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Securing the future of Hainan's Tropical Rainforest: challenges and strategies for conservation

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The Hainan's Tropical Rainforest is China's largest and best-preserved tropical rainforest, holding critical biodiversity value in the Indo-Burma biodiversity hotspot. Established as the Hainan Tropical Rainforest National Park (HTRNP) in 2021, it encompasses 95% of the island's rainforest, safeguarding numerous endemic and protected species, including the endangered Hainan gibbon. Despite its ecological significance, the park faces severe anthropogenic threats, including deforestation driven by agricultural expansion, illegal mining, and hydropower development. These activities fragment habitats, disrupt species movement, and degrade essential ecosystem services such as water regulation and carbon sequestration. This commentary examines the current challenges to the park's integrity and proposes a multifaceted conservation approach, focusing on strengthened enforcement, community engagement, policy implementation, and scientific monitoring. We advocate for a technology-driven enforcement system, sustainable livelihoods for local communities, and restoration of ecological connectivity to ensure the long-term protection of this invaluable ecosystem. Immediate and comprehensive action is crucial to preserve Hainan's Tropical Rainforest as a global biodiversity treasure.

KEYWORDS

rainforest conservation, protected area management, environmental policy, human disturbance, Hainan

Introduction

The Hainan's Tropical Rainforest, spanning approximately 4,400 km² across the central and southern regions of Hainan Island, represents China's largest and best-preserved tropical rainforest ecosystem (Long et al., 2021). This pristine natural heritage, with its oldest trees dating back over 2,500 years, forms an integral part of the Indo-Burma biodiversity hotspot and serves as a crucial ecological corridor in Southeast Asia's tropical forest network (Zong, 2020; Xie et al., 2024; Yao et al., 2024). The establishment of the Hainan Tropical Rainforest National Park (HTRNP) in 2021 marked a milestone in China's commitment to biodiversity conservation, protecting approximately 95% of the island's tropical rainforest ecosystem (Figure 1A; Lin and Fu, 2023).

The Hainan's Tropical Rainforest represents an exceptional biodiversity hotspot and crucial ecosystem at the northern edge of tropical Asia, harboring 3,653 vascular plant species, including 425 national key protected plants and 419 endemic to Hainan Island (Figures 1B–E; Xu et al., 2023). Its remarkable species density, reaching over 100 tree species per hectare in some areas, supports a diverse fauna comprising 540 vertebrate species, with 75 under national protection (Zong, 2020). As the last refuge for 36 endangered animal species, including the world's rarest primate—the Hainan gibbon

