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Beyond Sequestration: Evaluating Mangrove Restoration through a Net Global Warming Potential Framework

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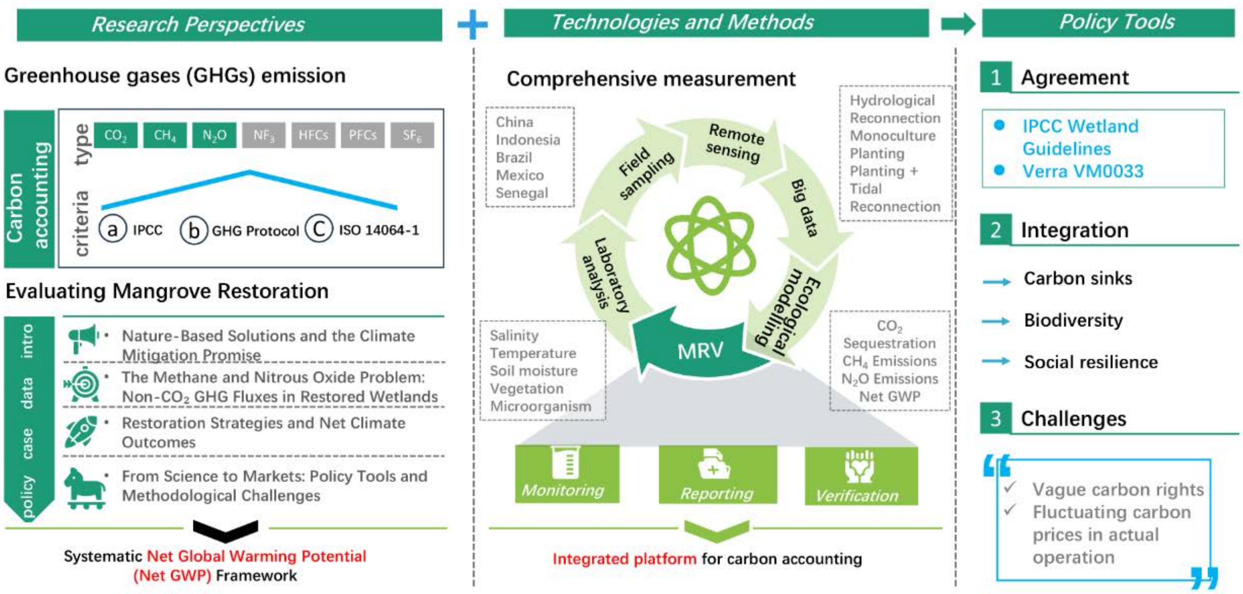
Abstract:

As a critical component of blue carbon ecosystems, mangroves have attracted increasing attention under the global climate change agenda. Their unique carbon storage mechanisms encompass both above-ground biomass and substantial soil organic carbon pools. However, most existing studies and policy assessments tend to overlook the emission dynamics of non-CO_2 greenhouse gases such as methane (CH_4) and nitrous oxide (N_2O), which may significantly distort evaluations of their net climate benefits. This study systematically reviews the mechanisms of carbon sequestration and non-CO_2 fluxes in mangrove ecosystems, compares climate and ecological co-benefits under different restoration strategies across regions, and examines the compatibility of current carbon market methodologies and policy instruments. Findings suggest the urgent need for an integrated assessment framework centered on Net Global Warming Potential (Net GWP), which incorporates ecological integrity, biodiversity recovery, and social co-benefits. Such a transition from carbon-centric to climate–ecology-oriented mangrove restoration is essential for achieving genuine mitigation outcomes and long-term ecosystem sustainability.

Keywords: Mangrove restoration; Blue carbon; Greenhouse gas fluxes; Net Global Warming Potential; Carbon market mechanism; Ecological policy evaluation

Graphical abstract



1. Introduction: Nature-Based Solutions and the Climate Mitigation Promise

Since the Industrial Revolution, human activities such as industrial emissions and vehicle exhaust have significantly increased atmospheric concentrations of greenhouse gases, triggering global-scale climate and environmental changes[1]. Climate change has led to abnormal heavy rainfall, prolonged droughts, and the expansion of desertification, all of which pose serious threats to ecosystems, water and soil resources, human livelihoods, and life safety[2].

