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Ecological Restoration of Rubber Monocultures: Strategies for Biodiversity and Ecosystem Recovery in Tropical Regions

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Keywords: biodiversity conservation | ecological restoration | framework species approach | natural regeneration | rubber plantation

ABSTRACT

Sustainable conversion of uneconomic rubber monocultures is essential for restoring degraded tropical rainforests and achieving the goals of the UN Decade on Ecosystem Restoration (2021–2030). Here, we discuss existing ecological restoration approaches that may be applicable to converting rubber monocultures in protected and marginal areas with high conservation value but less economic potential. Before selecting restoration interventions, practitioners should conduct comprehensive assessments of landscape context, land-use history, forest regeneration status, and resource availability. Natural forest regeneration is typically a low-cost restoration option for rubber monocultures that have encroached into protected areas, where nearby natural forest fragments can provide seed sources. In other marginal areas, assisted natural regeneration and active planting can promote more rapid recovery. The restoration strategies outlined here can support the restoration of 1,900,000 ha of rubber monocultures in marginal zones and other economically unsustainable monoculture plantation crops, thereby making a significant contribution to global restoration targets by 2030.

Liang Song and Sujan Balami contributed equally to this study.

Summary

Rubber plantations have replaced vast areas of tropical rainforests, harming biodiversity, and often failing to deliver economic benefits in marginal or protected areas. This paper explores practical ways to restore these monoculture plantations to healthy and diverse forests. Key strategies include:

(1) Letting forests regrow naturally where possible, especially near existing forest fragments.

(2) Assisting recovery by removing invasive species or thinning rubber trees to help native plants thrive.

(3) Active planting of key tree species to speed up restoration, particularly in heavily degraded areas.

Restoration success depends on involving local communities along with compensating landowners for lost income. Governments, businesses, and conservation programs can help by funding restoration or supporting agroforestry systems that blend rubber production with biodiversity protection. By combining these approaches, we can restore degraded lands, protect wildlife, and contribute to meet global restoration goals by 2030.

- **Practitioner Points**
  - **Tailored Restoration Strategies**: Natural regeneration is typically a low-cost restoration option for rubber monocultures that have encroached into protected areas, where nearby remnant natural forest fragments can provide seed sources. In other marginal areas, assisted natural regeneration and active planting can promote more rapid recovery.
  - **Economic Incentives and Community Engagement**: Restoration efforts must address landowners' economic concerns to ensure long-term success. Compensation for ecosystem services (e.g., carbon sequestration, water security, etc.) through government policies, market mechanisms, or payments for ecosystem services can incentivize participation. Some smallholder farmers may prefer agroforestry transitions if direct rainforest restoration lacks immediate financial benefits.

1 | Introduction

Tropical rainforests harbor high levels of biodiversity, store approximately 30% of the global gross forest carbon pool, and provide timber and non-timber forest products (NTFPs) (Myers et al. 2000; Pan et al. 2024). Despite global conservation efforts, tropical rainforests continue to be replaced by plantation crops such as rubber (*Hevea brasiliensis* (Willd. ex A. Juss.) Müll.Arg.) (Grogan et al. 2018). According to FAOSTAT (2023), rubber plantations cover more than 13.58 million hectares in tropical regions, primarily in Southeast Asia and sub-Saharan Africa (Earthsight 2018; Hurni and Fox 2018). This expansion has resulted in massive ecological loss, valued at up to $1.34 trillion in Southeast Asia alone, which accounts for around 90% of global rubber production (Wang and Zhang 2025). Fagan et al. (2022) estimated that, in the humid tropics, tree plantations have encroached upon 9.2% of accessible protected areas. A more recent study in Southeast Asia reported that over 1 million hectares of rubber monocultures are located within Key Biodiversity Areas (Wang et al. 2023). The spread of monocultures into protected areas poses a serious threat to biodiversity, as these areas serve as the last refuges for threatened species and ecosystems (Laurance et al. 2012).

Previous research from the same region found that between 2005 and 2010, approximately 1.9 million hectares of rubber monocultures were established in environmentally unsuitable marginal areas, such as at higher elevations, on steeper slopes, and in regions with more frost and lower temperatures (Ahrends et al. 2015). Rubber monocultures in these marginal areas are economically unsustainable due to reduced yields, prolonged maturation times, shorter harvesting periods, and greater susceptibility to disease (Rao et al. 1998; Ahrends et al. 2015; Chen et al. 2016). This highlights that the conversion of tropical rainforests to rubber monocultures in protected and marginal areas has detrimental effects on biodiversity and fails to deliver expected economic returns (Yi et al. 2014). There is an urgent need to restore these monocultures to rainforest ecosystems to improve tropical biodiversity integrity, ecosystem functions, and associated services.

Global analyses have identified significant restoration opportunities across the tropics (Brancalion et al. 2019; Edwards et al. 2021), and various restoration strategies, such as natural regeneration, assisted natural regeneration, applied nucleation, and planting, have shown potential (Uebel et al. 2017; Holl et al. 2020; Elliott et al. 2022; Williams et al. 2024). However, successful examples of rainforest restoration from tropical plantation crops remain limited and fragmented (Paterno et al. 2024; Zemp et al. 2023; Liu and Qi 2025). Most current research has examined the ecological impacts of rainforest conversion to rubber monocultures, with findings consistently advocating for agroforestry systems as a sustainable alternative (Huang et al. 2022; Liu and Qi 2025). However, agroforestry has different restoration goals and is unlikely to reverse the biodiversity loss caused by monocultures (Gibson et al. 2011; Liu et al. 2021).

Here, we explore a range of ecological restoration strategies that may be applied to restore rubber monocultures in protected and marginal areas to semi-natural forest ecosystems that, as far as possible, resemble the biodiversity and ecological functions of the primary tropical rainforests. We also highlight the key challenges that must be addressed to implement these restoration strategies effectively.

