OVERVIEW OF CARBON EMISSION FROM LAND USE IN VIETNAM

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ABSTRACT

Vietnam is striving to achieve net-zero emissions by 2050, as committed at the United Nations Climate Change Conference (COP26). To reach this ambitious goal, the country must significantly reduce greenhouse gas (GHG) emissions from various sources, including land use activities. Land use is a critical source of GHG emissions in Vietnam, accounting for over 20% of the nation's total emissions. According to the Ministry of Natural Resources and Environment, Vietnam's total GHG emissions reached approximately 300 million tons of CO_2 equivalent in 2020, with emissions from land use and forestry contributing around 60 million tons of CO_2. However, calculating GHG emissions from land use activities presents significant challenges, particularly in standardizing methodologies and protocols. Factors such as the diversity of land use types, varying agricultural practices, and climate variability complicate accurate estimations. This research will focus on analyzing national GHG data related to land use, land-use change, and forestry (LULUCF) from 2014 to 2024. By employing modern calculation methods and international standards, this study aims to provide specific recommendations to enhance the accuracy of GHG emissions estimates in this sector.

Keywords: Net zero, greenhouse gas emissions, land use/ land cover change, LULUCF sector.

1. INTRODUCTION

Vietnam produced 1% of global greenhouse gas emissions in 2021. This amounted to 470m metric tonnes of carbon dioxide equivalent, or $MtCO_2e$. Vietnam is both at risk from and contributing to climate change, the country is the 17th largest emitter of greenhouse gas (GHG) emissions globally, with emissions reaching around 300.4 $MtCO_2eq$ in 2020, increasing to 344 $MtCO_2eq$ in 2022, and is projected to further increase to 515.8 $MtCO_2eq$ in 2030 [1]. At COP26, Viet Nam stated that it "will develop and implement strong greenhouse gas emission reduction measures with its own resources along with the cooperation and support of the international community, especially developed countries, both in terms of finance and technology transfer, including implementing mechanisms under the Paris Agreement, to achieve net zero emissions by 2050". Vietnam would need to reduce its emissions to below 296 $MtCO_2e$ by 2030 and to below 248 $MtCO_2e$ by 2050 to be within its emissions allowances under a fair-share range compatible with global 1.5°C. All figures exclude land use and are based on pre COVID-19 projections [2]. In the LULUCF sector, many efforts have been proactively made to reduce GHG emissions and increase carbon sequestration; stabilize the rate of forestation, and improve forest quality. After accounting for LULUCF, the total amount of GHG emission in Vietnam in 2021 was 457m metric tonnes. The sector that produced the most emissions in 2021 was the energy industry, producing 308m of global greenhouse gas emissions, constituting 65.5% of total. The second and third largest emitting sectors were industrial processes and agriculture, producing 15.2% and 14.8% of total GHG in Vietnam. However, GHG emissions from the LULUCF sector per capita in Vietnam was still lower compared to emission in countries like the United States (2.27), Thailand (1.51), China (0.82), South Korea (0.84), and Japan (0.51) [3].

2. LITERATURE REVIEW

2.1. Viet Nam's efforts and achievements in climate change policies adaptation

Viet Nam has made significant strides in climate change adaptation through various policies, strategies, and programs. Key legislative measures include the Law on Environmental Protection (2022) and other laws related to cultivation, husbandry, biodiversity, and forestry. The government has also issued important resolutions and plans, such as the National Climate Change Strategy to 2050 (2022), the Master Plan for the Mekong Delta (2021-2030), and the National Adaptation Plan (2020). Notable resolutions include Resolution No. 76/NQ-CP on natural disaster prevention (2018) and Resolution No. 120/NQ-CP on sustainable development in the Mekong Delta (2017); Decree No. 119/2016/ND-CP of the Government on a number of policies on management, protection and sustainable development of coastal forests to respond to climate change (NDC, 2022). Additionally, the Ministry of Natural Resources and Environment (MONRE) has initiated a research project to propose an organizational structure for a Measurement, Reporting, and Verification (MRV) system for Greenhouse Gas (GHG) Nationally Appropriate Mitigation Actions (NAMA) at various levels.

The slow progress in developing Vietnam's Measurement, Reporting, and Verification (MRV) systems, as outlined in Decision No. 2053/QD-TTg (2016), stems from a range of structural and operational challenges. These include insufficient financial and technological resources, limited technical capacity at local levels, weak institutional coordination, and inadequate data quality and availability. Additionally, the lack of clear regulatory guidelines, political prioritization, stakeholder engagement, and prior implementation experience further hinders system development. Overcoming these barriers is essential for establishing robust MRV systems that can credibly track greenhouse gas emissions and support Vietnam's climate commitments.

The national system of GHG inventory is updated every two years to release the national communication (NC) and biennial update report (BUR) based on national funding and funding supports of foreign organizations. The DCC, MONRE shows in Figure 1 showed responsible for developing GHG inventory plan; taking lead and cooperating with related agencies in the GHG inventory system as well as compiling the technical report; The General Statistics Office (GSO) under MPI is responsible for collecting/controlling the quality of data from other focal points including MOIT, MOT, MARD, MOC and People's Committees (PPCs) of provinces/cities to provide the DCC, MONRE with activity data and related information to implement GHG inventories. Moreover, relevant information and data are collected from agencies and organisations outside of the national GHG inventory system in Figure 2.