Mangroves possess strong carbon sequestration capacity and represent a critical pathway to reduce atmospheric CO_2 and mitigate global warming[3]. However, due to human activities such as aquaculture pond construction and farmland reclamation, global mangrove ecosystems are under increasing threat[4]. In China, the presence of large areas of idle ponds has led to “pond-to-forest” and “farmland-to-forest” conversion becoming key strategies for mangrove restoration.

Reports suggest that the rate of global temperature rise over the past 50 years (0.13°C per decade) is nearly twice that of the previous century. By the end of the 21st century, global temperatures are expected to rise by 1.1 to 6.4°C [5]. As thermophilic species, mangroves are primarily limited in their poleward distribution by temperature. Consequently, global warming may have positive effects on mangrove development, including enhanced growth and expansion into higher latitudes, providing new opportunities for assisted colonization. Studies estimate that a 2°C rise in temperature could transform previously unsuitable zones into areas viable for mangrove growth. In China, the mangrove distribution zone could shift northward by approximately 2.5 degrees of latitude, potentially expanding the natural range from Fuding, Fujian, to Zhejiang Province, with introduced species extending even further to Hangzhou Bay. Mangrove species once restricted to Hainan could potentially thrive across coastal Guangdong[6]. Since 1998, more than 2,000 mu of mangrove forest has been established in southern Zhejiang. For instance, after 2019, nearly 1,000 mu of new plantations were established in Niyu, Dongtou District of Wenzhou, with plans to introduce new species and further expand mangrove coverage[7].

Unlike upland forests, mangroves thrive in waterlogged, anoxic soils that significantly restrict oxygen availability. These conditions stimulate microbial processes such as methanogenesis, resulting in the production and emission of methane (CH_4). Indeed, wetlands—including mangrove ecosystems—are recognized as the largest natural source of atmospheric methane globally. However, current assessments of mangrove carbon sinks often neglect these non-CO_2 greenhouse gases such as CH_4 and N_2O, potentially leading to an overestimation of their net climate benefit[8]. This complex greenhouse gas balance challenges the conventional blue carbon policy frameworks that focus solely

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on carbon sequestration as the metric of success.

In response, this paper proposes adopting Net Global Warming Potential (Net GWP) as the central indicator for evaluating the climate mitigation performance of mangrove restoration. By integrating CO_2 uptake with CH_4 and N_2O emissions, Net GWP provides a more scientifically comprehensive and dynamic assessment framework. This review will synthesize existing literature to systematically analyze carbon sequestration mechanisms in mangroves, key drivers of non-CO_2 gas emissions, differences in climate outcomes across restoration strategies, and the methodological gaps within carbon market policies. Mangroves protect more than 15 million people annually from flood risks and prevent over USD $65 billion in property damage[9]. Ultimately, it aims to offer a climate-oriented perspective for mangrove restoration planning and evaluation.

Despite widespread recognition of their ecological value, mangroves remain among the world's most threatened ecosystems[10]. Between 2000 and 2010, global mangrove loss occurred at a rate of 0.12% per year, which slowed to 0.07% annually from 2010 to 2020[11]. Climate change—including alterations in rainfall patterns, rising temperatures, sea level rise, and increased storm intensity—has significant regional impacts on mangrove ecosystems[12]. In addition, human activities such as aquaculture, agriculture, tourism, and urban development continue to reduce the spatial extent of mangroves.

Studies estimate that global mangrove ecosystems standing stock approximately 11.2 to 11.7 Pg C in total[13], while China's mangroves contribute about 5.5 to 6.91 Tg C[14]. The global carbon burial rate of mangroves is around 38.3 Tg C per year, with Chinese mangroves contributing about 0.05 Tg C annually[15]. The decline in mangrove coverage over past decades has resulted in substantial carbon stock losses and increased greenhouse gas emissions. It is estimated that between 0.7 to 1.2 Pg C is released annually from mangrove soils into the atmosphere, accounting for 10–15% of total carbon emissions from global terrestrial soils[16].Therefore, conserving and restoring mangrove ecosystems is of critical importance for mitigating climate change and enhancing the resilience of coastal ecological systems.

