Jurnal Manajemen Hutan Tropika, *32*(2), 121–127, April 2026
EISSN: 2089-2063
DOI: 10.7226/jtfm.32.2.121

Scientific Article
ISSN: 2087-0469

Evaluating Enrichment Planting for Tropical Forest Restoration: A Case Study of *Erythrophleum fordii* and *Manglietia conifera* in Central Vietnam

Nguyen Toan Thang[1*], Dao Trung Duc[1], Nguyen Trong Minh[2], Trinh Ngoc Bon[1], Truong Trong Khoi[1], Vu Tien Lam[1], Nguyen Van Tuan[1], Hoang Van Thanh[1], Nguyen Huy Hoang[1], Pham Tien Dung[1], Tran Hoang Quy[1], Tran Van Do[1]

[1]Silviculture Research Institute, Vietnamese Academy of Forest Sciences, Hanoi, Vietnam 100000
[2]Viet Nam National University of Forestry, Xuan Mai Town, Hanoi, Vietnam 100000

Received May 24, 2025/Accepted August 27, 2025

Abstract

This study evaluates the long-term effectiveness of enrichment planting as a restoration strategy in Central Vietnam, focusing on the performance of Erythrophleum fordii *and* Manglietia conifera*. A restoration site was established in 2006 using a line planting over a 1-ha area, with no fertilizer applied and minimal tending during the first three years. After 18 years,* E. fordii *demonstrated superior growth performance, with a larger diameter at breast height* (*21.1 cm*) *and standing volume* (*94.56 m^{-3} ha^{-1}*)*, while* M. conifera *showed a lower diameter at breast height* (*16.8 cm*) *and standing volume* (*55.15 m^{-3} ha^{-1}*)*. Survival rates differed significantly between species, with* E. fordii *achieving 88.0% compared to 73.3% for* M. conifera*. Notably,* M. conifera *had better stem quality* (*90.9%*) *compared to* E. fordii (*80.8%*)*. Regression analysis revealed weak to moderate correlations between growth parameters for* E. fordii*, indicating complex growth dynamics, while* M. conifera *exhibited minimal correlations, suggesting other factors influence its development. These findings highlight the species-specific trade-offs and complementary roles in mixed-species planting. This research provides descriptive evidence of the potential for enrichment planting to establish valuable tree species in degraded forests, emphasizing the importance of species selection and management strategies for achieving restoration objectives in sustainable forest management.*

Keywords: *mixed-species enrichment, restoration goals, species-specific trade-offs, sustainable timber management, tropical forest restoration*

**Correspondence author, email*: *nguyentoanthangfsiv@gmail.com*

Introduction

Forests in tropical regions play a pivotal role in global biodiversity conservation, carbon sequestration, and providing livelihoods for local communities (Artaxo et al., 2022). Vietnam's tropical forests, once covering vast expanses, have experienced significant deforestation and degradation due to agricultural expansion, logging, and infrastructure development (Meyfroidt & Lambin, 2008). These activities have not only reduced forest cover but also impacted ecosystem services and biodiversity. To address these challenges, various forest restoration strategies have been employed, among which enrichment planting has gained prominence as an effective approach for rehabilitating degraded forests and enhancing their ecological and economic value (Sovu et al., 2010; Kefyalew et al., 2023).

Enrichment planting involves the deliberate introduction of valuable tree species into degraded or secondary forests to accelerate recovery and improve forest composition (Ashton et al., 2001; Paquette et al., 2009; Sovu et al., 2010). This technique is particularly suited for tropical regions where natural regeneration alone is insufficient to restore degraded ecosystems within reasonable timeframes (Chazdon, 2008). In Vietnam, enrichment planting has been widely adopted in restoration projects, especially in areas dominated by evergreen broadleaf forests, which are among the most threatened ecosystems.

Despite widespread application, several knowledge gaps persist regarding enrichment planting effectiveness. Limited long-term performance data (>15 years) exists for tropical enrichment systems, particularly regarding species-specific growth comparisons in Southeast Asian contexts (Sovu et al., 2010). Additionally, there is insufficient understanding of mixed-species interactions in enrichment systems and optimal species combinations for different site conditions (Marshall et al., 2022). Most studies focus on short-term establishment success rather than long-term productivity and sustainability outcomes (Paquette et al., 2009). A systematic review of enrichment planting literature in Southeast Asia reveals that most studies (>70%) focus on establishment success (1–5 years) rather than long-term performance outcomes. Furthermore, limited comparative data exists on species-specific growth patterns and mixed-species interactions in tropical monsoon climates. Specifically, no long-term studies (>15 years) have compared *Erythrophleum fordii* and *Manglietia conifera's* performance in enrichment systems, creating a significant knowledge gap that this

Jurnal Manajemen Hutan Tropika, *32*(2), 121−127, April 2026
EISSN: 2089-2063
DOI: 10.7226/jtfm.32.2.121

Scientific Article
ISSN: 2087-0469

research addresses.

