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Sustainability Analysis of the Rawa Aopa Watumohai National Park

Analisis Keberlanjutan Taman Nasional Rawa Aopa Watumohai

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ABSTRACT

Rawa Aopa Watumohai National Park (*Taman Nasional* Rawa Aopa Watumohai-TNRAW) is a critical conservation area in Southeast Sulawesi, facing high pressure from land degradation, deforestation, and unsustainable resource use. This research aimed to analyze the ecological, economic, and social sustainability of TNRAW following the implementation of the Land and Forest Rehabilitation (RHL) program. The analysis used the Rapid Appraisal for Sustainability (RAPS) method with a Multidimensional Scaling (MDS) and collected data through field observations, focus group discussions, and interviews with key stakeholders. The results revealed that the social dimension had a relatively high sustainability status (88.12), indicating strong community participation and effective conflict-resolution mechanisms. In comparison, the economic dimension was in a fairly sustainable status (59.13), driven primarily by high community income and employment opportunities. The ecological dimension was in a low sustainability status (35.29) due to limited biodiversity, suboptimal species selection, and insufficient maintenance and protection activities, underscoring the need to strengthen ecological restoration strategies. Furthermore, this research highlighted the need to improve rehabilitation efforts by focusing on restoring biodiversity, establishing robust long-term monitoring systems, and implementing integrated management approaches. These management strategies should align with the ecological, economic, and social goals of conservation areas to ensure sustainable outcomes.

KATA KUNCI
rehabilitasi lahan dan hutan, keberlanjutan, multi dimensional scaling*, restorasi bentang alam Hutan, Taman Nasional Rawa Aopa Watumohai*

INTISARI

Taman Nasional Rawa Aopa Watumohai (TNRAW) adalah kawasan konservasi di Sulawesi Tenggara yang menghadapi tekanan tinggi dari degradasi lahan, deforestasi, dan pemanfaatan sumber daya yang tidak berkelanjutan. Penelitian ini bertujuan untuk menganalisis keberlanjutan ekologi, ekonomi, dan sosial TNRAW setelah program rehabilitasi hutan dan lahan (RHL) dilaksanakan. Analisis dilakukan menggunakan metode Rapid Appraisal for Sustainability *(RAPS) dengan* Multidimensional Scaling *(MDS), serta data yang dikumpulkan melalui observasi lapangan, diskusi kelompok terarah, dan wawancara dengan para pemangku kepentingan kunci. Hasil penelitian mengungkapkan bahwa dimensi sosial memiliki status keberlanjutan yang relatif tinggi (88,12), yang menunjukkan partisipasi masyarakat yang kuat serta mekanisme resolusi konflik yang efektif. Sebagai perbandingan, dimensi ekonomi memiliki status keberlanjutan yang cukup (59,13), yang ditopang oleh pendapatan masyarakat dan peluang kerja yang tinggi. Dimensi ekologi memiliki status keberlanjutan yang rendah (35,29) karena keragaman hayati yang terbatas, seleksi spesies yang kurang optimal, serta kurangnya kegiatan perawatan dan perlindungan yang menggarisbawahi pentingnya strategi restorasi ekologi. Selain itu, penelitian ini juga menyoroti pentingnya upaya rehabilitasi yang mengarah pada restorasi keragaman hayati, pembangunan sistem pemantauan jangka panjang yang andal, serta penerapan pendekatan pengelolaan yang terintegrasi dan selaras dengan tujuan ekologi, ekonomi, dan sosial kawasan konservasi untuk memastikan hasil yang berkelanjutan.*

Introduction

Land-use changes in recent decades have significantly contributed to the global climate crisis, particularly through large-scale deforestation and the intensification and expansion of agriculture in developing countries (Khuc et al. 2018). These processes have accelerated wetland degradation and biodiversity loss, leading to a decline in ecosystem services. Land degradation remains a major challenge in achieving Sustainable Development Goals (SDGs) 13 and 15, which emphasize climate action and the protection, restoration, and sustainable use of terrestrial ecosystems (Arneth et al. 2021). Southeast Sulawesi Province has experienced substantial forest change over the last two decades. Between 2001 and 2025, the province lost approximately 590 thousand ha of tree cover (19% of its 2000 tree-cover extent), while 96% of recent tree-cover loss (2021–2025) occurred within natural forests, highlighting increasing pressure on forest ecosystems and the urgent need for effective forest landscape restoration (Global Forest Watch 2025), driven by land conversion, extractive industries, and agricultural expansion, particularly oil palm plantations (Khuc et al. 2018). These pressures have increasingly affected conservation areas, including national parks such as the Rawa Aopa Watumohai National Park (*Taman Nasional* Rawa Aopa Watumohai-TNRAW).

TNRAW was established pursuant to the Decree of the Minister of Forestry No. 756/Kpts-II/1990, covering an area of 105,194 ha. The park's flora is highly diverse, with 323 plant species, and several types of fauna, including rare endemic species. TNRAW is one of the most important conservation areas in Indonesia, characterized by a unique ecosystem of swamp forests, savannas, and lowland forests that support various endemic species, including maleo birds (*Macrocephalon maleo*), anoa (*Bubalus* spp.), and babirusa (*Babyrousa babyrussa*). In recent decades, TNRAW has faced serious threats from deforestation, land conversion, forest fires, and unsustainable exploitation of natural resources, such as plantations and mining, leading to the loss of natural beauty, biodiversity, and the capacity of ecosystems to provide services, such as water supply, flood prevention, and carbon sequestration.