2. The Methane and Nitrous Oxide Problem: Non-CO_2 GHG Fluxes in Restored Wetlands

Global climate change has emerged as one of the most pressing environmental challenges of our time, manifesting through shifts in atmospheric composition, biodiversity loss, rising global temperatures, sea-level rise, and increased frequency of extreme weather events such as floods and droughts [17]. Among the greenhouse gases (GHGs), carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) are the three most influential contributors to anthropogenic climate forcing[18], with their combined radiative impact now far exceeding the magnitude of natural climatic fluctuations[19]. Although mangrove ecosystems have long been recognized for their exceptional carbon storage potential, increasing attention has been drawn to the complex behavior of non-CO_2 gases—particularly CH_4 and N_2O—in shaping their net climate benefits. This is especially critical during the early stages of ecological restoration, when soil disturbance, fluctuating hydrology, and inputs of organic matter can intensify anaerobic conditions and stimulate microbial processes such as methanogenesis and denitrification, thereby enhancing CH_4 and N_2O emissions.

Empirical data from the saline-alkaline wetlands of the Yellow River Delta provide a representative case. A study comparing four vegetation types—bare mudflat, Tamarix chinensis, Suaeda glauca, and Phragmites australis—revealed consistent net CH_4 uptake across all sites, with average fluxes of –11.2, –22.6, –35.5, and –30.2 $\mu g \cdot m^{-2} \cdot h^{-1}$, respectively. In contrast, CO_2 fluxes were uniformly positive, ranging from 109.7 to 312.4 $mg \cdot m^{-2} \cdot h^{-1}$, while N_2O exhibited pronounced spatial variability, from –0.72 to 2.41 $\mu g \cdot m^{-2} \cdot h^{-1}$ [20]. These results form the basis of Figure 1 and Table 1, which capture diurnal temperature fluctuations across different soil layers and the statistical associations between temperature and GHG fluxes. Collectively, they underscore the significance of thermal controls on non-CO_2 emissions in restored wetlands[21]. The N_2O flux in restored mangrove systems of the Yellow River Delta exhibits substantial spatial variability, ranging from –0.72 to 2.41 $\mu g \cdot m^{-2} \cdot h^{-1}$, strongly influenced by vegetation type and soil moisture conditions[20]. As shown in Figure 1, the diurnal variation in temperature across different vegetation types (bare flat, Tamarix, Suaeda, and Phragmites) and soil depths (surface to 20 cm) reveals notable differences in microclimatic dynamics. Table 1 presents correlation coefficients between temperature (air and soil at multiple depths) and fluxes of CO_2, CH_4, and N_2O. For instance, in Phragmites communities, N_2O emissions were significantly positively correlated with soil moisture at 0–10 cm depth ($P < 0.01$), as detailed in Table 2, highlighting soil water availability as a key driver of denitrification processes. Additionally, Table 3 indicates a significant negative correlation ($r = -0.293$) between soil electrical conductivity at the 10 cm layer and CH_4 flux, suggesting that high salinity may suppress methanogenic microbial activity. These data collectively underscore that the net climate impact of restored mangroves is shaped not only by CO_2 sequestration but also by the complex and dynamic interactions of non-CO_2 greenhouse gas emissions with underlying environmental variables.

