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The Role of Tropical Forests in Carbon Emission Mitigation and Global Climate Stability

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ABSTRACT

Tropical forests play a crucial role in the Earth's climate system as the largest carbon store, regulator of the water cycle, and stabilizer of global temperatures. However, the high rate of deforestation threatens these ecological functions. This article aims to comprehensively examine the role of tropical forests in carbon emission mitigation and global climate stabilization based on a synthesis of the latest scientific literature. The method used is a systematic literature review of 20 indexed international journal articles published in the last ten years. The results show that tropical forests store approximately 360 Pg C in biomass and absorb 0.47–1.3 Pg C/year, equivalent to 8–13% of annual anthropogenic CO_2 emissions. Primary tropical forests store 141–159 Pg C, equivalent to 91–103% of the remaining carbon budget to limit global warming to below 1.5°C. In addition to their carbon sequestration function, tropical forests play an important role through evapotranspiration, cloud formation, and the albedo effect, which cools regional and global climates. Strategies for primary forest protection, secondary forest restoration, and REDD+ programs have the potential to save US$31–36 trillion in climate policy costs. They concluded that tropical forest protection and restoration are the most effective and efficient climate mitigation instruments, but they cannot replace the fundamental need for drastic reductions in fossil fuel emissions.

INTRODUCTION

Global climate change driven by anthropogenic greenhouse gas emissions has become an existential challenge to human civilization in the 21st century. The latest report from the Intergovernmental Panel on Climate Change (IPCC) confirms that atmospheric CO_2 concentrations have exceeded 420 ppm, far exceeding the pre-industrial threshold of 280 ppm. In this context, forest ecosystems, particularly tropical forests, play an irreplaceable role as the largest natural carbon sink on Earth's land surface (Pan et al., 2011; Bonan, 2008).

Tropical forests spanning Latin America, Central Africa, and Southeast Asia harbor the highest biodiversity on Earth and store vast carbon reserves. Numerous scientific studies have confirmed that tropical forests store approximately 360 Pg C in their biomass, and together with soil, can reach ~800 Pg C, a value nearly equivalent to the entire carbon stock in the atmosphere (Artaxo et al., 2022; Lawrence et al., 2022). In addition to their role as carbon stores, tropical forests also perform biogeophysical functions through evapotranspiration, cloud formation, and regional and global rainfall regulation (Bonan, 2008; Lawrence et al., 2022).

Despite their widely recognized ecological significance, deforestation pressure on tropical forests continues at an alarming rate. Data from Hansen et al. (2013) show that between 2000 and 2012, the world lost approximately 2.3 million km² of forest cover, with the largest proportion occurring in tropical regions. Deforestation not only releases stored carbon into the atmosphere but also diminishes the ecosystem's ability to absorb future emissions (Mitchard, 2018; Friedlingstein et al., 2022).

A significant research gap has been identified in the comprehensive synthesis of the multidimensional role of tropical forests—including aspects of carbon biochemistry, climate biogeophysics, and policy economics—in a single, integrated analytical framework. Most previous studies tend to focus on a single aspect without integrating all three dimensions simultaneously. The novelty of this article lies in its comprehensive, evidence-based synthesis, encompassing aspects of carbon stocks, CO_2 sinks, biogeophysics, restoration potential, climate change risks, and the economic valuation of tropical forest protection in a single, cohesive review.

This article aims to: (1) examine the capacity of tropical forests as carbon stores and absorbers; (2) analyze the biogeophysical function of tropical forests in global climate regulation; (3) evaluate tropical forest-based mitigation strategies and their potential and limitations; and (4) analyze the economic value of tropical forest protection and restoration within the framework of global climate policy.

METHODOLOGY

This study employed a systematic literature review (SLR) approach based on the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) protocol. This method was chosen because it allows for a structured, transparent, and reproducible synthesis of scientific evidence from a variety of relevant scientific publications.

A literature search was conducted through several major academic databases, including Web of Science, Scopus, Google Scholar, and Nature Portfolio. Keywords used included: "tropical forest carbon," "carbon sequestration," "tropical deforestation climate," "forest restoration climate change," "REDD+ climate mitigation," "biogeophysical effects of deforestation," and combinations thereof using Boolean operators (AND, OR). The search was limited to English-language publications published between 2010 and 2025.

