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Research Article

Blue carbon stock assessment and climate resilience potential of mangrove forest in Hung Thang commune, Vietnam

Hla Phong Ko[1], Pham Hong Tinh[2], Nguyen Thuy Duong[1,*]

[1] Vietnam Japan University, Vietnam National University, Hanoi, Vietnam
[2] Faculty of Environment, Hanoi University of Natural Resources and Environment, Hanoi, Vietnam

*Corresponding Email: ntduonga@vnu.edu.vn

Abstract

Mangrove forests are vital blue carbon sinks that contribute to climate change mitigation and coastal resilience. This study assessed the carbon stock and spatial–temporal dynamics of a mangrove forest in Hung Thang commune, Hai Phong Province, Vietnam, via a combination of field measurements, soil organic carbon (SOC) analysis, and normalized difference vegetation index (NDVI)-based remote sensing models. The results revealed that mangroves in the Hung Thang community store an average of 87.42 tC ha^{-1}, with SOC accounting for approximately 19% of the total carbon. A generalized additive model (GAM) analysis revealed a consistent increase in carbon stocks between 1996 and 2024, highlighting the impact of reforestation and restoration activities. This study provides critical data to strengthen measurement, reporting, and verification (MRV) systems for climate policy frameworks, including those related to REDD+ initiatives. The integration of field-based observations with remote sensing technologies highlights an approach for monitoring ecosystem-based climate mitigation. The findings emphasize the ability to integrate machine learning and AI-based tools into predictive carbon mapping and to optimize restoration planning, the role of mangroves in climate-resilient development pathways, and support evidence-based policy-making for sustainable coastal management.

Introduction

Mangrove forests are widely recognized as one of the most carbon-dense and productive ecosystems on Earth. They accumulate organic matter both above and below ground at rates that exceed those of many terrestrial forests while simultaneously delivering a suite of ecological services, including shoreline protection, storm surge buffering, habitat provision, and nutrient cycling (Alongi, 2014; Donato et al., 2011; Hoyos-Santillan et al., 2025). These dual functions — carbon sequestration and coastal protection — have made mangroves central to debates on climate change mitigation and adaptation. The Intergovernmental Panel on Climate Change (2022) emphasized that the persistence of these ecosystems is crucial for climate-resilient

development pathways, particularly in regions where coastal communities are highly vulnerable to environmental hazards. However, despite their value, the global mangrove area has shrunk to approximately 14–15 million hectares, with losses continuing at 0.3–0.6% annually, largely due to aquaculture expansion, infrastructure growth, and unsustainable exploitation (Contessa et al., 2023; Jiang et al., 2025; Primavera et al., 2012; Lee et al., 2019).

Vietnam's experience reflects these global dynamics in stark terms. The country's mangrove area declined from approximately 408,500 hectares in 1943 to fewer than 157,000 hectares by the year 2000 (Bao et al., 2018; Nguyen et al., 2021; Vietnam Ministry of Agriculture and Rural Development, 2016; Vu et al.,

2022). Much of this decline was attributed to the development of aquaculture and war-related damage. Extensive rehabilitation efforts have been directed mainly toward the Mekong Delta since the 1990s, given its strategic importance for national food security and coastal defense (Murdiyarso et al., 2015; Tinh et al., 2022a; b). These initiatives have substantially increased mangrove coverage, especially in northern coastal provinces such as Quang Ninh, Hai Phong, Hung Yen, and Ninh Bình (Quang Ninh, Hai Phong, Thai Binh, and Nam Dinh Provinces before July 2025). The mangrove forest in Hai Phong Province has been a focal point for restoration since the late 1990s, supported by both domestic and international programs. The dominant plant species include *Sonneratia caseolaris*, *Kandelia obovata*, and *Aegiceras corniculatum*. Nevertheless, mangrove degradation continues due to coastal erosion, sea-level rise, and unsustainable land use (Tinh, 2022a).

In addition to increasing forest area, recent forest development policies and strategies place greater emphasis on forest quality, biomass accumulation, and the enhancement of forest carbon stocks through sustainable forest management and ecosystem restoration. Vietnam was the first country to sign an agreement to participate in the World Bank's Forest Carbon Partnership Fund (FCPF) in 2008 and was selected as one of the first nine pilot countries for the United Nations' UN-REDD program in 2009. The REDD+ program (Reducing Emissions from Deforestation and Forest Degradation and the Role of Conservation, Sustainable Forest Management, and Enhancing Forest Carbon Stocks) is an international mechanism established by the United Nations Framework Convention on Climate Change (UNFCCC) to reduce greenhouse gas emissions through efforts to limit deforestation and forest degradation in developing countries. REDD+ not only protects forests but also includes sustainable forest management, conservation, and enhancement of forest carbon stocks. The Vietnam National REDD+ program, officially approved by the Prime Minister in Decision No. 419/QD-TTg in 2017, is one of the most important forest policies in Vietnam. The Vietnam Forest Development Strategy 2021–2030, with a vision to 2050, issued with Decision 523/QD-TTg in 2021, also clearly identifies forest management, protection, and biodiversity conservation in forest ecosystems as one of the three orientations for Vietnam's forest development. Afforestation and reforestation policies constitute a core component of the national climate change mitigation strategy issued under Decision No. 896/QD-TTg in 2022.

Understanding mangroves' capacity to store carbon and withstand climatic pressures is therefore essential for developing effective restoration and conservation strategies. Under the Warsaw Framework for REDD+, participating countries are required to establish robust national forest monitoring systems and transparent measurement, reporting and verification (MRV) frameworks to quantify changes in forest carbon stocks and related emission reductions or eliminations (Food and Agriculture Organization, 2018; United Nations Framework Convention on Climate Change, 2014). Therefore, accurate estimation of forest biomass, particularly aboveground biomass (AGB), is a fundamental technical requirement, as biomass serves as the primary representative indicator of forest carbon stocks and forms the basis for national greenhouse gas inventories and REDD+ outcome-based payments (Intergovernmental Panel on Climate Change, 2019). However, the effectiveness of these policies depends heavily on the accuracy and management of uncertainty in biomass and carbon stock estimates.

