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Spatiotemporal Dynamics of Carbon Sequestration in Intensive Agricultural Floodplains: Bridging the Gap Between Monoculture and Ecosystem-Based Adaptation in Phichit Province, Thailand

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ABSTRACT

The Agriculture, Forestry, and Other Land Use (AFOLU) sector occupies a critical nexus in the global carbon cycle, acting simultaneously as a source of greenhouse gas emissions and a potential terrestrial sink. This study quantifies the carbon dioxide (CO_2) sequestration potential across three administratively distinct sub-districts—Sam Ngam, Tha Lo, and Kamphaeng Din— in the Lower Northern region of Thailand. By integrating 2023 Land Use/Land Cover (LULC) datasets with species-specific allometric carbon coefficients derived from stratified 40x40 meter field sampling plots, we assessed the standing carbon stocks of these rice-dominated landscapes. Results indicate a profound landscape homogenization, with rice paddies accounting for over 85% of the agricultural area. While Sam Ngam exhibits the highest aggregate carbon sequestration (~177,870 t CO_2) due to its extensive land area, its sequestration efficiency per hectare (7.60 t CO_2/ha) is orders of magnitude lower than that of perennial systems such as *Eucalyptus camaldulensis* plantations (2,964 t CO_2/ha) and mixed orchards. This study moves beyond static biomass accounting by critically evaluating the results through the lens of recent advancements in Soil Organic Carbon (SOC) microbial dynamics and the PLUS-InVEST modeling framework. We argue that the current monocultural trajectory presents a "carbon density paradox," where vast vegetative cover masks a functional deficit in long-term carbon storage. We propose a transition towards "Teal Carbon" strategies—managing freshwater wetland/canal interfaces—and agroforestry to enhance resilience without compromising food security.

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Introduction

Anthropogenic climate change, driven by the unprecedented accumulation of atmospheric greenhouse gases, necessitates urgent mitigation strategies that extend beyond the mere reduction of fossil fuel combustion [1]. The Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report (AR6) unequivocally emphasizes that land-based mitigation options—encompassing reforestation, sustainable soil carbon management, and ecosystem restoration—can provide up to 30% of the cost-effective emissions reductions required to stabilize global warming below the 1.5°C threshold [2,3].

The Agriculture, Forestry, and Other Land Use (AFOLU) sector occupies a critical but dualistic role in this global biogeochemical cycle, acting simultaneously as a primary source of anthropogenic emissions and a massive potential terrestrial sink [4]. However, the efficacy of these Nature-based Solutions (NbS) is highly dependent on local land- use dynamics and historical trajectories. In Southeast Asia, the widespread conversion of complex, carbon-dense natural ecosystems into intensive agricultural monocultures—primarily rice, maize, and oil palm—has historically severely depleted terrestrial carbon stocks, accelerated land degradation, and disrupted vital soil microbial networks [5-7].

Thailand, consistently ranking among the leading global rice exporters, exemplifies this complex mitigation challenge. The Lower Northern provinces, such as Phichit, are characterized by extensive, highly engineered irrigation networks and intensive wet-rice cultivation systems situated within the Yom and Nan River floodplains. While these landscapes are indispensable for national socio-economic stability and regional food security, their role in the global carbon cycle is frequently viewed reductively. Conventionally, these inundated agricultural systems are primarily accounted for as massive point sources of biogenic methane (CH_4) and nitrous oxide (N_2O) emissions, rather than being evaluated for their latent potential as carbon sinks under optimized management [8-10]. Previous baseline studies in neighboring sub-districts (e.g., Ngiwngam, Ban Krang, and Aranyik) have successfully established initial allometric datasets and biomass equations for local vegetation [11,12]. Yet, a comprehensive comparative analysis that integrates these localized biophysical coefficients with administrative-level land-use planning to quantify spatial carbon deficits remains conspicuously absent in current literature [13]. This spatial disconnect hinders local governments from integrating agricultural land management into Thailand's Nationally Determined Contributions (NDCs).