Among the species used in Vietnamese restoration programs, *E. fordii* and *M. conifera* stand out for their ecological importance and economic potential. These species serve important roles in regional biodiversity conservation and species preservation efforts, as they provide high-quality timber and non-timber forest products, making them valuable for sustainable forest management (Doc et al., 2015; Thanh et al., 2023).

E. fordii, commonly referred to as "ironwood," is a medium- to large-sized evergreen tree native to Southeast Asia (Wen et al., 2023). Known for its dense and durable timber, the species is highly resistant to termites and decay, making it a preferred material for construction and furniture. However, overharvesting and habitat loss have led to a dramatic decline in its natural populations, classifying it as a threatened species in Vietnam (Sein & Mitlöhner, 2011). Similarly, *M. conifera* is an evergreen broadleaf species valued for its timber. Despite its economic significance, limited information is available regarding its natural distribution and ecological characteristics, which complicates conservation and restoration efforts (Ha et al., 2022). The success of enrichment planting projects depends on various factors, including site selection, species compatibility, planting techniques, and post-planting management (Chazdon, 2008). The complex topography and tropical monsoon climate of Central Vietnam provide both opportunities and challenges for implementing such projects (Pilarczyk & Nuoi, 2005).

This study addresses the identified knowledge gaps by providing 18-year longitudinal data on species performance, comparing growth characteristics of two economically important species, and evaluating species-specific responses to enrichment planting conditions in Central Vietnam's monsoon climate. This study aims to evaluate the effectiveness of enrichment planting as a restoration strategy in Central Vietnam, focusing on the performance of *E. fordii* and *M. conifera* by analyzing long-term growth with the following specific objectives: 1) evaluate the long-term growth performance and survival of both species in enrichment planting systems, 2) analyze growth relationships and architectural differences between species, and 3) assess the potential for mixed-species restoration in Central Vietnam.

Methods

Study site A restoration site of *M. conifera* and *E. fordii* was established in 2006 by local farmers as part of an enrichment silviculture practice in Nghe An Province, Central Vietnam (N19°44′26″, E104°58′48″), at an elevation of 173 m above sea level. The site was previously degraded through selective logging activities (2000-2005), resulting in clear indicators of forest degradation, including canopy openness of 60–70% (compared to 10–20% in intact forests), basal area of 9–13 m² ha^{-1} (versus 25–35 m² ha^{-1} in natural forests), presence of invasive grasses (*Imperata cylindrica*, *Chromolaena odorata*), soil compaction from logging machinery, and absence of natural regeneration of climax species. The site is characterized by an evergreen broadleaved forest dominated by species such as *Schima wallichii*, *Cinnadenia paniculata*, *Lithocarpus ducampii*, *Syzygium wightianum*, and *Lithocarpus dealbatus*. Notably, *M. conifera* is absent from this area, and *E. fordii* is scarce due to previous overharvesting. The natural vegetation consists of tropical evergreen broadleaf forests, although significant areas have been modified by human activities. The forest stand exhibits a density of 350–450 stems per hectare, a canopy height of 14–16 m, an average stem diameter of 20–25 cm, and a canopy cover ranging from 0.4 to 0.5.

The area features a complex topography characteristic of the region's mountainous terrain. It experiences a tropical monsoon climate with distinct wet and dry seasons. Annual precipitation ranges from 1,500 to 2,000 mm, with the majority occurring during the rainy season (May to October). The mean annual temperature fluctuates between 22 °C and 25 °C, with significant diurnal and seasonal variations. Soils are predominantly ferralitic, developed from various parent materials, including limestone and metamorphic rocks. These soils are shallow, well-drained, and poor in humus content. The region occasionally experiences extreme weather events, such as tropical storms during the monsoon season and periodic droughts during the dry season (November to April).

The restoration site, which spans 1 ha (0.5 ha for each species), employed a line planting technique. This involved creating 2-m-wide cleared strips by removing all understory vegetation (shrubs and herbaceous plants) below 1 m in height. Canopy trees and vegetation above 1 m were retained to maintain partial shade and forest structure. The distance between planting lines was 3 m. Within each line, *M. conifera* and *E. fordii* were mixed-planted in a 1:1 ratio, with 5 m between individual trees, resulting in a spacing of 5 m × 5 m. Planting holes measuring 40 cm × 40 cm × 40 cm were prepared. Seedlings used were 0.5–0.7 m in height with root collar diameters of 0.8–1.2 cm. No fertilizer was applied at planting or afterward. Tending was conducted during the first three years after planting, consisting of weeding, soil mounding around seedlings (a common practice in Central Vietnam's monsoon climate to improve drainage during wet seasons and enhance water retention during dry periods), and vine cutting.

