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Sustaining European Beech Forests: Multi-criteria Evaluation of Management Regimes in the Eifel Region Using Long-Term Simulation[1]

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독일 아이펠 지역 유럽 너도밤나무 숲의 미래: 장기 시뮬레이션을 통한 산림 관리 방식의 다기준 평가[1]

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ABSTRACT

This study compared and evaluated the long-term sustainability of three forest management regimes - conventional shelterwood cutting (Bk), near-natural selective cutting (Bn), and unmanaged reserves (Bt) - in European beech (Fagus sylvatica) forests located in the Eifel region of Germany through a 500-year simulation. Three key sustainability evaluation criteria were assessed: ecological stability (based on volume variability), economic efficiency (based on annual timber yield), and model predictability (based on GAM model fit). Using a Multi-Criteria Decision Analysis (MCDA) framework, each management regime was compared through a weighted composite index. Results showed that Bn management achieved the highest overall performance, while maintaining a balance between ecological resilience and appropriate productivity. On the other hand, Bt forests showed high ecological stability but low economic feasibility, and Bk forests showed high productivity and predictability but the lowest ecological stability. Sensitivity analysis confirmed that, although rankings may vary depending on the weight factor of evaluation criteria, the Bn showed relatively consistent performance under various scenarios. This study provides a quantitative basis for developing sustainable forest management policies and suggests the importance of a balanced management strategy that considers ecological and economic values and long-term predictability.

KEY WORDS: SUSTAINABLE FOREST MANAGEMENT, EUROPEAN BEECH, ECOLOGICAL STABILITY, ECONOMIC EFFICIENCY, MCDA

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요 약

본 연구는 독일 아이펠 지역의 대표적인 유럽 너도밤나무(Fagus sylvatica) 숲을 대상으로, 세 가지 산림관리방식인 산벌, 택벌, 보존림의 지속가능성을 500년간의 장기 시뮬레이션을 통해 비교·분석하였다. 생태적 안정성, 경제적 효율성, 모델 예측성이라는 세 가지 핵심 평가 기준을 중심으로 다기준 의사결정 분석(MCDA)을 적용하였다. 시뮬레이션 결과, 택벌 방식은 생태적 회복력과 적절한 생산성을 균형 있게 유지하며 가장 높은 종합 평가를 보였다. 반면, 보존림은 높은 생태 안정성을 보였으나 경제성에서는 낮은 수치를 나타냈고, 산벌은 높은 생산성과 예측력을 보였지만 생태 안정성에서 가장 낮은 결과를 보였다. 민감도 분석 결과, 평가 기준의 가중치에 따라 순위가 달라질 수 있으나, 택벌관리 방식은 다양한 시나리오에서 비교적 일관된 성과를 보였다. 본 연구는 지속가능한 산림관리정책 수립을 위한 정량적 근거를 제공하며, 생태·경제적 가치와 장기적 예측성을 고려한 균형 잡힌 관리전략의 중요성을 시사한다.

주요어: 산림관리, 유럽 너도밤나무 숲, 생태적 안정성, 경제적 효율성, 다기준 의사결정 분석

INTRODUCTION

European beech (Fagus sylvatica) forests are a keystone ecosystem in Central Europe, providing essential ecological services such as carbon sequestration, biodiversity conservation, and sustainable timber production (Martinez et al. 2022). Their ecological and economic importance has made them a focal point for long-term forest planning and conservation strategies. In the Eifel region of Germany, these forests are managed under diverse silvicultural regimes, including conventional shelterwood cutting, near-natural selective cutting, and unmanaged reserves (Pommerening, 2023). Each regime reflects a unique set of priorities, ranging from timber production to ecological preservation, and is shaped by distinct historical, institutional, and ecological contexts.

While each management approach serves its own intended purpose, the increasing complexity of forest governance under climate change and societal demand for multifunctionality calls for comparative, integrated assessments (Chaudhary et al., 2016). A direct comparison of management regimes can be challenging due to differing goals and operational contexts. However, evaluating these systems based on shared indicators such as carbon storage, biodiversity maintenance, and economic yield can reveal trade-offs, complementarities, and opportunities for adaptive integration (Duncker et al., 2012). Comparative analysis thus becomes not a matter of ranking, but a means of understanding functional diversity and supporting more informed, balanced decision-making (Bradford & D'Amato, 2012).