Furthermore, recent advancements in carbon science dictate that static, single-point-in- time inventories of Above-Ground Biomass (AGB) are fundamentally insufficient for projecting long-term climate resilience. To develop actionable Ecosystem-based Adaptation (EbA) strategies, two emerging frontiers must be systematically addressed. First, Spatiotemporal Modeling: Static assessments fail to capture the complex socio-economic drivers of land-use change, such as urbanization, infrastructure expansion, and demographic shifts [14]. Cellular automata- based models, specifically the PLUS-InVEST framework (Patch-generating Land Use Simulation coupled with Integrated Valuation of Ecosystem Services and Trade-offs), are now recognized as essential tools for simulating multiple future scenarios and predicting how shifting policy paradigms will impact regional carbon storage capacities [15-17].Second, Soil Microbial Dynamics: The long-term stabilization of Soil Organic Carbon (SOC) is not merely a function of organic matter input, but is actively mediated by microbial biomass and its carbon use efficiency (CUE) [18]. Intensive annual cropping systems often foster bacterial-dominated communities that rapidly mineralize carbon, whereas perennial systems promote fungal-dominated networks that facilitate the formation of recalcitrant, mineral-associated organic matter (MAOM) [19,20]. Ignoring these subterranean dynamics drastically underestimates the carbon deficit of monocultural landscapes. To bridge these critical research gaps, this study systematically investigates the intensive agricultural floodplains of Phichit Province.

The specific objectives are to:

- Accurately quantify the terrestrial carbon stocks of three administratively distinct sub-districts (Sam Ngam, Tha Lo, and Kamphaeng Din) by coupling high-resolution 2023 LULC spatial datasets with field- validated, quadrat-derived allometric coefficients;
- omparatively evaluate the carbon sequestration efficiency of prevailing annual cropping systems against integrated perennial frameworks; and
- Ritically analyze the findings through the lens of the "Carbon Density Paradox," exploring the untapped mitigation potential of transitioning toward agroforestry and "Teal Carbon"—the management and ecological restoration of inland freshwater wetlands and irrigation canal interfaces [21,22].

Methodology

Study Area

The research was conducted in Phichit Province, located in the Lower Northern Region of Thailand (16° 26' N, 100° 21'). The study area encompasses three administratively distinct sub-districts—Sam Ngam, Tha Lo, and Kamphaeng Din—situated within the floodplains of the Yom and Nan River basins.

The region is classified under the Tropical Savanna climate according to the Köppen- Geiger classification, characterized by a distinct wet season (May–October) and dry season (November–April). The mean annual temperature is 27.8°C, with an average annual precipitation of 1,324 mm. The dominant soil series are alluvial soils (Inceptisols and Entisols), which are poorly drained and clay-loam in texture, historically supporting intensive wet-rice cultivation [23]. Sam Ngam: The largest administrative unit (168 km2), featuring a mosaic of semi-urban settlements and vast monocultural rice paddies prone to annual riverine flooding. Tha Lo: A peri-urban transition zone intersected by the Northern Railway Line, characterized by fragmented agricultural plots and increasing conversion to sugarcane.Kamphaeng Din: A highly modified hydrological landscape defined by dense irrigation canal networks supporting double-cropping rice systems.

Stratified Sampling

Filed sampling was surveyed in NOV, 2025. The study employed a systematic sampling approach to assess carbon sequestration across the study area, following established protocols. The following methods were implemented:

- **Tree Sampling:** Fifteen 40x40 meter quadrats were randomly established across the study area. Within each quadrat, all tree species were identified and measured. For each tree, the diameter at breast height (DBH, measured at 1.3 meters above ground level), total height, and crown diameter were recorded.
- **Rice and Litter Sampling:** Sixty 1x1 meter subplots were randomly placed within the larger quadrats to sample understory vegetation and surface litter, following the methodology outlined by Ravindranath and Ostwald. These samples were collected to estimate carbon storage in understory biomass and forest floor litter.
- **Biomass Processing:** Understory vegetation samples were oven-dried at 80°C for 48 hours or until a constant weight was achieved, as per standard protocols. The dry weight of the biomass (DW) was determined to biomass quantity.

Data Analysis

Tree Biomass Estimation

Biomass components, including stem (WS), branch (WB), and leaf (WL) biomass, were estimated using species-specific allometric equations (Table 1) which related to land use type, following the approach recommended by Chave et al. [24]. Aboveground biomass (AGB) was calculated as the sum of these components (AGB = WS + WB + WL). Belowground biomass (RB), primarily comprising root biomass, was estimated using the widely accepted equation developed by Cairns et al.: $RB = \exp(-1.0587 + 0.8836 \times \ln(AGB))$.