The Forest and Land Rehabilitation (RHL) program is a critical effort to restore ecological function. The success of the RHL program is measured not only by tree planting but also by its long-term sustainability across ecological, economic, and social dimensions. Recent studies have emphasized the importance of integrating these dimensions into forest landscape restoration to achieve sustainable outcomes (Chazdon et al. 2016; Mansourian et al. 2017). Recent restoration studies further recommend evaluating ecological, social, economic, and institutional dimensions simultaneously because restoration success depends on interactions among these dimensions rather than ecological outcomes alone (César et al. 2021; Vincent et al. 2021). Additionally, adaptive management and community-based approaches have been widely recognized as critical factors in improving the effectiveness and long-term sustainability of rehabilitation programs (Erbaugh et al. 2020; Schweizer et al. 2021).

Recent studies also emphasize that successful forest landscape restoration depends on integrated governance, collaboration among multiple stakeholders, and continuous adaptive management across different governance levels to achieve long-term sustainability (Wiegant et al. 2022; Beeton et al. 2024; Kleinschmit et al. 2024). Ecologically, TNRAW is crucial in maintaining local hydrological and climatic balance. This area serves as a water catchment, supporting the livelihoods of local communities and agriculture. Although the RHL program was established to restore vegetation cover, enhance biodiversity, and improve soil quality, rehabilitation efforts often failed without a sustainability-based approach, due to plant death, insufficient monitoring, or continued anthropogenic pressure. This shows the need to evaluate the effective implementation of the RHL program and to identify factors that determine its sustainability.

From an economic perspective, the RHL program in TNRAW must deliver tangible benefits to local communities to ensure long-term support. Many rehabilitation efforts have followed a top-down method and lacked active community participation, thereby failing to foster a sense of ownership. However, communities surrounding TNRAW depend on forest resources for their livelihoods, such as

firewood, non-timber forest products (NTFPs), and agricultural land. This shows that when the RHL program fails to address economic needs, pressure on the forest will persist. For example, limited livelihood alternatives often lead to participation in illegal logging or encroachment.

Social aspects are essential in the sustainability of the RHL. This is because local community participation in the planning, implementing, and monitoring of rehabilitation is crucial to the successful implementation of the RHL program. However, communication gaps often exist between TNRAW management, the government, and the community, leading to resistance or indifference. Tenure conflicts and land disputes can also hinder implementation when not managed properly. Analyzing the level of community participation, the effectiveness of the outreach method, and the presence of local institutions supporting the RHL program will help better understand the social dynamics and formulate more inclusive strategies to ensure the successful implementation of the RHL program in the initial phase, alongside community acceptance and sustainability.

Global climate change increases the urgency of this research because TNRAW serves as a significant carbon store and RHL, which contribute to climate change mitigation by sequestering CO_2 emissions. However, erratic rainfall patterns and rising temperatures impact the success of the RHL. For example, planted seedlings may fail to thrive due to drought or increased pest infestations, underscoring the need to consider climate change adaptation in the rehabilitation program design. From a policy perspective, the results of this research can serve as a reference for the government and TNRAW managers in developing more effective rehabilitation strategies. Currently, the RHL program is often viewed as a short-term project with limited funding, which undermines its sustainability. Therefore, research related to the sustainability analysis of the RHL program in TNRAW is crucial to restoring damaged ecosystems and ensuring that rehabilitation efforts provide long-term benefits to the ecology, economy, and community. Without a holistic method integrating these three dimensions, the RHL program is prone to becoming a ceremonial activity. The results are expected to provide scientific and practical contributions to conservation area management in Indonesia, particularly in addressing the increasingly complex challenges of environmental degradation and climate change.

Therefore, this research aimed to analyze the ecological, economic, and social sustainability of TNRAW following the implementation of the RHL program across these dimensions, including identifying key leverage attributes influencing sustainability and providing strategic recommendations to improve the sustainability of TNRAW effectively. The results of this research contributed to the development of more integrated and adaptive forest management strategies in Indonesia. Recent studies have proposed integrated social-ecological assessment frameworks for evaluating forest landscape restoration, emphasizing balanced consideration of ecological integrity, social participation, and livelihood improvement (Löhr et al. 2024).

Methods

Time and Location

This research was conducted in TNRAW, South Konawe Regency, Southeast Sulawesi, Indonesia, from June to August 2025 (Figure 1). TNRAW is one of Indonesia's important conservation areas, characterized by diverse ecosystems including swamp forests, savannas, and lowland forests. The RHL program in TNRAW has been implemented in several degraded zones within and around the park to restore ecological functions, improve vegetation cover, and support biodiversity conservation. These rehabilitation activities have been carried out periodically as part of conservation and land recovery efforts, particularly in areas experiencing degradation due to land conversion, fire, and human disturbance.