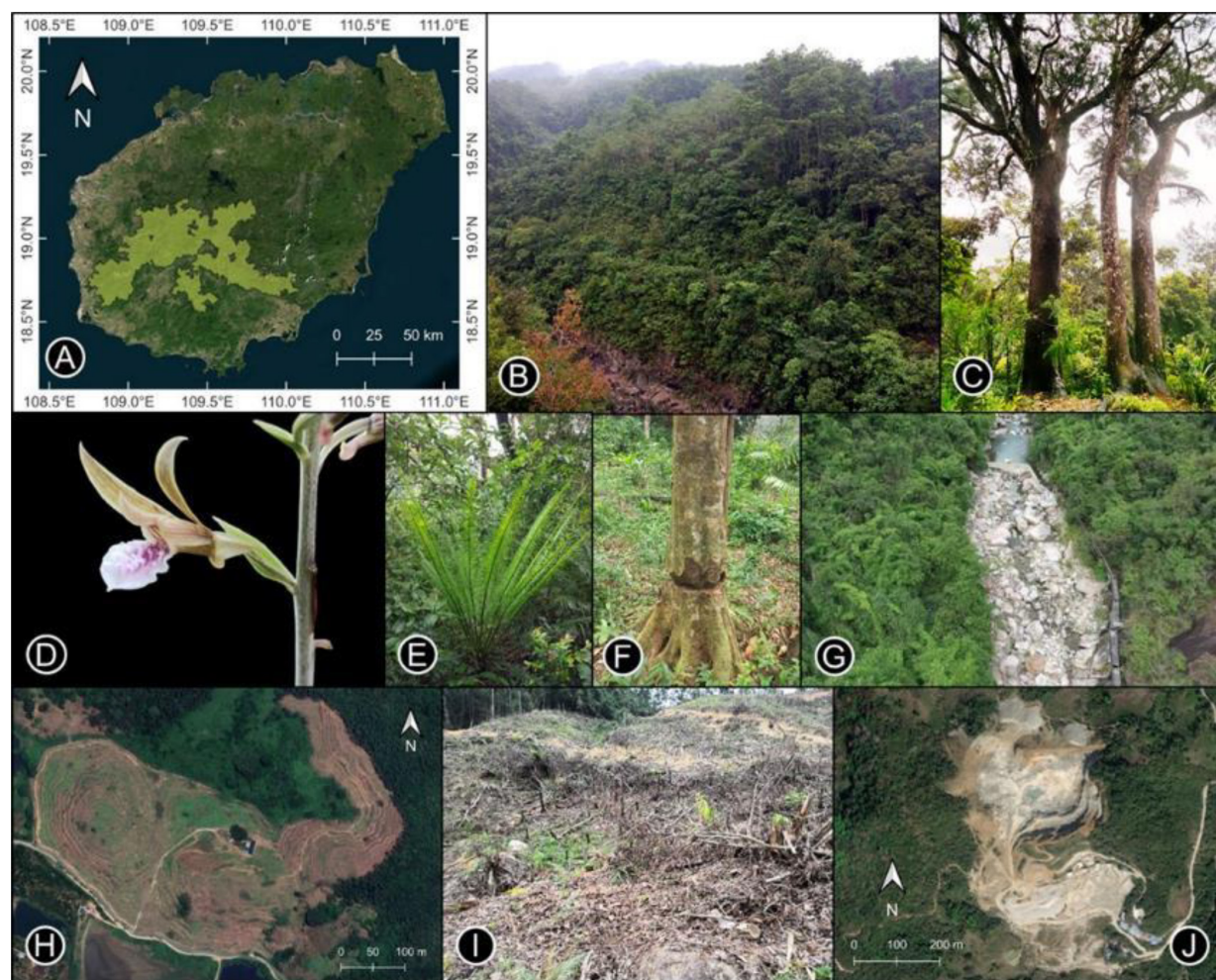


FIGURE 1

Geographic context, biodiversity representation, and anthropogenic impacts in Hainan Tropical Rainforest National Park (HTRNP). (A) Geographic location of HTRNP (light green) within Hainan Island, encompassing 4,400 km² (12.98% of the island's total area). (B) Representative intact tropical rainforest community physiognomy. (C) Large and old *Dacrydium pectinatum* in Diaoluo Mountain, exemplifying old-growth forest characteristics. (D) *Eulophia graminea*, a national second-class protected orchid species. (E) *Cycas taiwaniana*, a national first-class protected cycad species. (F) Forest degradation resulting from intentional anthropogenic disturbance. (G) Hydropower station construction within the protected area, showing significant downstream channel disruption and exposed riverbed (source: Central Ecological and Environmental Protection Supervision and Coordination Bureau, 2023). (H) Conversion of ecological public welfare forest to coffee plantation (Bing satellite imagery). (I) Forest clearance for cash crop cultivation. (J) A quarry site showing lack of ecological restoration efforts (Bing satellite imagery).

(*Nomascus hainanus*)—whose population has plummeted by 99.98% over the past 50 years to just 35 individuals (Zhang and Zang, 2018), this ecosystem plays a vital role in biodiversity conservation (Long et al., 2021; Du et al., 2024). The biodiversity index stands at an impressive 6.28, placing it on par with the Amazon rainforest in Brazil (Xu et al., 2023). The forest's unique geographical position makes it an invaluable natural laboratory for studying climate change impacts on tropical ecosystems, while its intact structure provides essential ecological services, offering crucial insights for global conservation strategies and environmental research.

Despite its exceptional ecological value and critical role in biodiversity conservation, climate regulation, and scientific research, the Hainan's Tropical Rainforest faces mounting anthropogenic pressures that threaten its integrity (Du et al., 2024; Wang et al., 2024). The HTRNP encompasses areas inhabited by

ethnic minorities such as the Li and Miao communities. These communities have historically relied on economic activities like rubber and betel nut cultivation, which are significant contributors to deforestation and habitat fragmentation within the park (Wei et al., 2024). While ecological relocation programs have been implemented, participation among local residents remains limited, and some areas continue to experience unsustainable activities.

Recent investigations by the Central Ecological and Environmental Protection Inspectorate have revealed a disturbing pattern of ecosystem degradation driven by various human activities (Figures 1F–J; Central Ecological and Environmental Protection Supervision and Coordination Bureau, 2023). These threats not only jeopardize individual species and their habitats but also compromise the forest's ability to provide essential ecosystem services that millions of people depend upon. The persistence of illegal activities within the National Park boundaries, coupled

TABLE 1 Threats and conservation actions for the Hainan Tropical Rainforest National Park.