Advances in blue carbon research have underlined the need for integrated approaches that link field measurements, laboratory analysis, and geospatial monitoring (Dahl et al., 2025; Donato et al., 2011; Nguyen et al., 2021; Pham et al., 2019). Soil organic carbon (SOC), in particular, is now recognized as the largest carbon pool in mangrove ecosystems, yet its accumulation patterns in recently restored and monoculture stands remain uncertain (Alongi et al., 2021; Crooks and Megonigal, 2023; Hanh et al., 2018). Parallel progress in Earth observations has made remote sensing indispensable for scaling field data to the landscape level. Vegetation indices, such as the normalized difference vegetation index (NDVI), have proven effective in estimating biomass and mapping temporal changes in mangroves in Vietnam and across Southeast Asia (Bao et al., 2018; Nguyen et al., 2021). Complementary statistical techniques, notably generalized additive models (GAMs), are increasingly applied to capture nonlinear recovery trajectories and to project future dynamics in forest cover and carbon stocks.

Several studies have investigated blue carbon stocks in northern Vietnam, providing valuable insights into the carbon storage capacity of various mangrove species and the impact of site conditions. Hanh et al. (2018) quantified carbon stocks in the Hai Lang mangrove area of Quang Ninh Province, reporting a carbon storage of approximately 175.52 t C ha^{-1}, with soil carbon accounting for nearly 70% of the total carbon. Similarly, Hanh et al. (2014) examined soil carbon in *Sonneratia caseolaris* plantations in Thai Binh Province and reported that planted mangroves stored significantly more carbon (72–86 t C ha^{-1}) than did degraded or unplanted areas. Hanh et al. (2017) analyzed the carbon sink potential of *S. caseolaris* plantations in mangrove forests in the Chan Hung commune (Tien Lang district, according to administrative boundaries before July 1, 2025), which are aged 10–13 years, demonstrating their role in enhancing carbon accumulation in biomass. More recent research by Nguyen et al. (2021)

utilized Sentinel-2A satellite data combined with field measurements to estimate above- and below-ground carbon stocks in mangroves in Kien Hai Commune (in Dai hop and Bang La communes according to administrative boundaries before July 1, 2025), highlighting the effectiveness of remote sensing for large-scale blue carbon mapping.

This study provides a comprehensive assessment of blue carbon in mangroves in the Hung Thang commune, evaluating spatial and temporal changes in mangrove cover and carbon stocks from 1996–2024. It utilizes field measurements, laboratory analyses, NDVI-based mapping, and GAM analysis. By combining empirical fieldwork with geospatial and statistical modeling, this study aims to provide both ecological insights and policy-relevant evidence on the role of planted mangroves in northern Vietnam's blue carbon strategy.

Materials and methods
1) Sampling site, sample collection, and analysis

Field measurements and soil sample collection were conducted in the mangrove forest in the Hung Thang commune. The Hung Thang commune is located in the Red River Delta of northern Vietnam (Figure 1). The climate in this area is classified as humid subtropical (Cwa) under the Köppen–Geiger system, characterized by hot, humid summers with heavy monsoon rainfall and mild, drier winters. The average annual rainfall is 1,800–1,900 mm, and the mean annual temperature is 23–24 °C. Since 1996, large-scale mangrove restoration projects have been implemented in this region to protect aquaculture and coastal settlements, with a primary focus on three species: *Sonneratia caseolaris*, *Aegiceras corniculatum*, and *Kandelia obovata* (Figure 2). These species were selected for their ecological adaptability, rapid growth, and effectiveness in stabilizing intertidal zones, making them central to restoration and climate resilience strategies in northern Vietnam.

The mangrove forests of the Hung Thang Commune are dominated by three planted species—*Sonneratia caseolaris*, *Kandelia obovata*, and *Aegiceras corniculatum*—forming distinct mono-species and mixed-species plantations. *S. caseolaris* plantations occur mainly as low- to medium-density stands (300–1,000 trees ha^{-1}) with relatively large stem diameters and tall canopies, reflecting early-stage coastal protection plantings. In contrast, mixed-species stands dominated by *K. obovata* and *A. corniculatum* presented greater stem densities (2,000–2,900 trees ha^{-1}), smaller individual tree sizes, and greater structural complexity. These contrasting stand types were intentionally selected to examine how species composition and planting density influence above- and belowground carbon storage under comparable geomorphological and climatic conditions.

To capture the variability in the mangrove plantations of the mangrove forest in Hung Thang commune, 15 plots of 10 × 10 m were established following a stratified random sampling approach. Stratification was based on species composition (monoculture stands vs. mixed stands) and age class (young, middle-aged, and mature plantations) to ensure that both structural and ecological diversity were represented. The monoculture plots (n = 9) were dominated by *Sonneratia caseolaris*, reflecting the prevalence of this species in early restoration efforts. The mixed-species plots (n = 6) included combinations of *Kandelia obovata* and *Aegiceras corniculatum*, representing later stages of restoration aimed at improving resilience and biodiversity. Within each plot, all trees with a diameter ≥2 cm were measured for diameter at breast height (DBH), total height (H), and crown diameter. This dataset was then used to apply species-specific allometric equations for aboveground biomass (Eqs. 1–3 in Table 1) and belowground biomass (Eqs. 4–6 in Table 1). Soil cores were collected at the center of each plot to a depth of 100 cm at 20 cm intervals, ensuring consistency between vegetation and soil sampling. The bulk density and carbon content were analyzed in the laboratory as described in the following section.

2) Carbon stock estimation

Mangrove forest biomass was estimated to assess the capacity of this ecosystem to accumulate organic matter and store carbon. In this study, biomass was calculated by integrating field survey data with published allometric equations and using key forest parameters such as tree diameter and height. Both AGB and belowground biomass (BGB) components were considered to derive total biomass and corresponding carbon stocks. Detailed explanations of the methodology and calculation procedures are presented in the following sections, while the main equations used for biomass estimation are summarized in the table below for ease of reference and comparison (Table 1).