The implementation of RHL in TNRAW involved tree planting, maintenance, and protection activities across selected rehabilitation sites, with support from government agencies, park management authorities, and local communities. Community participation played an important role, particularly in planting and maintenance stages, to strengthen ecological restoration while also supporting local livelihoods. The study focused on areas directly associated with RHL

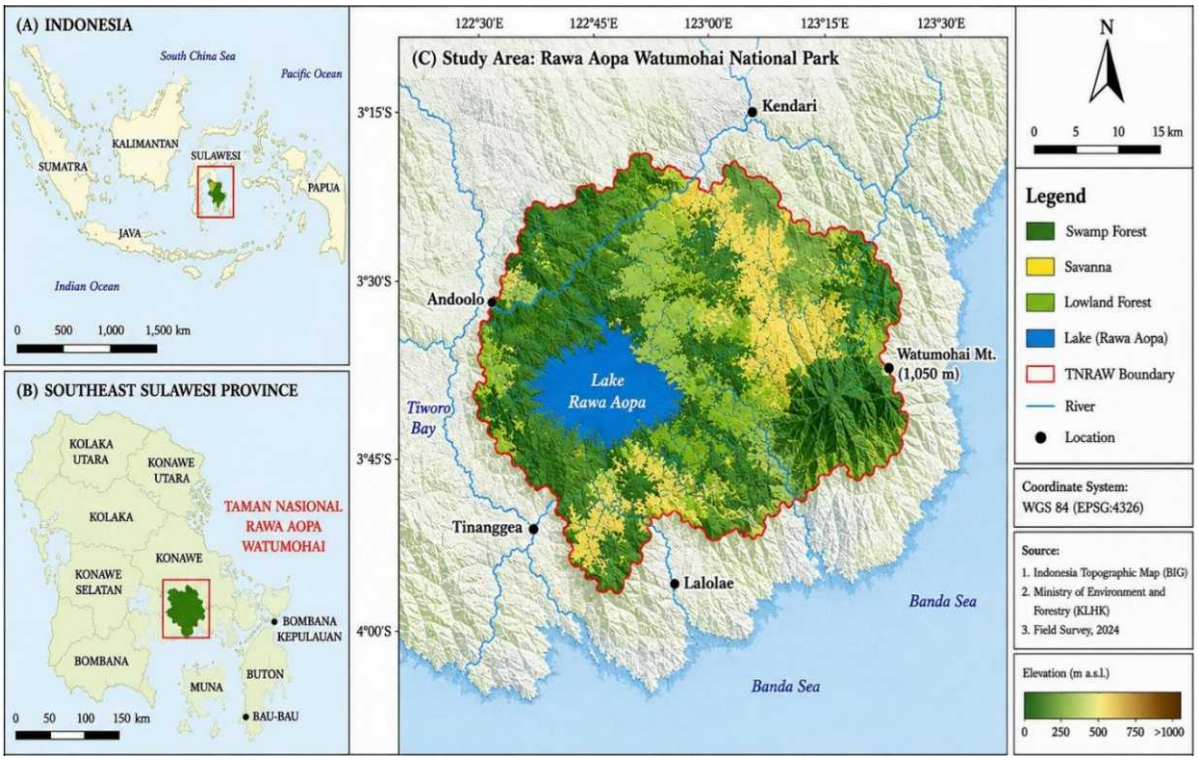

Figure 1. Study area of the Forest and Land Rehabilitation (RHL) program in Rawa Aopa Watumohai National Park (TNRAW), Southeast Sulawesi, Indonesia. The map illustrates TNRAW's general conservation landscape, within which RHL activities were implemented across several degraded zones.

implementation, as presented in Figure 1, which illustrates the general location of TNRAW and the rehabilitation context within the conservation landscape.

Data Collection

This research used a survey-based method combining both qualitative and quantitative approaches through primary and secondary data sources. Primary data were collected through in-depth interviews, field observations, and Focus Group Discussions (FGDs). Respondents were purposively selected based on their participation in and relevance to the implementation of the RHL program, including representatives from government institutions (Forestry Service, BAPPEDA, Environmental Agency), park management authorities, local community leaders, and community members.

Secondary data were obtained from official documents, government reports, TNRAW management records, rehabilitation program reports, statistical publications, and relevant scientific literature. These secondary sources were used to support the identification of rehabilitation areas, historical program context, ecological conditions, and policy frameworks related to RHL implementation in TNRAW. This method ensured that the data incorporated both expert judgment from relevant institutional stakeholders such as Forestry Service, TNRAW management, Regional Development Planning Agency (BAPPEDA), Environmental Agency, and the Non-Government Organizations (NGOs), as well as community perspectives. Multi-stakeholder collaboration enhances restoration effectiveness by integrating ecological objectives with local knowledge and community priorities (Christmann et al. 2025).

Data Analysis

Sustainability Appraisal

The sustainability analysis applied the Rapid Appraisal for Sustainability (RAPS) method, consisting of ecological, economic, and social dimensions with Multidimensional Scaling (MDS) that transformed multidimensional data into a two-dimensional ordination space. Selection of these three dimensions followed the widely accepted sustainability concept, which emphasized the

integration of environmental integrity, economic viability, and social equity (Löhr et al. 2024). The analysis used RAPFISH software (or equivalent analytical tools), which was commonly applied in sustainability assessment.

The rapid appraisal for sustainability was carried out in several stages:

1. Identification of sustainability indicators for each dimension

Identification of the indicators within each dimension followed the RHL procedures in a combination of literature review and FGDs with stakeholders (Table 1). The FGD process included discussions with experts and local stakeholders to ensure consistency of the selected attributes with the local context of TNRAW and showed real conditions in the field. These indicators served as essential tools, ensuring that the ordination results accurately represented the multidimensional data.

