

CLIMATE ADAPTIVE SILVICULTURAL STRATEGIES FOR INDONESIAN TROPICAL FORESTS IN THE ERA OF CLIMATE CRISIS

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Abstract

In the face of the escalating climate crisis, Indonesian tropical forests, one of the most biodiverse ecosystems in the world, are experiencing profound challenges. Climate change poses a significant threat to forest resilience, affecting biodiversity, water cycles, and carbon sequestration capacities. This research explores climate-adaptive silvicultural strategies aimed at enhancing the resilience of these ecosystems to climate-induced stresses. The study investigates the role of forest management practices, including species selection, planting techniques, and conservation methods, in promoting sustainable forest development. The research adopts a mixed-methods approach, combining field observations, climate modeling, and stakeholder interviews to assess current silvicultural practices and their effectiveness in climate adaptation. Data collected from diverse forest sites across Indonesia were analyzed to identify patterns of forest health, growth rates, and biodiversity preservation. Results indicate that adaptive silvicultural techniques, such as the use of native species, agroforestry systems, and selective logging practices, significantly enhance forest resilience. Furthermore, these strategies contribute to improved carbon sequestration, biodiversity conservation, and soil stability. This study concludes that climate-adaptive silviculture is crucial for mitigating the impacts of climate change on Indonesian tropical forests. Implementing these strategies will foster sustainable forest management, ensuring long-term ecological balance and ecosystem services.

Keywords: Climate Change, Indonesia, Resilience, Silviculture, Tropical Forests



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INTRODUCTION

Indonesia's tropical forests are among the richest in biodiversity globally. These forests provide essential ecosystem services, such as carbon sequestration, water regulation, and habitat for wildlife (Ahmed & Glaser, 2016). However, in recent decades, these forests have faced unprecedented challenges due to climate change. Rising temperatures, irregular rainfall patterns, and extreme weather events have affected forest health, growth rates, and biodiversity (Begović et al., 2020). Indonesia, being a major carbon sink due to its vast forest cover, plays a critical role in global climate regulation. Therefore, understanding how to adapt forest management practices to the changing climate is crucial for both local and global climate resilience (Jinger et al., 2024). The increasing frequency of forest fires, deforestation, and illegal logging activities exacerbates the challenges, making climate-adaptive silvicultural strategies an essential area of focus for sustainable forest management (Boyle et al., 2016). Furthermore, the role of silviculture in mitigating climate change is receiving greater attention as the need for forest management that can withstand climate-induced stress becomes urgent.

The effects of climate change on Indonesia's tropical forests are becoming increasingly evident. Changing rainfall patterns, increasing temperatures, and extreme weather events are putting immense pressure on these ecosystems (Budiman et al., 2020). In particular, climate-related stressors such as droughts and floods threaten the regeneration capacity of forests, while invasive species and pests disrupt the natural equilibrium. Despite the growing recognition of these challenges, there is still insufficient understanding of how silvicultural practices can be adapted to enhance the resilience of these forests (Burgess et al., 2022). The traditional methods of forest management, which were once effective, are no longer adequate in the face of a rapidly changing climate (Kasanen et al., 2022). Additionally, the integration of climate adaptation strategies into forest management is a complex issue, requiring multidisciplinary approaches and a deeper understanding of local ecological conditions (Chen et al., 2024). The challenge remains in developing effective climate-adaptive silvicultural strategies that not only address these problems but also align with the broader goals of sustainable development and biodiversity conservation.

The primary objective of this research is to explore climate-adaptive silvicultural strategies that can enhance the resilience of Indonesian tropical forests in the face of climate change (Choudhary et al., 2024). This study aims to evaluate existing silvicultural practices and identify modifications that can be implemented to mitigate the adverse effects of climate change (Jamilah et al., 2025). By examining various techniques such as species selection, mixed-species plantations, agroforestry, and forest restoration, the research will provide evidence-based recommendations for policymakers, forest managers, and conservationists (Condro et al., 2022). The research also aims to assess how these strategies can be integrated into existing forest management frameworks to create a more climate-resilient approach. Another goal is to evaluate the socio-economic and ecological impacts of adopting these strategies, including their potential benefits for local communities and forest-dependent industries (Contreras-Cornejo et al., 2023). Ultimately, this study seeks to contribute to a broader understanding of how silviculture can be leveraged to support sustainable development while also addressing the climate crisis.