2.1) Estimation of aboveground biomass

Accurately quantifying the AGB of mangroves is essential for blue carbon assessment, but the suitability of equations varies with species morphology and site conditions. In this study, species-specific models were selected from published literature to reflect the characteristics of northern Vietnamese plantations. For *Sonneratia caseolaris*, the allometric model of Komiyama et al. (2005) was applied: AGB = 0.0673 × (ρ)$^{0.976}$ × (DBH)$^{2.004}$ (Eq. 1), where ρ = wood density (0.54 g cm^{-3}) and DBH is the tree diameter at breast height (cm).
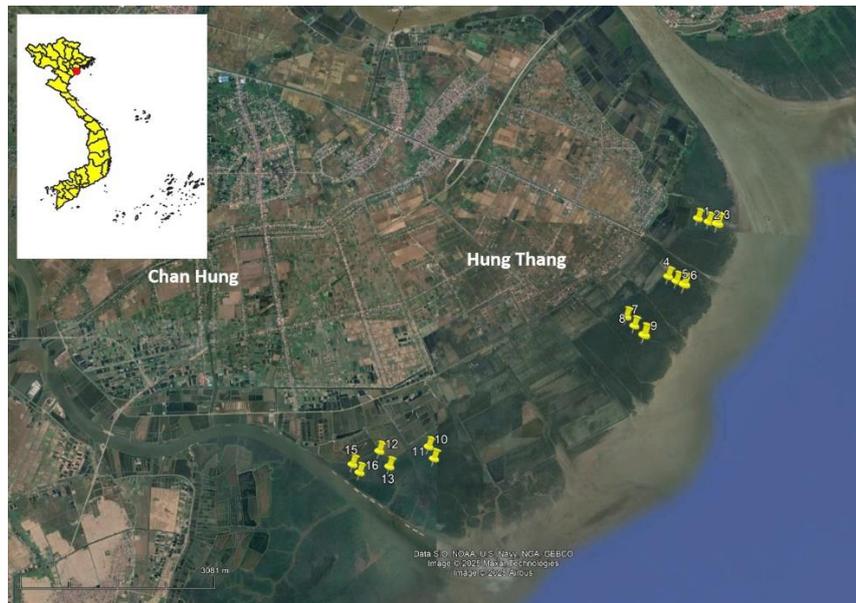
Figure 1 Map of the study sites in the 15 investigated plots.

Table 1 Summary table of equations

Equation No.	Formula	Calculation	Source
1	$AGB = 0.0673 \times (\rho)^{0.976} \times (DBH)^{2.004}$	AGB *of S. caseolaris*	Komiyama (2005)
2	$AGB = 3.1253 \times (CD^2 \times Height)^{0.9063}$	AGB *of A. corniculatum*	Fu and Wu (2011)
3	$AGB = 0.04975 \times D_{30}^{1.94748}$	AGB *of K. obovata*	Tran (2017)
4	$BGB = 0.199 \times (DBH)^{2.22}$	BGB *of S. caseolaris*	Komiyama (2005)
5	$BGB = 0.01420 \times D_{30}^{2.12146}$	BGB *of K. obovata*	Hanh et al. (2016)
6	$BGB = AGB \times 0.24$	BGB *of A. corniculatum*	Fu and Wu (2011)

Remark: AGB: Aboveground biomass; BGB: Belowground biomass; DBH: Tree diameter at breast height; ρ = Wood density; CD: Canopy diameter; D_{30}: Stem diameter measured at 30 cm above the basal flare.

This model is consistent with IPCC guidelines (Eggleston, 2006) and is directly applicable to field measurements of DBH and height. Although more recent works have tested remote sensing-integrated models (Quang et al., 2022; Tran et al., 2017), Eq. 1 was selected for its simplicity and reliability in plantation stands. For *Aegiceras corniculatum*, DBH-based models are often less accurate because of their shrub-like growth form. Instead, the equation of Fu and Wu (2011) was adopted, which incorporates crown diameter and tree height: AGB = 3.1253 × ((crown diameter)² × height)^0.9063 (Eq. 2). This model better reflects the architecture of *A. corniculatum* in dense, low-stature plantations typical of Vietnam's northern deltas. For *Kandelia obovata*, the equation of Hanh et al. (2016), developed specifically for plantations in the Red River Delta, was selected: AGB = 0.04975 × D_{30}1.94748 (Eq. 3), where D_{30} is the stem diameter measured at 30 cm above the basal flare. This approach addresses the measurement challenges posed by basal swelling and low bifurcation, making it more reliable than generic DBH models for young plantations.

2.2) Estimation of belowground biomass

The BGB was also estimated via species-specific models. For *S. caseolaris*, Komiyama et al. (2005) reported that BGB = 0.199 × (DBH)^2.22 (Eq. 4). For *K. obovata*, Hanh et al. (2016) developed a site-specific root equation: BGB = 0.01420 × D_{30}^2.12146 (Eq. 5). For *A. corniculatum*, BGB was calculated via a root-to-shoot ratio of 0.24 × AGB, following Fu and Wu (2011): BGB = AGB × 0.24 (Eq. 6). Both AGB and BGB were converted to carbon via the IPCC (2006) default carbon fraction of 0.47.

2.3) Soil organic matter

Soil organic carbon (SOC) was quantified in accordance with national standards (TCVN 8941: 2011) (Vietnam Ministry of Science and Technology, 2011). The LOI method was first used to estimate organic matter, and the van Bemmelen factor (1.724) was applied to convert organic matter to SOC: SOC (%) = OM (%)/1.724 (Eq. 7). In parallel, the Walkley–Black wet oxidation method was applied to determine the total organic carbon (TOC) content. A regression analysis was then performed to align the LOI-based SOC estimates with the Walkley–Black results, following the validation strategy employed by Kauffman & Donato (2012) and Howard et al. (2014). This dual approach improves accuracy and enables correction of method-specific biases.

Figure 2 Photographs of the plant species including a) *Sonneratia caseolaris* trees; b) *Sonneratia caseolaris* flowers, leaves, and fruits; c) *Kandelia obovata* trees; d) *Kandelia obovata* leaves and fruits; e) *Aegiceras corniculatum* trees; and f) *Aegiceras corniculatum* flowers and leaves.

3) Mangrove mapping and temporal analysis
3.1) NDVI mapping

Satellite imagery from Landsat 8/9 and Sentinel-2A collected in 2024 was used to map the extent of mangroves and assess temporal changes. The NDVI was computed as follows: NDVI = (NIR - RED)/(NIR + RED) (Eq. 8). The mangrove pixels were classified via supervised classification with an NDVI threshold > 0.2. Regression analysis was then used to link the field-estimated AGB with the NDVI values to generate spatial estimates of biomass. This method is consistent with other Vietnamese studies (Pham et al., 2017; Primavera et al., 2012), which reported high accuracy in mapping mangrove cover and biomass dynamics. Comparisons with remote sensing studies in Hai Phong (Quang et al., 2022; Tran et al., 2017) confirm that NDVI-based classification is a robust approach for detecting mangrove extent and estimating biomass in northern Vietnam, making it

particularly suitable for tracking restoration outcomes and assessing long-term carbon sequestration potential.