International frameworks such as those developed by the FAO, UNECE, and FSC emphasize the importance of measurable criteria for sustainable forest management, including ecological integrity, productivity, and the reliability of monitoring systems (Linser et al., 2018; Macdicken et al., 2015; Marx & Cuypers 2010). In response to these evolving requirements, this study applies a structured, long-term evaluation framework across three key domains: ecological stability, economic efficiency, and model predictability. These categories were selected for their ability to capture the multidimensional nature of sustainability spanning ecosystem resilience, resource use, and data-informed forecasting.

A 500-year simulation model was used to compare forest dynamics under three management regimes, with results synthesized through Multi-Criteria Decision Analysis (MCDA) (Didion et al., 2007; Schwenk et al., 2012). This integrative approach enables both quantitative comparison and sensitivity testing across different value weightings, aligning scientific analysis with practical policy needs. Ultimately, the findings aim to support the development of adaptive, evidence-based forest management strategies that are robust under environmental uncertainty and reflective of diverse stakeholder values (Cosyns et al., 2020).

MATERIALS AND METHODS

1. Study Area and Data Collection

This study was conducted in the Eifel region of Rhineland-Palatinate, Germany, focusing on European beech (Fagus

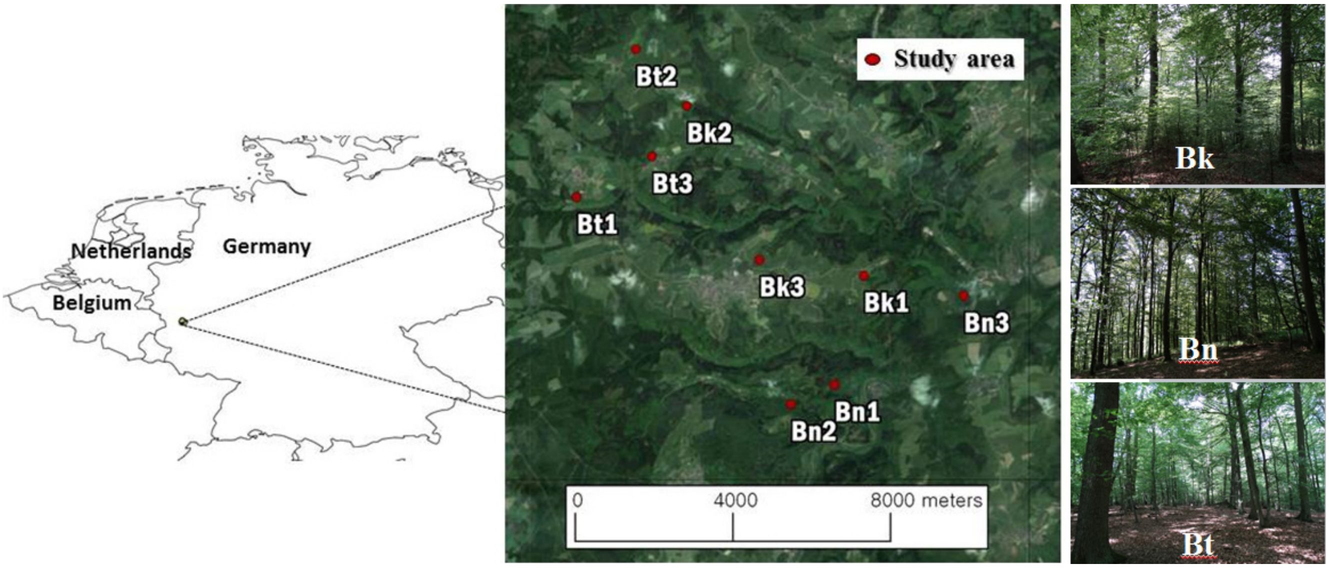

Figure 1. Study area and forest management regimes: Conventional shelterwood cutting (Bk), near-natural selective cutting (Bn), and unmanaged reserve forest (Bt).

sylvatica) forests located in Hümmel (743 ha) and Wershofen (400 ha). Hümmel has been unmanaged for over 18 years, while Wershofen was managed until 2006. Both areas are situated in the low mountain zone (414–495 m elevation) and are dominated by beech and spruce (Leiter and Hasenauer 2023). Forest management types were categorized as conventional shelterwood cutting (Bk), near-natural selective cutting (Bn), and unmanaged reserves (Bt). Nine sample plots of 30 m × 50 m (0.15 ha) were established.