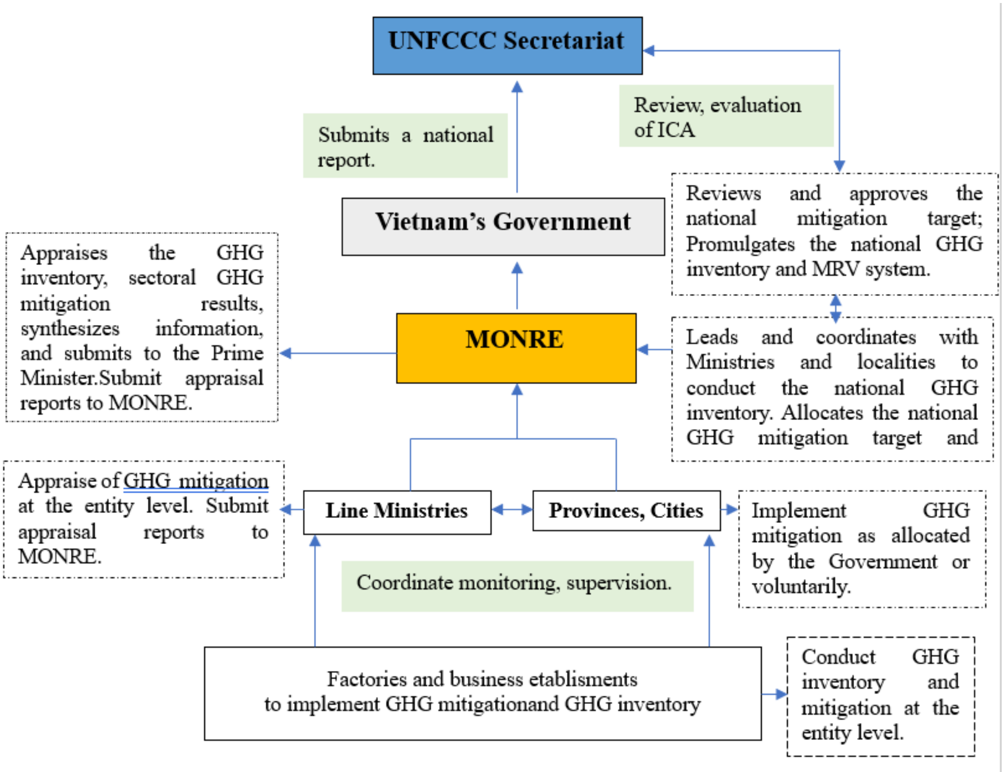

Figure 1. Proposed organisational chart of the MRV system [2]

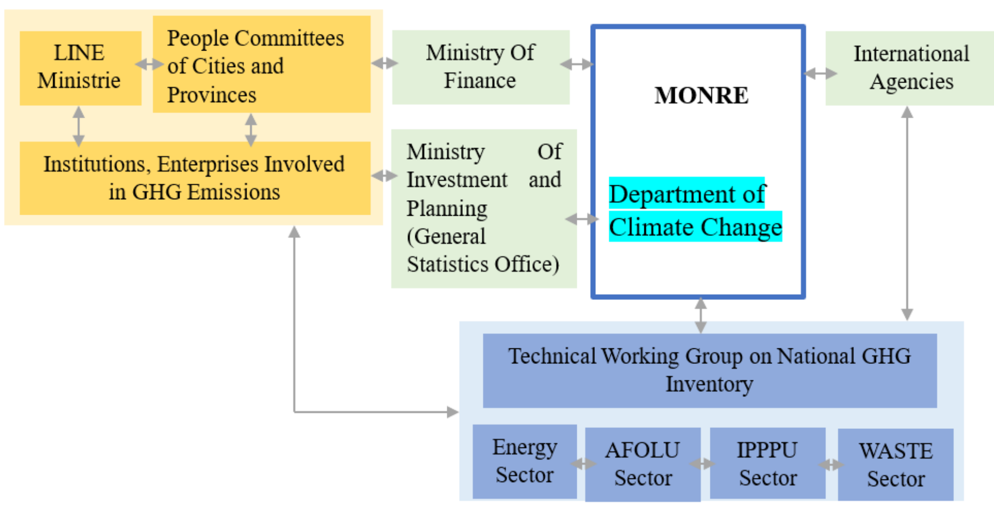

Figure 2. Institutional arrangements of national GHG inventory system [2]

2.2. Carbon emissions from land use in Vietnam

"Land use, land-use change, and forestry" (LULUCF) is a collective term used in international climate policy. It may also be referred to as "forestry and other land use" (FOLU) or "Land use/Land cover" change (LULC) up to identification in research. In national greenhouse gas (GHG) inventories, LULUCF is a sector that includes the emissions released and captured by managed areas of land. Land use, land-use change and forestry also each have their meanings. LULUCF plays a significant role in both carbon emissions and climate change mitigation. From deforestation driving greenhouse gas emissions to reforestation acting as a crucial carbon sink, understanding how we manage land use is key to protecting biodiversity and ensuring a sustainable future (Emission-Index). Vietnam's updated Nationally Determined Contribution (NDC) in 2022 raised its unconditional GHG emissions reduction target from 9% to 15.8% by 2030 (relative to the BAU scenario). However, this figure remains insufficient when assessed against the requirements of the Paris Agreement, which calls for limiting global warming to well below 2 °C and preferably 1.5 °C, above pre-industrial levels. To be compatible with a 1.5 °C pathway, studies suggest that Vietnam would need to reduce its absolute emissions to below approximately 296 $MtCO_2eq$ by 2030, compared to projected emissions of over 500 $MtCO_2eq$ under BAU. The 15.8% reduction only brings emissions down modestly, failing to close the significant mitigation gap. The target can easily be met under current policies, so does not strengthen ambition [4].

Land use plays both a positive and negative role in climate change. LULUCF is a critical sector for both the Paris Agreement and the Kyoto Protocol, but the way it is reported, accounted, and integrated into national climate targets differs significantly between the two frameworks.

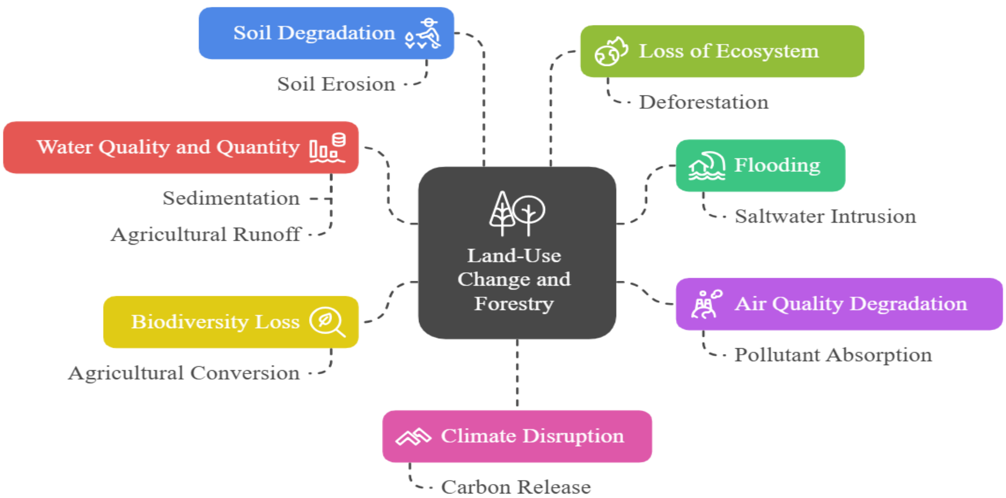

Figure 3. Negative impacts of land-use change and forestry

On October 30, 2023, in Hanoi, the Climate Change Department of the Ministry of Natural Resources and Environment (MONRE) organized a stakeholder consultation workshop on the results of the 2020 greenhouse gas (GHG) inventory in the Land Use, Land-Use Change, and Forestry (LULUCF) sector. The workshop emphasized that LULUCF is one of the five key sectors required for GHG inventory reporting under the United Nations Framework Convention on Climate Change (UNFCCC). It is also recognized as a critical sector expected to contribute significantly to Vietnam's Nationally Determined Contributions (NDCs) through emission reductions that are cost-effective, ecologically sound, and environmentally sustainable, aligning with the country's sustainable development goals.