2 | Restoration Framework

As with other degraded forest ecosystems, tropical rainforest restoration in rubber monocultures can adopt one or a combination of the following three approaches: (1) natural regeneration, (2) assisted natural regeneration, and (3) tree planting (Lamb 2011), which represent an increasing gradient of restoration intervention intensity (Chazdon et al. 2021). Elliott et al. (2013) emphasized that the choice among these approaches should be guided by the degree of forest degradation at the landscape level. The expansion of rubber monocultures over large areas has led to extensive degradation, including the replacement of multispecies forests with monospecies forests dominated by a single canopy layer and the fragmentation of native forest patches (Xu et al. 2014). This has also resulted in widespread soil degradation, characterized by nutrient imbalance due to chronic fertilization, increased bulk density due to compaction, and reduced soil water content resulting from elevated surface runoff and evapotranspiration (Tan et al. 2011; Li et al. 2012). On steep slopes and at high elevations, these effects are intensified by substantial surface runoff and erosion (Li et al. 2013).

Restoring rubber monocultures in protected and marginal areas can be organized in two different phases: (1) the identification and prioritization of restoration sites using remote sensing and field surveys, followed by an assessment of degradation levels, and (2) the implementation of appropriate restoration interventions based on assessment outcomes (Figure 1). National-level data on protected areas are generally well maintained, enabling the identification of rubber monocultures in protected areas through analyses of temporal changes in remote sensing imagery (Chen et al. 2016). For example, Wang et al. (2023) successfully applied a plant phenology-based remote sensing method to distinguish monocultures from other forest types. Similarly, monocultures on steep slopes and at higher elevations can also be detected using remote sensing data (Liu et al. 2023), which can be complemented by field surveys and interviews with smallholder farmers to locate low-yielding areas. Generating maps that highlight priority conservation zones and potential restoration sites would be valuable in guiding these efforts.

Given their high conservation value, rubber monocultures within protected areas should be prioritized for restoration. Restoring these areas can immediately provide suitable sites for high plant diversity, particularly when adjacent to remnant forests. Restoration can also reconnect fragments of natural forests (Liu et al. 2019), promoting seed dispersal and enhancing the likelihood of restoration success. Increasing landscape connectivity has been shown to benefit biodiversity (Liévano-Latorre et al. 2025). Marginal areas at higher elevations and steeper slopes should also be prioritized, as rubber yields are generally very low in these regions. However, there is a risk that farmers may clear such lands to cultivate more profitable cash crops such as pineapple, banana, or tea (Zhang et al. 2019). While such land-use changes may support food security and local economies, rainforest restoration remains feasible if farmers are compensated for the opportunity costs, which are often not prohibitive.

Once suitable restoration sites are identified, assessing their degradation level is key to selecting appropriate restoration interventions. Important considerations include landscape context, land-use history, and resource availability (Holl and Aide 2011). Landscape factors, such as proximity to forest remnants, the presence of invasive species, seed dispersal agents, and fire occurrence, will affect both the regeneration rate and the quality of the regenerated forest and can help determine the most suitable restoration approach (Bardino et al. 2023). Land-use history, including monoculture age and fertilization intensity, affects soil conditions and plant establishment. Finally, resource availability and infrastructure, such as financial support, labor, and the capacity of local nurseries to supply native seedlings, will also determine restoration choices.

2.1 | Restoration by Natural Regeneration

Among the various approaches for restoring degraded lands, natural regeneration is one of the most widely applied methods (Crouzeilles et al. 2017; Chazdon et al. 2021). This approach involves preventing further disturbance at the site and allowing the spontaneous recovery of biodiversity, community structure, and ecological function through natural succession (Chazdon and Guariguata 2016). Natural regeneration is most suitable for less degraded sites that are in vicinity of remnant forest patches, which can serve as sources of propagules (Chazdon and Guariguata 2016). It is also a low-cost method, making it especially feasible for large-scale forest restoration. This approach is appropriate for restoring rubber monocultures and was shown to increase plant species richness as well as soil carbon and nitrogen concentrations under specific conditions (Zeng et al. 2021; Figure 2a,b). Monocultures that have encroached into protected areas are often adjacent to natural

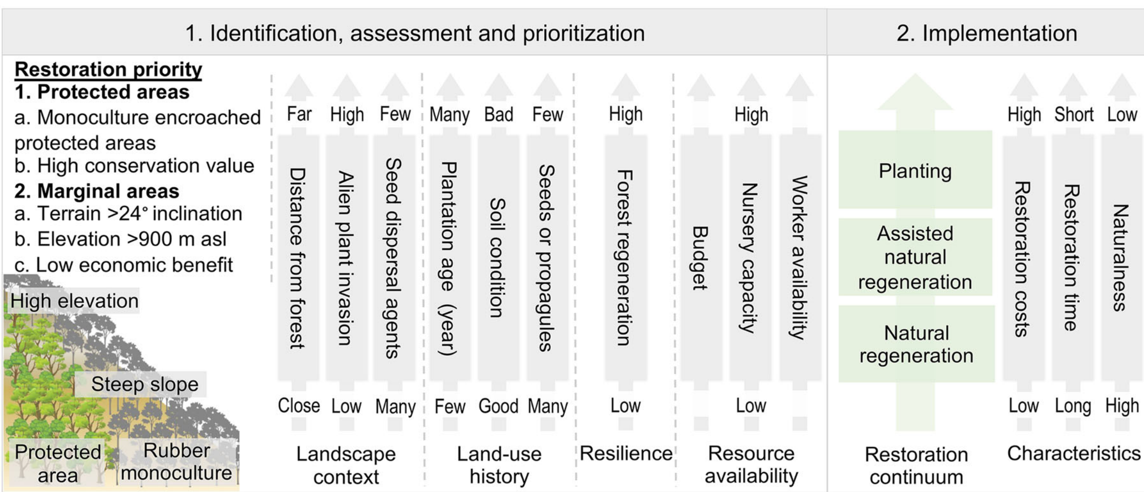

FIGURE 1 | Stepwise restoration framework for rubber monocultures in protected and marginal areas.