A long-term simulation spanning 500 years was performed using the tree growth model described by Byun et al. (2024), which incorporates seedling establishment, tree growth, height and diameter increment, and mortality due to competition. The model was parameterized to reflect the ecological characteristics and management history of the Eifel region. Stem volume (m^3/ha) were generated for each plot, and mean values were calculated by management type. These simulations enabled the analysis of long-term volume trajectories and ecological dynamics under varying levels of silvicultural intervention.

In developing the evaluation framework for this study, we referred to internationally recognized guidelines for criteria and indicators for sustainable forest management (e.g., Guidelines for the Development of a Criteria and Indicator Set for Sustainable Forest Management-UNECE (2019)). Such frameworks typically encompass a broad array of sustainability dimensions, including ecological, economic, and institutional criteria. The evaluation criteria were categorized into three core domains: ecological stability, economic efficiency, and model predictability. This tripartite structure reflects the foundational pillars of sustainable forest management by balancing ecological resilience, economic viability, and the technical robustness of simulation-based projections. This classification is consistent with established approaches in sustainability science (e.g., Balana et al., 2010; Clark and Matheny, 1998), and provides a holistic and interpretable basis for assessing trade-offs among different management regimes.

2. Assessment of Ecological Stability

Ecological stability was assessed based on the interannual variability of simulated stem volume over the 500-year simulation period. Following previous studies (e.g., Bai et al., 2004; De Keersmaecker et al., 2014), the coefficient of variation (CV) (Eq. 1) of annual stem volume was used as a proxy for temporal variability, with lower CV values indicating higher ecological stability.

$$Coefficient\,of\;Variation(CV) = \frac{\delta}{\mu} \qquad \text{(Eq. 1)}$$

δ: Standard deviation of stem volume by year
μ: Average stem volume by year

For each forest management type, the mean CV across the three plots was calculated. To express ecological stability as a standardized index, the metric 1−CV was used (Eq. 2), where values closer to 1 indicate greater stability. This approach reflects the inverse relationship between temporal variation and ecosystem resilience, as a more stable forest exhibits less year-to-year fluctuation in productivity.

$$Ecological\,Stability = 1 - \overline{CV} \qquad \text{(Eq. 2)}$$

$\overline{CV}$: Average of the annual coefficients of variation over the entire simulation period

3. Assessment and Normalization of Economic efficiency

Economic efficiency in this study was evaluated using the mean annual timber yield (m^3/ha/year) derived from simulation outputs for each forest management type. This metric serves as a proxy for the productive capacity and economic return potential of each regime. To enable direct comparison across management categories, the yield values were normalized using min-max scaling, thereby allowing for the assessment of relative economic efficiency on a standardized scale (Vacik & Lexer, 2014). The normalization formula applied was:

$$Normalized\,Economic\,Efficiency = \frac{\chi - \chi_{\min}}{\chi_{\max} - \chi_{\min}} \qquad \text{(Eq. 3)}$$

x: the mean annual timber yield (m^3/ha/year) for a given management type

x_{min}: the minimum timber yield observed across all management types

x_{max}: the maximum reference yield, drawn from average values reported by Banas et al. (2018)

By applying this normalization, we aimed to reflect the relative economic potential of each silvicultural approach, independent of their absolute production scale, while grounding the maximum benchmark in empirical literature.

4. Assessment of Model predictability

Model predictability was assessed by fitting a Generalized Additive Model (GAM) to the simulated annual forest stem volume (m^3/ha) time series. The GAM takes the form:

$$y = \beta_0 + f(x) + \epsilon \qquad \text{(Eq. 4)}$$

where f(x) is a smooth spline function of time, β_0 is the intercept, and ϵ is the error term (He et al., 2021). This approach allows for flexible modeling of nonlinear trends in long-term forest growth dynamics. The coefficient of determination (R^2) was used to evaluate the goodness-of-fit, and the p-value of the quadratic term was examined to assess the statistical significance of the observed nonlinearity. The smoothness parameter of the spline was optimized during model fitting to effectively capture both gradual and abrupt changes in volume trends over time.

To further evaluate model reliability, we calculated the Generalized Cross Validation (GCV) score and the GCV-based R^2. The GCV score estimates the model's prediction error (i.e., mean squared error) using a penalized likelihood approach, offering a robust metric for comparing predictive performance across management types (Fewster et al., 2000). This evaluation provides insight into the temporal consistency and reliability of simulated growth patterns, which are essential for assessing the data-driven foresight of each forest management strategy.