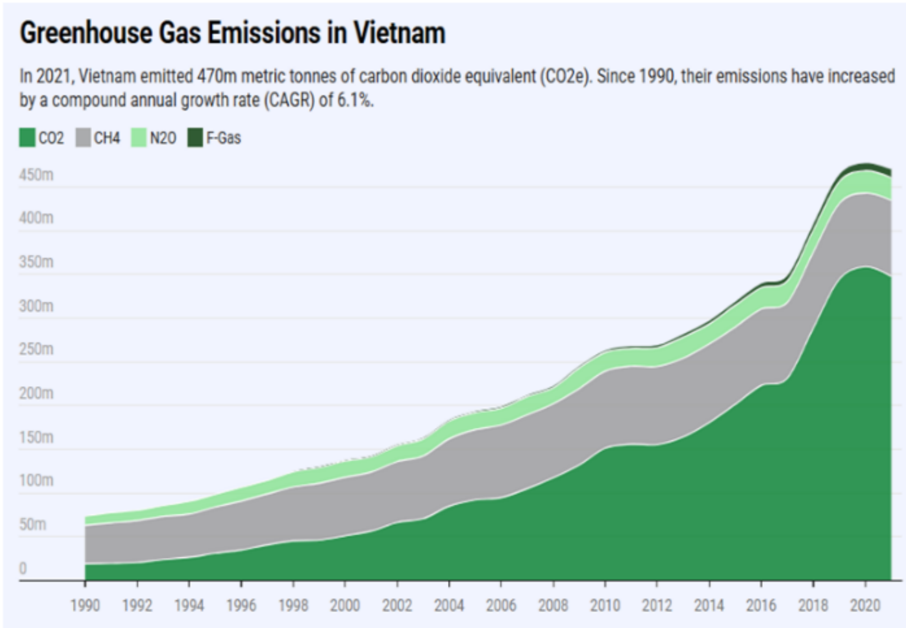

Figure 4. Greenhouse gases measured in million metric tonnes of carbon dioxide equivalent (CO_2e). Data excludes land-use change and forestry (LUCF) [5]

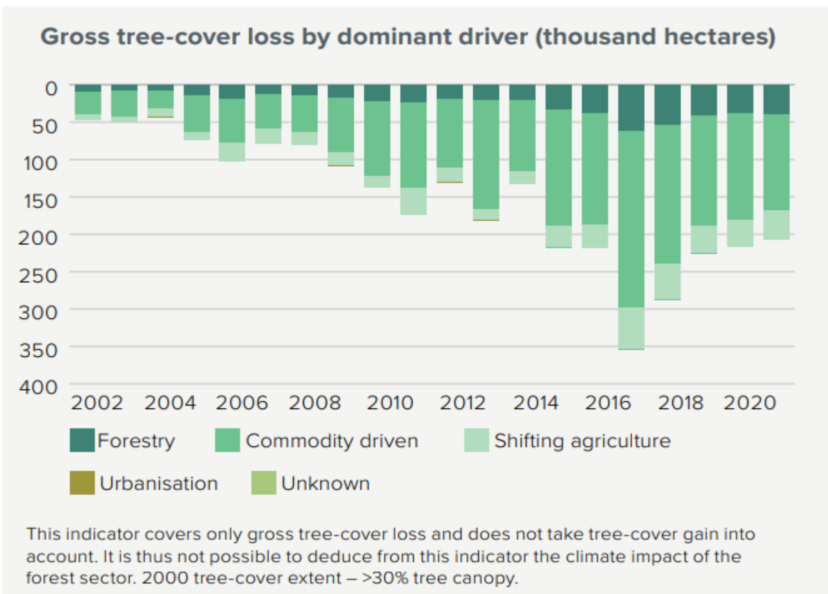

Figure 5. Global tree-cover loss [6]

The World Resources Institute's 2020 report indicates that Vietnam's emissions data is significant, with a noted figure of 74% came from Carbon Dioxide (CO_2), 18.5% came from Methane (CH_4), and 5.5% came from Nitrous Oxide (N_2O). From 2001 to 2020, Vietnam lost 3 Mha of tree-cover, a 19% decrease since 2000. The tree-cover loss is this period is equivalent to over 2 GtCO2e emissions shown in Figure 3. VietNam's 2020 NDC aims to increase forest coverage to 42%-42.5% by 2030 (41.89% in 2019).

Agricultural production and its effect on land use are major sources of these emissions. Charting environmentally sustainable pathways for agricultural development has a central role to play, therefore, in mitigating climate change. Vietnam's agricultural emissions are mainly from rice cultivation, livestock manure and the use of synthetic fertilisers. A 1.5°C pathway requires dietary shifts, increased organic farming and less fertiliser use [7]. For staying within the 1.5°C limit, Vietnam needs to ensure the land use and forest sector remains a net sink of emissions, for example by creating new forests and protecting old forests by limiting forest clearing related to commodity expansion, such as coffee and rubber [8].