Data collection Sample plots, each measuring 1,000 m² (25 m × 40 m), were established using stratified random sampling based on topographic position within the restoration site to ensure representation of site variability. While our 1-ha study represents a pilot-scale implementation typical of farmer-managed restoration, the results are applicable to similar site conditions in Central Vietnam, though landscape-level extrapolation requires caution. Within each plot, all surviving stems of *M. conifera* and *E. fordii* were measured for diameter at breast height ($D_{1.3}$, cm), total height (H, m), height to crown base (H_{cb}, m), and crown diameter (D_c, m). Dead stems were recorded to estimate survival rates.

Surviving stems were classified into three quality categories: good, medium, or poor. Good stems were characterized by straight growth, a symmetrical crown, and absence of disease. Poor stems were identified as having curved trunks, asymmetrical crowns, and signs of disease. Medium stems exhibited characteristics intermediate between the good and poor categories.

Data *analysis* Standing volume (V; m^3) was estimated as $V = GHf$, note $G = (3.14\ (D_{1.3}/100)^2)/4$, H is total height, and f is stem form factor, set at 0.5 (Forest Inventory and Planning Institute, 2002). We acknowledge that this form factor represents a simplified approximation. Comparison with regional equations for similar species and uncertainty analysis indicated potential errors of ±10% (Forest Inventory and Planning Institute, 2002). Additionally, we lack comprehensive baseline data of initial forest conditions, which limits the ability to quantitatively assess restoration gains over time or compare pre- and post-intervention conditions.

Means and standard errors were calculated for all parameters of both species. Comparative analyses were conducted to assess interspecific differences in each parameter and identify the better-performing species. Regression analyses were used to examine the relationships between stem diameter and total height, stem diameter and crown diameter, and stem diameter and height to crown base, separately for each species and for the combined dataset. These regression models provide baseline relationships but do not account for potential confounding factors such as topographic variation, competition with surrounding vegetation, or micro-site conditions. The statistical procedures included descriptive statistics, t-tests, linear regression, and correlation analysis. While nonlinear or mixed-effects models may better capture complex growth dynamics, linear regression was selected as a baseline framework due to limited sample size and convergence issues. All statistical analyses were performed using SAS 9.2 (SAS Institute Inc., Cary, NC, USA), with the significance level set at p-value = 0.05.

Results

The growth parameters of *M. conifera* and *E. fordii* were evaluated over an 18-year post-planting period. Analysis revealed significant differences for growth parameters between two species, except stem height (H) (Table 1). *E. fordii* demonstrated superior diameter at breast height ($D_{1.3}$) with 21.1 ± 1.0 cm compared to that of *M. conifera* (16.8 ± 1.2 cm). Total height (H) measurements were comparable between species, with *M. conifera* reaching 14.9 ± 0.4 m and *E. fordii* attaining 14.4 ± 0.5 m. Height to crown base (H_{cb}) was significantly greater in *M. conifera* (6.7 ± 0.5 m) relative to *E. fordii* (5.2 ± 0.4 m), while crown diameter (D_c) exhibited an inverse relationship with *E. fordii* displaying significantly larger values (6.1 ± 0.5 m versus 4.6 ± 0.3 m). *M. conifera* exhibited superior stem quality (90.9%) but lower survival rates (73.3%) compared to *E. fordii* (80.8% and 88.0%, respectively). Notable differences were observed in standing volume, with *E. fordii* achieving 94.56 $m^3\ ha^{-1}$, substantially exceeding 55.15 $m^3\ ha^{-1}$ of *M. conifera*. These findings suggest species-specific trade-offs between growth parameters and survival rates at this site.

The relationships among growth parameters for *E. fordii* were analyzed through three distinct correlations with $D_{1.3}$ (Figure 1). Analysis revealed varying degrees of association between parameters. H showed a weak but significant positive correlation with $D_{1.3}$ (R^2 = 0.09, p-value = 0.03), following the regression equation $y = 0.15x + 11.19$ H_{cb} demonstrated no significant relationship with $D_{1.3}$ (R^2 = 0.01, p-value = 0.73), as evidenced by the nearly horizontal regression line ($y = 0.03x + 4.57$). The strongest correlation was observed between D_c and $D_{1.3}$, exhibiting a positive relationship of moderate (Cohen, 1988) strength according to Cohen's guidelines (R^2 = 0.31, p-value = 0.00) described by the equation $y = 0.28x + 0.29$. The scatter plots indicate considerable phenotypic variation within the population, with data points displaying notable dispersion around the regression lines, particularly in the relationship between H and $D_{1.3}$. These findings suggest that while some growth parameters of *E. fordii* are significantly correlated with trunk diameter, the relationships are generally moderate to weak, indicating complex growth patterns influenced by multiple factors.