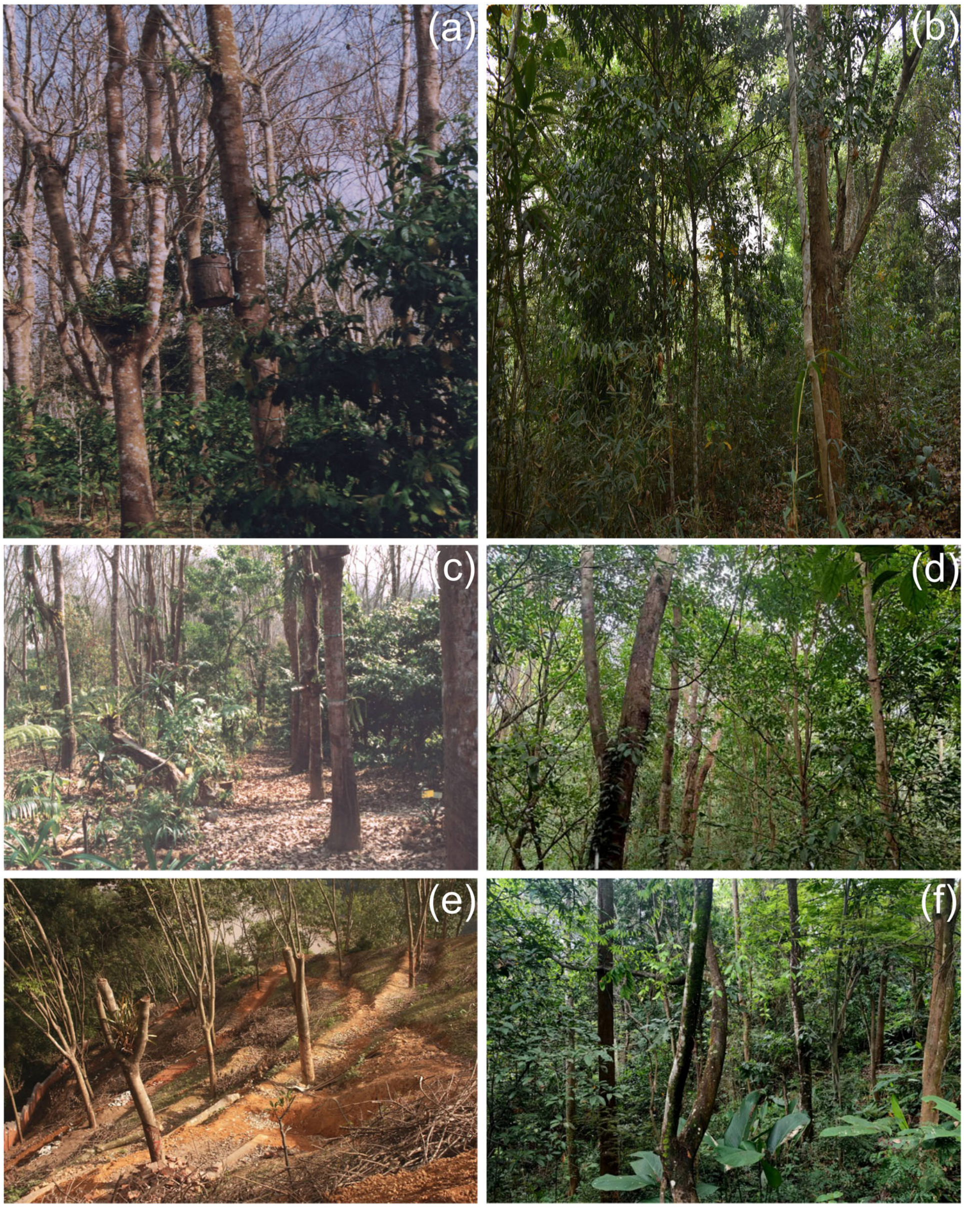

FIGURE 2 | (a) Rubber monocultures in early 1993 and (b) current physiognomy after natural regeneration in Xishuangbanna Tropical Botanical Garden (XTBG); (c) Rubber monocultures in 1993 and (d) current physiognomy after gap replanting in XTBG; (e) Rubber monocultures in 2003 and (f) current physiognomy developed after standing thinning and plantations in Yourantai of Jinghong, SW China. (Picture sources: a, c by Xiao-Bao Deng, b, e by Sujan Balami and Gerard Burgermeister, respectively, and d, f by Liang Song).

forests with high plant diversity, which can provide abundant propagules for forest regeneration, making natural regeneration a viable strategy for these areas (Du et al. 2024). Likewise, rubber monocultures at higher elevations are frequently interspersed with remnant natural forests, which can support regeneration. Natural forest patches are also often retained on steep slopes due to the difficulty of cultivation, making natural regeneration feasible in marginal areas near such slopes. Furthermore, recently established rubber monocultures may not have undergone extensive soil degradation and could retain viable soil seed banks or propagules, further supporting restoration through natural regeneration. However, several environmental (e.g., canopy light conditions, soil moisture, nutrient content) and biotic (e.g., plant competition, aggressive weeds, invasive species, absence of mycorrhizal fungi) factors can inhibit the establishment and growth of native seedlings on restoration sites (Lamb 2011; Sansevero et al. 2017). Invasive plants such as *Mucuna bracteata*, *Chromolaena odorata*, and *Mimosa pudica* are common in rubber monocultures (Sankaran et al. 2014; Lan et al. 2022). These factors can significantly delay the regeneration process; in such cases, assisted natural regeneration or active planting should be considered as alternative approaches.

2.2 | Restoration by Assisted Natural Regeneration

Assisted natural regeneration aims to accelerate the dispersal, establishment, and growth of native plants in restoration sites that show some degree of natural regeneration. Simple interventions such as protection from disturbances (e.g., grazing and fire), enhancement of seed dispersal or seedling establishment (e.g., irrigation, fertilization), and management of competing vegetation (e.g., grasses) can accelerate the recovery of native vegetation at relatively low cost (Chazdon et al. 2021). Several methods of assisted natural regeneration can be implemented sequentially to achieve successful restoration (Shono et al. 2007).

In the context of rubber monocultures, pruning and thinning of rubber strands, along with the removal of weedy and invasive herbs, vines, shrubs, lianas, and ferns, can support natural regeneration, provided that financial resources and labor are available. For instance, removing invasive plants or weeds in thinned monoculture stands was shown to promote the establishment and growth of native seedlings (Uebel et al. 2017). However, in rubber monocultures growing on steep slopes, intensive weeding may increase the risk of soil erosion (Liu, Blagodatsky, et al. 2016; Neyret et al. 2020).