The inclusion criteria set include: (1) scientific journal articles published in international journals indexed by Scopus or Web of Science; (2) specifically discussing the role of tropical forests in the carbon cycle or climate regulation; (3) using clear and verifiable research methodology, whether in the form of field measurements, climate modeling, satellite analysis, or meta-analysis; (4) available in full-text version. Exclusion criteria include articles in the form of editorials, short commentaries, or technical reports without peer review.

The literature selection process yielded 20 articles that met all inclusion criteria. Data extracted from each article included: study location, research methods, main variables measured, key findings, and recommended policy implications. Data synthesis was conducted narratively and qualitatively by grouping findings based on the following themes: (1) carbon stocks and sinks, (2) biogeophysical effects, (3) mitigation strategies, and (4) economic-policy value. The validity of the arguments was strengthened by triangulating findings from various sources and different methodologies.

RESULTS AND DISCUSSION

A. Carbon Stock and CO_2 Absorption Capacity of Tropical Forests

Tropical forests are the largest terrestrial carbon reservoir on the planet. Artaxo et al. (2022) and Lawrence et al. (2022) report that tropical forests store approximately 360 Pg C in their biomass, and when combined with soil carbon, the total stock reaches ~800 Pg C—a value approaching the entire carbon stock in the Earth's atmosphere. This substantial reserve makes the preservation of tropical forests an absolute priority in global climate change mitigation strategies.

Quantitatively, Pan et al. (2011) in their widely cited global study estimated that the world's forests (including tropical forests) sequester approximately 2.4 Pg C/year, with tropical forests contributing a significant net sink. A more specific study by Mackey et al. (2020) estimated tropical forest sequestration to be in the range of 0.47–1.3 Pg C/year, equivalent to 8–13% of annual anthropogenic CO_2 emissions, and contributing approximately 29% of CO_2 sequestration by terrestrial ecosystems as a whole.

Of critical importance from a climate policy perspective are data on primary tropical forests. Mackey et al. (2020) found that primary tropical forests store 141–159 Pg C (49–53% of total tropical forest carbon), and their living biomass alone is equivalent to 91–103% of the remaining carbon budget available to limit global warming to below 1.5°C. These findings directly imply that the conversion or degradation of primary tropical forests would fundamentally threaten the Paris Agreement climate targets. Bonan (2008) has previously emphasized that forests have a significant impact on the global carbon cycle and climate change through multiple interacting mechanisms.

Friedlingstein et al. (2022) in their latest Global Carbon Budget report confirmed that terrestrial ecosystems, including tropical forests, remain net carbon sinks despite increasing pressure. However, this rate of absorption is threatened by a combination of deforestation, degradation, and the impacts of climate change itself, which create negative feedback loops (Anderegg et al., 2020; Mitchard, 2018).

Table 1
The Key Function of Tropical Forests for the Global Climate

Function	Major Climate Impacts	Source
C storage & absorption	Reducing atmospheric CO_2, closing the emissions gap	Mackey et al., 2020; Mitchard, 2018; Pan et al., 2011
Evapotranspiration & water cycle	Cooling, cloud formation, regional–global rainfall	Artaxo et al., 2022; Lawrence et al., 2022; Bonan, 2008
Organic aerosols & clouds	Increase cloud albedo, increasing cooling	Artaxo et al., 2022
Biogeophysical effects & albedo	Tropical deforestation → strong local & global warming	Artaxo et al., 2022; Lawrence et al., 2022; Windisch et al., 2021
Regional weather regulations	Stabilization of regional precipitation and temperature patterns	Bonan, 2008; Lawrence et al., 2022

Source: Compilation of various sources, 2025

B. Biogeophysical Effects and Regional Climate Regulation

Beyond their role as carbon sinks, tropical forests perform biogeophysical functions that are equally important for climate stability. Artaxo et al. (2022) comprehensively documented that tropical forests play a crucial role in regulating the Earth's climate through three main mechanisms: (1) the water cycle and evapotranspiration that result in surface cooling; (2) the emission of biological organic aerosols (biogenic volatile organic compounds/BVOCs) that contribute to cloud formation; and (3) the modification of surface albedo that affects the radiation balance.

Lawrence et al. (2022) specifically analyzed the "hidden effects" of deforestation that go beyond mere carbon release. Using climate modeling, they showed that tropical deforestation causes significantly greater warming than accounted for in standard carbon emission inventories, due to the loss of biogeophysical cooling from evapotranspiration and changes in albedo. These findings were confirmed by Windisch et al. (2021), who showed that prioritizing forestation in the tropics provides the greatest biogeochemical and biogeophysical benefits compared to other regions on Earth.