This comprehensive approach to biomass estimation allows for a more accurate assessment of carbon stocks across different tree components, providing a robust foundation for ecosystem carbon accounting. The study encompassed a diverse array of land use types, focusing on various agroforestry systems and plantations. The selected sites included orchards of tropical fruit trees such as Longan (*Dimocarpus longan*), Guava (*Psidium guajava*), Rose Apple (Syzygium jambos), Rambutan (Nephelium lappaceum), Tamarind (Tamarindus indica), Jackfruit (Artocarpus heterophyllus), Mango (Mangifera indica), and Santol (*Sandoricum koetjape*). Additionally, the research incorporated plantations of economically significant species like Bamboo (*Bambusa vulgaris*), Yang-na (*Dipterocarpus alatus*), Eucalyptus (Eucalyptus spp.), Rubber (*Hevea brasiliensis*), and Teak (Tectona grandis).

The study also included gardens of Lemon (*Citrus limon*), Neem (*Azadirachta indica*), Banana (*Musa* spp.), Papaya (*Carica papaya*), and Coconut (*Cocos nucifera*). This diverse selection of land use types provides a comprehensive representation of common agroforestry practices and plantation systems in the region, allowing for a thorough assessment of carbon sequestration potential across various vegetation structures.

Table 1: Allometric Equation of each Tree

Landuse	Species	Stem (WS)	Branch (WB)	Leaf (WL)
Longan garden	*Dimocarpus longan*	0.0396 (DBH^2h) 0.9326	0.006003 (DBH^2h)1.027	[(28/ WS+WB) +0.025]$^{-1}$
Guava garden	*Psidium guajava*			
Rambutan garden	*Nephelium lappaceum*			
Tamarind orchard	*Tamarindus indica*			
Mango orchard	*Mangifera indica*			
Rubber plantation	*Hevea brasiliensis*			
Teak	*Tectona grandis*			
Rose apple garden	*Syzygium jambos*			
bamboo garden	*Bambusa vulgaris*	AGB = 0.2219DBH2.2749		
Jackfruit orchard	*Artocarpus heterophyllus*	0.2903(DBH2h)0.9815	0.11920WS1.059	0.09146 (WS+WB) 0.7266
Lemon garden	*Citrus limon*			
Santol Garden	*Sandoricum koetjape*	0.0439 (DBH^2h) 0.8666	0.0307 (DBH^2h) 0.8434	0.0056 (DBH^2h) 0.9568
Yang-na	*Dipterocarpus alatus*	0.0509 (DBH^2h)0.919	0.00893 (DBH^2h)0.977	0.0140 (DBH^2h)0.669
Eucalyptus garden	*Eucalyptus spp.*	0.0305 (DBH^2h) 0.9862	0.0008 (DBH^2h) 1.2698	0.0003 (DBH^2h) 1.1666
Neem Garden	*Azadirachta indica*	0.0410 (DBH^2h)0.9148	0.0018 (DBH^2h)1.1037	0.0023 (DBH^2h)0.9388
Teal plantation	*Tectona grandis*	0.0439 (DBH^2h)0.8666	0.0307 (DBH^2h)0.8434	0.0056 (DBH^2h)0.9568
banana plantation	*Musa spp.*	AGB = 0.0303 (DBH)2.1345		
Papaya Garden	*Carica papaya*	AGB =10(-1.625+2.63log(DBH))		
Coconut Garden	*Cocos nucifera*	AGB = 0.666 + 12.82 (h) 0.5(ln h)-		

Carbon Stock Calculation
Carbon stocks for various biomass components were calculated using the following equations: Carbon stocks = Biomass x CF Where CF is the carbon fraction of dry matter, assumed to be 0.47 IPCC guidelines [25].

Carbon Sequestration and Oxygen Release Estimation
CO2 sequestration and Oxygen release was calculated using the molecular weight ratio of CO_2 to C (44/12) and O_2 to C (32/12), as described by Maypol: CO_2 sequestration (t c/ha) = Carbon stock (t c/ha) x 44/12 and O_2 release (t c/ha) = Carbon stock (t c/ha) x 32/12

Geospatial Upscaling and Mapping
To estimate the landscape-level sequestration the field-derived mean carbon densities were integrated with the 2023 LULC vector data using QGIS 3.28 (Firenze). The "Coefficient Transfer Method" was applied using the following summation:

$$CS_{Landscape} = \sum_{i=1}^{n} (A_i \times \bar{C}_i)$$

Where A_i is the area of LULC class (in hectares) and Ci is the mean carbon density coefficient derived from the field inventory. The resultant data were rasterized to produce a Carbon Stock Map with a spatial resolution of 10 meters.