Figure 2 presents the relationships among growth parameters for *M. conifera*. The analysis reveals weak correlations across all parameters. H exhibited a negligible correlation with $D_{1.3}$ (R^2 = 0.01, p-value = 0.66), with a regression equation of $y = 0.03x + 14.30$, indicating that tree

Table 1 Growth parameters of two studied species after planting 18 years

	D (cm)	H (m)	H_{cb} (m)	D_c (m)	Good quality stems (%)	Survival rate (%)	Standing volume (m^3/ha)
Manglietia conifera	16.8 ± 1.2 a	14.9 ± 0.4	6.7 ± 0.5 a	4.6 ± 0.3 a	90.9	73.3	55.15
Erythrophleum fordii	21.1 ± 1.0 b	14.4 ± 0.5	5.2 ± 0.4 b	6.1 ± 0.5 b	80.8	88.0	94.56

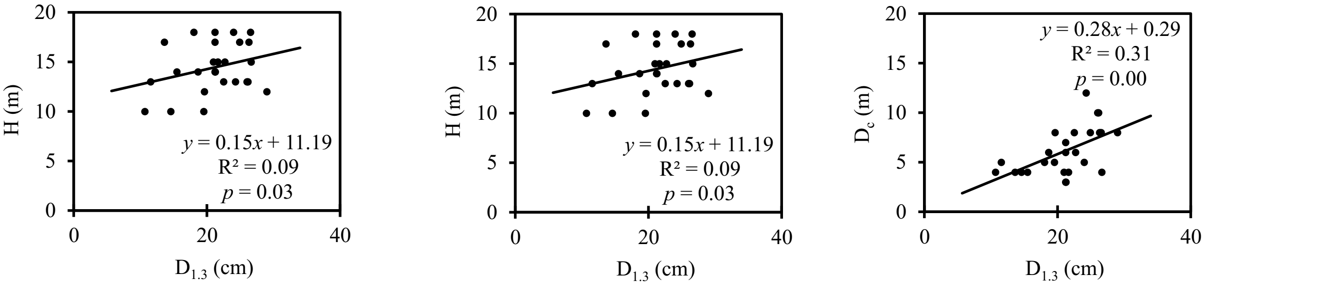

Figure 1 Relationships among growth parameters for *Ery-throphleum fordii*.

height remains relatively constant regardless of trunk diameter. H_{cb} showed a marginally stronger but still weak positive relationship with $D_{1.3}$ (R^2 = 0.14, p-value = 0.08), described by $y = 0.14x + 4.35$, though this relationship failed to achieve statistical significance at the conventional p-value = 0.05 level. D_c demonstrated minimal correlation with $D_{1.3}$ (R^2 = 0.05, p-value = 0.33), following the equation $y = 0.03x + 3.87$. The scatter plots reveal substantial variation around the regression lines, particularly evident in the height measurements. These findings suggest that the growth parameters of *M. conifera* develop largely independently of trunk diameter, indicating that other environmental or genetic factors may play more significant roles in determining these architectural characteristics.

Combined analysis of growth parameters for both *M. conifera* and *E. fordii* reveals intriguing patterns in their dimensional relationships (Figure 3). When examining the pooled data, $D_{1.3}$ proved to be a poor predictor of all three growth parameters. The relationship between H and $D_{1.3}$ yielded a negligible coefficient of determination (R^2 = 0.02) with no statistical significance (p-value = 0.31), as expressed by the equation $y = 0.06x + 13.47$. Similarly, H_{cb} showed virtually no correlation with $D_{1.3}$ (R^2 = 0.01, p-value = 0.66), following $y = 0.03x + 5.40$. In contrast, crown diameter (D_c) emerged as the only parameter exhibiting a meaningful relationship with $D_{1.3}$, demonstrating a moderate positive correlation (R^2 = 0.24) that was highly significant (p-value = 0.00), described by $y = 0.18x + 2.05$. The considerable scatter observed in all three relationships, particularly pronounced in the height measurements, underscores the complex nature of tree architecture and suggests that species-specific growth strategies may be masked when data are pooled across species.

Discussion

This study highlights the performance of enrichment planting as a restoration strategy for degraded tropical forests, focusing on the long-term growth performance (Bernard et al., 2021) of *E. fordii* and *M. conifera* in Central Vietnam. The findings reveal significant differences in growth parameters and survival rates between the two species, underscoring the need for species-specific management practices to optimize restoration outcomes (Chaonan & Feng, 2024).

The superior growth performance of *E. fordii* (Table 1), as evidenced by its greater diameter at breast height and standing volume compared to *M. conifera*, aligns with its ecological traits and adaptability to tropical environments (Sein & Mitlöhner, 2011). The average $D_{1.3}$ of *E. fordii* (21.1 cm) and its standing volume (94.56 m^3/ha) reflect its potential for timber production, supporting its inclusion in restoration projects aimed at economic and ecological benefits. Previous studies have similarly reported the high timber quality and growth potential of forest trees in Southeast Asia (Zhao et al., 2011; Wen et al., 2023). Conversely, *M. conifera* exhibited higher stem quality (90.9%) but lower survival rates (73.3%) compared to *E. fordii*. This discrepancy appears to be related to its sensitivity to site conditions and competition, which warrants further investigation into its ecological requirements. The weak correlations between $D_{1.3}$ and other growth parameters for *M. conifera* suggest that genetic or micro-environmental factors might significantly influence its development. This finding aligns with observations from other studies on species with similar growth patterns (Huang et al., 1997).