If these interventions fail to sufficiently promote natural regeneration, active planting may be the only viable option for restoration. Nonetheless, field monitoring of restoration sites can be helpful for assessing natural regeneration potential and informing decisions on whether planting is necessary. In some cases, the choice to plant should not rely solely on the failure of natural or assisted natural regeneration. When sufficient resources are available, planting can be a proactive strategy to accelerate rainforest recovery or to shape the composition of the restored forest by, for example, increasing the density of endangered tree species, those that disproportionately support wildlife (e.g., *Ficus*), or species that provide valuable NTFPs.

2.3 | Restoration by Planting

Restoration by planting can significantly reduce restoration time, but is usually impractical for large areas unless resources are abundant (e.g., financial support and the capacity of local nurseries to supply native tree seedlings). The two major considerations in restoration planting are: (1) which species to plant, and (2) which planting method to use. We do not recommend planting single species unless the restoration goal explicitly requires it (e.g., for timber production). The framework species approach and maximum diversity method are two widely accepted strategies for selecting species for restoration planting.

The framework species approach involves planting 6–30 key native tree species whose flowers and fruits attract wildlife that, in turn, disperse seeds from nearby natural forests (Elliott et al. 2022). The maximum diversity method aims to plant as many species as can successfully establish in degraded forests (Lamb 2011). This method may include the selection of large-seeded plant species, often dependent on large mammals for seed dispersal, or endangered and vulnerable species with high conservation value. It is particularly suited to sites far from forest remnants or other sources of propagules. Another important factor in restoring rubber monocultures is whether to thin the rubber stand, and if so, to what extent. In dense rubber plantations, shade-tolerant plant species may be required.

Once appropriate species are selected, planting can be done via direct seeding or by transplanting nursery-grown seedlings. Direct seeding allows for a more diverse species mix, while seedling transplantation typically results in higher seedling survival rates (Palma and Laurance 2015). If local nurseries have high production capacity, seedling transplantation is preferable. An innovative technique—planting vegetative stakes—can also be used for species that regenerate from stem cuttings. This method was applied successfully in restoration of abandoned tropical pastures in Central America (Zahawi and Holl 2009) and in degraded tropical forest in southwest China (Dai 2023). It is particularly useful for transplanting keystone tropical species such as *Ficus* spp. (Dai 2023; Zahawi and Leighton Reid 2018), making it suitable for the framework species approach or applied nucleation (Holl et al. 2020).

Restoration by planting in rubber monoculture can be done either with or without stand thinning. For example, gap replanting (Figures 2c,d and 3a) involves planting in natural gaps without thinning the rubber stand (Joshi et al. 2000; Li et al. 2013, Figure 2c,d). Alternatively, some rubber monocultures can also be restored by other innovative planting methods that involve rubber stand thinning, such as thinning followed by planting, especially in monocultures with high tree density (Figures 2e,f and 3b), or the applied nucleation approach (Figure 3c).

In these thinning methods, we do not recommend the complete removal of rubber trees at the onset. Remaining rubber trees can continue to yield latex (providing supplementary income to landowners), contribute to belowground carbon storage, and function as nurse trees that offer shade and protection to young seedlings of mid- and late-successional species (Rappaport and Montagnini 2014; Piotto et al. 2020). Additionally, they may help suppress herb and liana invasions. In smallholder-managed farms, where rubber is often densely planted, thinning or pruning the canopy layer may be necessary to facilitate restoration. Partial prunning can reduce competition for nutrients and water between rubber trees and new plantings.

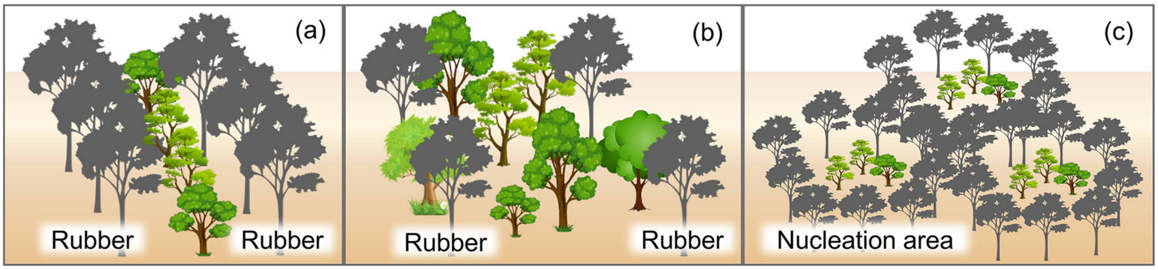

FIGURE 3 | Restoration by plantations method: (a) gap replanting, (b) stand thinning and planting, and (c) applied nucleation.

The applied nucleation method—also known as tree island planting—involves creating nucleation areas through a combination of planting and other innovative techniques such as artificial fauna shelters, seed bank enhancement, or the creation of specialized establishment sites (Figure 3c). These nucleation areas promote plant species recruitment and accelerate natural regeneration, eventually expanding and merging across the landscape. However, variables such as nuclei size, species selection, and planting density should be evaluated before wide-scale implementation. Although this technique has shown success in forest restoration in the Amazon and Sumatra (Bechara et al. 2016; Holl et al. 2020; Zemp et al. 2023), it was not yet applied to rubber monocultures. Nevertheless, it holds promise, particularly where large-scale planting is unfeasible. In rubber systems, applied nucleation may be optimized by establishing patches after stand pruning or thinning, selecting planting species based on life-history traits (e.g., pioneer vs. non-pioneer species), and considering seed dispersal mechanisms that enhance plant recruitment.

3 | Key Challenges to Overcome in Implementing Restoration in Rubber Monocultures

As we work toward ambitious goals for rainforest restoration, several challenges must be addressed to ensure the successful implementation of the proposed restoration framework. The most significant and immediate challenge is how to persuade landowners of the value of restoring rubber monocultures to rainforests. Strategies to achieve this vary depending on the type of landowner. For example, private companies owning unproductive rubber estates may be incentivized through reputational benefits, as they can market the restoration initiatives as environmentally and socially responsible, climate-positive actions. However, for local smallholder farmers, economic considerations are likely to be the decisive factor. Many smallholders prefer converting monocultures into alternative agricultural land uses that promise greater economic returns and food security, rather than restoring rainforest ecosystems. Therefore, motivating these farmers with realistic and tangible incentives is crucial.