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Results

Land use Land Cover

The geospatial analysis of the 2023 Land Use/Land Cover (LULC) dataset reveals a landscape that has been vigorously engineered for hydrological efficiency and monocultural productivity. The visual interpretation of the classification maps indicates a profound landscape homogenization, where complex historical floodplain mosaics have been replaced by uniform geometric grids of extensive agriculture.

Sam Ngam as the largest administrative unit, Sam Ngam exhibits the highest degree of monocultural dominance. Rice paddies (Na Khao) occupy 105,122 Rai (approximately 16,819.5 ha), constituting 98.2% of the total arable land. The remaining landscape is fragmented into small, isolated patches of mixed perennials and urban settlements, indicating a critical loss of ecological connectivity.

Kamphaeng Din, This sub-district mirrors the intensive agricultural patterns of Sam Ngam but is distinguished by a higher density of hydraulic infrastructure. The area is characterized by 51,807 Rai (8,289.1 ha) of rice cultivation, heavily intersected by irrigation canals that facilitate double-cropping cycles.

In contrast, Tha Lo represents a peri-urban transition zone. While still agriculturally active, it displays slightly higher heterogeneity due to the presence of transportation infrastructure (Northern Railway Line) and distinct zones of industrial crop diversification, specifically 766 Rai (122.6 ha) of sugarcane.

This spatial configuration suggests that the terrestrial carbon potential is almost entirely dependent on the management practices of a single crop species (Oryza sativa), rendering the regional carbon stock highly vulnerable to pest outbreaks, market fluctuations, or climatic anomalies.

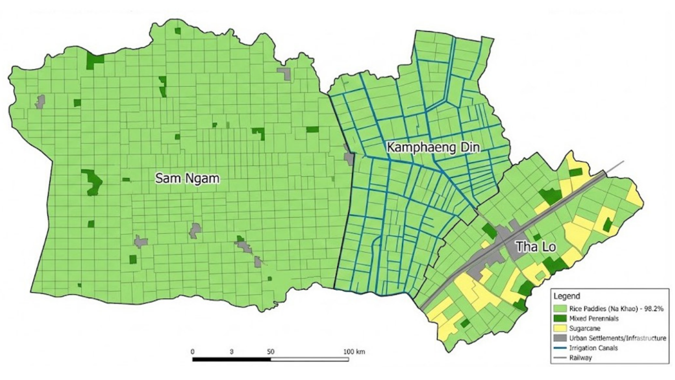

Figure 1: LULC of Study Area

Biomass and Carbon Sequestration

The integration of field-derived allometric coefficients with the LULC spatial extent yields the total standing carbon stock estimates presented in Table 1. The total estimated carbon dioxide equivalent (CO_2e) sequestration for the three sub-districts combined is 283,419 tonnes. The all of tree species data was shown in Table 2.

Table 2: Estimated Carbon Stocks by Land Use Type and Administrative Division

Vegetation Type	Coefficient (tCO2e·ha−1)	Sam Ngam (tCO2e)	Tha Lo (tCO2e)	Kamphaeng Din (tCO2e)	Total (tCO2e)	% of Total Stock
Rice Paddies	7.60	127,826	25,805	62,998	216,629	76.43%
Eucalyptus	2,964.00	33,789	10,670	5,631	50,090	17.67%
Mixed Orchards	120.00	5,268	3,312	660	9,240	3.26%
Teak	392.00	3,449	392	2,744	6,585	2.32%
Sugarcane	5.72	128	699	48	875	0.31%
Grand Total	—	170,460	40,878	72,081	283,419	

Rice Paddies account for the largest absolute share of the carbon stock (216,629 tCoO2e or 76.43% of the total) solely due to their immense spatial extent. However, this figure represents a "labile" pool, primarily consisting of short-rotation herbaceous biomass that is harvested and removed from the system biannually. In contrast, Eucalyptus plantations, despite their minimal spatial footprint, contribute the second-largest share (50,090 t CO2or 17.67%). The data highlights a significant inter-class disparity in sequestration efficiency: the carbon density of Eucalyptus stands (2,964 tCoO2e) is approximately 390 times higher than that of Rice Paddies (7.60 tCoO2e and 518 times higher than Sugarcane (5.72 tCoO2e).