5. Framework for Integrated Multi-criteria Assessment

To evaluate the long-term performance of the three forest management strategies, a Multi-Criteria Decision Analysis (MCDA) framework was applied. Forest management inherently involves complex trade-offs across ecological, economic, and predictive domains. MCDA provides a structured and transparent approach to integrate these multiple dimensions by assigning relative weights to each criterion and calculating composite scores (Diaz-Balteiro & Romero, 2008). This enables a holistic comparison of management regimes, even when each demonstrates strengths in different areas.

1) Weighting Scheme

The three evaluation criteria—ecological stability, economic efficiency, and model predictability—were assigned weights of 40%, 30%, and 30%, respectively. This weighting scheme reflects a prioritization of long-term forest volume, while still emphasizing the importance of economic viability and data-driven reliability. The final composite score was calculated using the following weighted formula:

$$\text{Composite Score} = 0.4\times\text{Ecological Stability} + 0.3\times\text{Economic Efficiency} + 0.3\times R^2 \text{ of GAM Model} \quad \text{(Eq. 5)}$$

where all input metrics were standardized to a 0–1 scale prior to aggregation.

2) Sensitivity Analysis

To assess the robustness of the evaluation results, a sensitivity analysis was conducted by varying the weights assigned to each criterion (Mendoza & Martins, 2006). Since composite scores can shift significantly depending on the prioritization of ecological, economic, or predictive objectives, this analysis helps evaluate the stability of the decision outcomes. By applying alternative weight combinations, we examined how the relative performance of each management strategy responds to changes in decision priorities. In this study, five different weighting scenarios were considered:

a. Applied Weighting (Ecological 0.4, Economic 0.3, Predictability 0.3),
b. Equal Weighting (0.33, 0.33, 0.33),
c. Ecological Priority (0.6, 0.2, 0.2),
d. Economic Priority (0.2, 0.6, 0.2), and
e. Predictability Priority (0.2, 0.2, 0.6).

Under each scenario, the overall composite scores for the three forest management regimes were recalculated. This approach enabled us to evaluate the sensitivity of the assessment outcome to changes in stakeholder priorities and to identify which regimes perform consistently across diverse valuation schemes.

RESULTS AND DISCUSSION

1. Stem Volume Dynamics

Unmanaged Reserves (Bt) exhibited the highest stem volume throughout the 500-year simulation. Initial values ranged from 503–508 m³/ha (Year 0), peaking at 855–918 m³/ha by Year 100, and stabilizing at 770–868 m³/ha by Year 200. These results reflect minimal anthropogenic disturbance, allowing natural regeneration and accumulation of biomass (Figure 2).

Selective Cutting (Bn) showed moderate stem volume, with gradual increases from 162–266 m³/ha (Year 0) to 275–331 m³/ha (Year 200). This aligns with sustainable harvesting practices that balance timber extraction and ecological retention, as observed in Caspian beech forests (Tavankar et al., 2017).

Shelterwood Cutting (Bk) experienced severe initial declines, dropping to 27 m³/ha within 20 years due to intensive canopy removal. While partial recovery occurred (reaching 100–500 m³/ha by Year 200), long-term volumes remained lower than Bt and Bn, highlighting the trade-off between short-term yield and long-term ecological stability.

2. Ecological Stability Assessment

To assess ecological stability, the coefficient of variation (CV) of annual stem volume over the simulation period was calculated for each forest management type. Lower CV values indicate more consistent growth patterns and, therefore, greater ecological stability. Ecological stability was quantified as 1-CV, with values closer to 1 representing higher temporal stability.

As shown in Table 1, the unmanaged reserves (Bt) exhibited the lowest CV (0.016) and consequently the highest ecological stability index (0.984). The near-natural selective cutting (Bn) approach also demonstrated high stability (CV = 0.060; stability = 0.940), while the conventional shelterwood cutting (Bk) showed substantially higher variability in stem volume (CV = 0.655; stability = 0.345).