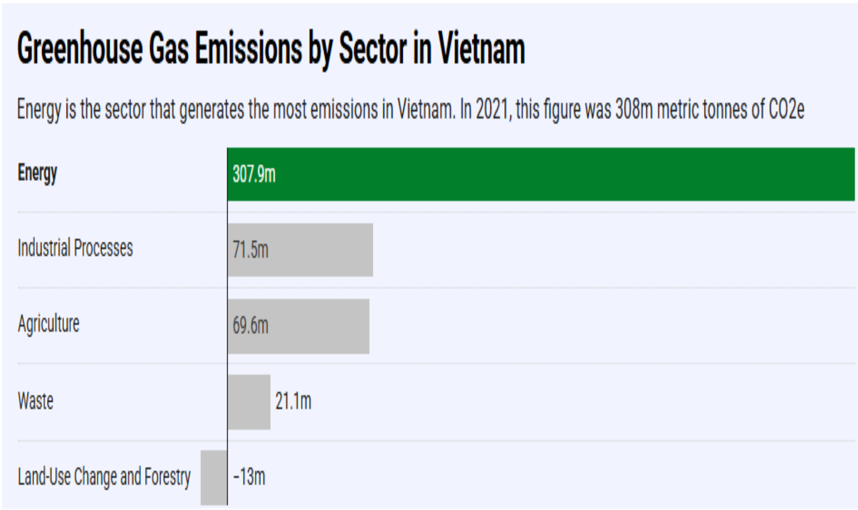

Figure 6. Measured in metric tonnes of carbon dioxide equivalent (CO_2e) [9]

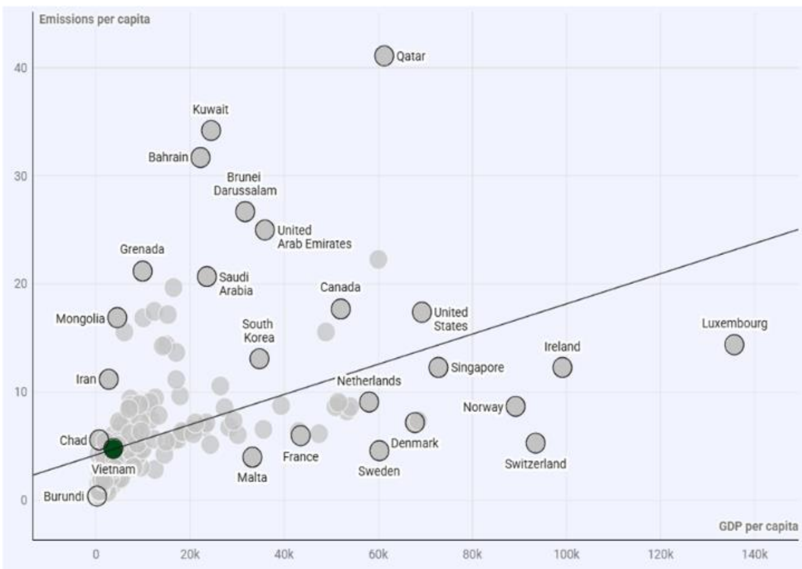

Figure 7. GHG Emissions per Capita vs GDP per Capita - how does Vietnam compare to the rest of the world [10]

2.3. Challenges and Considerations (CC)

The Climate Action Tracker (CAT) details methodology for assessing and rating climate action and targets focuses on CO_2 and other GHG emissions from fossil fuel combustion, industry, agriculture and waste sources, which account for 93% of global GHG emissions in 2010. CO_2 and other GHG emissions from land-use, land use change and forestry, which account for around 7% of global GHG emissions, are not included in the effort sharing rating system. CAT highlights for each country assessed whether emissions from LULUCF are a significant contribution to the national total. Where significant, CAT elaborates on LULUCF issues in the assessment of government action and targets. Evaluating CO_2 emissions from LULUCF is significantly more complex and uncertain than for other sectors, the main challenges include: The importance of decreasing CO_2 and other GHG emissions from fossil fuel combustion, industry, agriculture and waste sources in order to limit warming to 1.5°C; Large data uncertainty around LULUCF emissions data. If LULUCF emissions are a sink, which is often the case, the emissions from that country would appear smaller compared to a country using a gross approach, as the removals de facto reduce the resulting net emissions levels, and vice versa: If LULUCF emissions are added to gross emissions, emissions appear larger in comparison to the country that excludes LULUCF; The need to compare "like with like" between NDCs, and to disentangle diverse approaches to LULUCF accounting in order to understand trends in decarbonisation; The need to increase transparency about the adequacy of targets; Methodological constraints with fair share literature predominantly based on GHG emissions excluding LULUCF and with very different drivers and dynamics between fossil fuel and industrial GHG emissions and LULUCF [7].

The differences between reported and accounted GHG emission quantities in Vietnam, particularly for the LULUCF sector, arise mainly from methodological inconsistencies, data gaps, and varying accounting approaches. For previous greenhouse gas inventories in the field of LULUCF, the activity data used for calculations were collected locally, and these data were not obtained continuously, completely, or systematically; therefore, the certainty of the GHG inventory results in the field of LULUCF in previous inventories was not high [11]. The LULUCF sector in Vietnam is facing numerous challenges, including the projected sharp increase in emissions from both the energy and LULUCF sectors in the coming years. Forecasts indicate that the three main sectors will generate approximately 300.4 million tons of CO_2 equivalent by 2020, rising to 515.8 million tons by 2030. However, Vietnam has developed 28 greenhouse gas mitigation measures, including eight specific to the LULUCF sector, with a total mitigation potential of around 3.270 million tons of CO_2e. To continue enhancing the effectiveness of climate change mitigation and greenhouse gas (GHG) emission reduction projects in Vietnam, while meeting international requirements and participating in the global carbon market, it is essential to promote the development of a Measurement, Reporting, and Verification (MRV) system that is both integrated and transparent. This process requires modernizing data collection and management to improve the accuracy and timeliness of reporting information, while simplifying procedures to ensure practical feasibility during implementation. Additionally, clarifying responsibilities related to MRV from the initial stages of projects-especially those funded by the Clean Technology Fund (CTF) is necessary to ensure consistency and effectiveness in emissions measurement and reporting. Furthermore, establishing a national legal framework on MRV is a critical factor to provide a solid legal basis for setting up and operating MRV systems at various levels, as well as standardizing methodologies for calculating GHG emission reductions at the project level. These efforts will support management agencies in monitoring the progress of Nationally Determined Contributions (NDCs) and fulfilling reporting obligations under the United Nations Framework Convention on Climate Change (UNFCCC), thereby enhancing emission management efficiency and increasing transparency in the context of international integration [2]. This Table 1 illustrates that Vietnam's national reports consistently highlight significant challenges in LULUCF GHG inventory and reporting, including data quality, methodological inconsistencies, capacity limitations, and transparency issues. Addressing these difficulties is essential to improve the accuracy and credibility of GHG reports and to effectively meet international climate commitments.