2. Scoring of each indicator based on field data and expert judgment

The sustainability indicators were evaluated using an ordinal scoring system ranging from 0 (representing the poorest condition) to 4 (representing the best condition), following the Rapid Appraisal for Fisheries (RAPFISH) approach based on multidimensional scaling (MDS) (Kavanagh & Pitcher 2004; César et al. 2020). The scoring process incorporated expert judgment, field observations, and stakeholder perceptions obtained through interviews and FGDs. This approach enabled qualitative information to be transformed into quantitative data for RAPS–MDS analysis. Each indicator was initially scored on an ordinal scale from 0 to 4. These scores were then analyzed using Multidimensional Scaling (MDS) in the RAPS framework to generate sustainability index values on a 0–100 scale. The transformation from attribute scores to sustainability indices was based on ordination distances, where lower index values represented

Table 1. Sustainability criteria and indicators of the TNRAW

Sustainability Criteria (Variables)	Indicator	Scoring Criteria
Economic Dimension	1. Measurable value of the benefits of the TNRAW area as a preventative measure, and to reduce the magnitude of disasters 2. Increase in production amounts and income levels of communities around TNRAW 3. Job opportunities and business opportunities in the TNRAW utilization zone 4. Income level of the community around TNRAW 5. Product market 6. The economic value of the TNRAW area as a creator of microclimate stability is measured by the costs of handling its impacts. 7. Revenue obtained by the government from the management and utilization of TNRAW	Ordinal score (0 = worst condition; 4 = best condition)
Social Dimension	1. Conflict resolution mechanisms 2. Availability of community organizations in managing the TNRAW area 3. Availability of procedures for utilization of the TNRAW area 4. Community involvement in the management of the TNRAW area 5. Local cultural practices in the preservation of the TNRAW area	
Ecological Dimension	1. Demarcation of TNRAW area boundaries 2. Suitability of TNRAW area designation 3. Diversity of flora and fauna 4. Biodiversity management 5. Planting, maintenance, and protection activities in the TNRAW area 6. Protection of rare and endangered flora and fauna species that are characteristic of the TNRAW region	

Remarks: All sustainability indicators were scored using an ordinal scale from 0 (worst condition) to 4 (best condition), based on field observations, expert judgment, and stakeholder perceptions.

poorer sustainability conditions and higher values represented better sustainability performance (Ruhimat 2015).

3. Application of MDS to calculate sustainability index values

Leverage analysis was conducted by calculating the Root Mean Square (RMS) change in ordination when each attribute was systematically varied. Attributes with higher RMS values indicated greater sensitivity and stronger influence on sustainability status. Leverage analysis in the RAPS–MDS framework was used to identify sensitive attributes by examining the Root Mean Square (RMS) change in ordination results when individual attributes were systematically varied. In this context, RMS reflects the relative influence of each attribute on sustainability positioning rather than conventional statistical dispersion. Attributes with higher RMS values indicate greater sensitivity and stronger contribution to changes in sustainability status (Kavanagh & Pitcher 2004). Mathematically, RMS is expressed as in Equation 1, where x_i is the sustainability score of each indicator, $\bar{x}$ is the mean score, and n is the number of observations.

$$RMS = \sqrt{[\sum (x_i - \bar{x})^2 / n} \quad \text{..... Equation 1}$$

4. Classification of sustainability status into four categories:

Sustainability status was classified according to Ruhimat (2015), with index values of 0–25 indicating unsustainable, 25.01–50 indicating less sustainable, 50.01–75 indicating fairly sustainable, and 75.01–100 indicating sustainable. Each sustainability indicator was initially scored on an ordinal scale ranging from 0 (worst condition) to 4 (best condition). These attribute scores were then processed using the Multidimensional Scaling (MDS) procedure within the Rapid Appraisal for Sustainability (RAPS) framework. The MDS ordination results were subsequently transformed into a sustainability index ranging from 0–100 by normalizing ordination positions relative to the "bad" and "good" reference points. The 0–100 sustainability index reflects the relative sustainability position of each dimension, as determined by multidimensional analysis, rather than directly representing raw attribute scores.

Leverage Analysis and Sensitive Indicators

Leverage analysis was conducted for each sustainability dimension (economic, social, and ecological) to identify the sensitive indicators that most strongly influenced the sustainability index within each dimension. This procedure evaluated the Root Mean Square (RMS) change in ordination scores resulting from each indicator's systematic variation while holding the others constant, following the leverage approach in Rapid Appraisal (Kavanagh & Pitcher 2004). Indicators with higher RMS values reflected greater influence on the sustainability index and were therefore considered priority leverage factors.

Model Validation and Robustness Test

To evaluate the robustness and reliability of the sustainability analysis, a Monte Carlo simulation was used to assess the stability of MDS ordination results under scoring uncertainty, random error, and data variability. Monte Carlo analysis repeatedly randomized attribute scores within defined limits to assess the consistency of sustainability indices. Goodness-of-fit of the MDS model was assessed using stress (S) and the coefficient of determination (R^2). Following Kavanagh and Pitcher (2004), stress values below 0.25 indicate acceptable ordination fit, while higher R^2 values indicate stronger explanatory power of the ordination model.