3.2) Temporal analysis

The long-term dynamics of mangrove carbon were reconstructed via two complementary approaches. First, the IPCC stock-change method was applied to calculate the ecosystem carbon stock in a given year: $C(t)$ = Area(t) × BEF × CF (Eq. 9), where $C(t)$ is the carbon stock in year t, Area(t) is the mangrove extent, BEF is the biomass expansion factor, and CF is the carbon fraction (Eggleston, 2006). The mangrove extent was obtained from the Global Mangrove Watch dataset (1996–2020) and updated via the NDVI-derived classification for 2024. This method allows consistent comparisons with international greenhouse gas inventory standards. Second, a GAM was fitted to time series data from mangrove areas, and the carbon stock was estimated to capture nonlinear recovery patterns. GAMs were chosen over linear regression because restored mangrove systems often undergo distinct ecological phases, including degradation, early recovery, and accelerated growth (Wood, 2017; Yee et al., 1991). The GAM incorporated smoothing splines to model these transitions and was used to project the extent of mangroves and carbon sequestration to 2030. By combining the stock-change approach with GAM analysis, temporal assessment not only quantifies historical losses and gains but also identifies likely future trajectories of blue carbon storage under continued restoration (Howard et al., 2014; Kauffman and Donato, 2012). This dual approach strengthens both the robustness of the carbon estimates and their interpretive value for policy planning.

4) Policy integration and comparative analysis

A central aim of this study is to situate the mangrove forest in the Hung Thang commune within the broader discourse on climate resilience and policy integration. The methodological design was aligned with the MRV framework under REDD+ and Vietnam's Nationally Determined Contributions (NDCs). In addition to carbon accounting, the analysis offers comparative insights that can inform restoration strategies, climate mitigation policies, and adaptive coastal management approaches.

Results and discussion
1) Blue carbon stock in the mangrove forest at Hung Thang Commune

AGB and aboveground carbon (AGC) stocks were calculated for each plot to estimate the average carbon stock of the area (Table 2). The average carbon stock across all the sample plots was 87.42 tC ha^{-1}, consisting of AGC of 54.81 tC ha^{-1}, belowground carbon (BGC) of 16.09 tC ha^{-1}, and SOC of 16.52 tC ha^{-1} (Table 3). AGC was estimated via species-specific allometric equations (Eqs. 1–3), whereas BGC was derived via root equations (Eqs. 4–6).

The mixed-species plantations consistently outperformed the monocultures. Plots dominated by Kandelia obovata and Aegiceras corniculatum stored up to 101.51 tC ha^{-1}, comprising an AGC of 74.65 tC ha^{-1} and BGC of 26.86 tC ha^{-1}. In contrast, *Sonneratia caseolaris* monocultures averaged a total of 52.91 tC ha^{-1}, with an AGC of 42.76 tC ha^{-1} and a BGC of 10.15 tC ha^{-1} (Table 4). This clear difference reflects the species -specific growth patterns captured in the applied allometric equations (Fu and Wu, 2011; Hanh et al., 2016; Komiyama et al., 2005) [and supports earlier findings that mixed-species stands offer increased resilience and biomass accumulation (Howard et al., 2014). These results underscore the importance of using site-specific equations (Eqs. 1–6) accurate carbon quantification in plantation forests.

2) Soil organic carbon distribution

SOC contributed 16.52 tC ha^{-1} (18.9% of the total ecosystem carbon). The SOC stocks were highest in the surface layer (0–20 cm: 8.20 tC ha^{-1}) and declined with depth to 0.95 tC ha^{-1} at 80–100 cm (Figure 3). SOC was estimated via the LOI method and converted to TOC via the van Bemmelen factor (Eq. 7), with calibration against Walkley–Black TOC values. This depthwise decline reflects reduced organic inputs and increasing mineral dominance with depth, which is consistent with patterns observed in plantation mangrove systems. This is a plantation-dominated mangrove system, where carbon accumulation is primarily stored in standing biomass rather than long-term soil pools, unlike mature natural mangroves.

3) NDVI mapping and biomass distribution

Supervised classification of Landsat 8/9 and Sentinel-2 imagery revealed 969.6 ha of mangroves in 2024 (Figure 4). The NDVI was calculated (Eq. 8) and regressed against plot-level AGB estimates to produce the model: AGB = 934.59 × NDVI - 327.98 (Eq. 10)

Our study revealed a relatively weak relationship between the NDVI-derived biomass and field-measured aboveground biomass (AGB) (R^2 = 0.24), indicating that the NDVI explains only a limited proportion of the biomass variability in mangrove forests because of saturation effects and its sensitivity primarily to canopy greenness rather than structural attributes such as stem diameter, height, and wood density (Jeyapalu and Weerasinghe, 2024). Despite this low fit, the NDVI-based models avoided the overestimation observed when generic allometric–NDVI relationships were applied (Bao et al., 2018) and were robust for distinguishing mangroves from aquaculture and agricultural land, which is consistent with the findings of previous studies in other forest ecosystems (Nguyen et al., 2021; Pham et al., 2017).

Table 2 Estimation of AGB and AGC stocks from 15 plots in the mangrove forest along the coast of Hung Thang Commune, Hai Phong Province