These results suggest that the absence or minimization of active intervention, as seen in unmanaged and near-natural systems, leads to more stable forest dynamics over long timescales. The low fluctuation in stem volume under the Bt and Bn regimes may reflect more resilient stand structures and natural buffering capacities in response to environmental variation or competitive dynamics. In contrast, the relatively high interannual variability observed under shelterwood cutting (Bk) likely reflects periodic harvesting events and associated stand structural changes that temporarily reduce

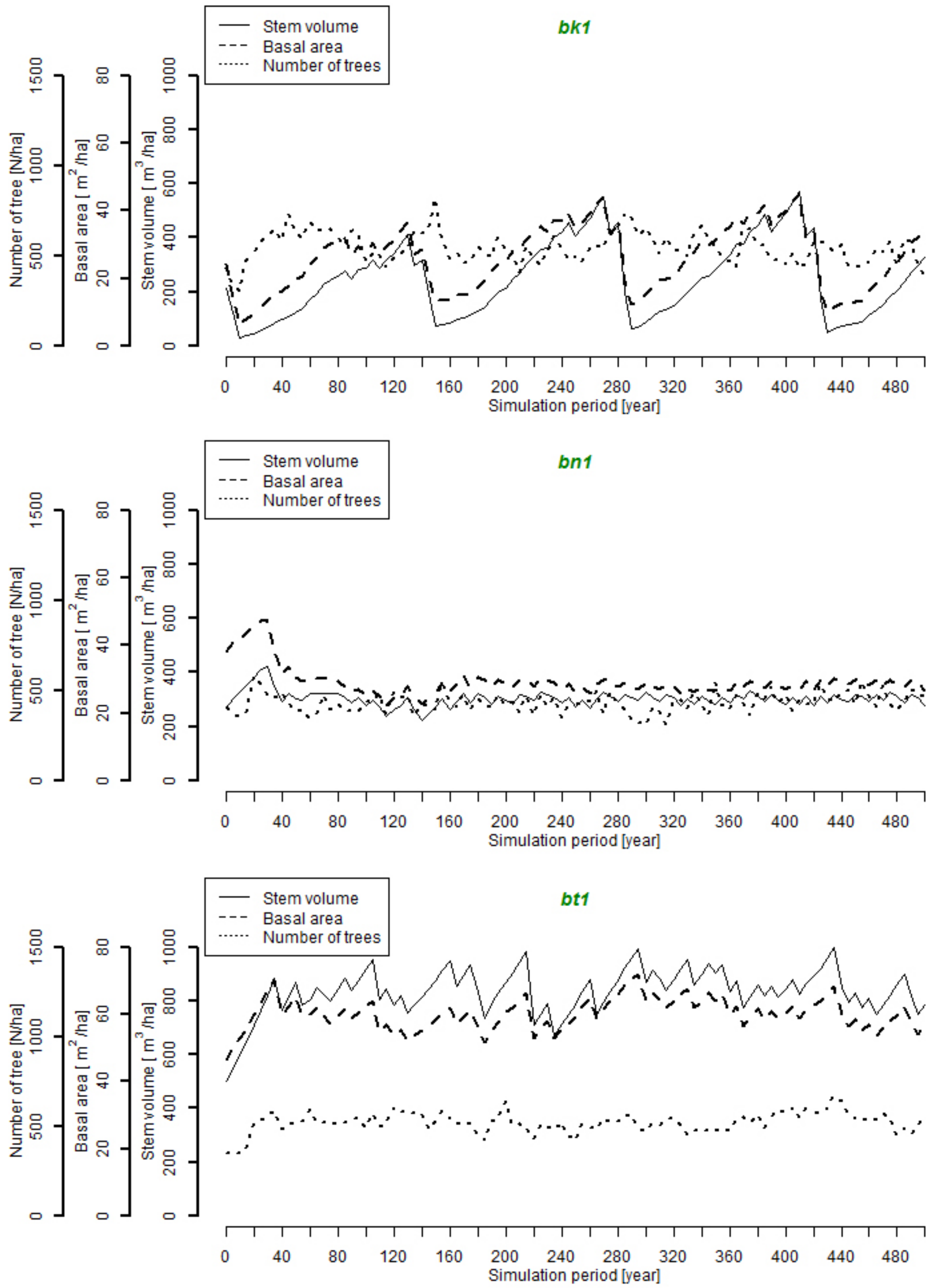

Figure 2. Simulated growth dynamics of stand volume, basal area, and tree density over time. Each graph shows one representative sample per management regime (Bk, Bn, Bt) for clarity and conciseness.

volume and disrupt stability.