Result and Discussion

Sustainability Appraisal of TNRAW

The results of the MDS ordination indicate that the TNRAW sustainability index varied across dimensions (Table 2). The economic dimension was fairly sustainable (59.13), showing moderate improvement in community livelihoods, although the current income level remained suboptimal. The social dimension showed the highest index value (88.12) and fell into the sustainable category, indicating strong community participation and institutional support. The ecological dimension showed the lowest index value (35.29) and fell into the less sustainable category, indicating that ecological restoration remained a major challenge.

Table 2. Sustainability index and category of each dimension

Dimension	Sustainability Index	Category
Economic	59.13	Fairly Sustainable
Social	88.12	Sustainable
Ecological	35.29	Less Sustainable

Remarks: Sustainability categories follow Ruhimat (2015)

Table 2 indicates that the social dimension fell in the sustainable category, while the economic dimension fell in the fairly sustainable category. The ecological dimension showed the lowest ordination value, indicating vulnerability and significant influence on overall sustainability. Therefore, attributes within the ecological dimension required greater attention, particularly biodiversity, species selection, and planting, maintenance, and protection activities. These three components represented the core pillars of field implementation. Weak or inappropriate practices in any of these aspects led to suboptimal rehabilitation outcomes and reduced sustainability of the RHL program. In this context, the use of native species should be given high priority to enhance ecological resilience and restoration. For example, in Vietnam, forest rehabilitation programs have successfully integrated native species planting on degraded lands while including local communities in species selection to increase awareness and support long-term sustainability (Zimmer et al. 2022). Table 2 also indicates a significant imbalance among the dimensions. Although social acceptance and stakeholder participation in the RHL program remained relatively strong, ecological restoration outcomes remained inadequate and require urgent attention. From a management perspective, the results showed that TNRAW implemented effective measures to build social engagement but had not achieved optimal ecological recovery. Therefore, TNRAW management needs to shift its focus toward strengthening ecological performance without compromising existing social gains.

Sensitive Indicators

The leverage analysis provided a clearer overview of sensitive indicators for each dimension (Table 3). The results showed that the most influential indicators were concentrated in the economic and ecological dimensions. Community income and employment opportunities played a dominant role, while biodiversity and planting management determined ecological sustainability. In the social dimension, conflict resolution served as the key factor supporting program stability. The results showed the need for integrated strategies combining economic incentives, ecological restoration, and social cohesion.

Economic Dimension

The key indicators that most influenced the economic dimension of the sustainability in TNRAW were the level of community income (14.71) and employment and business opportunities in the TNRAW utilization area (13.77), as summarized in Figure 2. Figure 2 showed that the RHL program in TNRAW helped surrounding communities by protecting the land and planting various tree species. This facilitated the creation of a conducive environment for animals and plants, making the area more attractive. The improvement attracted several visitors, including nature tourists and researchers from outside the area. The sale of Legal NTFPs, such as forest honey and rattan, sold as logs or processed into handicrafts like rattan chairs, beds, and others, provided an additional source of income.

Furthermore, food stalls selling local culinary specialties and kiosk businesses benefited the surrounding communities. Based on the analysis results, community income increased from IDR 812,500/month to IDR 1,293,750/month after its implementation in TNRAW. The implementation of the RHL program created business opportunities, such as photography services, local tour guides, and

Table 3. Sensitive indicators across sustainability dimensions

No.	Dimension	Indicator	RMS Value	Category
1	Economic	Community income	14.71	Highly sensitive
2	Economic	Employment opportunities	13.77	Highly sensitive
3	Ecological	Biodiversity	8.68	Moderately sensitive
4	Ecological	Biodiversity management	7.31	Moderately sensitive
5	Ecological	Planting and maintenance	6.77	Moderately sensitive
6	Social	Conflict resolution	11.88	Highly sensitive

Remarks: Sensitive indicators were identified based on relative RMS values derived from leverage analysis within each sustainability dimension; higher RMS values indicate greater influence on sustainability status. RMS values do not represent inferential statistical significance (p-values).

lodging rentals. Moreover, improvements in regulations regarding permitted areas required attention to optimize the benefits of TNRAW to increase community income. Since the majority are farmers, farming activities depend on TNRAW's ecosystem potential. Communities can grow various commodities on land designated for use within TNRAW. This area also served as a potential source of regional income through tourism, carbon dioxide emissions, and other environmental services, though with limited application.

Rehabilitation activities, particularly those related to the recovery and development of the tourism sector and micro, small, and medium enterprises (MSMEs), significantly impact the local economy, generating income and creating jobs. Previous research conducted by Aida et al. (2024) showed that increased tourism revenues contributed positively to economic growth, suggesting the sector's ability to generate significant income for local communities and to stimulate the development of related industries. Furthermore, community-based tourism has been recognized as an approach that empowers local communities through participatory resource management, which in turn can enhance income generation and stimulate local economic activities (Marlina 2019).