Interactions among environmental variables are further illuminated through multivariate correlation analyses. As shown in Table 2, soil water content at varying depths exhibited significant positive correlations with N_2O fluxes, particularly in Phragmites and Tamarix communities, where elevated soil moisture and total nitrogen appeared to stimulate denitrification pathways[22]. Conversely, CH_4 fluxes in the Suaeda plots were negatively correlated with shallow soil temperature ($r = –0.727$, $P < 0.01$), suggesting potential thermal suppression of methanotrophic activity[23]. Moreover, Table 3 presents evidence that soil electrical conductivity, serving as a proxy for salinity, may inhibit CH_4 production, with a notable negative correlation at the 10 cm depth ($r = –0.293$). These findings collectively highlight the intricate trade-offs between carbon sequestration and non-CO_2 emissions in mangrove restoration systems. They argue strongly for adopting a Net Global Warming Potential (Net GWP) framework that integrates CO_2 uptake with CH_4 and N_2O emissions, offering a more accurate and policy-relevant assessment of mangrove restoration's climate impact[24].

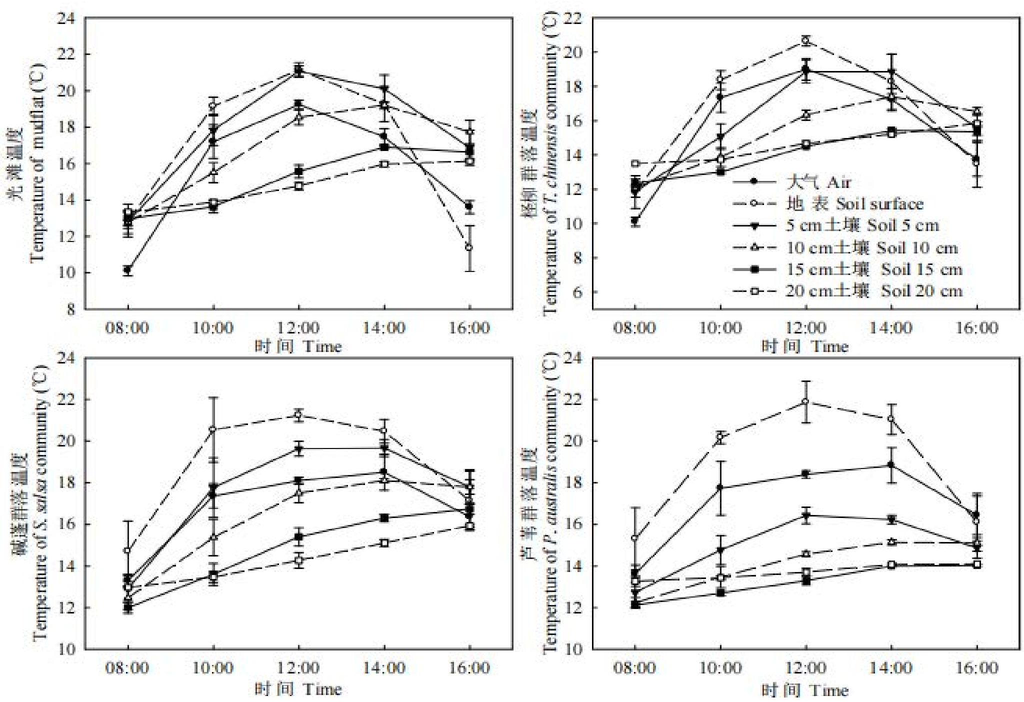

Figure 1. Diurnal variation of air and soil temperatures (0–20 cm) under four vegetation types in the saline wetlands of the Yellow River Delta.

Data source: Nie et al. (2012) [20]. Adapted from: Nie Y, Pei Y, Zhang L, et al. Dynamics of CH_4, CO_2 and N_2O Fluxes in Saline-Alkaline Soils of the Yellow River Delta, China. Advances in Environmental Protection, 2012, 2(3): 45–51.

Table 1. Relationships between air temperature and soil temperature at different depths and
changes in CO_2, CH_4 and N_2O fluxes of mudflat and different communities

	Greenhouse Gas	Air Temp	Soil Surface	Soil at 5 cm	Soil at 10 cm	Soil at 15 cm	Soil at 20 cm
Mudflat	CO_2	0.218	0.023	0.221	0.264	0.234	0.290
	CH_4	0.345	0.243	0.261	0.162	0.056	0.082
	N_2O	0.402	0.325	0.339	0.192	0.032	0.037
	CO_2	0.455	0.476	0.303	0.188	0.075	–0.002