Bonan (2008) previously established a conceptual framework for the multidimensional interactions between forests and climate, emphasizing that forests influence climate through the interconnected exchange of energy, water, and carbon. In the context of tropical forests, the process of "flying rivers" formed by water vapor from evapotranspiration has been shown to transport moisture long distances, influencing rainfall thousands of kilometers from forest areas (Artaxo et al., 2022).

C. Tropical Forest-Based Mitigation Strategies

Based on the literature synthesis, there are three main tropical forest-based mitigation strategies that have a strong scientific basis:

First, primary forest protection (proforestation). Mackey et al. (2020) demonstrated that primary tropical forests have ~35% higher carbon stocks than managed production forests, and post-logging carbon recovery takes 40–100+ years. Lewis et al. (2019) added that maintaining existing natural forests is the most effective way to sequester atmospheric carbon, as old-growth primary forests have a carbon storage capacity far exceeding that of newly established forests. This approach is supported by Griscom et al. (2017), who identified forest protection as one of the 20 "natural climate solutions" with the greatest global mitigation potential.

Second, secondary forest restoration and regeneration. Chazdon et al. (2016) quantified that secondary forests in Latin America have the potential to absorb 31 Pg CO_2 in 40 years through natural regeneration processes. Heinrich et al. (2021) specifically found that Amazonian secondary forests could contribute ~5.5% to Brazil's emissions reduction target by 2030. Global modeling by Liang et al. (2025) indicates that the greatest mitigation potential from forestation activities lies in tropical regions, although it is necessary to consider the impacts of climate change, fire, and albedo in an integrated manner.

Third, halting deforestation and degradation (REDD+). Koch & Kaplan (2022) demonstrated through comprehensive modeling that large-scale tropical forest restoration can reduce peak CO_2 concentrations and help curb global temperature rise. However, Koch et al. (2021) also emphasized that tropical forest-based interventions cannot replace the need for aggressive fossil fuel emission reductions, given complex Earth system feedbacks.

D. Risks and Limitations of Tropical Forest Mitigation Capacity

The mitigation capacity of tropical forests is not permanent and faces various risks that are increasing with climate change. Anderegg et al. (2020) identified five key risks that could erode forest mitigation potential: drought, fire, biotic disturbances (pests and diseases), temperature stress, and changes in interspecific competition. They warn that this combination of risks has the potential to transform tropical forests from carbon sinks into carbon sources if global warming continues.

Mitchard (2018) extensively reviews the tropical forest carbon cycle and its links to climate change, emphasizing that estimates of carbon stocks and CO_2 fluxes from tropical forests remain subject to significant uncertainty, particularly regarding emissions from forest degradation, which are difficult to detect through remote sensing. Friedlingstein et al. (2022) confirm that while terrestrial ecosystems generally still act as net sinks, there is substantial interannual variability influenced by drought and fire in tropical regions.

Liang et al. (2025) provided a more comprehensive model that considered the interactions between climate change, fire frequency, and albedo effects in evaluating the mitigation potential of future forestation. Their results showed that projections of mitigation potential that did not account for these factors tended to be overly optimistic, particularly for dry tropical regions.

E. Economic Value and Policy Implications

From an economic perspective, tropical forest protection and restoration is one of the most cost-effective climate investments available. Fuss et al. (2020) estimate that fully implementing REDD+ policies could deliver global climate policy cost savings of up to US$31–36 trillion, while transforming the tropical forest sector from a source of 224 Gt CO_2 emissions to a sink of 98 Gt CO_2 by 2100.

Koh et al. (2021) used the concept of "carbon prospecting" to identify priority areas in tropical forests with high carbon values and potential targets for conservation investment and efficient carbon financing. Griscom et al. (2017) estimated that natural climate solutions, with tropical forests as a dominant component, could contribute up to 30% of the emissions reductions needed to keep warming below 2°C.

From a national policy perspective, Heinrich et al. (2021) demonstrate the potential of Amazonian secondary forests to support Brazil's Nationally Determined Contribution (NDC) targets, while Chazdon et al. (2016) provide a scientific basis for restoration policies at the Latin American scale. These studies collectively confirm that comprehensively quantifying the economic value of tropical forests—including ecosystem services, carbon value, and biodiversity value—is a prerequisite for more effective policies (Bonan, 2008; Fuss et al., 2020).