Social Dimension

Social sustainability indicated that the TNRAW management was accepted and supported by the community, fostering a sense of ownership and a view of it as beneficial. Furthermore, the RHL program was integrated into farmers' and plantation owners' daily activities, helping prevent the perception of a temporary external project. This integration process positively impacted community participation and contributed to successful implementation, though it remained low in some areas, particularly during the monitoring and evaluation stage. However, participation in community-based organizations in Seychelles was a key determinant of participation in rehabilitation (Etongo et al. 2021). In Indonesian culture, local communities play a crucial role in conservation efforts by managing land according to traditional practices (Iswandono et al. 2016). Previous

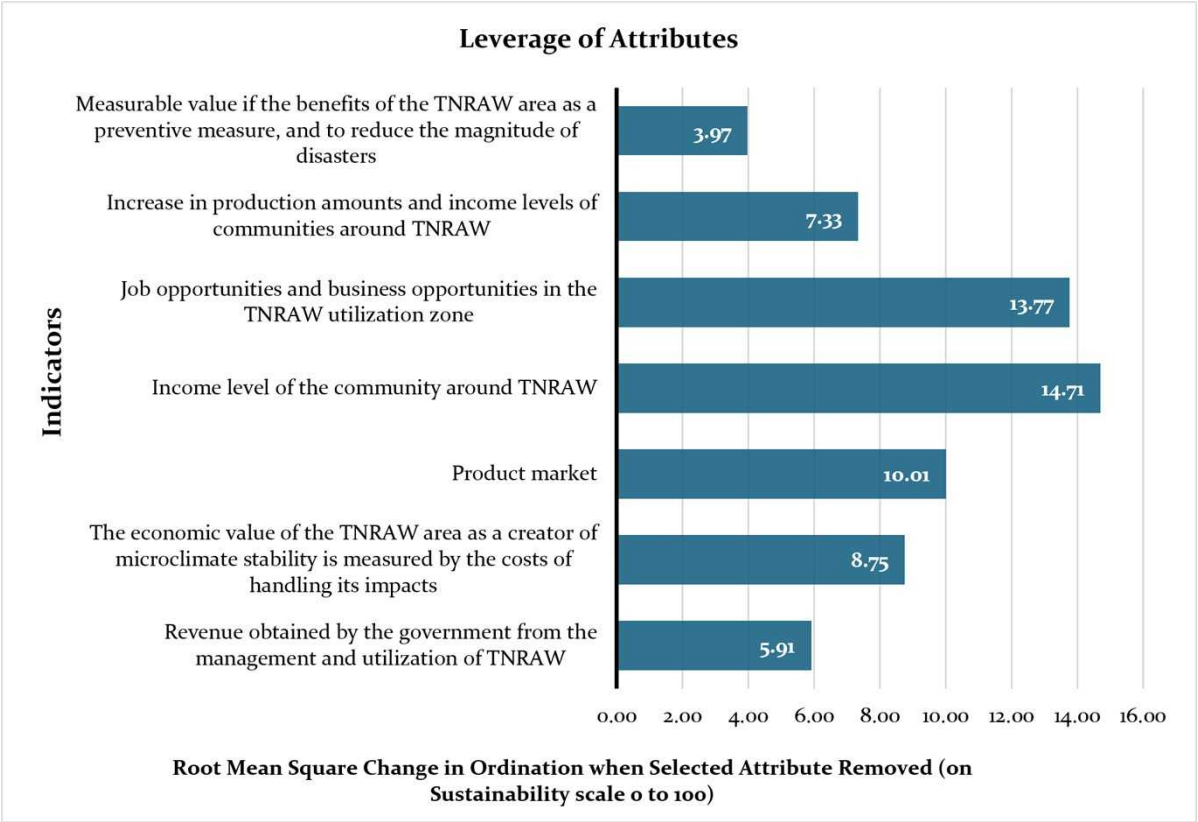

Figure 2. Leverage analysis of the economic dimension in TNRAW

generations have developed the concept of local wisdom, encompassing behaviors and actions that support the preservation of nature and ecosystems. Recent reviews emphasize that biodiversity should be considered a primary objective rather than a secondary outcome of forest restoration programs (Shelton et al. 2024; Brancalion et al. 2025). Local wisdom constitutes an essential foundation for guiding community behavior in managing natural resources and ensuring sustainable interactions with the environment. The conflict resolution mechanism became the most important indicator affecting the sustainability of the RHL (Figure 3). This finding confirms that collaborative governance and effective institutional arrangements are essential for strengthening stakeholder trust, reducing conflicts, and improving the long-term sustainability of forest landscape restoration programs (Beeton et al. 2024; Owusu et al. 2024). Recent systematic reviews have highlighted that forest landscape restoration should integrate environmental justice, inclusive participation, and equitable governance to achieve sustainable restoration outcomes (Shelton et al. 2024). Forest landscape restoration contributes not only to ecological recovery but also strengthens social cohesion and rural livelihoods when local communities actively participate in restoration activities (Ullah 2024).

