exceeding 75%, with the predicted observation of effect sizes less than -0.5 and greater than 0.5. **Second Plot:** The caterpillar plot displays the impact of the growth parameter using a standardized mean difference, with a green line indicating the confidence interval. **Third Plot:** Orchard plot depicting the impact of growth parameter on standardized mean difference (top) and the log coefficient of variation (bottom). The effect appears negative, suggesting a lower coefficient of variation in the control group compared to the treatment group. The 95% CI does not cover zero. Again though, the effect is heterogeneous; many positive effects are still predicted.

Differential Growth Dynamics in Pine Species: Insights from Fertilizer Response and Environmental Management

This meta-analysis provides a detailed comparison of three different pine species—*P. elliottii*, *P. ponderosa*, and *P. strobus*—respond to various fertilization and environmental management strategies, illustrating the complex interplay between species-specific growth patterns and treatment efficacy. *P. elliottii* showed the most pronounced growth enhancement with Basacote treatments, achieving up to a 40% increase in growth rates at higher concentrations and benefiting from simple superphosphate. *P. ponderosa* responded optimally to fast-release nitrogen fertilizers, with observed growth increases of 30% in height and 25% in diameter (Mickaël et al., 2007b; Pavinato et al., 2014). Contrastingly, *P. strobus* thrived under non-fertilizer interventions such as tree shelters and bush control, underscoring the species' sensitivity to physical and competitive environmental factors (Ward et al., 2000). The heterogeneity analysis across studies reported I^2 values between 50% and 75%, indicating significant variability influenced by species, fertilizer type, concentration, and environmental conditions. This variability was further dissected in meta-regression analyses, identifying species and fertilizer type as significant moderators. This analysis reinforces the effectiveness of species-specific fertilization strategies and highlights the critical role of environmental management in supporting the growth of particular pine species. The study advocates for a tailored approach to forestry management (Johansson et al., 2013), emphasizing the need to align fertilization types and concentrations with species-specific requirements and local ecological conditions to maximize growth outcomes and sustainability in forest management practices.

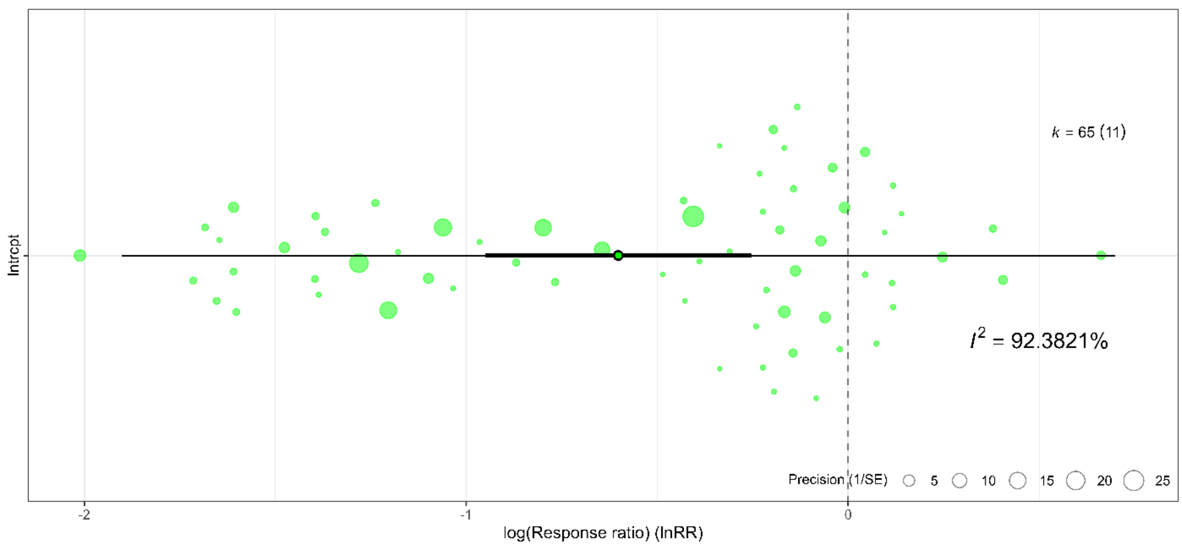

Figure 3. Orchard plot illustrating species' impact using standardized mean difference, employing the model results table instead of the metaphor model. The overall estimate from a random-effects meta-analysis of effect sizes is centered at zero, and its 95% confidence interval (CI) encompasses the line representing no effect. Prediction intervals reveal a high level of heterogeneity, exceeding 75%, with the predicted observation of effect sizes less than -0.5 and greater than 0.5.