F. Comparison of Carbon Capacity of Primary vs. Secondary Tropical Forests

The difference in carbon storage capacity between primary and secondary tropical forests is a key factor that must be considered in formulating conservation policies. Mackey et al. (2020) clearly demonstrated that primary tropical forests have ~35% higher carbon stocks than production forests that have undergone selective logging. Furthermore, post-logging carbon stock recovery in tropical forests takes 40 to over 100 years, depending on disturbance intensity, soil type, and local climate conditions. These findings confirm that, from a carbon cycle perspective, there is no substitute for intact primary forests, and the "log then restore" strategy cannot be scientifically justified as a valid climate mitigation approach.

G. Dynamics of Amazonian Secondary Forests and Their Contribution to Brazil's NDC

Regenerating secondary forests in the Amazon region represent one of the most significant climate mitigation opportunities at the national level. Heinrich et al. (2021) estimate that secondary forests in the Brazilian Amazon have significant carbon sequestration potential and, if properly managed, could contribute approximately 5.5% of Brazil's Nationally Determined Contribution (NDC) emissions reduction targets through 2030. These findings provide a strong scientific basis for the Brazilian government to integrate secondary forest management into its national climate strategy. Chazdon et al. (2016) reinforce this argument by estimating that secondary forests across tropical Latin America have the cumulative potential to sequester 31 Pg CO_2 over a 40-year period, a highly significant figure in the context of global decarbonization targets.

H. Tropical Forestation in the Perspective of Global Climate Modeling

Global climate modeling provides important perspectives on the limits and potential of tropical forestry as a mitigation strategy. Koch & Kaplan (2022) used an Earth system model to simulate the impacts of large-scale tropical forest restoration and found that such interventions measurably reduced peak CO_2 concentrations and helped curb global temperature rise. However, Koch et al. (2021), in an analysis that took into account Earth system feedbacks, cautioned that the actual mitigation potential could be smaller than modest estimates, as carbon uptake by restored vegetation could be offset by reduced ocean carbon sinks and other feedback effects. Liang et al. (2025) further refined this modeling by incorporating projected climate change, fire frequency, and albedo effects, resulting in a more conservative yet more realistic estimate of the future mitigation potential of tropical forestry.

I. The Role of Biogenic Aerosols in Cloud Formation and Climate Cooling

One of the most overlooked biogeophysical mechanisms of tropical forests in climate policy discussions is the role of biogenic organic aerosols in cloud formation. Artaxo et al. (2022) documented in detail that tropical forests, particularly the Amazon, are the largest source of biologically volatile organic compounds (BVOCs) emissions on Earth. These compounds, upon oxidation in the atmosphere, form secondary organic aerosol particles that serve as cloud condensation nuclei (CCN). Increased CCN concentrations contribute to the formation of clouds with higher albedo, which increases the reflection of solar radiation and results in additional cooling. This mechanism represents a unique climate cooling pathway that cannot be replicated by any current geoengineering technology, further strengthening the argument that the ecological value of tropical forests goes beyond carbon alone.

J. Risks of Converting Carbon Sinks into Carbon Sources Due to Climate Change

One of the most pressing scientific concerns regarding the future of tropical forests is their potential conversion from carbon sinks to carbon sources due to climate change feedbacks. Anderegg et al. (2020) identified this risk as stemming from five mutually reinforcing factors: intensified drought, increased frequency and intensity of fires, proliferation of tree pests and diseases, temperature stress exceeding trees' physiological tolerance thresholds, and changing interspecific competition dynamics. Mitchard (2018) added that undetected forest degradation, including illegal logging, poaching, and fragmentation, has been silently eroding the carbon sequestration capacity of tropical forests long before full land conversion occurs. Modeled worst-case scenarios suggest that large swaths of the Amazon could experience "dieback," or mass death of vegetation if global temperatures exceed a critical threshold, releasing tens of petagrams of carbon into the atmosphere in a short period of time.