These findings are consistent with previous studies reporting that reduced variation in forest productivity is associated with higher ecological resilience and long-term ecosystem stability (Ding et al., 2024; Tilman, 1999). From a sustainability perspective, these results highlight the ecological advantages of low-intensity or passive management strategies in maintaining stable forest productivity.

3. Economic efficiency Assessment

Timber yield was used as a proxy for economic efficiency, measured in terms of average annual timber

Table 1. Coefficient of Variation (CV) and Ecological Stability (1–CV) of Annual Stem Volume under Different Forest Management Types

Management Type	Coefficient of variation(CV)	Ecological stability (1-CV)
Bk (Shelterwood Cutting)	0.655	0.345
Bn (Selective cutting)	0.060	0.940
Bt (Reserves)	0.016	0.984

Table 2. Timber volume and Normalized Economic Efficiency of Forest Management Types

Management Type	Timber volume(m^3/ha/year)	Economic efficiency (x-min)/(max-min)
Bk (Shelterwood Cutting)	2.647	0.442
Bn (Selective cutting)	1.084	0.189
Bt (Reserves)	0.100	0.032

volume (m^3/ha/year) over the simulation period. To allow for relative comparison across forest management types, timber yield values were normalized using min–max scaling. The results are presented in Table 2.

The shelterwood cutting (Bk) regime produced the highest annual yield (2.647 m^3/ha/year), followed by near-natural selective cutting (Bn) at 1.084 m^3/ha/year, and unmanaged reserves (Bt) with the lowest yield (0.1 m^3/ha/year). Since no harvesting occurs in the unmanaged reserves (Bt), a minimum value of 0.1 was assigned to prevent excessive skewing in the normalization process. Based on normalization, economic efficiency indices were calculated as 0.442 for Bk, 0.189 for Bn, and 0.032 for Bt, respectively.

These results indicate that intensive silvicultural systems such as shelterwood cutting yield higher short- to medium-term timber outputs, thus offering greater direct economic returns. In contrast, unmanaged or conservation-oriented regimes like Bt naturally produce minimal harvestable timber and score lower in economic efficiency when assessed solely by yield.

However, these outcomes should be interpreted within the broader context of sustainability. While Bk ranks highest economically, it also exhibited the highest variability in ecological stability. This trade-off highlights the need to balance economic performance with long-term ecological resilience. Furthermore, the relatively moderate output of the Bn system may offer a compromise, supporting moderate yield while maintaining ecological function.

This pattern reflects findings from previous studies (e.g., Banas et al., 2018), which note that lower-intensity systems may offer sustainable, though reduced, timber production while safeguarding ecosystem integrity. Thus, economic indicators must be evaluated alongside ecological and predictive dimensions to inform multifunctional forest management.

4. Model predictability Assessment

To assess the predictability of long-term forest dynamics under each management regime, a Generalized Additive Model (GAM) was fitted to the simulated annual stem volume data. The primary indicator of model predictability was the coefficient of determination (R^2), which reflects the proportion of variance explained by the fitted model. In addition, GCV-based R^2 values were examined to support the robustness of model performance over smoothed functions.

Table 3 presents the intercept estimates and significance levels derived from the Generalized Additive Models (GAM) for each forest management regime. All three regimes—Shelterwood cutting (Bk), Selective cutting (Bn), and Reserves (Bt)—show statistically significant intercepts ($p < 0.0001$), indicating strong baseline differences in modeled forest growth patterns. The intercept estimate for the Reserves (Bt) was the highest at 833.36, followed by Selective cutting (Bn) at 303.5, and Shelterwood cutting (Bk) at 247.36. The associated t-values (ranging from 39.35 to 139.6) further support the robustness of these estimates, with particularly strong model confidence observed for Bn and Bt.

Table 3. Intercept Estimates and Significance Levels from Generalized Additive Models (GAM)

Management	Intercept Estimate	Standard Error	t Value	Pr>|t|
Shelterwood cutting (Bk)	247.36	6.29	39.35	<0.0001
Selective cutting (Bn)	303.50	2.31	131.50	<0.0001
Reserves (Bt)	833.36	5.97	139.60	<0.0001

These intercept estimates reflect inherent differences in baseline productivity or structural state across forest management regimes. The notably high intercept for the Reserves (Bt) suggests that unmanaged forests may retain greater accumulated biomass or structural complexity at the outset, likely due to the absence of disturbance and long-term natural development. In contrast, the lower intercept observed for Shelterwood cutting (Bk) may be attributed to more frequent harvesting cycles that reset stand development stages.