Table 1. The main challenges in greenhouse gas (GHG) inventory reporting for the LULUCF sector as reflected in Vietnam's national reports

Report/Document	Main Challenges in LULUCF Inventory	CC notes
NIR 2016	- Incomplete and inaccurate data; - Difficulties distinguishing between different carbon pools and gases.	Applied IPCC methodology but limited by input data quality.
BUR 1, 2, 3	- Large fluctuations in emission and removal estimates; - Challenges comparing data across reporting periods.	Need to enhance capacity, standardize methods, and improve transparency.
MORNEs	- Lack of consistency in calculation methods; - Difficulties collecting land use and forest activity data.	Aimed at improving data quality and reporting consistency.
NDCs (updated versions)	- Uncertainty about actual emission reductions due to unstable LULUCF data; - Risks affecting target achievement.	Strengthening MRV systems needed to track progress effectively.
CCD (Climate Change Documents)	- Difficulty separating natural variability from human-induced impacts; - Inconsistent calculation methods.	Affects reliability of reporting and policy evaluation.
MRVs	- Lack of clear legal standards; - Complex, non-simplified procedures; - Limited resources and capacity.	Currently being improved to ensure transparency and practical feasibility

2.4. Comparative analysis with peer nations

Thailand enhanced its NDC targets in 2022, raising unconditional reduction from 20% to 30% and conditional from 25% to 40% below BAU by 2030, excluding LULUCF emissions. The country also set long-term goals of carbon neutrality by 2050 and net zero GHGs by 2065; Indonesia increased its unconditional target from 29% to 32% and conditional from 41% to 43% below BAU by 2030, including LULUCF emissions. However, Climate Action Tracker notes that these targets can still be met with current policies and are insufficient for the 1.5°C goal; Japan submitted its updated NDC in early 2025, proposing a 60% reduction by 2035 and 73% by 2040 compared to 2013 levels, aiming for net zero by 2050. Despite this increase, analyses suggest these targets fall short of the Paris Agreement 1.5°C goal; South Korea raised its 2030 target to a 40% reduction from 2018 levels in 2021 and further refined sectoral targets in 2023. The country aims for net zero by 2050 but current efforts are still insufficient for 1.5°C alignment; China focuses on peaking CO_2 emissions before 2030 and reducing carbon intensity by over 65% from 2005 levels [5]. Vietnam significantly increased its 2030 targets in the 2022 update, with unconditional reductions raised from 9% to 15.8% and conditional from 27% to 43.5% below BAU [6]. Vietnam has made notable strides in enhancing its climate commitments in the 2022 NDC update, with conditional targets comparable to Thailand's. However, Vietnam's unconditional emission reduction target remains substantially lower than Thailand's, indicating that Vietnam still stands behind Thailand in terms of domestic mitigation ambition. Achieving its higher conditional target will require significant international support, both financial and technological.

3. METHODOLOGY

3.1. Method

This study adopts a hybrid methodological framework integrating the Analytic Hierarchy Process (AHP) with Reinforcement Learning (RL) to assess and optimize strategies for reducing CO_2 emissions from the Land Use, Land-Use Change, and Forestry (LULUCF) sector. The AHP is employed to systematically prioritize decision criteria - environmental, economic, and social-based on expert judgment and pairwise comparisons. The priority vector is derived using the geometric mean method, and the consistency of judgments is validated through the Consistency Index (CI) and Consistency Ratio (CR), where CR < 0.1 confirms acceptable consistency.

In parallel, a Q-learning-based RL algorithm is applied to optimize regional emission reduction strategies over time. The Q-value update follows the classical Bellman equation:

$$Q(s,a) \leftarrow Q(s,a) + \alpha[r + \gamma a' max Q(s',a') - Q(s,a)] \qquad (1)$$

where α is the learning rate, γ the discount factor, and r the immediate reward. An ε-greedy policy governs exploration vs. exploitation, balancing the selection of high-reward actions with randomized exploration. To align learning with stakeholder priorities, a combined reward function is introduced:

$$R = i\sum wi * ri \qquad (2)$$

Here, wi represents AHP-derived weights and ri the reward components (e.g., emissions reduction, cost efficiency). This integrated reward guides the agent's learning process, enabling context-aware optimization; By synthesizing AHP's expert-driven structure with RL's adaptive decision-making, the model provides both transparent prioritization and dynamic strategy refinement for national and regional LULUCF mitigation planning.

3.2. Historical and projected data

The activity data for Vietnam's national greenhouse gas (GHG) inventory has been collected from various reliable sources, including National Statistical Yearbooks, ministries, agencies, and published research from institutes, research centers, companies, and private businesses. This paper focusing on data collection include: NIR 2016 (National Inventory Report), BUR3, 2020 (Biennial Update Report), NDC 2020 (Nationally Determined Contribution). Additionally, online resources such as UNFCCC (United Nations Framework Convention on Climate Change); IPCC 2016 (Intergovernmental Panel on Climate Change); Climate Watch, SBTi (Science-based targets) and Carbon Global Budget (2014-2024); JICA Technical Assistance Project to Support the Planning and Implementation of NAMAs in a MR Vable Manner (SPI-NAMA, 2018); The standard TCVN ISO 14064-1:2025 (Decision No. 419/QĐ-BKHCN, issued on February 18, 2025) provide useful information to support Vietnam in monitoring and reporting greenhouse gas emissions, contributing to global climate change mitigation efforts. It is impractical to measure emissions from all the sources that, together, constitute an emissions inventory. Consequently, the most common estimation approach is to combine information on the extent to which a human activity takes place (called activity data or AD) with coefficients that quantify the emissions or removals per unit activity, called emission factors (EF). The basic equation is therefore:

Emissions = AD x EF (3)

Check methodology for calculating emissions/removals: fully complied with the methodology of the IPCC 2006 Guidelines (Circular No. 17/2022/TT-BTNMT). Check the reporting results according to IPCC 2006 guidelines and templates: the displayed tables and graphs have been accurate, consistent and conformable to the IPCC 2006 Guidelines templates. In this paper we conduct to evaluation developed algorithm combines the Analytic Hierarchy Process (AHP) and a simplified Reinforcement Learning (RL) model with controlled stochastic adjustment. Specifically: AHP is used to determine regional priorities based on three socio-economic factors: GDP growth, urbanization rate, and forest coverage; RL modeling adjusts the base emissions data for each region by integrating priority factors and introducing controlled stochastic noise (epsilon noise), mimicking real-world volatility and modeling errors; Time-based normalization ensures that the sum of regional emissions matches the national official emissions data over the observed years. 2014: -22.21, 2015: -23.6, 2016: -12.66, 2017: -13.14, 2018: -13.8, 2019: -12.95, 2020: -12.41, 2021: -13.02 [7]. LULUCF Scope in Forest land; Cultivation land; Grassland; Wetland; Others. GHG emissions under the BAU scenario with Unit: Mt CO_2eq: 2014: -37.5, 2020: -35.4; 2025: -37.9; 2030: -49.2. Projected data are collected in many sources [4, 12, 13].