Ecological Dimension

In the ecological dimension, the indicators with the highest leverage values were diversity of flora and fauna species (8.68), biodiversity management (7.31), and planting, maintenance, and protection activities (6.77), as depicted in Figure 4. The RHL program introduced planting of bitti wood (*Vitex cofassus*) and red jabon. The species selection and their suitability to the available land played an important role in determining the success of the RHL program. The overall success of the RHL program decreased when non-indigenous or inappropriate species were introduced into swamp, savanna, or lowland ecosystems, as seedling mortality increased. Bitti wood showed excellent growth potential and high economic value. However, such practices may lead to competition for water and nutrients, potentially inhibiting the growth of surrounding native species if not properly managed (Arneth et al. 2021). Bitti fruit did not serve as a primary food source for key wildlife species in TNRAW, such as maleo and deer, thereby limiting its ecological contribution to food web restoration and potentially affecting the survival of

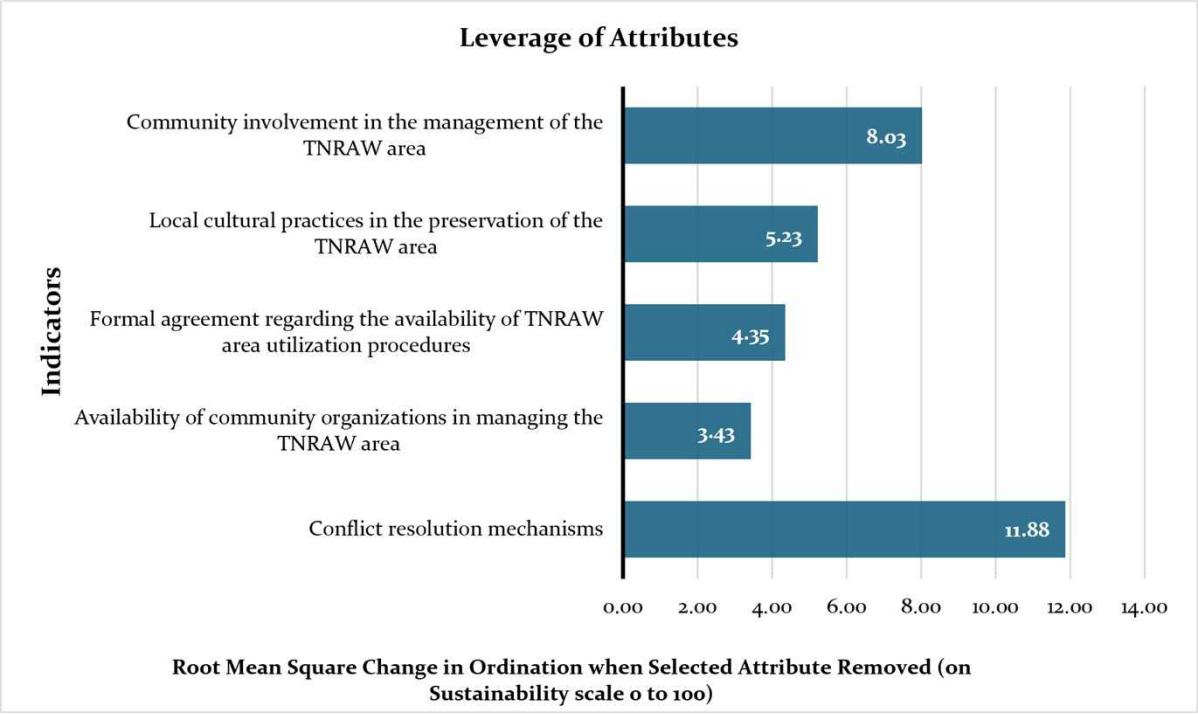

Figure 3. Leverage analysis of the social dimension in TNRAW

native species (Yumna et al. 2023).

Another indicator influencing sustainability status under ecological criteria was biodiversity management. Focusing on restoring native species diversity and ecosystem complexity in TNRAW strengthens the ecosystem and supports the long-term success of the RHL program. An effective ecological rehabilitation program prioritizes planting a diverse array of native flora, thereby enhancing ecosystem resilience and sustainability. Therefore, this research recommends proper biodiversity management as the most important investment to ensure that RHL outcomes remain persistent and sustainable over long-term ecological cycles.

Planting, maintaining, and protecting vegetation directly influenced ecological sustainability through a long-term process that begins with planting and continues with ongoing maintenance and protection. Each stage played a critical role in the ecological outcomes. Selecting appropriate species and managing vegetation structure and composition improve habitat quality and food biodiversity. These actions worked together to enhance overall ecological and ecosystem conditions. Forest landscape restoration should integrate biodiversity conservation with community livelihoods because ecological recovery is more likely to be sustained when local communities actively participate in restoration activities and governance processes (Fischer et al. 2023).

Model Reliability

The goodness-of-fit and Monte Carlo validation results (Table 4) confirmed that the sustainability model was reliable and robust. Stress values for all dimensions remained below 0.25, indicating that the ordination adequately represented multidimensional relationships with acceptable distortion levels (Kavanagh & Pitcher 2004). Meanwhile, R^2 values exceeding 0.94 indicated strong explanatory power, indicating that the selected sustainability attributes captured most of the dataset's variability. These results also suggested that uncertainty arising from differences in respondent scoring, expert judgment variability, and potential random error did not substantially alter the sustainability ordination outcomes. Monte Carlo analysis further supported model stability by demonstrating that variations in scoring inputs yielded relatively consistent sustainability index positions, thereby strengthening confidence in the assessment's reliability.