Plots	Species	Latitude	Longitude	Density (tree ha^{-1})	DBH- $D_{1.3}$ (m)	H (m)	CD (m)	AGB (ton ha^{-1})	AGC (ton ha^{-1})
1	*Sonneratia caseolaris*	20.651401	106.701033	300	0.68	7.67	-	53.46	25.12
2	*Sonneratia caseolaris*	20.651671	106.701319	600	0.70	7.47	-	151.08	71.01
3	*Sonneratia caseolaris*	20.651542	106.701200	300	0.70	12.20	-	61.49	28.90
4	*Sonneratia caseolaris*	20.651575	106.700958	600	0.66	10.05	-	101.76	47.83
5	*Sonneratia caseolaris*	20.651549	106.700589	1,000	0.58	9.45	-	139.61	65.62
6	*Sonneratia caseolaris*	20.629161	106.665938	900	0.50	12.36	-	89.91	42.26
7	*Sonneratia caseolaris*	20.629265	106.665722	600	0.38	7.94	-	33.42	15.71
8	*Sonneratia caseolaris*	20.629337	106.665593	1,000	0.33	5.77	-	45.91	21.58
9	*Sonneratia caseolaris & Aegiceras corniculatum*	20.628470	106.664795	1,000	0.69	5.19	1.96	122.62	57.63
10	*Kandelia obovata, Sonneratia caseolaris, and Aegiceras corniculatum*	20.628549	106.664954	2,700	0.38	3.04	1.30	65.63	30.85
11	*Kandelia obovata, Sonneratia caseolaris, and Aegiceras corniculatum*	20.622985	106.648033	2,000	0.95	6.37	3.07	213.20	100.20
12	*Kandelia obovata, Sonneratia caseolaris, and Aegiceras corniculatum*	20.622786	106.64822	2,900	0.82	6.16	1.98	273.47	128.53
13	*Kandelia obovata, Sonneratia caseolaris, and Aegiceras corniculatum*	20.622811	106.648557	2,000	0.91	6.23	2.39	143.16	67.29
14	*Kandelia obovata, Sonneratia caseolaris, and Aegiceras corniculatum*	20.622608	106.648743	2,500	0.47	7.64	-	126.88	59.63
15	*Kandelia obovata & Aegiceras corniculatum*	20.622307	106.648706	2,100	0.31	6.71	2.11	85.89	40.37

Table 3 Average carbon stock distribution in the mangrove forest at Hung Thang Commune (tC ha^{-1})

Carbon Pool	Mean (tC ha^{-1})	Percentage of Total (%)
Above-Ground C	54.81	62.7
Below-Ground C	16.09	18.4
Soil Organic C	16.52	18.9
Total	87.42	100

Table 4 Comparison of AGB, BGB, AGC, and BGC between mono-species and mixed-species stands

Category	*Sonneratia*-dominated (Plots 1–8)	Mixed-species (Plots 9–15)
Average AGB (t ha^{-1})	85.52 t ha^{-1}	149.29 t ha^{-1}
Average AGC (tC ha^{-1})	42.76 tC ha^{-1}	74.65 tC ha^{-1}
Average BGB (t ha^{-1})	21.58 t ha^{-1}	57.15 t ha^{-1}
Average BGC (tC ha^{-1})	10.15 tC ha^{-1}	26.86 tC ha^{-1}
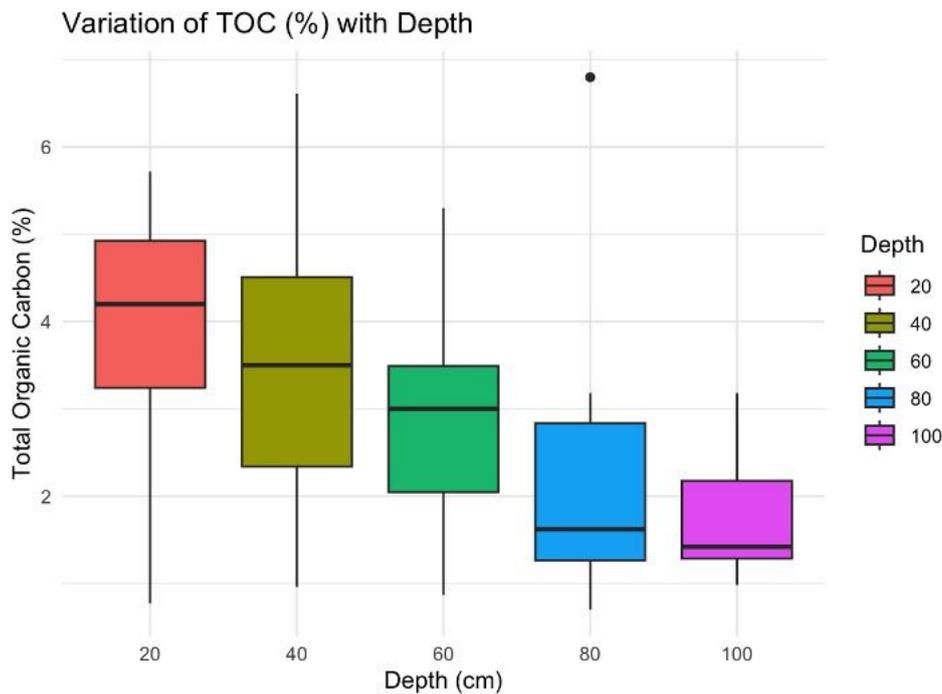
Figure 3 Boxplot showing the variation in total soil organic carbon (TSOC%) at different soil depths.

The low NDVI–AGB correlation highlights substantial uncertainty in pixel-level biomass and carbon stock estimates, although aggregation over larger spatial units (e.g., the commune scale) partially mitigates these errors, allowing NDVI-calibrated models to provide first-order estimates of the total extent of mangrove biomass. Similar limitations of simple vegetation indices have been widely reported, particularly in dense or structurally complex forests, where the NDVI often saturates at moderate to high biomass and fails to capture key structural variability (Intergovernmental Panel on Climate Change, 2019; Pham et al., 2020). Accordingly, NDVI-derived biomass maps should be interpreted as representing broad spatial patterns and relative biomass gradients rather than precise quantitative values. These findings reinforce that the NDVI alone is insufficient for high-accuracy biomass or carbon accounting in mangrove ecosystems and that integrative approaches incorporating radar or LiDAR structural data, red-edge or shortwave infrared bands, or machine learning–based multisensor models are increasingly recommended for robust AGB and carbon stock estimation, particularly for REDD+ and blue carbon initiatives (Food and Agriculture Organization, 2018; United Nations Framework Convention on Climate Change, 2014).

Despite the low predictive accuracy of the NDVI–AGB regression, the field-calibrated NDVI improved biomass mapping, especially compared with previous remote sensing studies in Hai Phong (Quang et al., 2022; Tran et al., 2017), which relied heavily on machine learning without plot-level validation. This combined approach strengthens the utility of the NDVI for monitoring restoration outcomes and carbon dynamics in plantation mangroves.

4) Temporal trends and GAM analysis

Mangrove cover declined sharply between 1996 and 2007 due to aquaculture expansion, reaching a minimum of ~700 ha (Figure 5). Since 2008, restoration

efforts have driven steady recovery, culminating in 969.6 ha in 2024 (Figure 5). Using the IPCC stock-change method (Eq. 9), carbon stocks increased from 52.1 tC ha^{-1} in 1996 to 87.4 tC ha^{-1} in 2024, with projections exceeding 110 tC ha^{-1} by 2030 if restoration continues.