The survival and growth trade-offs observed between the two species emphasize the importance of mixed-species

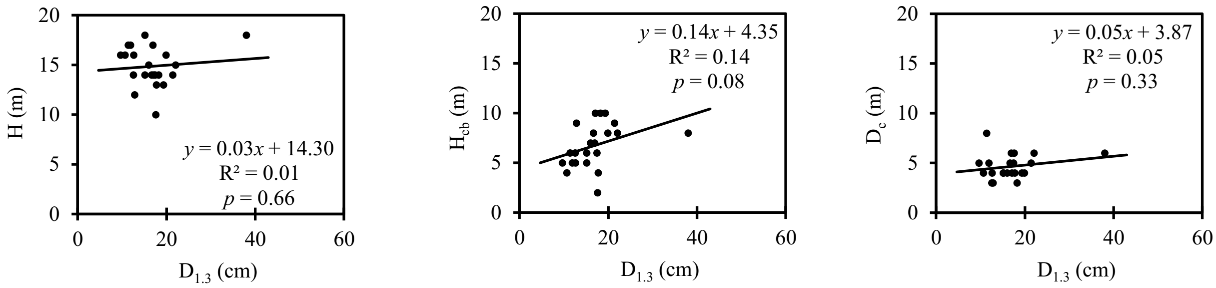

Figure 2 Relationships among growth parameters for *Manglietia conifera*.

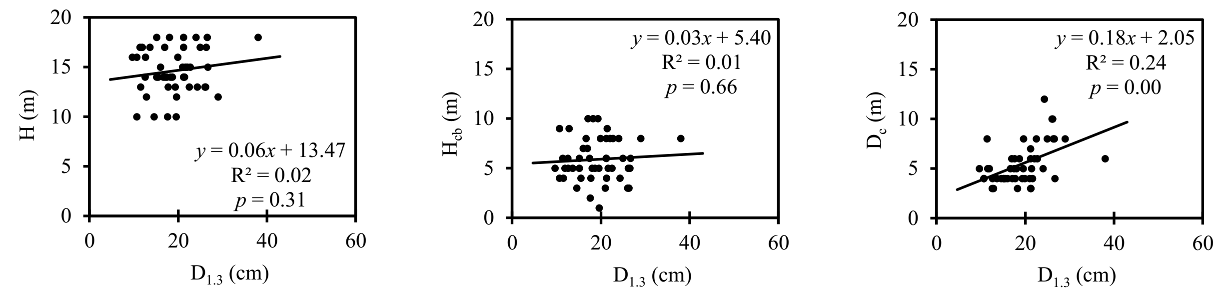

Figure 3 Relationships among growth parameters for both species combined.

Jurnal Manajemen Hutan Tropika, *32*(2), 121−127, April 2026
EISSN: 2089-2063
DOI: 10.7226/jtfm.32.2.121
Scientific Article
ISSN: 2087-0469

restoration sites (Corsa et al., 2018). Mixed restoration approaches can enhance biodiversity and ecosystem resilience by mimicking natural forest dynamics and reducing vulnerability to pests and diseases (Ashton et al., 2001; Sovu et al., 2010). The use of mixed-species arrangements, as implemented in this study, contributes to a balanced trade-off between ecological and economic goals, aligning with global trends in sustainable forest management (Paquette et al., 2009).

The species demonstrate complementary functional traits that support mixed-species management: *E. fordii* exhibits shade tolerance with broader crowns and a gap-phase regeneration strategy, achieving higher survival rates (88%) and superior volume production. In contrast, *M. conifera* displays light-demanding characteristics with narrow crowns, better natural pruning (higher crown base), and superior stem quality (90.9%). These architectural differences indicate that *E. fordii* may be better suited for understory conditions, while *M. conifera* performs optimally in higher light environments. The moderate correlation (Cohen, 1988) between $D_{1.3}$ and D_c in *E. fordii* (R^2 = 0.31) indicates its growth strategy focused on crown development, though this relationship requires validation through physiological evidence and direct light interception measurements to confirm light capture optimization. In contrast, the weak correlations across growth parameters for *M. conifera* suggest that its growth may be less reliant on above-ground competition and more influenced by below-ground factors, such as root development and nutrient uptake (James, 2003). These species-specific growth strategies highlight the necessity of tailored management practices to support their coexistence and maximize restoration site productivity (Chazdon, 2008; Sein & Mitlöhner, 2011).