As shown in Table 4, the shelterwood cutting (Bk) regime exhibited the highest level of model predictability, with an R^2 of 0.780 and a GCV-based R^2 of 0.802. This suggests that stem volume trends under this intensive management regime were well captured by the model, likely due to more structured and periodic changes resulting from timber interventions. The reserves (Bt) regime followed with a moderate model fit ($R^2 = 0.588$), reflecting long-term biomass accumulation with relatively consistent growth, though potentially influenced by natural variability not explicitly captured by the model. Lastly, the selective cutting (Bn) regime showed the lowest R^2 (0.583), suggesting slightly less model-explained variability compared to Bt.

In terms of model fit (Table 4), the shelterwood cutting (Bk) regime showed the highest model fit, with an R^2 of 0.780 and a GCV-based R^2 of 0.802, indicating that stem volume trends under intensive management were well explained by the GAM. The reserves (Bt) regime showed moderate predictability ($R^2 = 0.588$), followed closely by the selective cutting (Bn) regime ($R^2 = 0.583$). Although Bn exhibited the lowest raw R^2 value, its low GCV score suggests smoother and more consistent long-term volume dynamics.

These results indicate that forest management regimes involving higher management intensity, such as shelterwood cutting, may yield more predictable stem volume trends over time, as indicated by higher model fit (R^2). In contrast, regimes with moderate intensity (Bn) or no treatment (Bt) appear to exhibit more complex or variable growth patterns, which may reduce the model's explanatory power and long-term predictability. Such variability could stem from natural stand dynamics, heterogeneous competition, or the absence of consistent harvesting patterns.

5. Integrated Multi-Criteria Assessment

To synthesize the performance of each forest management regime across ecological, economic, and predictive dimensions, a weighted Multi-Criteria Decision Analysis (MCDA) was applied. Each indicator was assigned a weight reflecting its relative importance: ecological stability (0.4), economic efficiency (0.3), and model predictability (0.3). The resulting composite score represents the integrated performance of each regime in promoting long-term sustainable forest management. The results are summarized in Table 5.

The near-natural selective cutting (Bn) regime achieved the highest overall composite score (0.608), due to its strong ecological stability (0.94) and balanced performance in predictability and economic efficiency. While its timber yield was lower than that of shelterwood cutting, its ecological contribution significantly elevated its composite score.

The unmanaged reserves (Bt) regime followed closely with a score of 0.579, also demonstrating high ecological

Table 4. Model Fit Statistics and Cross-Validation Metrics for Forest Management Type

Management	R^2(Model Fit)	GCV Score	GCV-based R^2
Shelterwood cutting (Bk)	0.780	4421	0.802
Selective cutting (Bn)	0.583	227	0.713
Reserves (Bt)	0.588	2745	0.624

Table 5. Integrated Composite Scores of Forest Management Regimes

Management Type	Ecological Stability (W:0.4)	Economic Efficiency (W:0.3)	Model Predictability (W:0.3)	Composite Score
Bk	0.345	0.442	0.779	0.505
Bn	0.940	0.190	0.583	0.608
Bt	0.984	0.032	0.587	0.579

stability (0.984) and moderate predictability (0.587). However, its limited economic return (0.032) reduced the overall score. reflecting its strengths in long-term forest conservation rather than economic output.

In contrast, the shelterwood cutting (Bk) regime, despite ranking highest in model predictability (0.779) and economic efficiency (0.442), scored the lowest in ecological stability (0.345), resulting in a final composite score of 0.505.

The results provide a quantitative basis for comparing forest management regimes. The MCDA framework reveals that no single management type excels across all criteria, but near-natural management offers the most balanced sustainability outcomes in this case.

6. Sensitive analysis on Multi-Criteria Weighting Scenarios

To test the robustness of the integrated assessment, a sensitivity analysis was performed by varying the weights assigned to the three key evaluation criteria—ecological stability, economic efficiency, and model predictability. This analysis explored how different decision priorities affect the relative performance of the forest management regimes. Figure 3 illustrates the resulting trade-off patterns among the three management regimes under five weighting scenarios—Applied, Equal, Ecological Priority, Economic Priority, and Predictability Priority. Each polygon represents the composite score of a management regime (Bk = shelterwood cutting, Bn = near-natural selective cutting, Bt = unmanaged reserve) under each scenario, highlighting how shifts in decision emphasis influence overall performance.