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Tamarix	CH_4	0.252	0.159	0.533*	0.705**	0.675**	0.673**
	N_2O	–0.014	–0.169	0.221	0.532*	0.619*	0.655**
	CO_2	–0.397	–0.257	–0.431	–0.561*	–0.598*	–0.622*
Suaeda	CH_4	–0.620*	–0.674**	–0.647**	–0.519*	–0.398	–0.247
	N_2O	–0.168	–0.236	–0.127	–0.007	0.018	0.078
	CO_2	0.107	0.355	0.165	–0.114	–0.180	–0.260
Phragmites	CH_4	–0.025	–0.146	0.037	0.277	0.358	0.443
	N_2O	–0.552*	–0.343	–0.558*	–0.688**	–0.676**	–0.648**

Note: *$P < 0.05$; **$P < 0.01$

Table 2. Relationships between soil water content at different depths and changes

in CO_2, CH_4 and N_2O fluxes of mudflat and different com- munities

	Greenhouse Gas	Soil Surface	Soil at 5 cm	Soil at 10 cm	Soil at 15 cm
Mudflat	CO_2	0.303	0.080	–0.454	–0.004
	CH_4	0.697*	0.438	–0.070	–0.440
	N_2O	0.430	0.060	0.285	–0.425
	CO_2	0.140	0.227	0.032	–0.279
Tamarix	CH_4	–0.190	–0.225	–0.359	–0.373
	N_2O	0.142	0.090	–0.422	–0.242
	CO_2	0.189	–0.546	0.369	0.651
Suaeda	CH_4	–0.185	–0.327	–0.024	0.222
	N_2O	0.224	–0.263	0.345	0.522
	CO_2	–0.291	–0.085	0.229	–0.182
Phragmites	CH_4	0.001	–0.011	–0.039	0.431
	N_2O	0.486	0.113	0.003	–0.097

Note: *$P < 0.05$; **$P < 0.01$。

Table 3. Relationships between soil electrical conductivity at different depths and changes

in CO_2, CH_4 and N_2O fluxes ofmudflat and different com- munities

	Greenhouse Gas	Soil Surface	Soil at 5 cm	Soil at 10 cm	Soil at 15 cm
Mudflat	CO_2	-	-	-	-
	CH_4	-	-	-	-
	N_2O	-	-	-	-
Tamarix	CO_2	-	0.037	–0.293	–0.173
	CH_4	-	–0.270	–0.244	0.003
	N_2O	-	0.495	0.465	0.413
Suaeda	CO_2	0.169	–0.129	0.368	–0.160
	CH_4	0.264	–0.639	0.024	–0.570
	N_2O	0.213	–0.600	–0.333	–0.090
Phragmites	CO_2	0.264	0.038	–0.011	0.233
	CH_4	0.187	0.054	–0.056	–0.089
	N_2O	0.066	–0.003	–0.090	0.141

Note: -indicates undetected electrical conductivity due to exceeding the measurement range of the conductivity meter; $*P < 0.05$; $**P < 0.01$。

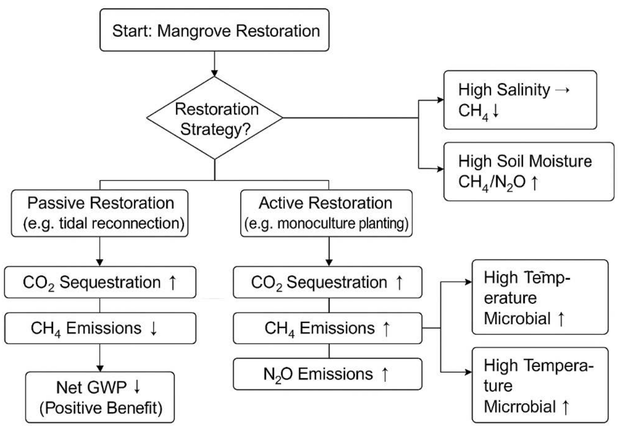

Figure 2 Climate impact pathways of mangrove restoration strategies and environmental influences

3. Case Comparisons: Restoration Strategies and Net Climate Outcomes

To better understand the underlying trade-offs between CO_2 uptake and non-CO_2 gas emissions across restoration strategies, Figure 2 presents a conceptual framework of the Net GWP assessment model.