Restoration costs may potentially be covered through a range of sources, including corporate actors such as rubber companies aiming to enhance their environmental and social governance performance, or rubber sustainability platforms like the Global Platform for Sustainable Natural Rubber (GPSNR), which has made public commitments to support the socially equitable greening of the rubber industry (GPSNR 2025). Government agencies committed to climate adaptation and mitigation initiatives, or similar policies, may also provide financial support. Additionally, public funding mechanisms, such as payments for ecosystem services (e.g., carbon sequestration) offer another potential avenue for covering restoration expenses (Liu et al. 2023).

These considerations highlight the importance of reducing restoration costs. One strategy is to focus primarily on restoration via natural regeneration. Another is to integrate native economic species during planting efforts to generate revenue that can subsidize restoration costs, incorporating establishment and management costs into broader business plans (Harrison et al. 2020; Werden et al. 2024). In situations where smallholder farmers are highly reluctant to pursue proposed rainforest restoration, transitioning monocultures into rubber-based agroforestry systems may be a more acceptable option. This approach incorporates economically valuable intercrops, potentially offering satisfactory returns to smallholders while simultaneously supporting biodiversity (Warren-Thomas et al. 2019). Rubber agroforestry has been found to improve soil properties, reduce soil erosion, and support local livelihoods (Guo et al. 2006; Liu, Zhu, et al. 2016; Hua et al. 2021). However, it is important to acknowledge that the biodiversity benefits of agroforestry systems are generally more limited compared to those of rainforest restoration. The broader societal value of restoration should also be emphasized. For example, engaging and employing local communities in the restoration of rubber monocultures can bolster local economies, enhance ecosystem services (e.g., water security), and increase the success of restoration efforts (Elliott et al. 2018).

Other challenges revolve around the logistical requirements for the implementation of restoration strategies at scale. For assisted natural regeneration and planting approaches, site preparation activities, such as weeding, pruning, and stand thinning, require substantial labor and equipment. Integration with local labor markets and livelihoods will be necessary. Additionally, infrastructure for seed collection, storage, and nursery development is critical for producing large numbers of seedlings needed for planting. Establishing best practices for site preparation, native species selection, and large-scale propagation of diverse plant species is essential. In particular, planting requires careful decision-making regarding species selection and site-specific methods. Ongoing research and development efforts are needed to refine and optimize these restoration practices.

4 | Conclusions

Rubber plantations, which cover over 13 million hectares in tropical regions, have resulted in significant ecological degradation. A substantial portion of these plantations is located within priority conservation areas and economically marginal production sites. Urgent action is thus required to restore these areas, particularly in light of growing concerns regarding tropical biodiversity conservation and the need to reduce global carbon emissions.

Governments should enforce strict regulations to prevent further expansion of rubber monocultures, especially in protected and marginal areas, recognizing such encroachments as environmental offenses. Simultaneously, the rapid recovery of degraded tropical rainforest from rubber monocultures in these areas must be prioritized. Governments, research institutions, and other stakeholders should focus on collecting data to identify unsustainable rubber monoculture areas and implement appropriate restoration interventions.

As outlined in this article, the selection of suitable ecological restoration methods should be informed by assessments of context-dependent factors such as landscape context, land-use history, and the availability of resources for restoration. Natural regeneration is generally a simple and cost-efficient approach. However, dispersal limitations and environmental or biotic barriers can delay forest recovery and may lead to the permanent loss of certain species. In such cases, the framework species approach may be more appropriate, especially when it targets large-seeded, dispersal-limited, or rare and endangered species to meet their specific conservation needs.

Importantly, the success of each restoration intervention should be systematically monitored and evaluated to enable adaptive management and inform any need for additional actions. Networked restoration experiments offer a robust framework for implementing such evaluations (Gellie et al. 2018). For restoration plans at regional or national scales, participation from local stakeholders is essential (Holl 2017). Monitoring a wide range of socioeconomic (e.g., community acceptance and involvement) and ecological factors (e.g., species composition across trophic levels, community structure, ecosystem function) as well as ecosystem services will help to develop effective, bottom-up restoration measures for monocultures in protected and marginal areas.

Author Contributions

Liang Song, Gbadamassi G. O. Dossa, Rhett D. Harrison conceptualized the manuscript. Liang Song, Sujan Balami, Gbadamassi G. O. Dossa wrote and edited the manuscript; Wei-Guo Liu, Philippe Thaler, Thomas Cherico Wanger, David P. Edwards, Maria Mei Hua Wang, Yong-Ping Yang, Rhett D. Harrison reviewed and edited the manuscript.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The authors have nothing to report.

References

Ahrends, A., P. M. Hollingsworth, A. D. Ziegler, et al. 2015. "Current Trends of Rubber Plantation Expansion May Threaten Biodiversity and Livelihoods." *Global Environmental Change* 34: 48–58. https://doi.org/10.1016/j.gloenvcha.2015.06.002.

Bardino, G., G. Di Fonzo, K. Walker, M. Vitale, and J. S. Hall. 2023. "Landscape Context Importance for Predicting Forest Transition Success in Central Panama." *Landscape Ecology* 38, no. 9: 2307–2321. https://doi.org/10.1007/s10980-023-01694-y.

Bechara, F. C., S. J. Dickens, E. C. Farrer, et al. 2016. "Neotropical Rainforest Restoration: Comparing Passive, Plantation and Nucleation Approaches." *Biodiversity and Conservation* 25, no. 11: 2021–2034. https://doi.org/10.1007/s10531-016-1186-7.

Brancalion, P. H. S., A. Niamir, E. Broadbent, et al. 2019. "Global Restoration Opportunities in Tropical Rainforest Landscapes." *Science Advances* 5, no. 7: eaa3223. https://doi.org/10.1126/sciadv.aav3223.

Chazdon, R. L., D. A. Falk, L. F. Banin, et al. 2021. "The Intervention Continuum in Restoration Ecology: Rethinking the Active Passive Dichotomy." *Restoration Ecology* 32, no. 8: e13535. https://doi.org/10.1111/rec.13535.