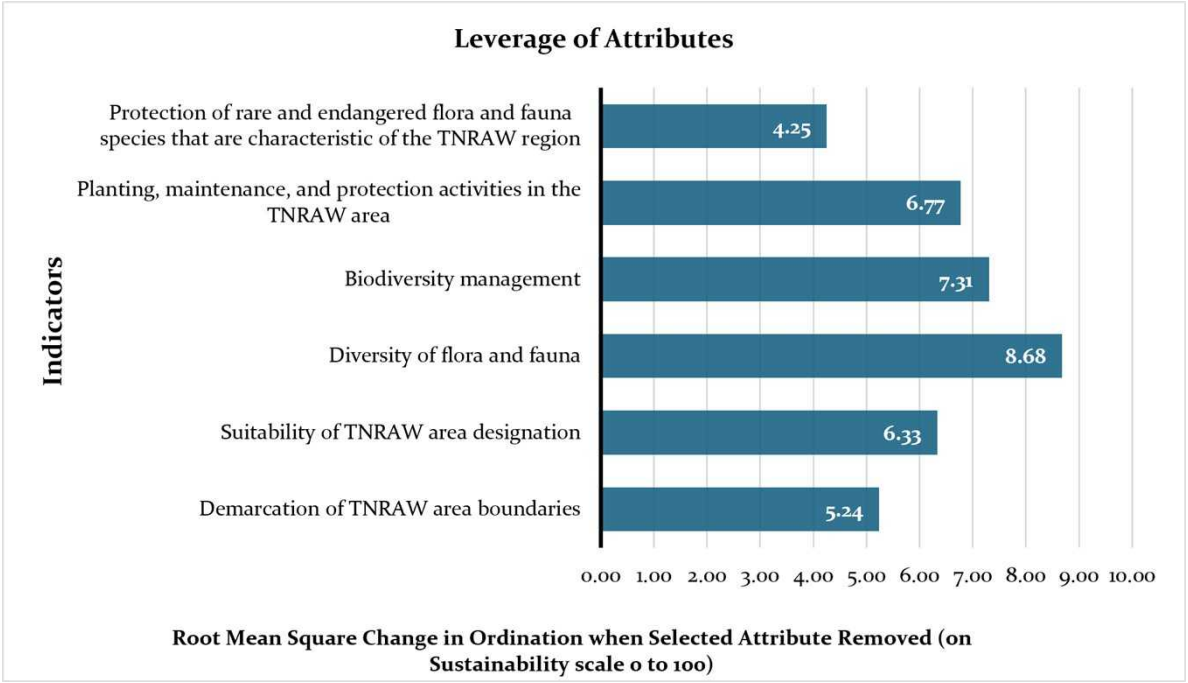

Figure 4. Leverage analysis of the ecological dimension in TNRAW

Table 4. Sustainability index and goodness-of-fit of the RHL program in TNRAW

Dimension	Stress (S)	R^2 (RSQ)	Interpretation
Economic	0.1477	0.9420	Good fit
Social	0.1529	0.9408	Good fit
Ecological	0.1502	0.9432	Good fit

Remarks: Stress values <0.25 indicate acceptable MDS ordination fit, while higher R^2 values indicate stronger explanatory power and more reliable sustainability representation (Kavanagh & Pitcher 2004).

Strategies to Improve Sustainability

Based on the results, this research suggested several strategies to improve TNRAW's sustainability. First, TNRAW management should prioritize biodiversity-based restoration by promoting the use of native species that are ecologically suitable and resilient to local environmental conditions. Second, there was a need to improve the quality of planting, maintenance, and monitoring activities to ensure higher survival rates and long-term ecosystem recovery. Third, although the economic dimension was moderately sustainable, efforts should be made to strengthen community-based livelihood programs, such as agroforestry and NTFP development, to enhance economic incentives for local communities. This was important for sustaining community participation and reducing pressure on forest resources. Fourth, TNRAW management should continue to strengthen the participatory method, given the strong performance of the social dimension. These included community engagement, conflict resolution mechanisms, and multi-stakeholder collaboration. Maintaining social cohesion was also essential to support long-term program sustainability. Fifth, there was a need for integrated management strategies that simultaneously address ecological, economic, and social dimensions. Recent evidence further indicates that restoration initiatives are more successful when governments establish long-term institutional commitments, strengthen policy coordination, and promote adaptive governance supported by continuous learning and stakeholder participation (Mansourian et al. 2022; Wiegant et al. 2022). This included improving institutional coordination, ensuring sustainable funding mechanisms, and implementing adaptive management practices based on continuous monitoring and evaluation. The results showed that achieving sustainability TNRAW requires a balanced approach, prioritizing ecological restoration while maintaining strong social support and improving economic benefits for local communities. Successful restoration programs require balancing global environmental objectives with local livelihood needs through interdisciplinary governance and stakeholder collaboration (Mansourian et al. 2025).

Conclusion

This research shows that TNRAW's sustainability was unbalanced, with strong, moderate, and weak performance in the social, economic, and ecological dimensions, respectively. The results indicate that although community participation has been established, ecological restoration remains the main challenge. The results provided a valuable contribution by identifying key leverage factors influencing sustainability and providing an integrated assessment using the RAPS–MDS method. From a management perspective, the results showed the need to prioritize ecological restoration, particularly biodiversity improvement, species selection, and post-planting management. Therefore, this research recommends that TNRAW management strengthen biodiversity-based restoration, improve monitoring and maintenance systems, enhance community-based economic programs, and reinforce institutional coordination through adaptive management methods. Overall, achieving sustainable rehabilitation requires a balanced strategy that integrates ecological, economic, and social dimensions.

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