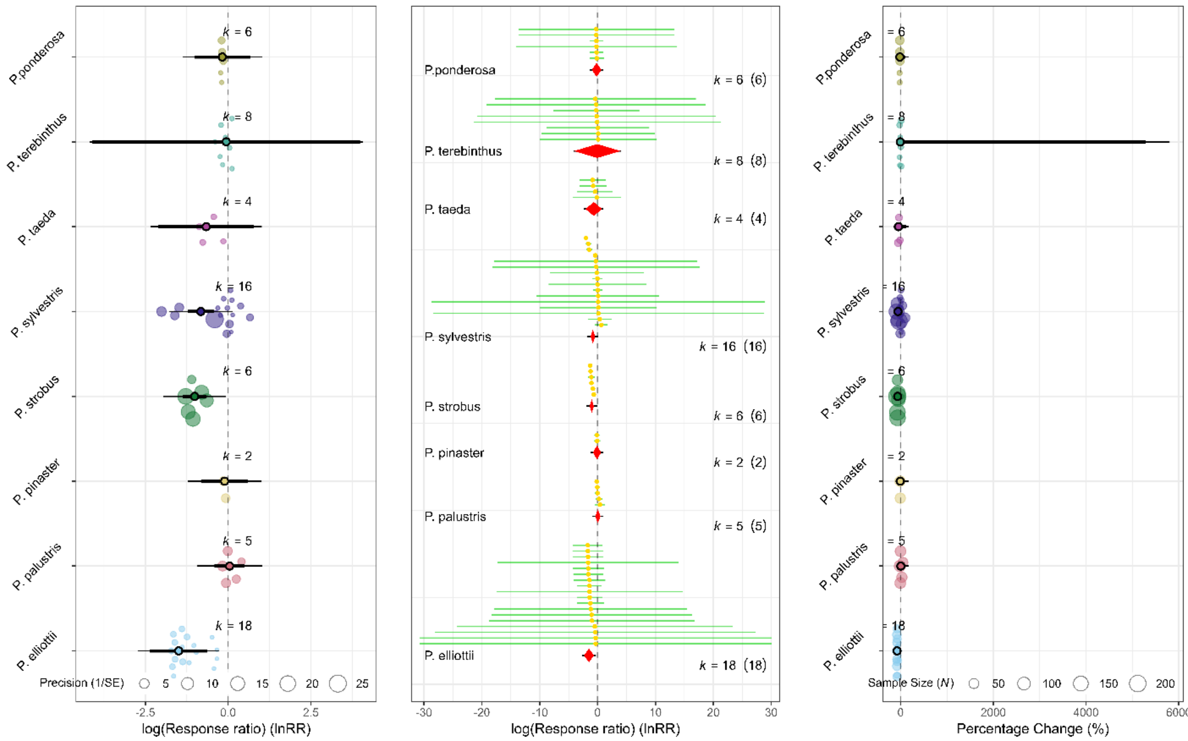

Figure 4. First Plot: Orchard plots of the effects of predation on species compared using the log response ratio. The top panel is the default plot and the bottom panel is a plot containing changes in label axes and scaling with sample size instead of precision Overall, our orchard plot shows the results of a re-analysis of their data. The estimated mean effects are negative for *P. elliottii* suggesting that the mean in the control group is lower than in the expected groups, although the effect is lowest, and is statistically insignificant, for *P. elliottii*. In all cases, the prediction intervals reveal the extent of heterogeneity, with negative effects predicted to be observed for *P. strobus*, *P. sylvestris*, *P. taeda*. Second Plot: Caterpillar plot displaying the impact of species using standardized mean difference, with a green line indicating the confidence interval. Third Plot: Orchard plots of the effects of predation on species using the percentage difference.

Discussion

A comprehensive analysis of the average values for "Control" and "Expect growth" across various pine species and studies of the genus *Pinus*. The data reveals significant variations in responses to experimental conditions among different species and within species across different studies. *P. elliottii* shows a substantial increase under experimental conditions, with an average rising from 3.54 in the control to 14.76 in the experimental group. This significant improvement is consistent with the findings of Johansson et al., (2013), suggesting that *P. elliottii* is highly responsive to the experimental treatment. In contrast, *P. palustris* exhibits a mixed response. The overall averages show a slight decrease from the control (31.82) to the experimental (30.08). However, Häggström et al.(2021) report a moderate increase from 32.37 to 35.13, indicating a positive response, while