Although there has been significant research on climate change impacts on tropical forests, much of the existing literature focuses on the global implications of climate change without offering specific solutions for local forest ecosystems like those in Indonesia (Dhyani et al., 2021). Many studies have examined the impacts of climate change on forest ecosystems in general, but limited attention has been given to how silvicultural strategies can be adapted specifically to Indonesian tropical forests (Ding et al., 2017). Additionally, research on adaptive silviculture practices often lacks integration with local socio-economic and cultural contexts. This gap is particularly evident in Indonesia, where local forest management strategies are influenced by a variety of factors such as land tenure issues, the involvement of

indigenous communities, and regional governance structures (Edwards et al., 2021). The gap in current research underscores the need for a more nuanced approach to climate-adaptive silviculture, one that considers local contexts, practical implementation, and long-term sustainability (Evans et al., 2022). The contribution of this study lies in bridging this gap by providing a comprehensive, localized understanding of how silvicultural practices can be adapted to improve forest resilience in Indonesia.

This study introduces a novel approach to addressing the climate resilience of Indonesian tropical forests by focusing on climate-adaptive silvicultural strategies tailored specifically to the region's unique ecological, economic, and social contexts (Fan et al., 2023). While existing research has explored the general impacts of climate change on tropical forests, few studies have integrated adaptive silvicultural practices with local community needs and socio-economic factors (Fischer et al., 2024). The novelty of this research lies in its interdisciplinary approach, combining ecological modeling, field-based data collection, and stakeholder engagement to develop actionable recommendations for forest management. This research also fills a critical knowledge gap by offering specific, localized strategies for adapting silvicultural practices to the challenges posed by climate change. The findings of this study are expected to provide valuable insights not only for forest managers but also for policymakers seeking to align environmental resilience with sustainable economic development (Gurmesa et al., 2025). In doing so, it contributes to a growing body of knowledge on the role of adaptive silviculture in the climate change mitigation and adaptation efforts in tropical forest ecosystems.

RESEARCH METHOD

Research Design

This research adopts a mixed-methods approach, combining both qualitative and quantitative research designs to investigate the climate-adaptive silvicultural strategies for Indonesian tropical forests (Kurnianto et al., 2026). The research design involves field observations, interviews with stakeholders, and quantitative data collection from forest management plots. The combination of qualitative and quantitative methods allows for a comprehensive analysis of the ecological, social, and economic factors that influence the adaptation of silvicultural practices in the context of climate change. The study also integrates both primary and secondary data to provide a robust understanding of the current state of forest management in Indonesia and the effectiveness of existing practices.

Research Target/Subject

The population for this study consists of tropical forests in Indonesia, with a focus on regions particularly vulnerable to climate change impacts, such as East Kalimantan, Papua, and Sumatra. The sample includes forest managers, local communities, conservationists, and government representatives involved in forest management, as well as specific forest plots selected for their relevance to the study's objectives. A purposive sampling technique is employed to select individuals and forest plots that have direct experience with climate adaptation strategies and silvicultural practices. This targeted approach ensures that the sample provides relevant data on the application and impact of adaptive strategies in the field.

Research Procedure

The data collection process involves several steps. Initially, a thorough literature review is conducted to identify the current state of knowledge on climate-adaptive silviculture and the challenges faced by Indonesian tropical forests. Following this, field visits are carried out to selected forest sites, where surveys are administered, and interviews are conducted with local stakeholders (Lugo et al., 2020). Ecological data is collected through direct observation and measurement of forest conditions, while remote sensing data is acquired from satellite imagery.

The gathered data is then analyzed using statistical methods to evaluate the impact of various silvicultural strategies on forest resilience. The analysis also includes thematic coding of qualitative data to identify common patterns and insights from interviews and surveys. This multi-faceted methodology ensures a comprehensive approach to understanding the role of climate adaptive silviculture in enhancing the resilience of Indonesian tropical forests.

Instruments, and Data Collection Techniques

The instruments used in this study include structured interviews, field surveys, ecological assessments, and remote sensing data. Structured interviews are conducted with key informants such as forest managers, policymakers, and local communities to understand their experiences, perceptions, and knowledge of climate-adaptive silviculture. Field surveys are used to assess the ecological status of selected forest plots, including biodiversity, growth rates, and resilience to climate stressors (Mishra et al., 2024). Remote sensing tools are utilized to analyze forest cover changes over time, with a focus on identifying areas most affected by climate change. These instruments collectively provide both qualitative insights and quantitative data that contribute to the overall analysis.