Chazdon, R. L., and M. R. Guariguata. 2016. "Natural Regeneration as a Tool for Large-Scale Forest Restoration in the Tropics: Prospects and Challenges." *Biotropica* 48, no. 6: 716–730. https://doi.org/10.1111/btp.12381.

Chen, H., Z.-F. Yi, D. Schmidt-Vogt, et al. 2016. "Pushing the Limits: The Pattern and Dynamics of Rubber Monoculture Expansion in Xishuangbanna, SW China." *PLoS One* 11, no. 2: e0150062. https://doi.org/10.1371/journal.pone.0150062.

Crouzeilles, R., M. S. Ferreira, R. L. Chazdon, et al. 2017. "Ecological Restoration Success Is Higher for Natural Regeneration Than for Active Restoration in Tropical Forests." *Science Advances* 3, no. 11: 1–7. https://doi.org/10.1126/sciadv.1701345.

Dai, Q. 2023. *Exploring the Cuttings Propagation Technique With Ficus and Evaluating Its Use in the Applied Nucleation Restoration in Tropical Regions*, 1–76. University of Chinese Academy of Sciences.

Du, C., D. Li, X. Yang, et al. 2024. "Diversity of Understory Herbaceous Plants During Succession in Rubber Plantations in National Park of Hainan Tropical Rainforest, China." *Journal of Tropical Ecology* 40: e23. https://doi.org/10.1017/s0266467424000221.

Earthsight. 2018. *The Coming Storm: How Secrecy and Collusion in Industrial Agriculture Spell Disaster for the Congo Basin's Forests*, 1–19. Earthsight. https://docs.wixstatic.com/ugd/624187_a3688b61a2c84ec9aad89efea8ffc6db.pdf.

Edwards, D. P., G. R. Cerullo, S. Chomba, et al. 2021. "Upscaling Tropical Restoration to Deliver Environmental Benefits and Socially Equitable Outcomes." *Current Biology* 31, no. 19: R1326–R1341. https://doi.org/10.1016/j.cub.2021.08.058.

Elliott, S., D. Shannon, P. Nippanon, and R. Amphon. 2018. "Where Science Meets Communities: Developing Forest Restoration Approaches for Northern Thailand." *Natural History Bulletin of the Siam Society* 63, no. 1: 11–26. https://cdn.forru.org/publication-files/forru-0000083-0001-en.pdf.

Elliott, S., N. Tucker, D. P. Shannon, and P. Tiansawat. 2023. "The Framework Species Method: Harnessing Natural Regeneration to Restore Tropical Forest Ecosystems." *Philosophical Transactions of the Royal Society of London, Series B: Biological Sciences* 378: 20210073. https://doi.org/10.1098/rstb.2021.0073.

Elliott, S. D., D. Blakesley, and K. Hardwick. 2013. *Restoring Tropical Forests: A Practical Guide*. Kew Publishing.

Fagan, M. E., D.-H. Kim, W. Settle, et al. 2022. "The Expansion of Tree Plantations Across Tropical Biomes." *Nature Sustainability* 5, no. 8: 681–688. https://doi.org/10.1038/s41893-022-00904-w.

FAOSTAT. 2023. https://www.fao.org/faostat/en/#data/QCL.

Gellie, N. J., M. F. Breed, P. E. Mortimer, R. D. Harrison, J. Xu, and A. J. Lowe. 2018. "Networked and Embedded Scientific Experiments Will Improve Restoration Outcomes." *Frontiers in Ecology and the Environment* 16, no. 5: 288–294. https://doi.org/10.1002/fee.1810.

Gibson, L., T. M. Lee, L. P. Koh, et al. 2011. "Primary Forests Are Irreplaceable for Sustaining Tropical Biodiversity." *Nature* 478, no. 7369: 378–381. https://doi.org/10.1038/nature10425.

GPSNR. 2025. https://sustainablenaturalrubber.org.

Grogan, K., D. Pflugmacher, P. Hostert, O. Mertz, and R. Fensholt. 2018. "Unravelling the Link Between Global Rubber Price and Tropical Deforestation in Cambodia." *Nature Plants* 5, no. 1: 47–53. https://doi.org/10.1038/s41477-018-0325-4.

Guo, Z., Y. Zhang, P. Deegen, and H. Uibrig. 2006. "Economic Analyses of Rubber and Tea Plantations and Rubber-Tea Intercropping in Hainan, China." *Agroforestry Systems* 66, no. 2: 117–127. https://doi.org/10.1007/s10457-005-4676-2.

Harrison, R. D., T. Swinfield, A. Ayat, S. Dewi, M. Silalahi, and I. Heriansyah. 2020. "Restoration Concessions: A Second Lease on Life for Beleaguered Tropical Forests?" *Frontiers in Ecology and the Environment* 18, no. 10: 567–575. https://doi.org/10.1002/fee.2265.

Holl, K. D. 2017. "Restoring Tropical Forests From the Bottom Up." *Science* 355, no. 6324: 455–456. https://doi.org/10.1126/science.aam5432.

Holl, K. D., and T. M. Aide. 2011. "When and Where to Actively Restore Ecosystems?" *Forest Ecology and Management* 261, no. 10: 1558–1563. https://doi.org/10.1016/j.foreco.2010.07.004.

Holl, K. D., J. L. Reid, R. J. Cole, F. Oviedo-Brenes, J. A. Rosales, and R. A. Zahawi. 2020. "Applied Nucleation Facilitates Tropical Forest Recovery: Lessons Learned From a 15-Year Study." *Journal of Applied Ecology* 57, no. 12: 2316–2328. https://doi.org/10.1111/1365-2664.13684.

Hua, M. W. M., E. M. Warren-Thomas, and T. C. Wanger. 2021. Rubber Agroforestry: Feasibility at Scale. Mighty Earth. https://research.bangor.ac.uk/portal/files/40328214/Mighty_Earth_Agroforestry_Rubber_Report_May_2021.pdf.

Huang, I. Y., K. James, N. Thamthanakoon, et al. 2022. "Economic Outcomes of Rubber-Based Agroforestry Systems: A Systematic Review and Narrative Synthesis." *Agroforestry Systems* 97, no. 3: 335–354. https://doi.org/10.1007/s10457-022-00734-x.