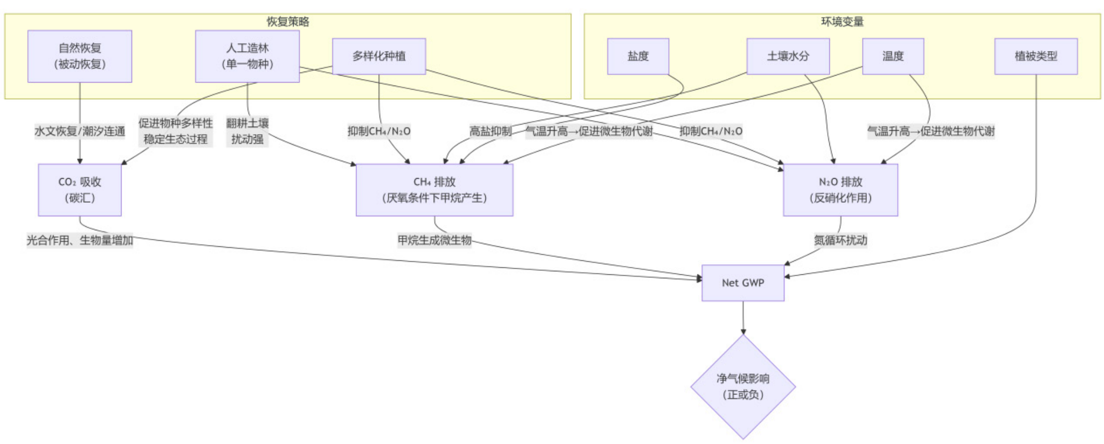

Figure 3 Conceptual framework of Net GWP under mangrove restoration strategies.

Mangroves, as a key component of coastal blue carbon ecosystems, possess substantial capabilities for carbon capture and long-term storage. Their carbon pools consist primarily of vegetative biomass and soil carbon, with shifts in these proportions indicating internal ecological dynamics[25]. A range of environmental variables—including climate conditions, hydrological patterns, geographical setting, and species composition—can significantly influence the total carbon stock within mangrove ecosystems. Spatial heterogeneity is also evident in global mangrove carbon distribution: tropical mangroves generally store more carbon than those in subtropical zones, and Southeast Asia's mangrove carbon stocks exceed those found in Africa and the Americas. At the species level, marked differences exist, with mangroves belonging to Rhizophoraceae and Heritieraceae families typically holding more carbon than those in Moraceae or Combretaceae[26].

Current estimates place the global mangrove carbon stock between 11.2 and 11.7 Pg C[27], with China accounting for 5.5–6.91 Tg C[28]. Globally, the average carbon burial rate in mangrove systems is approximately 38.3 Tg C per year, whereas China contributes roughly 0.05 Tg C annually[29]. However, mangrove deforestation and degradation over recent decades have led to a decline in total carbon storage and elevated atmospheric emissions. It is estimated that between 0.7–1.2 Pg C is released annually from mangrove soils, representing 10–15% of total global terrestrial soil carbon emissions[30]. Hence, conserving and restoring

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mangroves is essential not only for mitigating climate change but also for enhancing the resilience of coastal ecological systems[31].

In China's southeastern coastal provinces—particularly Guangdong, Guangxi, Fujian, and Hainan—restoration efforts have intensified under national programs such as "returning aquaculture ponds to mangroves" and "reforestation on abandoned land." According to Xu et al.[32], under projected climate warming scenarios, the potential geographic range of mangrove species is expected to shift northward, possibly expanding suitable habitat by nearly one-third, reaching as far as Zhejiang Province or even Hangzhou Bay. Carbon sink potential may rise to 0.05 Tg C per year, with projected negative emissions exceeding 6 Mg CO_2-eq per hectare. Nevertheless, most restoration projects still rely heavily on monoculture planting, which poses risks such as increased CH_4 emissions and unstable N_2O fluxes during early establishment phases[33]. In addition, limited species diversity hinders the return of birds and benthic fauna, slowing overall ecological recovery.