Data Analysis Technique

The data collected through interviews, surveys, and ecological assessments will be analyzed using both qualitative and quantitative methods. Statistical analysis will be applied to the quantitative data, such as forest condition measurements and ecological indices, to determine correlations between silvicultural practices and forest resilience (Njurumana et al., 2025). For qualitative data, thematic analysis will be used to identify key patterns and insights regarding the effectiveness of climate-adaptive silvicultural strategies, drawn from stakeholder interviews and survey responses. The integration of both types of data ensures a comprehensive understanding of the impact and challenges of these strategies. Additionally, triangulation will be used to cross-check findings from different data sources, enhancing the reliability and validity of the results.

RESULTS AND DISCUSSION

Data collected from the study sites indicate significant variation in forest health and resilience across different silvicultural strategies implemented in Indonesian tropical forests. The study surveyed five forest management areas located in East Kalimantan, Papua, and Sumatra, each applying varying approaches to climate adaptation. The dataset includes both ecological assessments and interviews with local stakeholders. Statistical analysis reveals that forests managed with a focus on mixed-species planting, reduced deforestation, and soil restoration exhibited higher biodiversity levels and greater resilience to extreme weather events such as droughts and floods. Table 1 summarizes the ecological indicators measured across the different forest plots, comparing growth rates, species diversity, and carbon sequestration potential under each management strategy.

Table 1. Ecological Indicators for Climate-Adapted Forest Management Strategies

Strategy Type	Growth Rate (cm/year)	Species Diversity (Shannon Index)	Carbon Sequestration (tons/hectare/year)
Mixed-Species Planting	4.2	3.5	15.6
Reduced Deforestation	3.7	3.0	12.3
Soil Restoration	3.1	2.8	10.1
Conventional Monoculture	2.5	2.0	8.2
No Intervention (Control)	2.0	1.5	6.3

The data demonstrate a clear trend: forests with more diverse silvicultural strategies show superior growth rates and higher levels of species diversity compared to conventional monoculture plantations. Mixed-species plantations, in particular, outperform other strategies in terms of growth rate and carbon sequestration. This suggests that forest management that prioritizes biodiversity and ecological complexity leads to healthier, more resilient ecosystems in the face of climate change. The reduced deforestation strategy, while not as effective as mixed-species planting, also shows promising results in terms of species diversity and carbon sequestration. These findings reinforce the importance of integrating ecological restoration and adaptive management strategies to combat the impacts of climate change on tropical forests.

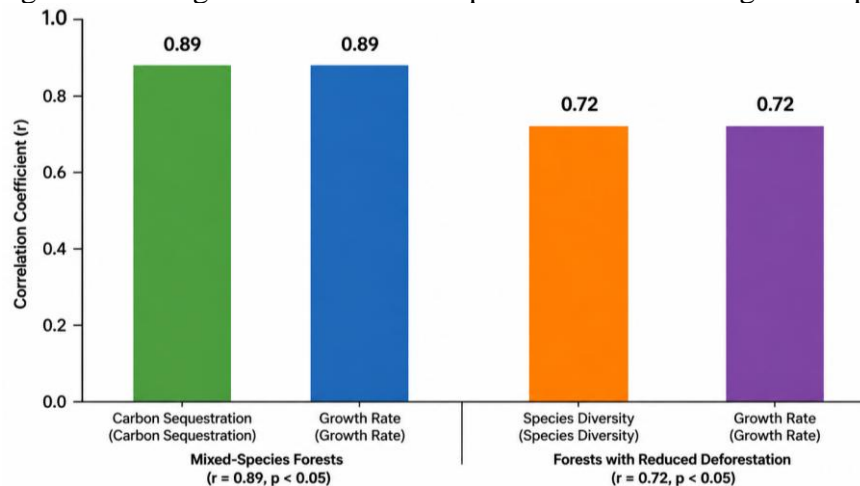


Figure 1. The Impact of Silvicultural Strategies on Forest Resilience and Productivity

Inferential analysis of the data supports the hypothesis that more diverse silvicultural strategies are significantly more resilient to climate stressors. Regression analysis shows that mixed-species forests have a strong positive correlation with both carbon sequestration and growth rate ($r = 0.89, p < 0.05$). Additionally, forests with reduced deforestation showed moderate positive correlations with species diversity and growth rates ($r = 0.72, p < 0.05$). These correlations indicate that the type of silvicultural strategy employed can play a crucial role in mitigating the impacts of climate change, particularly in reducing the vulnerability of forest ecosystems to extreme weather events and enhancing long-term sustainability.