After 18 years, competition between species is evident, particularly affecting *M. conifera* survival rates. Management recommendations include 1) immediate selective thinning to reduce competition and enhance growth of best-formed individuals, 2) maintaining a mixed-species composition with approximately a 60:40 ratio (*E. fordii*:*M. conifera*), 3) reducing current stand density to ~250 stems ha^{-1} to optimize timber quality and growth rates, and 4) implementing future thinning cycles every 5–7 years until final harvest.

The role of post-planting management cannot be overstated in influencing the success of enrichment planting (Marchall et al., 2022). Tending practices, including weeding and soil mounding, were crucial in the early stages of this project, reducing competition and improving seedling establishment (South et al., 2011). The absence of fertilizer application highlights the potential for low-input restoration techniques, which are particularly relevant for resource-limited contexts. This approach aligns with findings from similar studies emphasizing the cost-effectiveness of minimal-input strategies in tropical forest restoration (Artaxo et al., 2022; Kefyalew et al., 2023).

The climatic and edaphic conditions of the study site also played a critical role in shaping the outcomes. The tropical monsoon climate, characterized by distinct wet and dry seasons, imposes significant stress on planted species, particularly during the dry season (Hofhansl et al., 2020). Ferralitic soils, which are shallow and low in organic matter, further exacerbate these challenges. Species selection must therefore prioritize traits such as drought tolerance and nutrient efficiency to ensure successful establishment in such environments (Ha et al., 2022; Pilarczyk & Nuoi, 2005).

Comparison with other natural regeneration areas showed minimal tree establishment (<100 stems ha^{-1} after 18 years) with predominantly pioneer species, supporting the need for active restoration interventions (Ministry of Agriculture and Rural Development, 2010; Millet et al., 2013). However, we acknowledge that the absence of control treatments linits stronger conclusions about enrichment planting effectiveness compared to natural regeneration.

The findings of this study contribute to the broader understanding of species-specific responses to enrichment planting in degraded tropical forests (Rodrigo et al., 2021). By demonstrating the contrasting growth patterns and ecological roles of *E. fordii* and *M. conifera*, this research underscores the importance of diversifying species selection to achieve multifunctional restoration objectives. Genetic diversity within these species represents an important factor influencing restoration success and should be investigated in future studies to identify superior genotypes for restoration purposes. Such research should also investigate their interactions with other native and non-native species to optimize restoration site performance (Thanh et al., 2023).

Monitoring and evaluation are essential components of long-term restoration projects (Jeffrey et al., 2006). The 18-year data presented in this study provide valuable insights into the growth dynamics of the planted species and their responses to environmental and management factors. Such longitudinal studies are critical for refining restoration practices and ensuring their alignment with ecological and socio-economic goals (Clémentine et al., 2024). Incorporating remote sensing technologies and advanced statistical models could further enhance the monitoring of restoration outcomes and inform adaptive management strategies (Meyfroidt & Lambin, 2008; Paquette et al., 2009).

Local farmers implemented the enrichment planting as part of government-supported forest restoration programs, contributing labor and maintenance during the establishment phase. Economic incentives, such as income from timber and non-timber forest products, can further motivate community participation and support long-term conservation goals. This participatory approach aligns with global best practices in community-based forest management (Chazdon, 2008; Sovu et al., 2010). For example, farmers in Dong Van Commune reported using thinning-derived wood for domestic needs and received technical training under government reforestation programs (Ministry of Agriculture and Rural Development, 2010).

This study provides descriptive evidence of the potential for enrichment planting as a viable strategy for establishing valuable tree species in degraded tropical forests in Central Vietnam. By leveraging the complementary traits of *E. fordii* and *M. conifera*, mixed-species restoration can contribute toward achieving a balance between ecological and economic objectives. However, the success of such projects depends on careful species selection, tailored management practices, and active community involvement. Future research should focus on scaling up these findings to broader landscapes and exploring innovative approaches to enhance the resilience and functionality of restored forests. As findings are site-specific, caution should be taken in generalizing to broader ecological areas without further multi-site verification.

Conclusion

The findings of this study provide descriptive evidence of the performance of enrichment planting as a promising approach for establishing valuable tree species in degraded tropical forests in Central Vietnam. Over an 18-year period, *E. fordii* exhibited superior growth performance with a significantly larger diameter at breast height (21.1 cm) and standing volume (94.56 m^3 ha^{-1}) compared to *M. conifera*, which had a diameter at breast height of 16.8 cm and a standing volume of 55.15 m^3 ha^{-1}. Additionally, *M. conifera* displayed higher stem quality (90.9%) but lower survival rates (73.3%) than *E. fordii* (80.8% and 88.0%, respectively). The study highlighted species-specific trade-offs, such as *E. fordii* demonstrating a larger crown diameter (6.1 m), which supports efficient crown development, while *M. conifera* had a greater height at the crown base (6.7 m), indicating structural differences in growth strategies. Regression analysis revealed weak to moderate correlations between growth parameters for *E. fordii*, suggesting complex growth dynamics, while *M. conifera* exhibited negligible associations, implying its growth is influenced by other factors. These results emphasize the complementary roles of the two species, with *E. fordii* being suitable for timber production and *M. conifera* contributing to ecological diversity and aesthetic quality. While these results demonstrate successful species establishment and growth, future research with control treatments is needed to conclusively evaluate the effectiveness of enrichment planting compared to natural regeneration. Additionally, genetic diversity within these species should be investigated to identify superior genotypes, and adaptive management strategies should be developed to optimize their potential in mixed-species restoration sites, ensuring sustainable forest restoration and biodiversity conservation.