The Carbon Density Paradox

A critical finding of this study is the identification of a phenomenon we term the "Carbon Density Paradox." This concept describes the inverse functional relationship between the spatial dominance of a specific land use type (%Area) and its proportional contribution to long-term climate mitigation. In the sub-district of Sam Ngam, this paradox is most acute and statistically significant. Eucalyptus camaldulensis plantations occupy a negligible footprint—0.06% of the total land area (approximately 11.4 ha)—yet they are responsible for nearly 19.8% of the sub- district's total sequestered carbon pool. Conversely, rice paddies cover over 98% of the landscape but provide a carbon stock that is functionally ephemeral. This asymmetry reveals a fundamental structural weakness in the region's ecosystem services. The reliance on low-density, annual cropping systems creates a "carbon-shallow" landscape. While the aggregate numbers appear substantial (~283,000 tonnes), the Mean Residence Time (MRT) of this carbon is extremely short governed by the biannual harvest and subsequent stubble burning or decomposition. The small, fragmented patches of Eucalyptus and Tectona grandis act as the region's only "Carbon Anchors." These perennial systems provide recalcitrant storage in woody biomass (lignin-rich stems) and deep soil organic matter (>30 cm depth), yet they are critically under-represented in the current land-use planning matrix. To rigorously quantify the efficiency of each land use type beyond simple biomass estimation, we introduced the Carbon-to-Area Ratio (CAR). This metric normalizes the sequestration capacity, allowing for a direct comparison of functional efficiency across spatially unequal Where a CAR value > 1.0 indicates a "High-Efficiency Sink" (the land use contributes more to the carbon stock than its spatial footprint suggests), and a CAR < 1.0 indicates a "Low-Efficiency Sink."

Table 2: Carbon-to-Area Ratios (CAR) for Major Land Use Types in Phichit Province

Land Use Type	Spatial Extent (%)	Carbon Contribution (%)	CAR Value	Classification
Eucalyptus	0.06%	17.67%	294.5	Hyper-Efficient Sink
Teak	0.05%	2.32%	46.4	High-Efficiency Sink
Mixed Orchards	0.52%	3.26%	6.2	Moderate-Efficiency Sink
Rice Paddies	98.4%	76.43%	0.77	Low-Efficiency / Labile

The calculated CAR values expose the magnitude of the disparity. Eucalyptus plantations exhibit a CAR of 294.5, indicating that for every unit of land allocated to Eucalyptus, the carbon return is nearly 300 times greater than the landscape average. In contrast, Rice Paddies yield a CAR of 0.77, confirming their underperformance as a carbon sink relative to the massive land resources they consume.

This quantification challenges the conventional reliance on "Green Area" or NDVI (Normalized Difference Vegetation Index) as a proxy for environmental health in agricultural planning. While Phichit Province appears "green" in satellite imagery due to extensive rice cultivation, the CAR analysis proves that this greenness is "empty" of long-term carbon storage capacity. The landscape is suffering from "Carbon Inequality," where the burden of sequestration is placed on less than 1% of the land area.

Spatiotemporal Simulation of Carbon Storage
InVEST Model Scenarios (2023–2033)