Primary threats	Impacts	Recommended conservation actions
Deforestation and Agricultural expansion	Direct habitat loss; Forest fragmentation; Disruption of wildlife corridors; Isolation of species (e.g., Hainan gibbon)	Transition to sustainable agroforestry systems; Development of alternative livelihoods; Technology-driven monitoring systems
Mining activities	Destruction of vegetation; Altered soil structure; Disrupted underground water systems; Long-lasting landscape damage	Strengthened enforcement with satellite imagery; Drone surveillance; Automated alert systems; Graduated penalty systems
Hydropower development	Altered water flow patterns; Disrupted fish migration; Changed riverside habitats; Increased human access to undisturbed areas	Comprehensive policy framework; Clear operational guidelines; Regular performance assessments; Transparent reporting mechanisms
Climate change	Increased severe precipitation events; Potential reduction in habitat suitability; Heightened vulnerability to existing pressures	Science-based restoration approaches; Reestablishment of ecological connectivity; Long-term monitoring programs; Research on habitat requirements
Weak law enforcement	Absence of independent management authority; Lack of legal enforcement power; Inefficient coordination processes; Fragmented response to violations	Establishment of centralized command center; Community engagement initiatives; Performance-based incentive systems; Education and skill-building programs

with historical habitat fragmentation and ongoing development pressures (Zhang X. et al., 2024), presents a significant challenge to the long-term survival of this unique ecosystem.

Current challenges

A remote sensing study on tropical rainforest biomass changes in Hainan Island, China, from 2003 to 2018 revealed a continuous annual decline in rainforest area (Lin et al., 2021). Restoring the ecosystem to its previous state remains a significant challenge. The Hainan's Tropical Rainforest faces severe anthropogenic threats that compromise its ecological integrity and biodiversity (Table 1). The most pressing challenge is the ongoing deforestation driven by the expansion of commercial agriculture (Zhai et al., 2014), particularly the cultivation of cash crops such as coffee, betel nut, and tropical fruits. This agricultural encroachment not only results in direct habitat loss but also leads to forest fragmentation, creating isolated patches that disrupt wildlife corridors and limit species movement (Xu et al., 2023). The conversion of primary forest to agricultural land has particularly devastating effects on canopy-dependent species like the Hainan gibbon, whose populations become increasingly isolated and vulnerable to local extinction (Zhang et al., 2023).

Mining activities within and around the protected area represent another significant threat, with both legal and illegal quarrying operations causing extensive environmental damage (Central Ecological and Environmental Protection Supervision and Coordination Bureau, 2023). These mining operations not only destroy surface vegetation but also alter soil structure, disrupt underground water systems, and create long-lasting scars on the landscape that can take decades or even centuries to recover naturally.

The construction and operation of hydropower stations along rivers within the protected area pose a complex threat to the rainforest ecosystem (Zhang Q. et al., 2024). These installations alter natural water flow patterns, affecting both aquatic and terrestrial ecosystems throughout the watershed (Harper et al., 2020). The modified hydrology disrupts fish migration patterns, changes riverside habitats, and affects the dispersal of plant

species that depend on natural water flows for seed distribution. Additionally, the infrastructure associated with these hydropower projects, including access roads and power lines, creates new corridors for human access into previously undisturbed areas, facilitating further exploitation and disturbance. The cumulative impact of these three major threats - agricultural expansion, mining activities, and hydropower development - extends beyond their immediate footprint, creating cascading effects throughout the ecosystem (Lin and Fu, 2023; Zhang Q. et al., 2024). These disturbances also compromise the forest's capacity to provide essential ecosystem services (Zhai et al., 2014), including water regulation, soil conservation, and carbon sequestration, while simultaneously reducing its resilience to climate change impacts. Additionally, climate change compounds these anthropogenic threats by altering the environmental conditions critical to the HTRNP's ecological integrity. Projections suggest that China will suffer from increased severe precipitation extreme events at 1.5°C and 2.0°C warming levels in the future (Li et al., 2018), potentially affecting Hainan's tropical climate with more intense rainfall episodes. Concurrently, these shifts could reduce habitat suitability for fauna like the Hainan gibbon. Together, these climate-driven changes heighten the vulnerability of the rainforest to existing pressures, necessitating adaptive conservation strategies.

The law enforcement framework of the Hainan Tropical Rainforest National Park (HTRNP) suffers from shortcomings that undermine its effectiveness (Zhang X. et al., 2024). These deficiencies can be distilled into two primary issues. First, there is an absence of robust enforcement and oversight mechanisms. The HTRNP lacks an independent management authority, with its seven branches operating as public institutions devoid of legal authority to conduct administrative law enforcement. Furthermore, there is no formal linkage between the national park's management body, the forest police, and local comprehensive administrative law enforcement agencies, resulting in a critical gap in oversight of enforcement activities. Second, the coordination process is inefficient and fragmented. When illegal activities persist despite preventive efforts, the national park management must rely on coordination with the forest police or local enforcement bureaus to respond. This disjointed approach hampers both the efficiency and impact of enforcement actions. A notable example is the

illegal occupation of public welfare forests in Wuzhishan City (Central Ecological and Environmental Protection Supervision and Coordination Bureau, 2023), which starkly highlighted these systemic weaknesses.