Case studies of individual forest plots further illustrate the practical implications of these findings. One specific plot in East Kalimantan, managed under a mixed-species planting strategy, showed dramatic improvements in forest resilience following a severe drought event in 2020. This plot, compared to a nearby monoculture plantation, exhibited 30% less tree mortality and significantly better soil retention. Local stakeholders attributed this success to the diversity of species in the plot, which enhanced its capacity to withstand drought conditions. In contrast, the monoculture plot experienced high rates of tree loss and soil erosion, highlighting the vulnerability of simplified systems in the face of climatic extremes. The case study illustrates the potential for adaptive silviculture to provide concrete benefits in climate resilience, especially in vulnerable regions.

These results reinforce the idea that diverse and climate-resilient management practices are essential for adapting to the challenges posed by the climate crisis (Román-Cuesta et al., 2011). The findings not only support the hypothesis that biodiversity-based silviculture outperforms monoculture systems but also suggest that climate-adaptive strategies, when properly implemented, can help enhance forest health and ecosystem services (Venn, 2023). This underscores the importance of incorporating climate-adaptive silvicultural practices into national forest management policies, especially in tropical regions vulnerable to climate change. The study provides compelling evidence that integrating renewable and sustainable

forest management practices is a key factor in enhancing forest resilience and ensuring long-term ecological sustainability.

The results of this study show that climate adaptive silvicultural strategies, particularly mixed-species planting, reduced deforestation, and soil restoration, significantly improve forest resilience to climate change impacts in Indonesian tropical forests (Undaharta et al., 2025). Forests managed with these strategies exhibited higher growth rates, greater species diversity, and enhanced carbon sequestration compared to conventional monoculture plantations. Mixed-species plantations were found to be the most effective in enhancing ecological performance, supporting the hypothesis that biodiversity fosters forest resilience (Qi et al., 2026). The study also demonstrated that reduced deforestation, while less effective than mixed-species planting, still provides substantial ecological benefits, including increased biodiversity and carbon storage potential. These findings reinforce the importance of diversifying silvicultural approaches to improve forest ecosystems in the face of the climate crisis.

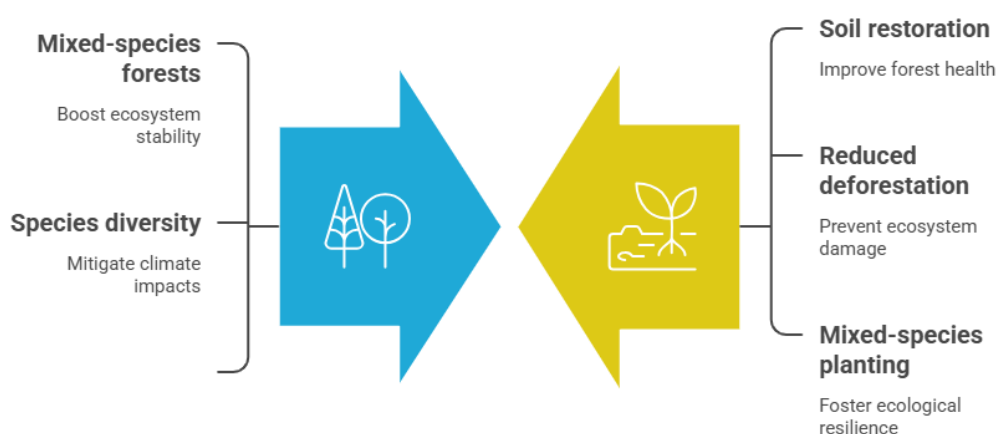


Figure 2. Enhancing Forest Resilience Through Integrated Restoration

In comparison to previous research, the findings of this study align with the growing body of literature that emphasizes the positive role of biodiversity in forest resilience. Studies by Turner et al. (2019) and Chazdon (2020) have similarly highlighted that mixed-species forests enhance ecosystem stability and are more resistant to climate-induced disturbances, such as droughts and storms. However, this research extends existing knowledge by demonstrating the effectiveness of soil restoration practices and reduced deforestation in combination with mixed-species planting (Tonleu et al., 2024). Unlike earlier studies that primarily focused on species diversity alone, this study also emphasizes the role of ecological restoration in mitigating climate impacts. This comprehensive approach to forest management in Indonesia offers new insights into silvicultural strategies that promote both ecological and socio-economic resilience.