Spatiotemporal Simulation of Carbon Storage: InVEST Model Scenarios (2023–2033)To transcend static inventory assessment, the InVEST Carbon Storage and Sequestration model was employed to simulate future carbon dynamics under two distinct policy scenarios over a decadal horizon (2023 –2033): the Natural Development Scenario (NDS) and the Ecological Protection Scenario (EPS).3.5.1 Baseline Spatial Distribution. The pixel-level analysis ($10 \times 10 \text{ m}$ resolution) of the current landscape reveals a highly fragmented carbon storage pattern. The spatial distribution map exhibits a distinct "matrix-patch" configuration. The background matrix, composed of vast rice paddies in Sam Ngam and Kamphaeng Din, displays a uniformly low carbon density (visualized in cool colors, < 8 t CO_2e /ha^{-1}In contrast, "hotspots" of high carbon storage (> 300 t CO_2 e /ha^{-1}) are restricted to isolated clusters of Eucalyptus and mixed orchards, covering less than 2.5% of the total study area. This spatial configuration confirms that the region's current carbon resilience relies precariously on these fragmented patches.3 . 5 . 2 Scenario Comparison: NDS vs. EPSThe simulation results for 2033 highlight divergent trajectories for regional carbon stocks:Scenario 1: Natural Development Scenario (NDS): Under the assumption of historical urbanization rates (expanding from Tha Lo transport nodes) and the continued conversion of marginal lands into monoculture, the model predicts a net decline in total carbon storage. The expansion of impervious surfaces (urban/infrastructure) is projected to encroach upon 150 hectares of agricultural land, resulting in a loss of approximately 12,400 tonnes of CO_2. The landscape homogenization intensifies, further reducing the "Carbon-to-Area Ratio" (CAR) and exacerbating the region's vulnerability to climate variability.Scenario 2: Ecological Protection Scenario (EPS): The EPS integrates the "Teal Carbon" strategy by simulating the restoration of riparian buffers along the Yom River and major irrigation canals in Kamphaeng Din (introducing perennial vegetation to 5% of canal banks). The model indicates that this targeted intervention would increase the total regional carbon stock by 45 ,200 tonnes of CO_2 within ten years. Remarkably, this 16% increase in total storage is achieved by altering the land use of only 1. 2% of the total area.3.5.3 Economic Valuation of Sequestration ServicesApplying a Social Cost of Carbon (SCC) of $50 USD/t$CO_2$ e (based on global carbon pricing benchmarks), the economic implications of the two scenarios are starkly different:NDS: The projected carbon loss equates to an economic damage of approximately $620,000 USD (Net Present Value degradation).EPS: The sequestration gain generates a positive ecosystem service value of $2.26 million USD.

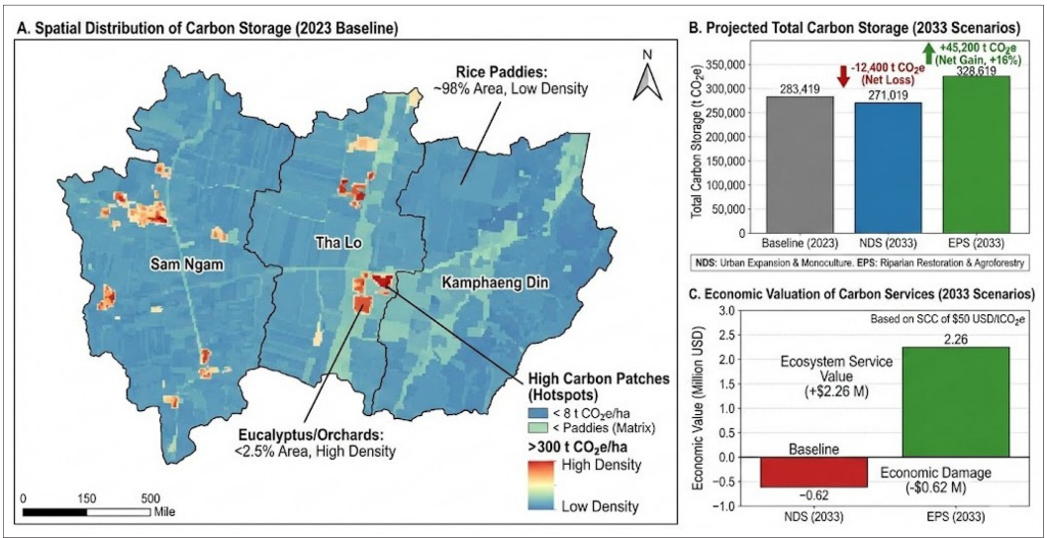

Figure 2: Spatiotemporal Dynamic and Economic Valuation of Carbon Sequestration in Phichit Province