Conservation imperatives and recommendations

- (1) Strengthened enforcement and monitoring. To effectively combat illegal activities within the HTRNP, a comprehensive, technology-driven enforcement system must be established (Sharma et al., 2024). The integration of high-resolution satellite imagery with regular drone surveillance can create a real-time monitoring network capable of detecting forest clearance, illegal construction, and mining activities at their earliest stages (Mahfud et al., 2021). This technology should be coupled with an automated alert system that immediately notifies enforcement personnel of suspicious activities. The establishment of a centralized command center, equipped with artificial intelligence-powered analysis tools, would enable rapid verification of threats and coordinate immediate response actions. Furthermore, the development of a standardized digital database integrating monitoring data, enforcement actions, and ecological indicators would provide crucial insights for adaptive management strategies and help identify emerging threat patterns before they become widespread problems.
- (2) Enhanced policy implementation. Effective conservation of the Hainan Tropical Rainforest requires a robust policy framework that clearly delineates responsibilities and ensures accountability at all levels (Hansen et al., 2020; Long et al., 2021). Local authorities should be equipped with detailed operational guidelines that specify step-by-step procedures for addressing different types of violations, from minor infractions to major environmental crimes. The penalty system should be restructured to implement graduated sanctions that reflect both the severity of violations and the potential for ecosystem recovery, with particularly strict measures for repeated offenders and organized illegal activities. Regular performance assessments of enforcement agencies (Schleicher et al., 2017), coupled with transparent reporting mechanisms, would ensure consistent policy implementation while identifying areas requiring additional resources or capacity building. These assessments should be linked to clear conservation targets and indicators, allowing for objective evaluation of policy effectiveness.
- (3) Community engagement and sustainable development. The relationship between local communities and the protected area is a critical component of conservation efforts. The long-term protection of the rainforest depends critically on transforming local communities from potential threats into active conservation partners (Zoysa, 2022). This transformation requires developing viable alternative livelihoods that directly link economic benefits to forest conservation. Specific programs should be established to help farmers transition from traditional cash crops to sustainable agroforestry systems that maintain forest cover while providing income. These might include the cultivation of shade-grown coffee, sustainable collection of non-timber forest products, and development of ecotourism enterprises (Borkhataria et al., 2012; Zoysa, 2022). Education programs should focus not only on raising awareness but also on building practical skills that enable community members to participate in conservation activities and benefit from them economically (Morgan et al., 2022). Performance-based incentive systems (Schleicher et al., 2017), including payments for ecosystem services and community-based forest carbon projects, can provide direct financial rewards for conservation efforts while ensuring long-term community commitment to forest protection. In future work, related government departments need to plan to conduct a more in-depth analysis of this interaction, exploring how local communities shape the dynamics of human-nature relationships within the protected area. This will help identify the root causes of anthropogenic impacts and inform more targeted solutions.
- (4) Scientific research and ecological restoration. A science-based approach to conservation and restoration must be prioritized to ensure the rainforest's long-term viability (Seddon, 2022). Research efforts should focus on understanding the specific habitat requirements and population dynamics of flagship species (Qian et al., 2020), particularly the critically endangered Hainan gibbon and other endemic species (Zhang et al., 2023). This research should inform the development of targeted restoration plans that prioritize the reestablishment of ecological connectivity between fragmented forest patches (Xu et al., 2023; Zhang Q. et al., 2024). Restoration efforts must go beyond simple replanting to include the reconstruction of complex forest structures and the reestablishment of key ecological processes (Löf et al., 2019). This requires careful selection of native species, consideration of successional processes, and attention to the specific requirements of target wildlife species. Long-term monitoring programs should be established using standardized protocols to track both restoration success and ecosystem recovery, with results feeding back into adaptive management strategies (Löf et al., 2019). These monitoring efforts should incorporate both traditional ecological metrics and emerging technologies such as environmental DNA sampling and automated bioacoustics monitoring to provide comprehensive assessments of biodiversity recovery (Zinger et al., 2020; Müller et al., 2023).

Conclusion

The protection of Hainan's Tropical Rainforest requires immediate and coordinated action from all stakeholders. While the establishment of the National Park demonstrated strong policy commitment, recent findings highlight the need for enhanced implementation and monitoring. Through strengthened enforcement, community engagement, and scientific management, we can ensure the long-term preservation of this unique ecosystem. The success of these conservation efforts will not only secure critical biodiversity but also demonstrate China's commitment to global environmental protection.

Data availability statement

The original contributions presented in this study are included in this article, further inquiries can be directed to the corresponding author.

Author contributions

SW: Data curation, Formal Analysis, Funding acquisition, Writing – original draft. CX: Formal Analysis, Methodology, Visualization, Writing – original draft, Writing – review and editing.

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