In contrast, a community-based approach in Sulawesi, Indonesia, employs passive restoration (natural regrowth) through tidal reconnection and preservation of native propagules in formerly degraded mangrove sites. This method maintains consistently low emissions of CH_4 and N_2O, and Net GWP becomes negative by year five, reaching approximately –7 Mg CO_2-eq·ha^{-1} annually[34]. Concurrently, faunal diversity has shown rapid recovery: bird diversity indices have increased by over 60%, and populations of fish and crabs have also rebounded, strengthening local livelihoods and community resilience[35].

In Senegal's Saloum Delta, government-NGO partnerships have established blue carbon conservation zones that emphasize the protection of fragmented mangrove patches through natural regeneration and assisted planting. These efforts include restrictions on aquaculture development and the creation of ecological buffers to stabilize early-stage microhabitats. Net GWP in these regions has remained between –5.1 and –6.7 Mg CO_2-eq·ha^{-1}[36], and controlled N_2O emissions further underscore the project's effectiveness. Additionally, the restoration has bolstered oyster fisheries and ecotourism, demonstrating synergies between climate mitigation and local economic development.

Meanwhile, in the Yucatán Peninsula of Mexico, carbon offset programs funded by foreign investment have promoted large-scale plantations using non-native mangrove species such as Rhizophora mangle. Although these projects initially exhibit robust CO_2 sequestration, their location in low-salinity estuarine zones has led to substantial CH_4 emissions—reaching an annual average of 1.5 g·m^{-2}·yr^{-1}—offsetting much of the CO_2 benefit[37]. Additionally, the dominance of a single species and soil disruption have delayed biodiversity recovery in these regions.

Net GWP outcomes vary substantially across sites due to environmental and ecological heterogeneity. For instance, high soil moisture and temperature stimulate microbial activity, elevating CH_4 and N_2O emissions even under CO_2 uptake. In contrast, higher salinity can suppress methanogenesis, resulting in more favorable GWP balances. Moreover, restoration approaches such as passive hydrological reconnection tend to preserve microbially stable environments, while monoculture planting may disturb soil carbon dynamics, leading to elevated non-CO_2 fluxes. Comparative data from studies in Indonesia, Brazil, and China further illustrate how these factors contribute to a wide range of Net GWP results (see Table 4).

Table 4. Cross-site comparison of greenhouse gas outcomes under different mangrove restoration strategies.

Country/Region	Restoration Type	CO_2 Sequestration (Mg C/ha/yr)	CH_4 Emissions (kg CH_4/ha/yr)	N_2O Emissions (kg N_2O/ha/yr)	Net GWP (Mg CO_2-eq/ha/yr)
Indonesia	Passive (Hydrological Reconnection)	5.2	120	10	-2.5
Brazil	Active (Monoculture Planting)	6.8	340	28	1.1
China	Mixed (Planting + Tidal Reconnection)	4.5	200	15	-0.8

Taken together, these regional cases highlight the trade-offs between carbon sequestration and non-CO_2 GHG emissions in mangrove restoration. While carbon-market-driven monoculture plantations may achieve rapid carbon gains, they often fall short in terms of ecological completeness and may neglect warming feedbacks from CH_4 and N_2O. In contrast, strategies grounded in ecological processes and community engagement appear more likely to yield stable, long-term climate and biodiversity co-benefits[38]. Therefore, future restoration policies should move beyond carbon-centric frameworks toward ecosystem-based approaches, incorporating Net GWP assessments and ecological integrity metrics to maximize genuine net climate benefits[39].