Hurni, K., and J. Fox. 2018. "The Expansion of Tree-Based Boom Crops in Mainland Southeast Asia: 2001 to 2014." *Journal of Land Use Science* 13, no. 1–2: 198–219. https://doi.org/10.1080/1747423x.2018.1499830.

Joshi, L., M. Van Noordwijk, G. Wibawa, S. Hardiwinoto, and T. Sukandi. 2000. "Gap Replanting—An Emerging Trend in Rejuvenation of Jungle Rubber Agroforests in Jambi, Indonesia." In *Workshop on Cultivating (in) Tropical Forests: The Evolution and Sustainability of Intermediate Systems Between Extractivism and Plantations*, edited by A. Heidi, A. Arild, B. Brian, M. Genevieve, R.-P. Manuel, and P. R. W. Vithanage: 73. European Union, European Tropical Forest Research Network (ETFRN) and Center for International Forestry Research. http://old.worldagroforestry.org/downloads/Publications/PDFS/PP00164.pdf.

Lamb, D. 2011. *Regreening the Bare Hills*. Springer Netherlands. https://doi.org/10.1007/978-90-481-9870-2.

Lan, G., B. Chen, C. Yang, R. Sun, Z. Wu, and X. Zhang. 2022. "Main Drivers of Plant Diversity Patterns of Rubber Plantations in the Greater Mekong Subregion." *Biogeosciences* 19, no. 7: 1995–2005. https://doi.org/10.5194/bg-19-1995-2022.

Laurance, W. F., D. Carolina Useche, J. Rendeiro, et al. 2012. "Averting Biodiversity Collapse in Tropical Forest Protected Areas." *Nature* 489, no. 7415: 290–294. https://doi.org/10.1038/nature11318.

Li, H., Y. Ma, W. Liu, and W. Liu. 2012. "Soil Changes Induced by Rubber and Tea Plantation Establishment: Comparison With Tropical Rain Forest Soil in Xishuangbanna, SW China." *Environmental Management* 50, no. 5: 837–848. https://doi.org/10.1007/s00267-012-9942-2.

Li, Y., X. Deng, M. Cao, Y. Lei, and Y. Xia. 2013. "Soil Restoration Potential With Corridor Replanting Engineering in the Monoculture Rubber Plantations of Southwest China." *Ecological Engineering* 51: 169–177. https://doi.org/10.1016/j.ecoleng.2012.12.081.

Liévano-Latorre, L. F., J. M. De Almeida-Rocha, A. Akama, et al. 2025. "Addressing the Urgent Climate and Biodiversity Crisis Through Strategic Ecosystem Restoration in Brazil." *Biological Conservation* 302: 110972. https://doi.org/10.1016/j.biocon.2025.110972.

Liu, C.-A., M.-Y. Liang, J.-W. Tang, Y.-Q. Jin, Z.-B. Guo, and K. H. M. Siddique. 2021. "Challenges of the Establishment of Rubber-Based Agroforestry Systems: Decreases in the Diversity and Abundance of Ground Arthropods." *Journal of Environmental Management* 292: 112747. https://doi.org/10.1016/j.jenvman.2021.112747.

Liu, H., S. Blagodatsky, M. Giese, F. Liu, J. Xu, and G. Cadisch. 2016. "Impact of Herbicide Application on Soil Erosion and Induced Carbon Loss in a Rubber Plantation of Southwest China." *Catena* 145: 180–192. https://doi.org/10.1016/j.catena.2016.06.007.

Liu, J., and D. Qi. 2025. "Research Progress of Rubber Forest Ecological Restoration Based on Citespace." *Highlights in Science, Engineering and Technology* 135: 172–186. https://doi.org/10.54097/2xws8356.

Liu, W., A. C. Hughes, Y. Bai, Z. Li, C. Mei, and Y. Ma. 2019. "Using Landscape Connectivity Tools to Identify Conservation Priorities in Forested Areas and Potential Restoration Priorities in Rubber Plantation in Xishuangbanna, Southwest China." *Landscape Ecology* 35, no. 2: 389–402. https://doi.org/10.1007/s10980-019-00952-2.

Liu, W., C. Zhu, J. Wu, and C. Chen. 2016. "Are Rubber-Based Agroforestry Systems Effective in Controlling Rain Splash Erosion?" *Catena* 147: 16–24. https://doi.org/10.1016/j.catena.2016.06.034.

Liu, W.-G., J.-Q. Zhang, Y. Yan, et al. 2023. "Encouraging the Reconversion of Rubber Plantations by Developing a Combined Payment System." *Global Ecology and Conservation* 43: e02415. https://doi.org/10.1016/j.gecco.2023.e02415.

Myers, N., R. A. Mittermeier, C. G. Mittermeier, G. A. B. da Fonseca, and J. Kent. 2000. "Biodiversity Hotspots for Conservation Priorities." *Nature* 403, no. 6772: 853–858. https://doi.org/10.1038/35002501.

Neyret, M., H. Robain, A. de Rouw, et al. 2020. "Higher Runoff and Soil Detachment in Rubber Tree Plantations Compared to Annual Cultivation Is Mitigated by Ground Cover in Steep Mountainous Thailand." *Catena* 189: 104472. https://doi.org/10.1016/j.catena.2020.104472.

Palma, A. C., and S. G. W. Laurance. 2015. "A Review of the Use of Direct Seeding and Seedling Plantings in Restoration: What Do We Know and Where Should We Go?" *Applied Vegetation Science* 18, no. 4: 561–568. https://doi.org/10.1111/avsc.12173.

Pan, Y., R. A. Birdsey, O. L. Phillips, et al. 2024. "The Enduring World Forest Carbon Sink." *Nature* 631, no. 8021: 563–569. https://doi.org/10.1038/s41586-024-07602-x.

Paterno, G. B., F. Brambach, N. Guerrero-Ramírez, et al. 2024. "Diverse and Larger Tree Islands Promote Native Tree Diversity in Oil Palm Landscapes." *Science* 386, no. 6723: 795–802. https://doi.org/10.1126/science.ado1629.