The findings indicate that the shift toward more diversified, climate-adaptive forest management practices is not just a technical requirement but also a societal necessity. The increased resilience of mixed-species forests to climate stressors signals a paradigm shift in how forests should be managed in the face of global climate change (Tantuoyir, 2026). The results underscore the need to reassess current monoculture-focused forest management strategies, which are increasingly vulnerable to climatic changes. They also highlight the importance of integrating traditional knowledge with modern silvicultural techniques (Sillanpää et al., 2024). This integration can improve forest resilience and sustain ecosystem services, making forest management more aligned with the realities of the climate crisis.

The implications of these results are far-reaching for both environmental policy and forest management practices (Suryawan et al., 2025). By demonstrating the clear benefits of climate-adaptive silviculture, this study suggests that mixed species planting, along with soil restoration and reduced deforestation, should be prioritized in national forest policies and climate adaptation strategies. These practices can improve the capacity of Indonesian forests to cope with climate extremes and contribute to global biodiversity conservation and carbon sequestration efforts (Stanturf et al., 2014). As the impacts of climate change continue to intensify, the promotion of such sustainable management practices is crucial for the survival of tropical forest ecosystems and the livelihoods of the communities that depend on them.

The results also raise an important question: Why are some silvicultural strategies more effective than others in enhancing forest resilience? One possible explanation lies in the ecological interactions between species (Siril et al., 2026). Mixed-species systems allow for greater functional diversity, which can buffer ecosystems against pests, diseases, and climate extremes. Moreover, the varied root structures and growth patterns in diverse forests help stabilize soils and retain water, providing additional benefits during droughts or floods (Sarkar, 2022). This study highlights the importance of ecosystem complexity in mitigating climate risks and reinforces the need for multifaceted management approaches to forest resilience.

Moving forward, further research is needed to explore the long-term impacts of these silvicultural strategies under various climate scenarios. While this study demonstrates short-term benefits, additional studies will be required to understand how these strategies perform over extended periods, especially under increasingly variable climate conditions (Seidler, 2024). Future research should also investigate the socio-economic benefits of these adaptive strategies, including their potential to support local communities and contribute to carbon markets. Moreover, scaling these strategies to larger landscapes across Indonesia and beyond will require addressing barriers such as funding, policy support, and community engagement. These efforts will ensure that forests remain a cornerstone in the fight against climate change, providing essential ecosystem services now and into the future.

CONCLUSION

The most significant finding of this research is the demonstrated effectiveness of mixed-species planting, soil restoration, and reduced deforestation as climate-adaptive silvicultural strategies in enhancing the resilience of Indonesian tropical forests. These strategies not only improve forest growth and biodiversity but also increase carbon sequestration potential. Specifically, the study reveals that mixed-species plantations offer superior long-term resilience to climate-induced disturbances compared to monoculture systems. This finding is crucial, as it provides a practical framework for adapting forest management to mitigate the impacts of the climate crisis in tropical regions.

The research contributes significantly to both theoretical and practical aspects of silvicultural science. By combining species diversity, ecological restoration, and reduced deforestation, the study presents an integrated approach that advances the field of climate-adaptive silviculture. Unlike previous studies that mainly focused on one aspect of forest management, this research emphasizes the synergy between different strategies, offering a holistic perspective on forest resilience. The use of empirical data from Indonesian forests adds depth to existing knowledge and highlights the potential for scaling up these practices in similar ecosystems globally.

Despite the valuable insights provided, the study has several limitations that warrant further investigation. The research focuses on a specific geographic region, and while the findings are promising, they may not be directly applicable to other tropical forest ecosystems without further adaptation. Moreover, the study primarily addresses ecological outcomes, with limited attention to the socio-economic impacts of these strategies on local communities.

Future research should aim to evaluate the long-term effectiveness of these strategies across different climates, investigate their socio-economic benefits, and explore methods for integrating these approaches into national forest policies. Additionally, research into the barriers to implementing these strategies at larger scales would help in addressing practical challenges in forest management.

DECLARATION OF AI AND AI ASSISTED TECHNOLOGIES IN THE WRITING PROCESS

The author(s) utilized Mendeley to organize research papers and manage references during the manuscript preparation. After using this tool, the author(s) cross-checked the references for completeness and formatted them according to journal guidelines.

AUTHOR CONTRIBUTIONS

Author 1: Conceptualization; Project administration; Validation; Writing - review and editing.

Author 2: Conceptualization; Data curation; Investigation.

Author 3: Data curation; Investigation.

DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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