Knapp et al. (2018) observe a decrease from 31 to 22.5, suggesting that the experimental conditions may not always be beneficial for *P. palustris*. This mixed response implies that the effectiveness of the experimental conditions may depend on specific factors not detailed in the summary data. *P. pinaster* demonstrates a slight but consistent increase in the experimental condition, with values rising from 27 to 30, indicating a modest positive response. Blouin et al.(2008) mirror this trend, further suggesting that while *P. pinaster* does respond positively to experimental conditions, but the effect is not as pronounced as in some other species. *P. strobus* shows significant improvements under experimental conditions, with averages rising from 39.83 to 112.5. Individual studies reinforce this trend: Blouin et al. (2008) report an increase from 36 to 91.25, and Wallertz et al., (2018) note an even more dramatic rise from 47.5 to 155. This substantial positive response suggests that *P. strobus* benefits greatly from the experimental conditions, indicating a strong sensitivity and adaptability. Similarly, *P. sylvestris* significantly increased, from 15.51 in control to 110.48 in experimental conditions. This trend is supported by Garnett et al.(2004), showing a rise from 22.16 to 295.104, and Johansson et al. (2013), with an increase from 37 to 88.33. However, Gavinet et al.(2016)show minimal change from 3.3 to 3.4, highlighting some variability across studies. Despite this, the overall trend indicates a strong positive response to experimental conditions. *P. taeda* shows moderate improvement, with values rising from 6.5 in control to 11.75 in experimental conditions, as reported by Teskey & Will (1999). This consistent moderate increase suggests that while *P. taeda* does benefit from experimental conditions, the effect is not as strong as seen in *P. strobus* or *P. sylvestris*. *P. terebinthus* presents minimal change, with control and experimental values being very close (3.34 to 3.59). Data from Gavinet et al. (2016) align with these averages, indicating a negligible impact from the experimental conditions. This suggests that *P. terebinthus* is less responsive or requires different conditions to see significant changes. *P. ponderosa* shows a slight increase from 8.8 in control to 10.53 in experimental conditions, consistent with the data from (Burgess & Wetzel, 2002). This moderate improvement indicates a positive but not pronounced response, similar to *P. taeda*. Overall, the experimental conditions generally enhance the measured parameter across most species, with *P. strobus* and *P. sylvestris* showing the most substantial increases.

The mixed responses within species like *P. palustris* highlight the complexity and potential influence of specific experimental setups or environmental factors, underscoring the importance of tailored approaches to optimize conditions for different species. Golev et al.(2020) reported a dramatic increase from 22.16 in control to 295.104 in experimental conditions, with nitrogen treatments showing even higher increases (from 19.45 to 364.625). Conversely, non-treated samples decreased from 33 to 17.02, indicating a strong dependence on the treatment for improved performance. Burgess and Wetzel (2002) reported a substantial increase in *P. strobus*, with values rising from 36 in control to 91.25 in experimental conditions. Similarly, Ward et al.(2000) showed a significant increase from 47.5 to 155, highlighting a robust positive response to the experimental conditions used in their study. (Lazcano et al., 2010) presented a slight increase from 8.8 to 10.533, showing a modest response to experimental conditions. This minimal change was consistent across nitrogen-treated samples, indicating the treatments did not have a significant impact. Gavinet et al. (2016) showed minimal variation with average values increasing only slightly from 3.31 in control to 3.49 in experimental conditions. This trend was consistent across different nitrogen treatments, suggesting that *P. terebinthus* is relatively unresponsive to the experimental conditions. Johansson et al., (2013)reported a moderate increase for *P. palustris*, with values rising from 32.36 in control to 35.13 in experimental conditions, indicating a positive but modest effect. Johansson et al. (2013) revealed a notable increase for *P. sylvestris*, with control values rising from 37 to 88.333 in experimental conditions. Nitrogen treatments showed increases from 16 to 70, and non-treated samples increased from 47.5 to 97.5, suggesting a significant positive response across different conditions. Knapp et al.(2018) reported a decrease in *P. palustris*, from 31 in control to 22.5 in experimental conditions, highlighting a negative impact. Lashley et al.(2017)showed a stable increase from 27 to 30, indicating a modest positive response. Pavinato et al.(2014)showed a significant increase for *P. elliottii*, from 3.54 to 14.76. Different treatments such as Basacote, nitrogen per cubic meter, and simple superphosphate all resulted in notable increases, indicating a strong positive response. Teskey & Will, (1999) demonstrated a moderate increase for *P. taeda*, with values rising from 6.5 to 11.75. Overall, the data indicates that while experimental conditions generally enhance growth parameters across most species, the degree of response varies significantly. This underscores the importance of tailoring experimental conditions to optimize growth responses for different *Pinus* species.