The GAM analysis identified three phases of the ecological trajectory: (i) degradation (1996–2007), (ii) recovery (2008–2020), and (iii) accelerated growth (2020–2024). By fitting smoothing splines, the GAM provided a more realistic representation of plantation growth dynamics than did linear regression. The model projected continued expansion to over 1,050 ha by 2030, validating the effectiveness of restoration (Figure 6). This dual approach (Eq. 9 + GAM) not only quantifies past dynamics but also anticipates future sequestration potential under ongoing management.
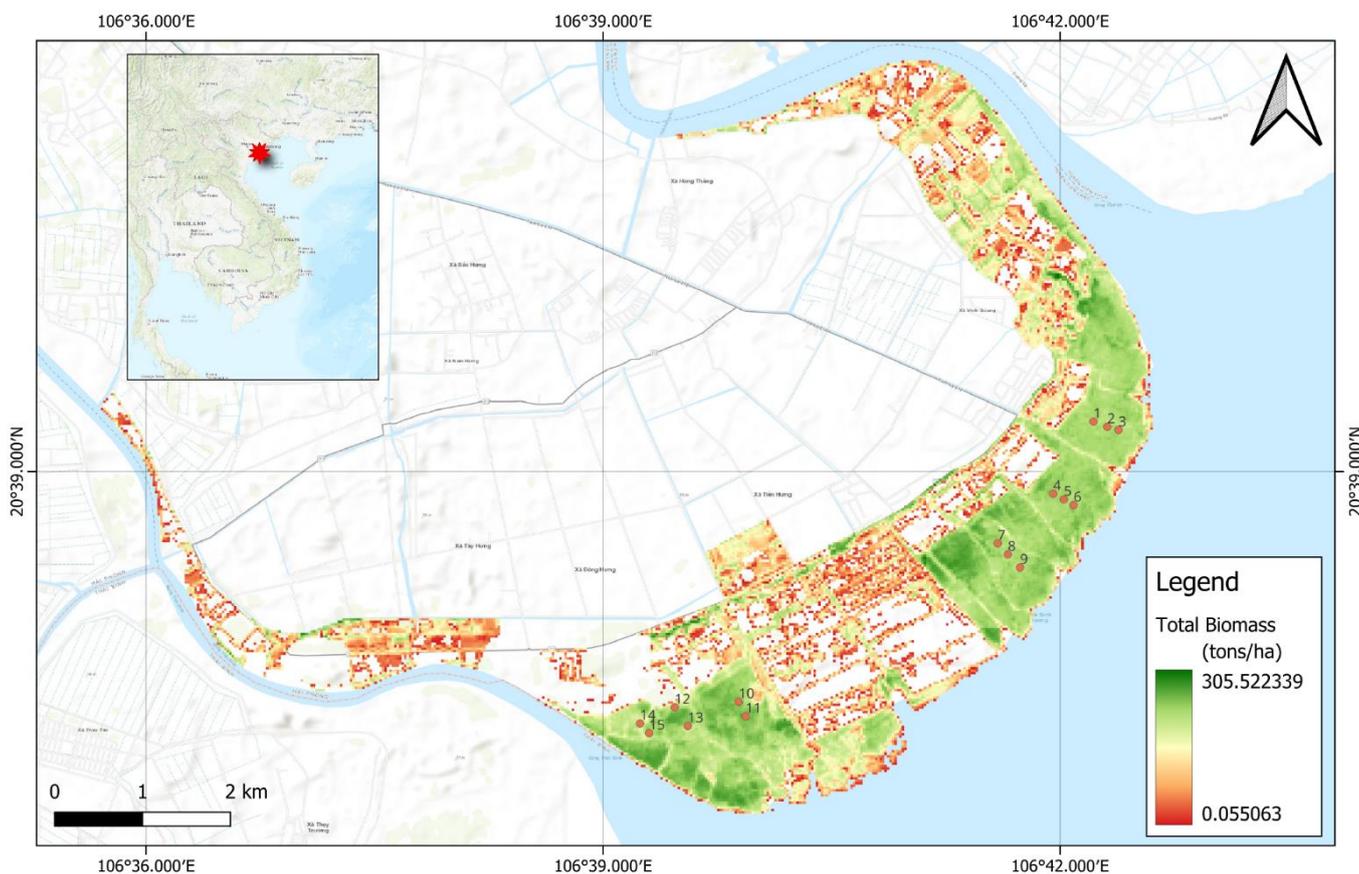

Figure 4 Map of mangrove forest in Hung Thang commune and biomass distribution (2024).
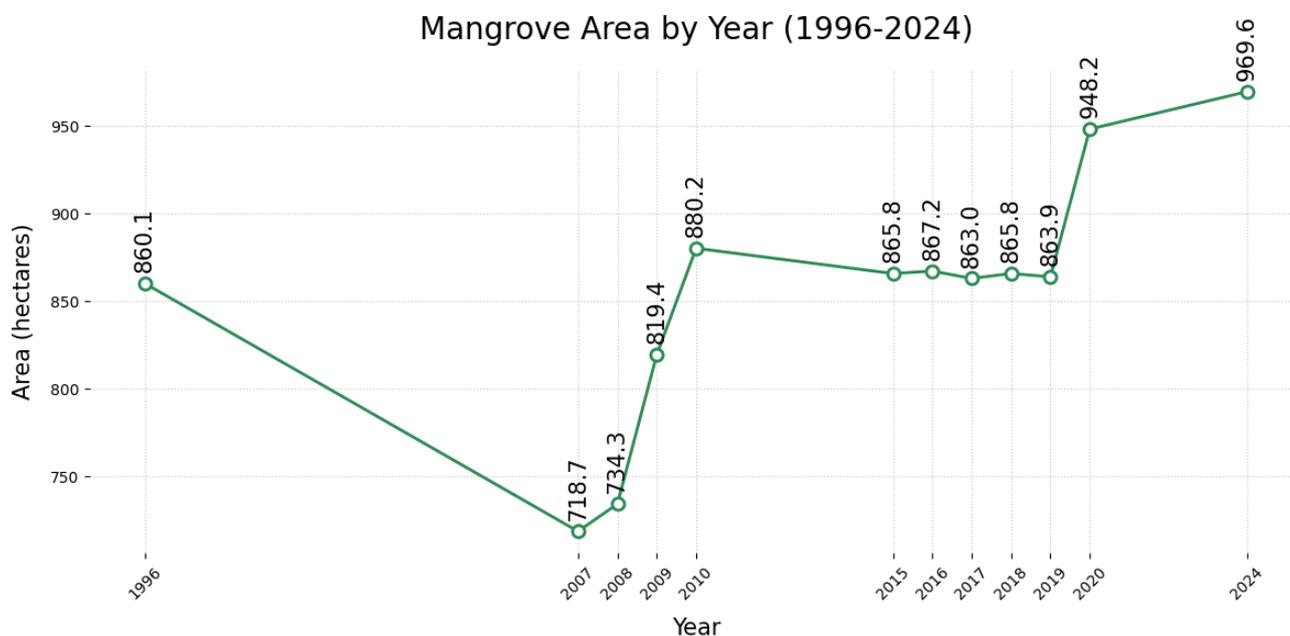