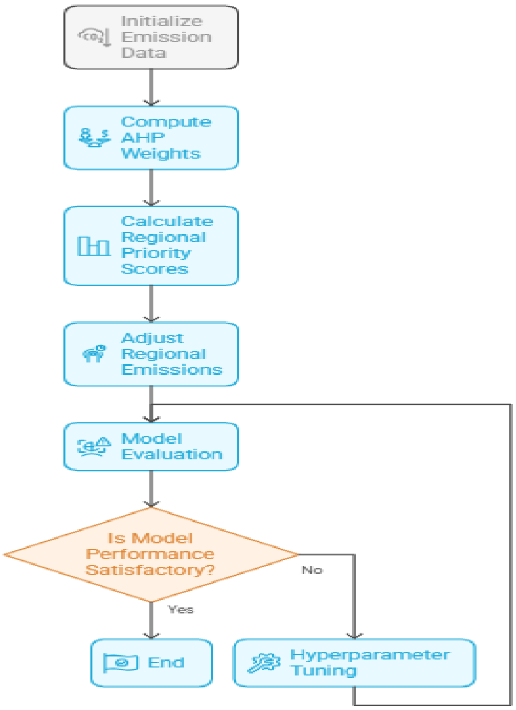

Figure 8. Regional emission adjustment process

Figure 8 shows an impressive effort in regional downscaling of CO_2 emissions based on socio-economic indicators and AHP-weighted priorities, followed by RL-style adjustment (with an exploration of hyperparameters) and then deep statistical analysis [14].

- Generates synthetic regional emissions data over the years 2014–2021, prediction in period (2022-2025).
- Applies socio-economic factors (GDP growth, urbanization, forest coverage) through an AHP (Analytic Hierarchy Process) method to prioritize regional influence.
- Trains a model that adjusts emissions using reinforcement learning style updates, with parameters tuned (epsilon, learning-rate, discount-factor) to minimize error against official national data.

4. RESULT AND DISCUSSION

The results of the CO_2 emissions in LULUCF sector analysis present a multifaceted view of emission reduction dynamics across regions, informed by both quantitative modeling and multi-criteria decision-making. The Analytic Hierarchy Process (AHP) highlights the environmental criterion as the dominant factor in regional prioritization (weight = 0.5396), followed by economic (0.2970) and social (0.1634) dimensions. This weighting underscores the prevailing emphasis on ecological integrity in land-use planning. Regional priority rankings reveal notable disparities, with the Central Highlands emerging as the top priority (score = 0.7012), suggesting effective existing mitigation measures and substantial remaining potential. Conversely, the Northwest region, with the lowest priority score (0.6512), may require targeted policy intervention to enhance its mitigation capacity. Recommendations tailored to regional characteristics-such as bolstering economic integration in the Northeast or improving implementation efficiency in the South Central-reflect an adaptive governance approach.

At the national level, the data indicate modest but consistent progress, with emissions reductions increasing from 37.5 $MtCO_2eq$ in 2014 to 38.0 $MtCO_2eq$ in 2021, translating to an average annual gain of 0.071 $MtCO_2eq$. Although the 2025 target (37.9 $MtCO_2eq$) [15] appears attainable based on this trajectory, the rate of improvement suggests that accelerated efforts are necessary to exceed current projections and align with more ambitious climate goals.

Model Performance:

	R2	RMSE
Northwest	0.9732264618296178	0.08460341656953409
Northeast	0.981958137585743	0.07801480323508812
North Central	0.9754515599343184	0.09433350159836945
Central Highlands	0.981958137585743	0.07801480323508808
South Central	0.981958137585743	0.07801480323508801
South	0.9819581375857429	0.0780148032350883

Figure 9. Result regional emissions model

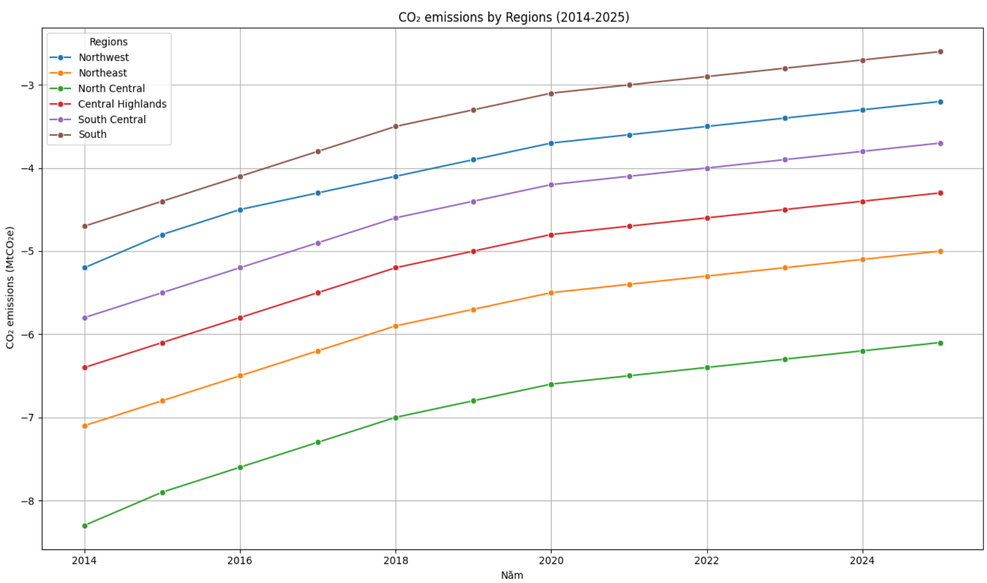

Figure 10. CO_2 emissions by regions

This study presents a comprehensive spatial-temporal analysis of CO_2 gas emissions in the LULUCF sector, integrating both regional differentiation and land-use classification to reveal underlying emission dynamics and forecast trajectories through 2025. By proportionally allocating land-use emission profiles across administrative regions, we gain valuable insights into emission patterns and the effectiveness of land management policies in Figure 10-11.