To maximize the benefits, it is recommended to tailor treatments to specific *Pinus* species, optimizing nitrogen levels for those showing significant positive responses, such as *P. strobus* and *P. sylvestris*. Long-term studies should be conducted to understand the sustained impact of these treatments, and a variety of experimental conditions should be explored to find the best combinations for each species. Developing standardized protocols for consistency across studies and investigating genetic factors that contribute to the variability in response can also help in creating more effective treatments. By following these recommendations, researchers and foresters can better optimize growth conditions for various *Pinus* species, enhancing their adaptability and productivity in different environments. The findings are consistent with other research in the field. For example, the significant positive response of *P. strobus* under experimental conditions mirrors results from studies by Mickaël et al.(2007b) and Ward et al.(2000). The dramatic increases in *P. sylvestris* observed by Golev et al., (2020) and Johansson et al., (2013)align with trends reported in broader forestry research, indicating high adaptability to nutrient enhancements (Gavinet et al., 2016; Teskey & Will, 1999; Wallertz et al., 2018). Similarly, the mixed responses seen in *P. palustris* across different studies (Burgess & Wetzel, 2002; Lazcano et al., 2010) reflect the complexities noted in other species' studies where environmental factors significantly influence outcomes. The moderate responses in *P. taeda* and *P. ponderosa* parallel findings by (Gavinet et al., 2016; Teskey & Will, 1999), suggesting consistent but less dramatic growth enhancements (Blouin et al., 2008; McKee et al., 1984; Mickaël et al., 2007a). The minimal changes in *P. terebinthus* align with observations by Gavinet et al., (2016) reinforcing the notion that certain species may require specific conditions or show limited responsiveness. These findings underscore the importance of context-specific research and the variability of species responses to experimental treatments across different environmental and experimental conditions (Dumas et al., 2021). Based on the comprehensive analysis of the data, several recommendations can be made to optimize growth conditions for various *Pinus* species. First, species such as *P. strobus* and *P. sylvestris* exhibit substantial positive responses to experimental conditions, particularly with nitrogen treatments. Therefore, it is recommended to prioritize nitrogen supplementation for these species to enhance growth and productivity.

Additionally, *P. elliottii* also demonstrates significant improvements under experimental conditions, indicating that similar treatment strategies could be beneficial. For species like *P. palustris*, which exhibit mixed responses, it is crucial to tailor the experimental conditions more carefully. Factors such as specific environmental conditions, soil type, and additional nutrients should be considered to maximize the positive effects observed in some studies. Long-term studies should be conducted to understand the sustained impact of these treatments and to identify the optimal combination of factors that promote growth. *P. pinaster*, which shows a modest positive response, can benefit from experimental conditions, but the effects may not be as pronounced as in other species. Further research is needed to explore additional treatments that could enhance growth for this species. For *P. taeda*, which shows moderate improvement, and *P. terebinthus*, which presents minimal change, it is recommended to explore alternative experimental conditions or additional supplements that might yield better results. Since *P. ponderosa* shows a slight increase, similar to *P. taeda*, the focus should be on optimizing current treatments and exploring new ones to enhance growth. Overall, the data indicates that while experimental conditions generally enhance growth parameters across most species, the degree of response varies significantly. This underscores the importance of tailoring experimental conditions to optimize growth responses for different *Pinus* species. To maximize the benefits, it is recommended to tailor treatments to specific *Pinus* species, optimizing nitrogen levels for those showing significant positive responses, such as *P. strobus* and *P. sylvestris*. Long-term studies should be conducted to understand the sustained impact of these treatments, and a variety of experimental conditions should be explored to find the best combinations for each species. Developing standardized protocols for consistency across studies and investigating genetic factors that contribute to the variability in response can also help in creating more effective treatments. By following these recommendations, researchers and foresters can better optimize growth conditions for various *Pinus* species, enhancing their adaptability and productivity in different environments.

Conclusion

The data analysis across various studies of the genus *Pinus* reveals significant variations in responses to experimental conditions, underscoring the importance of tailored approaches for optimizing growth. Species like *P. strobus* and *P. sylvestris* exhibit substantial positive responses, particularly to nitrogen treatments, suggesting that these species can benefit greatly from such experimental conditions. *P. elliottii* also shows significant improvement, indicating a high responsiveness to experimental treatments. Conversely, species such as *P. palustris* show mixed responses, highlighting the need for more carefully tailored experimental conditions that consider specific environmental factors and nutrient needs. *P. pinaster* demonstrates a modest positive response, suggesting potential for enhanced growth with optimized treatments. *P. taeda* shows moderate improvement, while *P. terebinthus* and *P. ponderosa* exhibit minimal to slight increases, indicating a need for further exploration of alternative or additional treatments. Overall, the findings underscore the necessity of customizing experimental conditions to the specific needs of each *Pinus* species to maximize growth and productivity. Recommendations include prioritizing nitrogen supplementation for responsive species, conducting long-term studies to understand sustained impacts, exploring a variety of experimental conditions, and developing standardized protocols for consistency. By implementing these strategies, researchers and foresters can enhance the adaptability and productivity of *Pinus* species in different environments, contributing to better forest management and ecological research outcomes.

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