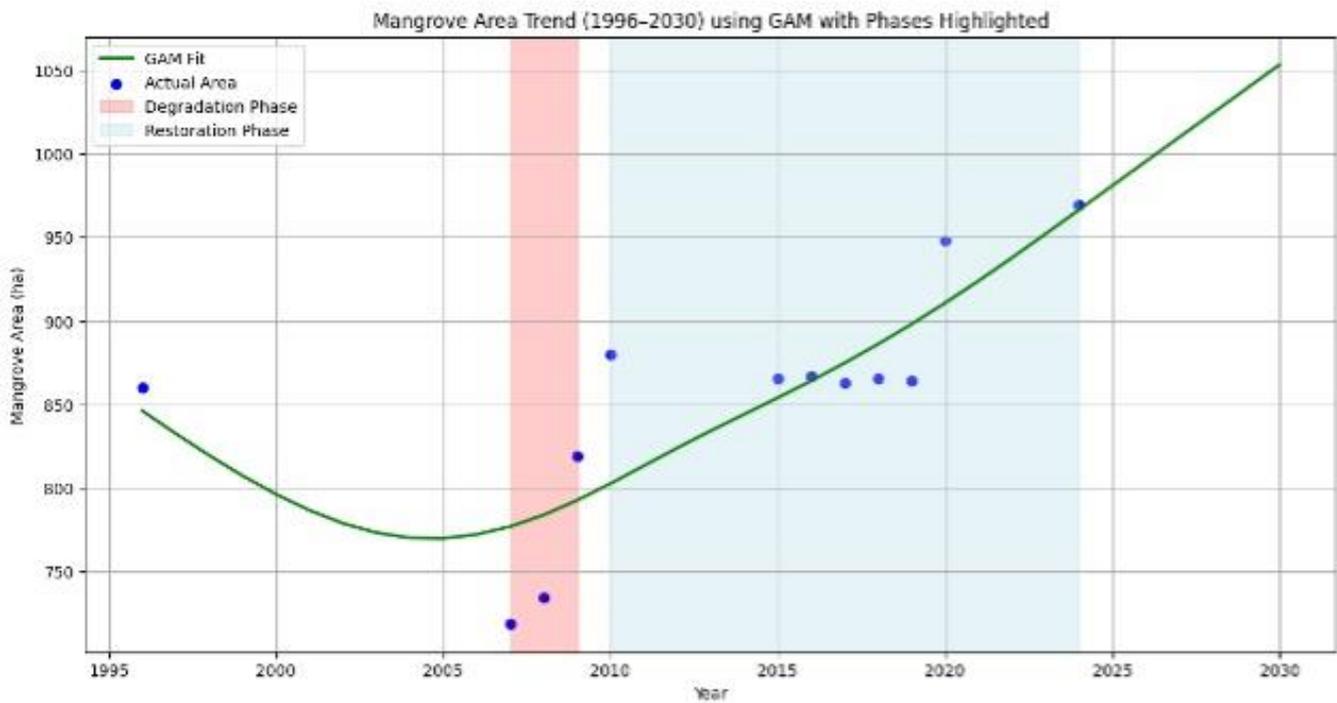**Figure 5** Temporal changes in mangrove forest area from 1996–2024.

Figure 6 Temporal trends in mangrove areas (1996–2030) in mangroves in the Hung Thang Commune using the GAM, with the degradation and restoration phases highlighted.

Table 5 Comparison of mangrove carbon stocks between Hung Thang and global estimates

Parameter	Hung Thang Commune (This study)	Global planted mangroves
AGC (tC ha^{-1})	54.81	50–200 (Hamilton and Casey, 2016)*
BGC (tC ha^{-1})	16.09	20–80 (Estimate)**
SOC (0–100 cm)	16.52	10–50 (Arifanti et al., 2021)*
Total ecosystem carbon (tC ha^{-1})	87.42	80–330
Area recovery rate	1.51% annually	0.5–1.5% annually (Lee et al., 2019)*

Remark: *Data for global planted mangroves were calculated from the data collected from the mentioned references; **: BGC is assumed to constitute 40% of AGC

5) Comparative insights

The results underscore the contrasts between plantation mangroves and natural systems. The natural mangroves in the Mekong Delta store >1,000 tC ha^{-1} (Nguyen et al., 2021), whereas the mangrove plantations in the Hung Thang commune remain below 100 tC ha^{-1} (Table 5). Indonesian mangroves exhibit exceptional SOC pools globally (Donato et al., 2011), whereas the Philippines has demonstrated successful community-based rehabilitation that integrates ecological and social benefits (Primavera et al., 2012).

Local comparisons are equally revealing. Previous studies in the Hai Phong area using radar and machine learning (Intergovernmental Panel on Climate Change; Pham et al., 2019) achieved strong classification accuracy but lacked calibration against field measurements. The present study's integrated framework—species-specific allometry, SOC regression, and NDVI mapping—addresses these gaps and produces estimates that are directly applicable to MRV and carbon policy frameworks.

Table 5 compares the carbon stocks and recovery rates of mangrove plantations in the Hung Thang Commune with those of global benchmarks for planted mangroves. While above-ground carbon stocks are broadly comparable to global plantation ranges, soil organic carbon remains substantially lower, reflecting the young age and managed nature of the plantations. The relatively high areal recovery rate observed in Hung Thang is driven primarily by active, policy-supported restoration efforts rather than advanced ecosystem maturity or increased carbon storage capacity, underscoring the need to distinguish between spatial recovery and long-term carbon accumulation in mangrove restoration assessments.