Acknowledgement

This research is funded by Vietnam Ministry of Agriculture and Environment under a project entitled “Nghiên cứu thực trạng và đề xuất giải pháp tổng hợp phục hồi rừng sản xuất là rừng tự nhiên lá rộng thường xanh nghèo theo hướng kinh doanh đa tác dụng và bền vững ở vùng Đông Bắc, Bắc Trung Bộ và Tây Nguyên”. We would like to thank anonymous reviewers for constructive comments on the manuscript.

References

Artaxo, P., Hansson, H. C., Machado, L. A. T., & Rizzo, L. V. (2022). Tropical forests are crucial in regulating the climate on Earth. *PLOS Climate*, *1*(8), Article e0000054. https://doi.org/10.1371/journal.pclm.0000054

Ashton, M. S., Gunatilleke, C. V. S., Singhakumara, B. M. P., & Gunatilleke, I. A. U. N. (2001). Restoration pathways for rain forest in southwest Sri Lanka: A review of concepts and models. *Forest Ecology and Management*, *154*(1–3), 409–430. https://doi.org/10.1016/S0378-1127(01)00512-6

Bernard, O. E., Gbenga, A. F., & Leah, B. S. (2021). A 17-year successional enrichment plantation of tree recruitment and restoration in a tropical rainforest forest. *Vegetos*, *34*(4), 750–760. https://doi.org/10.1007/S42535-021-00255-5

Chaonan, C., & Feng, L. (2024). Ecosystem restoration and management based on nature-based solutions in China: Research progress and representative practices. *Nature-Based Solutions*, *6*, Article 100176. https://doi.org/10.1016/j.nbsj.2024.100176

Chazdon, R. L. (2008). Beyond deforestation: Restoring forests and ecosystem services on degraded lands. *Science*, *320*(5882), 1458–1460. https://doi.org/10.1126/science.1155365

Clémentine, M., Élise, B., Gregory, M., Renaud, J., James, M. B., Laurent, T., & Thierry, D. (2024). Ecological restoration and rewilding: two approaches with complementary goals? *Biological Reviews*, *99*(3), 820–836. https://doi.org/10.1111/brv.13046

Cohen, J. (1988). *Statistical power analysis for the behavioral sciences* (2nd ed.). Lawrence Erlbaum Associates.

Corsa, L. C. L., Oleksandra, K., & Konstantin, V. K. (2018). Mixed-species versus monocultures in plantation forestry: Development, benefits, ecosystem services and perspectives for the future. *Global Ecology and Conservation*, *15,* Article e00419. https://doi.org/10.1016/j.gecco.2018.e00419

Doc, L. (2015). *Conservation and development of* Erythrophleum fordii *species in Ben En National Park, Thanh Hoa Province. Project summary report*. Department of Agriculture and Rural Development of Thanh Hoa Province, Vietnam.

Forest Inventory and Planning Institute (2002). *Forest inventory handbook*. Hanoi: Agriculture Publishing House.

Ha, C. C., Nguyen, T. C., Le, V. Q., Dang, V. H., Vu, Q. N., Cao, T. V. N., Nguyen, T. Y., Vu, V. S., & Phan, T. H. (2022). Some forestry characteristics of *Camellia tonkinensis* (Pit.) Cohen-Stuart at Ba Vi National Park. *Journal of Forest Science and Technology*, *3*, 48–52.

Hofhansl, F., Chacón-Madrigal, E., Fuchslueger, L., Jenking, D., Morera-Beita, A., Plutzar, C., Silla, F., Andersen, K. M., Buchs, D. M., Dullinger, S., Fiedler, K., Franklin, Hietz, P., Huber, W., Quesada, C. A., Rammig, A., Schrodt, F., Vincent, A. G., Weissenhofer, A., & Wanek, W. (2020). Climatic and edaphic controls over tropical forest diversity and vegetation carbon storage. *Scientific Reports*, *10*, Article 5066. https://doi.org/10.1038/s41598-020-61868-5

Huang, Z. L., Guo, G. Z., & Zhang, Z. P. (1997). A study about endangered mechanism of *Erythrophleum fordii*. *Acta Ecologia Sinica*, *17*(6), 671–676.