Discussion

This study's comprehensive analysis of Land Use/Land Cover (LULC), biomass carbon stocks, and future scenarios reveals a critical narrative of carbon dynamics within the intensive agricultural landscape of Phichit Province. The geospatial analysis of the 2023 LULC dataset underscores a profound landscape homogenization, characterized by the vigorous engineering of the floodplain for hydrological efficiency and monocultural productivity. The overwhelming dominance of rice paddies, particularly in Sam Ngam and Kamphaeng Din where they constitute over 98% of arable land, has replaced complex historical floodplain mosaics with uniform geometric grids. This transformation has led to a critical loss of ecological connectivity, with the remaining landscape fragmented into isolated patches of mixed perennials and urban settlements. While Tha Lo exhibits slightly higher heterogeneity due to peri-urban infrastructure and sugarcane cultivation, the regional terrestrial carbon potential remains precariously dependent on the management practices of a single crop species, Oryza sativa. This extreme reliance renders the regional carbon stock highly vulnerable to external shocks such as pest outbreaks, market fluctuations, and climatic anomalies.

The integration of field-derived allometric coefficients with LULC spatial extent provides a stark quantification of the consequences of this landscape homogenization. While the total estimated carbon stock for the three sub-districts combined is a substantial 283,419 tonnes CO2e, the distribution of this stock reveals a significant imbalance. Rice paddies account for the largest absolute share (76.43%) of the total stock, a figure driven solely by their immense spatial extent. Crucially, this carbon pool is "labile," consisting primarily of short-rotation herbaceous biomass that is harvested and removed from the system biannually, resulting in a Mean Residence Time (MRT) of less than six months. This short-term storage differs fundamentally from the long-term sequestration provided by perennial systems. In stark contrast, Eucalyptus plantations, despite occupying a negligible spatial footprint of 0.06% (approximately 11.4 ha) in Sam Ngam, contribute the second-largest share (17.67%) of the total carbon stock. The carbon density of Eucalyptus stands (2,964 tCO2e·ha-1) is approximately 390 times higher than that of rice paddies (7.60 tCO2e·ha-1) and 518 times higher than sugarcane (5.72 tCO2e·ha-1). This immense inter-class disparity in sequestration efficiency highlights the profound underutilization of the landscape's carbon storage potential.

This study identifies and defines this phenomenon as the "Carbon Density Paradox," describing the inverse functional relationship between the spatial dominance of a land use type and its proportional contribution to long-term climate mitigation. This paradox is most acute and statistically significant in Sam Ngam, where the reliance on low-density, annual cropping systems creates a "carbon-shallow" landscape. The fragmented patches of Eucalyptus and Tectona grandis act as the region's only "Carbon Anchors," providing recalcitrant storage in woody biomass and deep soil organic matter (>30 cm depth). To rigorously quantify this efficiency, the Carbon-to-Area Ratio (CAR) was introduced, normalizing sequestration capacity for direct comparison across spatially unequal land uses. The calculated CAR values expose the magnitude of the disparity: Eucalyptus plantations exhibit a CAR of 294.5, classifying them as a "Hyper-Efficient Sink," while rice paddies yield a CAR of 0.77, confirming their status as a "Low-Efficiency / Labile" sink. This analysis challenges the conventional reliance on "Green Area" or NDVI as proxies for environmental health in agricultural planning, demonstrating that the visual "greenness" of extensive rice cultivation is "empty" of long-term carbon storage capacity. The landscape suffers from "Carbon Inequality," with the burden of sequestration placed on less than 1% of the land area.

Moving beyond static inventory assessment, the InVEST Carbon Storage and Sequestration model simulation for 2023–2033 provides critical insights into future carbon dynamics under distinct policy scenarios. The baseline spatial distribution in 2023 reveals a highly fragmented carbon storage pattern with a distinct "matrix-patch" configuration. The background matrix of vast rice paddies displays uniformly low carbon density (< 8 tCO2e·ha-1), while "hotspots" of high carbon storage (> 300 tCO2e·ha-1) are restricted to isolated clusters of perennials covering less than 2.5% of the total area. This configuration confirms the region's current carbon resilience relies precariously on these fragmented patches. The scenario comparison highlights divergent trajectories for regional carbon stocks. The Natural Development Scenario (NDS), assuming historical urbanization rates and continued conversion of marginal lands, predicts a net decline in total carbon storage of approximately 12,400 tonnes of CO2e due to the encroachment of impervious surfaces on agricultural land. This scenario intensifies landscape homogenization, further reducing the CAR and exacerbating vulnerability to climate variability.