4. From Science to Markets: Policy Tools and Methodological Challenges

With the gradual recognition of nature-based climate response strategies in international policies, the market-oriented path of mangrove carbon sinks has also entered the carbon neutrality systems of various countries[40]. However, in the practice of incorporating mangroves into carbon trading mechanisms, scientific uncertainty and institutional barriers still pose serious challenges. On the one hand, the dynamic nature of carbon sequestration benefits makes it difficult to accurately estimate in actual projects[41]. Although there are mature technical methods for measuring vegetation and soil carbon storage, the release mechanism of non-CO_2 greenhouse gases such as CH_4 and N_2O in mangrove wetlands is limited by complex ecological factor interactions, including hydrological rhythms, soil salinity, and vegetation community composition[42]. The spatiotemporal flux fluctuations of these gases are significant, especially in the early stages of recovery, where biological disturbances and organic matter accumulation can trigger intense anaerobic reactions, leading to a rapid increase in non-CO_2 emissions, partially offsetting or even reversing the carbon sink effect[43]. Currently, most projects still use a simplified model with CO_2 absorption as the sole measurement indicator when calculating greenhouse gas emission reduction benefits, lacking systematic verification of non-CO_2 components, significantly underestimating the actual net warming effect and reducing the environmental authenticity of carbon credits[44].

On the other hand, at the methodological and policy institutional level, the current monitoring, reporting, and verification (MRV) system relied upon by mangrove carbon sequestration projects still faces applicability bottlenecks[45]. Although the IPCC Wetland Guidelines and Verra VM0033 provide accounting frameworks, they lack refined operational norms in non-CO_2 fluxes, underground carbon storage, and long-term system feedback, which limits their adaptability and expansion[46]. Meanwhile, the high cost of field sampling and laboratory analysis hinders the large-scale deployment of projects in developing countries or remote coastal zones[47]. Although remote sensing combined with ecological modeling has gradually become an alternative path, its data analysis accuracy, timeliness, and integration with existing methodologies still need further validation[48]. In addition, the mangrove carbon sequestration project is still subject to systemic obstacles such as vague land use rights, lack of legal definition of carbon rights, and large fluctuations in carbon prices in actual operation, which affect carbon income prediction and long-term investment returns[49]. Especially for projects with a single carbon target orientation, neglecting the integrity of ecosystem services and the sustainability of community participation often leads to a deviation from carbon sequestration and ecological restoration goals[50]. Therefore, in the future, it is necessary to promote the collaborative innovation of methodology and policy framework. It is recommended to introduce “Net Global Warming Potential” (Net GWP) as the evaluation core indicator, taking into account multi gas effects, and establish a multi-level MRV mechanism that is compatible with remote sensing, big data, and ecological models[51]. At the same time, in terms of institutional design, support should be given to the “multi benefit credit” mechanism that integrates carbon sinks, biodiversity, and social resilience, providing a scientifically credible, policy supported, and market active comprehensive path for mangrove restoration[52].

5. Conclusions

The mangrove ecosystem plays an important role in global climate governance, and its carbon fixation and ecological service functions provide a practical basis for natural emission reduction pathways[53]. However, the current evaluation system mostly uses CO_2 as the sole indicator, ignoring the emission impact of non-CO_2 greenhouse gases such as CH_4 and N_2O, which can easily overestimate the emission reduction contribution of projects[54]. By comparing cases from China, Indonesia, Senegal, and Mexico, it can be seen that the choice of restoration path directly affects the net climate benefits and ecological synergy value: single species afforestation can quickly accumulate carbon sinks, its performance in non CO_2 emission control and biodiversity restoration is limited; The strategy centered on natural processes and combined with community participation demonstrates more stable climate performance and ecological resilience[55]. Therefore, it is necessary to construct a multidimensional evaluation framework based on the Net GWP to systematically quantify the true contribution of mangrove projects between carbon balance and greenhouse gas balance[56]. At the same time, we should promote the coupling of methodology and policy mechanisms, improve the ecological adaptability of the MRV system, enhance the authenticity of the carbon credit environment, and guide the policy focus to shift from “carbon oriented” to “ecological oriented”, truly achieving the maximization of net climate benefits for

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mangrove restoration projects. Future restoration projects should prioritize passive strategies and conduct site-specific assessments to optimize net climate benefits under varying ecological conditions.

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