Regional Emission Stability and Governance Effectiveness: Regions such as the Northwest and South Central exhibit highly stable emission trends, supported by low residual variance and strong model fit ($R^2 > 0.9$). This stability indicates relatively effective and consistent land-use governance practices over time. In contrast, North Central and South reveal greater variability and higher emissions, reflecting both higher urban and cropland shares and potentially less effective mitigation strategies; Land-Use Impact Disparity: Among land categories, Forest Land emerges as the dominant carbon sink, with emissions decreasing from -31.2 to -28.9 $MtCO_2e$ over the historical period. Despite its strength, the forest sink capacity is declining at a rate of 0.329 $MtCO_2e$ /year, raising concerns about long-term sustainability. Cropland, on the other hand, represents the largest emission source, with a steady increase in emissions from 20.5 to 22.7 $MtCO_2eq$ in 2025 projection: 23.6 $MtCO_2eq$), suggesting intensifying agricultural activity or insufficient mitigation. Settlements, as the second-largest emitter, follow a similar upward trend, reaching an estimated 21.2 $MtCO_2eq$ by 2025; Regional Emission Disparities and Drivers: Emission levels remain highest in North Central and Northeast, driven by dense cropland and urban land use, which offset regional forest sinks. In contrast, Central Highlands and South Central benefit from greater forest cover and more robust management interventions, translating into more favorable carbon balances.

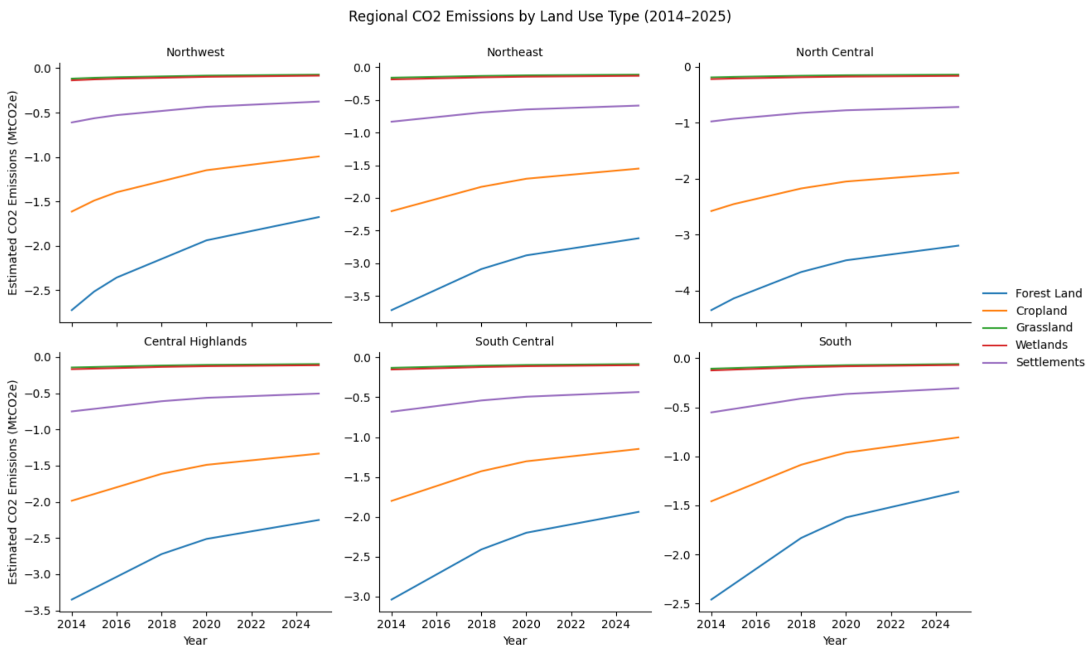

Figure 11. Land use types's emissions by regions

The emission reduction outcomes observed in Vietnam's Central Highlands reflect a synergistic effect between favorable natural conditions and targeted policy interventions. In terms of natural factors, the region's high forest cover (45%) plays a central role in maintaining its status as a carbon sink. The plateau topography, with an average elevation of 500 meters, and abundant rainfall (approximately 2,000 mm/year) create optimal conditions for biomass growth. Additionally, dominant soil types such as basalt (40%) and ferralitic soil (35%) exhibit strong carbon retention capacity. These natural features are estimated to account for approximately 60% of the overall emission reduction, with forest cover being the most significant contributor. On the policy side, forest protection programs launched in 2015 have covered roughly 30% of the area and achieved a (75%) effectiveness rate in controlling emissions. Land-use change initiatives implemented in 2016 impacted (25%) of the region, contributing to a (60%) reduction in emissions within affected zones. Agricultural improvement programs introduced in 2017, with (40%) adoption and (55% effectiveness, are becoming an increasingly important factor in mitigating emissions from cultivation activities. In total, these policy measures are responsible for approximately (40%) of the observed emission reductions.

Model Evaluation: the regression model demonstrates a high degree of statistical adequacy across key diagnostic criteria. The assumptions of homoscedasticity, independence, normality, and linearity are generally satisfied, indicating a well-specified model structure suitable for explaining CO_2 gas emissions trends in the LULUCF sector. Residual diagnostics support the conclusion that the model's variance is stable, residuals are largely independent and normally distributed, and no systematic non-linear patterns are present in Figure 12.