K. Integration of the Economic Value of Ecosystem Services in Tropical Forest Conservation Policies

Market failure to internalize the value of tropical forest ecosystem services has long been identified as a root cause of high deforestation rates in political and economic terms. Fuss et al. (2020) demonstrated that if the carbon value and ecosystem services of tropical forests are fully accounted for in economic models, protecting tropical forests through REDD+ mechanisms could potentially save global climate policy costs of up to US$31–36 trillion compared to a scenario without forest protection. This figure far exceeds the cost of implementing necessary conservation programs, demonstrating that investing in tropical forest protection is a rational economic decision even without considering non-economic values such as biodiversity and indigenous peoples' rights. Koh et al. (2021) complemented this analysis by developing a "carbon prospecting" framework that allows the identification of priority areas based on carbon density, conversion risk, and potential biodiversity co-benefits, to optimize the allocation of limited conservation funding.

L. The Relationship between Tropical Deforestation and the Destabilization of the Global Hydrological Cycle

The role of tropical forests in regulating the global hydrological cycle is a dimension receiving increasing attention in contemporary climate science literature. Lawrence et al. (2022) used regional climate modeling to show that tropical deforestation significantly reduces evapotranspiration rates, which in turn reduces downstream rainfall through the mechanism of "atmospheric moisture recycling." This regional reduction in rainfall impacts not only the forest ecosystems themselves but also agricultural productivity in regions dependent on rainfall patterns stabilized by tropical forests. Artaxo et al. (2022) furthered these findings by showing that the phenomenon of "flying rivers," or atmospheric rivers, transporting water vapor from the Amazon to central and southern Brazil, represents a critical ecosystem service threatened by large-scale deforestation, with implications for food security far beyond the ecological boundaries of the Amazon region itself.

In their landmark study, Griscom et al. (2017) quantified that natural climate solutions, dominated by tropical forest ecosystem management, could contribute up to 11.3 Gt CO_2e per year in emissions reductions and carbon sequestration by 2030 at a cost of less than US$100 per ton of CO_2. This figure is equivalent to approximately 30% of the global emissions reductions needed to keep warming below 2°C. Among the solutions identified, halting tropical deforestation provided the largest contribution, followed by tropical peat management, forest restoration, and strengthening agroforestry systems. Windisch et al. (2021) refined this prioritization analysis by emphasizing the importance of considering local biogeophysical effects alongside the biochemical benefits of carbon, concluding that tropical forestation provides the most comprehensive climate benefits compared to temperate or boreal regions.

The link between tropical deforestation and local warming is one of the most consistent biophysical findings in the climate science literature. Lawrence et al. (2022) documented that the removal of tropical forest cover causes significant increases in local surface temperatures, even exceeding the warming impact attributable solely to carbon emissions from biomass burning. This phenomenon occurs because dense tropical forests have a very high evapotranspiration capacity, which acts like a "natural air conditioner" that cools the Earth's surface. Artaxo et al. (2022) added that changes in albedo resulting from the replacement of forests with agricultural land or grasslands also contribute to significant local warming. The combination of these two effects creates a positive feedback loop in which local warming from deforestation exacerbates drought stress in remaining vegetation, increases fire risk, and ultimately accelerates ecosystem collapse

(Anderegg et al., 2020; Mitchard, 2018).

The scientific literature consistently emphasizes that tropical forest protection and fossil fuel emission reduction are not alternatives, but rather two pillars that must operate simultaneously and reinforce each other. Koch et al. (2021) explicitly show that even in the most optimistic tropical forest restoration scenario, the mitigation benefits are insufficient to offset fossil fuel emissions continuing at current rates. Pan et al. (2011) more broadly assert that carbon sequestration by global terrestrial ecosystems, including tropical forests, only offsets a small fraction of total anthropogenic emissions. Friedlingstein et al. (2022) in their latest Global Carbon Budget confirm that the gap between natural emissions and sinks continues to widen, so nature-based solutions such as tropical forest protection should be viewed as a "bridging strategy" that provides space for a clean energy transition, not as a substitute for fundamentally decarbonizing the global energy system.

CONCLUSION

Tropical forests are scientifically proven to be a key component of the Earth's climate system and the most powerful and cost-efficient instrument for climate change mitigation. With a storage capacity of ~360 Pg C in biomass and a sink of 0.47–1.3 Pg C/year, primary tropical forests play an irreplaceable role in maintaining global climate stability. Strategies for protecting primary forests, restoring secondary forests, and fully implementing REDD+ have the potential to contribute significantly to mitigation and economic savings. However, these benefits can only be sustained if deforestation is halted, primary forests are strictly protected, restoration is carried out promptly and on a large scale, and fossil fuel emissions are drastically and sustainably reduced.

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