Overall, the sensitivity analysis demonstrates that the Bn (near-natural) and Bt (reserves) regimes are more resilient to weight changes that favor ecological criteria, while Bk (shelterwood cutting) shows improved performance only when economic or predictability considerations are emphasized. These findings highlight the importance of aligning management choices with policy priorities. For ecologically oriented forest planning, Bn and Bt offer stronger long-term sustainability, whereas Bk may be better suited to scenarios emphasizing short-term productivity or forecasting reliability.

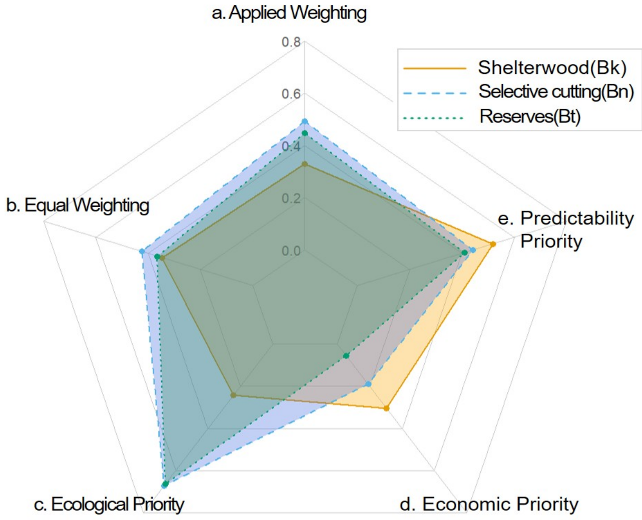

Figure 3. Scenario-based sensitivity analysis of three forest management regimes using multi-criteria decision analysis (MCDA).

This multi-scenario approach enhances the transparency of forest management evaluations and supports more informed and adaptable policy decisions in complex forest ecosystems.

7. Limitations and Scope

This study provides useful insights by comparing the long-term sustainability of forest management regimes, however, several limitations must be acknowledged. First, the analysis was based on a relatively small sample size, nine plots located exclusively in the Eifel region of Germany. The ecological conditions of the study area (e.g., elevation, soil, slope, moisture availability, and light conditions) may not fully represent the variability found across wider Central European or global temperate forests.

Second, although the simulation model incorporated detailed growth dynamics and historical management, it did not explicitly account for future disturbances such as pest outbreaks, extreme weather events, or climate change scenarios. As such, the findings should be interpreted with caution and considered most applicable to forests under similar ecological and management contexts.

Despite these limitations, this comparative study offers a useful framework for understanding the multi-dimensional outcomes of forest management and provides a foundation for more extensive, site-specific, or disturbance-inclusive future analyses.

8. Conclusion

This study evaluated the long-term sustainability of three forest management regimes—shelterwood cutting, near-natural selective cutting, and unmanaged reserves—using simulation modeling and multi-criteria decision analysis. Among the three, the near-natural regime demonstrated the most balanced performance across ecological, economic, and predictive dimensions. While unmanaged reserves showed the highest ecological stability, they offered limited economic returns. Conversely, shelterwood cutting yielded higher productivity and model predictability but lower ecological resilience. These findings highlight the importance of aligning management strategies with specific sustainability priorities. The applied evaluation framework offers a practical tool for comparing trade-offs and supporting informed decision-making (Duncker et al, 2012; Garcia-Gonzalo et al, 2013).

Future research should aim to broaden the ecological scope of the analysis by incorporating a greater diversity of site conditions, including variation in topography, slope, soil characteristics, and hydrological regimes. Additionally, including a wider range of species compositions such as mixed-species or uneven-aged stands would enhance the generalizability of the findings. Incorporating climate change projections into growth simulations would improve the long-term reliability of management evaluations. Moreover, expanding the criteria to include social acceptability, biodiversity indicators, and carbon credit mechanisms could support more holistic evaluations. Finally, linking simulation results with actual forest policy instruments and certification schemes (e.g., FSC, PEFC) (Linkevičius et al., 2019; Malek, 2022; Mikulková et al., 2015; Romero et al., 2017) would strengthen the relevance of this work to real-world decision-making processes.

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