6) Policy and climate implications

These findings are directly relevant for climate resilience (Table 6). Three major insights emerge: (1) Integration into MRV and REDD+: Planted mangroves, although younger and less carbon dense than natural forests, must be included in national MRV systems. The estimates provided here offer a calibrated dataset aligned with IPCC methods (Eggleston, 2006). (2) Species selection matters: Mixed-species plantations presented significantly higher stocks than monocultures did. Restoration

strategies should prioritize diverse stands to optimize both carbon storage and resilience to climatic stressors. (3) Comprehensive monitoring is critical: SOC accounted for the majority of the carbon in this study. Accurate SOC measurement, validated through regression methods, should remain a priority for Vietnam's carbon inventories.

Conclusions

This study demonstrated that the restored mangrove forests in Hung Thang commune, northern Vietnam, despite their relatively young age, already provide measurable contributions to blue carbon sequestration and coastal resilience. By integrating species-specific allometric equations, calibrated SOC analysis, and normalized difference vegetation index (NDVI)-based biomass estimation, the mean ecosystem carbon stock was quantified at 87.42 tC ha^{-1}, with SOC accounting for 19% of the total carbon. Temporal reconstruction via the IPCC stock-change method and generalized additive models identified three distinct phases—degradation (1996–2007), recovery (2008–2020), and accelerated growth (2020–2024)—with total carbon stocks increasing from 52.1 tC ha^{-1} in 1996 to nearly 87.4 tC ha^{-1} in 2024 and projected to exceed 110 tC ha^{-1} by 2030 under continued restoration.

From a policy and implementation perspective, these results provide empirical evidence that large-scale mangrove planting programs can effectively reverse historical carbon losses in northern Vietnam, although plantation forests still store less carbon than mature natural mangroves in the Mekong Delta. Importantly, this study offers a transferable methodological framework that aligns with Vietnam's National Forest MRV requirements, supporting more accurate inclusion of plantation mangroves in national greenhouse gas inventories and REDD+ reporting. At the global level, the integrated field–remote sensing approach adopted here is consistent with IPCC good-practice guidance and emerging international standards for blue carbon accounting under the Paris Agreement.

On the basis of these findings, three practical implementation pathways are recommended. First, plantation mangroves should be formally integrated into REDD+ and national MRV systems to ensure that their carbon sequestration benefits are fully recognized in Vietnam's NDC. Second, restoration strategies should prioritize mixed-species plantations to increase long-term carbon storage, ecological stability, and climate resilience, avoiding overreliance on monocultures. Third, long-term monitoring frameworks that combine SOC measurements, satellite-based NDVI mapping, and temporal modeling should be institutionalized to meet international requirements for transparency, accuracy, and comparability.

Overall, the Hung Thang mangrove forest serves as both a scientifically robust case study and a policy-relevant example of how ecosystem-based restoration can support climate mitigation, coastal protection, and community resilience simultaneously. Scaling up and refining such integrated restoration and monitoring approaches across northern Vietnam will be essential for achieving national climate commitments and advancing sustainable, climate-resilient coastal development pathways.

Study limitations

The uncertainty in the biomass and carbon stock estimates in this study arises from three main sources: (i) limitations of the NDVI-based above-ground biomass (AGB) estimation, (ii) methodological uncertainty in soil organic carbon (SOC) determination, and (iii) sampling intensity and spatial representativeness.

Uncertainty in AGB estimation is associated primarily with the low predictive accuracy of the NDVI–AGB regression model developed from field data ($R^2 = 0.24$). This reflects well-documented limitations of the NDVI in dense, structurally complex mangrove canopies, where index saturation reduces sensitivity to variations in stem diameter, tree height, and woody biomass, which together dominate the AGB. The NDVI is responsive mainly to canopy greenness and chlorophyll content and therefore captures only part of the structural variability influencing biomass. Consequently, NDVI-derived biomass and above-ground carbon maps are subject to considerable pixel-level uncertainty and should be interpreted as representing relative spatial patterns rather than precise plot-scale values. When aggregated at the commune scale, however, random errors are partially dampened, allowing NDVI-based mapping to provide reasonable first-order estimates of mangrove biomass distribution.

Additional uncertainty related to NDVI-based biomass estimation arises from model transferability. A comparison with a published NDVI–AGB relationship for *Sonneratia caseolaris* plantations (Tran and Le, 2018) revealed that externally derived models consistently overestimated biomass across the observed NDVI range when applied to Hung Thang commune (Supplementary Figure 1). These discrepancies are attributed to spatial mismatches between 10 × 10 m field plots and 30 × 30 m satellite pixels, NDVI saturation effects in high-biomass stands, and age- and structure-related variability within visually homogeneous plantations. The field-calibrated model developed in this study produced more conservative estimates aligned with the measured AGB, highlighting that local calibration reduces systematic bias even when the overall predictive power remains moderate.

Table 6 Policy recommendation with rationale and indicators/metrics

Policy area	Recommendation	Rationale	Indicator/Metric
NDC integration	Include mixed-species planting targets in Vietnam's NDC	Enhances ecological resilience and sequestration	≥60% *Aegiceras* & *Kandelia* in new projects
REDD+ standards	Adopt depth-adjusted SOC monitoring with LOI–TOC calibration	Improves SOC reporting accuracy	Calibration updated every 5 years
Carbon credit market	Price SOC as a separate carbon pool	Recognizes belowground carbon value	SOC credit baseline: USD 12 per tC

Data availability statement

Information and data used in the study will be disclosed upon request.

Author ORCID

Hla Phong Ko: 0009-0004-1395-5997
Pham Hong Tinh: 00009-0002-1293-253X
Nguyen Thuy Duong: 0000-0001-8580-4312

Author contributions

Hla Phong Ko: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – Original draft, Writing – Review & editing, Visualization, Funding acquisition
Pham Hong Tinh: Conceptualization, Methodology, Data curation, Writing – Review & editing, Supervision
Nguyen Thuy Duong: Conceptualization, Methodology, Data curation, Writing – Review & editing, Supervision, Funding acquisition

Conflicts of interest

The authors declare no competing financial or personal interests that could have appeared to influence the work reported in this paper.

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