Piotto, D., K. Flesher, A. C. P. Nunes, S. Rolim, M. Ashton, and F. Montagnini. 2020. "Restoration Plantings of Non-Pioneer Tree Species in Open Fields, Young Secondary Forests, and Rubber Plantations in Bahia, Brazil." *Forest Ecology and Management* 474: 118389. https://doi.org/10.1016/j.foreco.2020.118389.

Rao, P. S., C. K. Saraswathyamma, and M. R. Sethuraj. 1998. "Studies on the Relationship Between Yield and Meteorological Parameters of Para Rubber Tree (*Hevea brasiliensis*)." *Agricultural and Forest Meteorology* 90, no. 3: 235–245. https://doi.org/10.1016/s0168-1923(98)00051-3.

Rappaport, D., and F. Montagnini. 2014. "Tree Species Growth under a Rubber (*Hevea brasiliensis*) Plantation: Native Restoration via Enrichment Planting in Southern Bahia, Brazil." *New Forests* 45, no. 5: 715–732. https://doi.org/10.1007/s11056-014-9433-9.

Sankaran, K. V., T. V. Sajeev, and T. A. Suresh. 2014. "Invasive Plant Threats to Forests in the Humid Tropics: A Case Study From Kerala State, India." In *Proceedings of the International Conference on Invasive Alien Species Management*, edited by G. J. Thapa, N. Subedi, M. R. Pandey, S. K. Thapa, N. R. Chapagain, and A. Rana, 7–17. National

Trust for Nature Conservation. https://www.ntnc.org.np/iciasm/publications.

Sansevero, J. B. B., P. V. Prieto, A. Sánchez-Tapia, J. M. A. Braga, and P. J. F. P. Rodrigues. 2017. "Past Land-Use and Ecological Resilience in a Lowland Brazilian Atlantic Forest: Implications for Passive Restoration." *New Forests* 48, no. 5: 573–586. https://doi.org/10.1007/s11056-017-9586-4.

Shono, K., E. A. Cadaweng, and P. B. Durst. 2007. "Application of Assisted Natural Regeneration to Restore Degraded Tropical Forestlands." *Restoration Ecology* 15, no. 4: 620–626. https://doi.org/10.1111/j.1526-100x.2007.00274.x.

Tan, Z.-H., Y.-P. Zhang, Q.-H. Song, et al. 2011. "Rubber Plantations Act as Water Pumps in Tropical China." *Geophysical Research Letters* 38, no. 24. https://doi.org/10.1029/2011gl050006.

Uebel, K., K. A. Wilson, and L. P. Shoo. 2017. "Assisted Natural Regeneration Accelerates Recovery of Highly Disturbed Rainforest." *Ecological Management & Restoration* 18, no. 3: 231–238. https://doi.org/10.1111/emr.12277.

Wang, Y., P. M. Hollingsworth, D. Zhai, et al. 2023. "High-Resolution Maps Show That Rubber Causes Substantial Deforestation." *Nature* 623, no. 7986: 340–346. https://doi.org/10.1038/s41586-023-06642-z.

Wang, Y., and L. Zhang. 2025. "From Primary Forests to Rubber Plantations: A Huge Ecological Loss." *Innovation* 6, no. 5: 100836. https://doi.org/10.1016/j.xinn.2025.100836.

Warren-Thomas, E., L. Nelson, W. Juthong, et al. 2019. "Rubber Agroforestry in Thailand Provides Some Biodiversity Benefits Without Reducing Yields." *Journal of Applied Ecology* 57, no. 1: 17–30. https://doi.org/10.1111/1365-2664.13530.

Werden, L. K., R. J. Cole, K. Schönhofer, et al. 2024. "Assessing Innovations for Upscaling Forest Landscape Restoration." *One Earth* 7, no. 9: 1515–1528. https://doi.org/10.1016/j.oneear.2024.07.011.

Williams, B. A., H. L. Beyer, M. E. Fagan, et al. 2024. "Global Potential for Natural Regeneration in Deforested Tropical Regions." *Nature* 636, no. 8041: 131–137. https://doi.org/10.1038/s41586-024-08106-4.

Xu, J., R. E. Grumbine, and P. Beckschäfer. 2014. "Landscape Transformation Through the Use of Ecological and Socioeconomic Indicators in Xishuangbanna, Southwest China, Mekong Region." *Ecological Indicators* 36: 749–756. https://doi.org/10.1016/j.ecolind.2012.08.023.

Yi, Z.-F., G. Wong, C. H. Cannon, J. Xu, P. Beckschäfer, and R. D. Swetnam. 2014. "Can Carbon-Trading Schemes Help to Protect China's Most Diverse Forest Ecosystems? A Case Study From Xishuangbanna, Yunnan." *Land Use Policy* 38: 646–656. https://doi.org/10.1016/j.landusepol.2013.12.013.

Zahawi, R. A., and K. D. Holl. 2009. "Comparing the Performance of Tree Stakes and Seedlings to Restore Abandoned Tropical Pastures." *Restoration Ecology* 17, no. 6: 854–864. https://doi.org/10.1111/j.1526-100x.2008.00423.x.

Zahawi, R. A., and J. Leighton Reid. 2018. "Tropical Secondary Forest Enrichment Using Giant Stakes of Keystone Figs." *Perspectives in Ecology and Conservation* 16, no. 3: 133–138. https://doi.org/10.1016/j.pecon.2018.06.001.

Zemp, D. C., N. Guerrero-Ramirez, F. Brambach, et al. 2023. "Tree Islands Enhance Biodiversity and Functioning in Oil Palm Landscapes." *Nature* 618, no. 7964: 316–321. https://doi.org/10.1038/s41586-023-06086-5.

Zeng, H., J. Wu, X. Zhu, A. K. Singh, C. Chen, and W. Liu. 2021. "Jungle Rubber Facilitates the Restoration of Degraded Soil of an Existing Rubber Plantation." *Journal of Environmental Management* 281: 111959. https://doi.org/10.1016/j.jenvman.2021.111959.

Zhang, J. Q., R. T. Corlett, and D. Zhai. 2019. "After the Rubber Boom: Good News and Bad News for Biodiversity In Xishuangbanna, Yunnan, China." *Regional Environmental Change* 19, no. 6: 1713–1724. https://doi.org/10.1007/s10113-019-01509-4.