James, F. C. J. (2003). Lack of relationship between below-ground competition and allocation to roots in 10 grassland species. *Journal of Ecology*, *91*(3), 532–540. https://doi.org/10.1046/j.1365-2745.2003.00792.x

Jeffrey, E. H., Gerald, E. S., & Albert, R. (2006). Monitoring ecological processes for restoration projects. *Journal for Nature Conservation*, *14*, 161–171. https://doi.org/10.1016/j.jnc.2006.05.001

Kefyalew, K., Getaneh, G., Tesfaye, B., & Shiferaw, A. (2023). Rehabilitation options for degraded secondary forests in Adiyo district of Kaffa zone, Southwest, Ethiopia. *Trees, Forests and People*, *12*, Article 100394. https://doi.org/10.1016/j.tfp.2023.100394

Ministry of Agriculture and Rural Development. (2010). *The preparatory survey on the project for reforestation and sustainable management of protection forests in the Socialist Republic of Vietnam: Final report, Volume I: Main report.* Japan International Cooperation Agency

Marshall, A., Nelson, C. R., & Hall, J. S. (2022). Species selection and plantation management in enrichment planting with native timber species in the Panama Canal watershed. *Frontiers in Forests and Global Change*, *5*, Article 925877. https://doi.org/10.3389/ffgc.2022.925877

Meyfroidt, P., & Lambin, E. F. (2008). Forest transition in Vietnam and displacement of deforestation abroad. *Proceedings of the National Academy of Sciences*, *106*(38), 16139–16144. https://doi.org/10.1073/pnas.0904942106

Millet, J., Tran, N., Ngoc, N. V., Thi, T. T., & Prat, D. (2013). Enrichment planting of native species for biodiversity conservation in a logged tree plantation in Vietnam. *New Forests, 44*, 369–383. https://doi.org/10.1007/s11056-012-9344-6

Paquette, A., Hawryshyn, J., Senikas, A. V., & Potvin, C. (2009). Enrichment planting in secondary forests: A promising clean development mechanism to increase terrestrial carbon sinks. *Ecology and Society*, *14*(1), Article 31. https://doi.org/10.5751/ES-02781-140131

Pilarczyk, K. W., & Nuoi, N. S. (2005). Experience and practices on flood control in Vietnam. *Water International*, *30*(1), 114–122. https://doi.org/10.1080/02508060508691843

Rodrigo, C. P., César, P., Edson, V., & Gustavo, S. (2021). Technical and financial evaluation of enrichment planting in logging gaps with the high-value species *Swietenia macrophylla* and *Handroanthus serratifolius* in the Eastern Amazon. *Forest Ecology and Management*, *495*, Article 119380. https://doi.org/10.1016/j.foreco.2021.119380

Sein, C. C., & Mitlöhner, R. (2011). *Erythrophleum fordii* Oliver: *Ecology and silviculture*. Bogor: CIFOR.

South, D. B., Zwolinski, J. B., & Kotze, H. (2011). Early growth responses from weed control and planting larger stock of *Pinus radiata* are greater than that obtained from mechanical soil cultivation. *New Forests*, *22*(2), 199–211. http://doi.org/10.1023/A:1015648605949

Sovu, T., Tigabu, M., Savadogo, P., Odén, P. C., & Xayvongsa, L. (2010). Enrichment planting in a logged-over tropical mixed deciduous forest of Laos. *Journal of Forestry Research*, *21*(3), 273–280. https://doi.org/10.1007/s11676-010-0071-6

Thanh, D. T., Ying, Z., Thanh, N. C., Hung, D. Q., & Thao, D. T. (2023). Distribution and structural-functional attributions of *Erythrophleum fordii* Oliver in Bac Giang Province, Vietnam. *Caspian Journal of Environmental Sciences*, *21*(5), 1255–1264. https://doi.org/10.22124/cjes.2023.6975

Wen, C. -Y., Lian, J. -Y., Peng, W. -X., Wang, Z. -F., Yang, Z. -G., & Cao, H. -L. (2023). Genome assembly of *Erythrophleum fordii*, a special "ironwood" tree in China. *BMC Genom Data*, *24*, Article 73. https://doi.org/10.1186/s12863-023-01176-9

Zhao, Z. -G., Guo, J., Sha, E., Zeng, J., & Xu, J. -M. (2011). Natural distribution, endangered mechanism and conservation strategy of an endangered tree species, *Erythrophleum fordii* Oliv. S. Heok-Choh, S. A. Hamid, & L. Mei (Eds.), *Asia and the Pacific workshop*: *Multinational and transboundary conservation of valuable and endangered forest species* (pp. 113–116). IUFRO World Series.

Zimmer, H., Tran, L. D., Dang, T. T., Thi, H. L., Le, T. H., Lo, Q. T., Minh, D. L., & Nichols, J. D. (2022). Rehabilitating forest and marginal land using native species in mountainous northern Vietnam. *Trees, Forests and People*, *10*, Article 100323. https://doi.org/10.1016/j.tfp.2022.100323