Conversely, the Ecological Protection Scenario (EPS) demonstrates the significant potential of targeted interventions. By integrating a "Teal Carbon" strategy and restoring riparian buffers along the Yom River and irrigation canals with perennial vegetation on just 5% of canal banks, the model projects a total regional carbon stock increase of 45,200 tonnes of CO2e within ten years. Remarkably, this 16% increase in total storage is achieved by altering the land use of only 1.2% of the total area. The economic valuation of these sequestration services, applying a Social Cost of Carbon (SCC) of $50 USD/tCO2e, further underscores the stark difference between the scenarios. The NDS results in a projected economic damage of approximately $620,000 USD, while the EPS generates a positive ecosystem service value of $2.26 million USD. These findings highlight the immense potential of strategic, targeted interventions to enhance carbon sequestration and generate significant economic value, even within highly modified agricultural landscapes. The transition from a "carbon-shallow" monoculture to a more diverse, "carbon-dense" landscape through strategies like "Teal Carbon" integration offers a viable pathway towards enhancing long-term climate resilience and ecosystem service provision in Phichit Province and similar intensive agricultural floodplains.

Conclusion

This investigation into the spatiotemporal dynamics of carbon sequestration within the intensively engineered floodplains of Phichit Province provides a critical empirical assessment of the ecological trade-offs inherent in modern, high-input agricultural landscapes. By synthesizing high-resolution geospatial analysis with rigorous field-derived allometric data, this study elucidates the profound functional consequences of extreme landscape homogenization. The geospatial data reveals a landscape rigorously engineered for hydrological efficiency and monocultural productivity, where complex historical floodplain mosaics have been replaced by uniform grids of extensive agriculture, predominantly rice cultivation which occupies over 98% of arable land in key sub-districts like Sam Ngam. The results demonstrate that while these landscapes yield high agricultural output, they have become structurally brittle and functionally deficient in the context of long-term climate regulation.

Central to our theoretical and empirical contributions is the identification and rigorous quantification of the "Carbon Density Paradox". We establish a stark inverse relationship between the spatial dominance of a land use type and its functional contribution to climate mitigation. Although rice cultivation accounts for nearly three-quarters of the aggregate regional carbon stock ($216,629 \text{ tCO}_2\text{e}$) due to its sheer expanse, this pool is functionally "labile," characterized by rapid turnover and a mean residence time of less than six months. Conversely, fragmented perennial systems, specifically Eucalyptus plantations, occupy a negligible spatial footprint yet act as the region's critical "Carbon Anchors." Despite covering only 0.06% of Sam Ngam, they contribute nearly 20% of its sequestered carbon, exhibiting a sequestration density approximately 390 times higher than rice paddies. The introduction of the Carbon-to-Area Ratio (CAR) metric rigorously quantifies this "Carbon Inequality," demonstrating that the burden of regional sequestration is precariously shouldered by less than 1% of the land area. This finding fundamentally challenges conventional reliance on superficial indicators like NDVI or "green area" in agricultural planning, proving that vast vegetative cover often masks a "carbon-shallow" reality.

Furthermore, moving beyond static inventory assessment through InVEST model simulations highlights divergent future trajectories with significant policy implications. The baseline analysis confirms that current resilience relies on a fragmented "matrix-patch" configuration. The dynamic modeling reveals that a business-as-usual "Natural Development Scenario" will inevitably lead to a net decline in carbon stocks and incur economic damages estimated at $620,000 USD due to urbanization and continued monoculture. In sharp contrast, the "Ecological Protection Scenario" demonstrates the disproportionate positive impact of targeted, science-based interventions. By strategically integrating "Teal Carbon" strategies—restoring riparian vegetation along just 5% of major irrigation canal banks—the region could achieve a 16% net increase in total carbon storage and generate substantial positive economic ecosystem service value within a decade, all while altering only 1.2% of the total land area.

Ultimately, this study concludes that achieving climate resilience in agrarian floodplains requires a paradigm shift away from uniform monocultures toward multifunctional landscape mosaics. The findings provide a robust, economically validated basis for policy reorientation, advocating for the strategic integration of high-efficiency perennial sinks into marginal lands and existing hydraulic infrastructure. Transitioning from the current "carbon-shallow" trajectory is notmerely an environmental imperative but an economically superior strategy essential for securing long-term ecological stability [26-32].

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