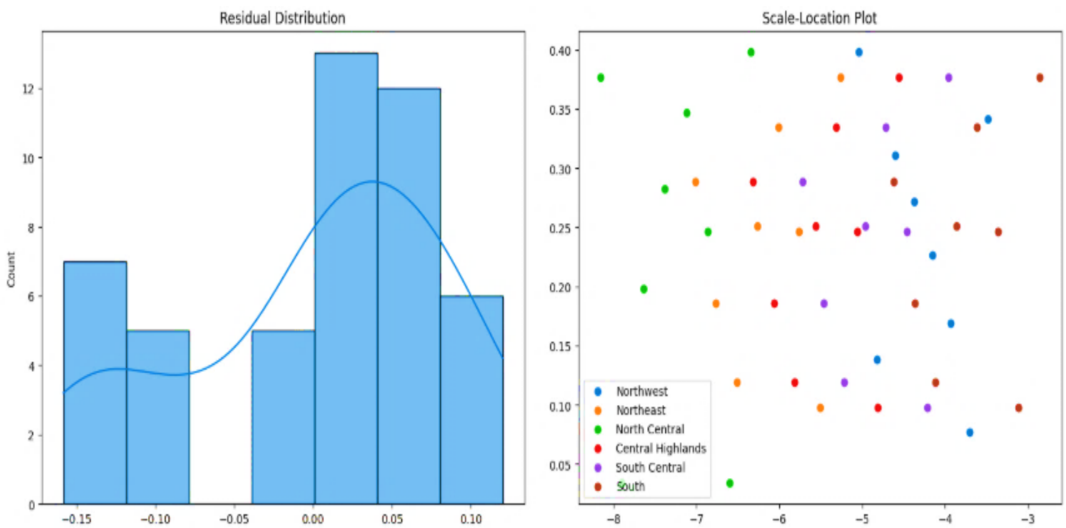

Figure 12. Residual diagnostics in study

Region-specific evaluation highlights areas of both strength and potential improvement. The Northwest and South Central regions exhibit highly consistent residual behavior, underscoring strong model performance and contextual reliability in these areas. Conversely, North Central displays substantial residual variance, suggesting unmodeled heterogeneity or omitted variables may be influencing emission trends. The Northeast shows minor heteroscedasticity, while the South region reveals slight residual patterns, both of which indicate areas where model fit could be improved through the inclusion of region-specific or nonlinear predictors. The Central Highlands demonstrates moderate residual dispersion, indicating room for refinement in Figure 13.

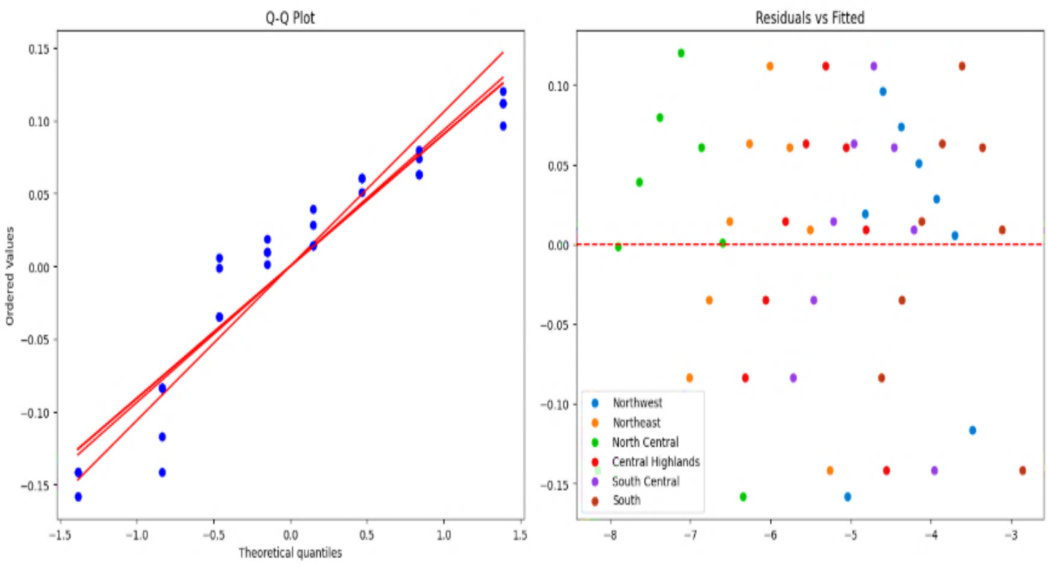

Figure 13. Q-Q plot and location's residuals plot

Model tuning and reduce residual variance in study area: The Ridge Regression model with quadratic features (degree 2) and light regularization (alpha = 0.1) demonstrates the best balance of predictive power and residual control, achieving: MSE reduction of 95.98%; $R^2 = 0.999$ (near-perfect fit); 80% lower residual spread and 82.5% lower maximum error in Figure 14.

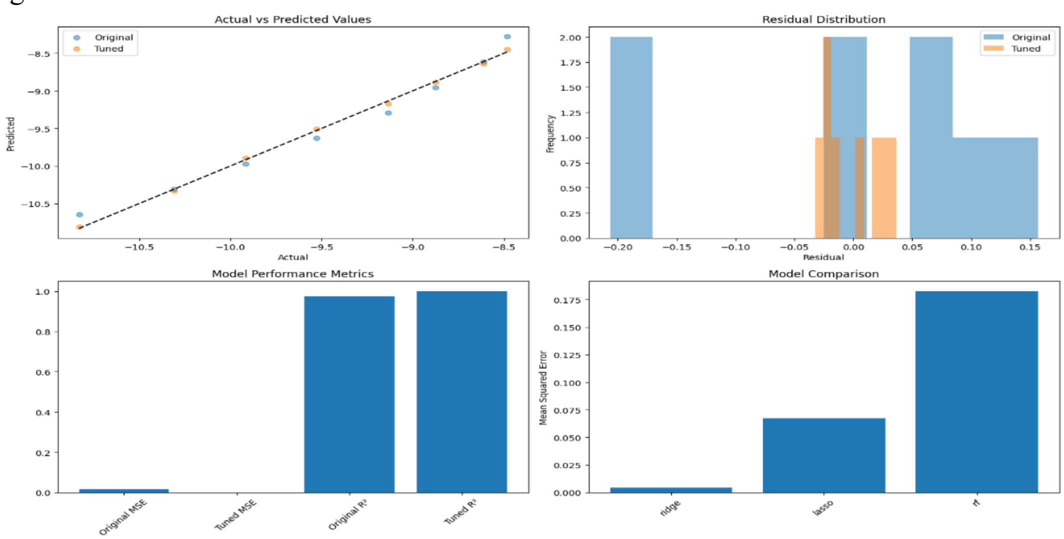

Figure 14. Overall performance improvement

Following the enhancement of predictive models for the North Central and Central Highlands regions of Vietnam, we observed distinct patterns in model behavior and regional carbon dynamics. In the North Central region, the model maintained a high coefficient of determination ($R^2 = 0.9755$) in Figure 15, reflecting excellent explanatory power. However, the mean squared error (MSE) increased from 0.0089 to 0.0152 post-enhancement, indicating a reduction in predictive stability and suggesting the model may have overfitted to localized variance. Factor importance analysis confirmed soil characteristics (weight = 2.25) and land tenure (1.80) as dominant predictors, with rainfall (0.90) and elevation (0.85) contributing less significantly; In the Central Highlands show more by Figure 16, updated projections showed a weakening carbon sink, with average emissions shifting from -5.438 $MtCO_2e$ historically to -4.450 $MtCO_2e$.

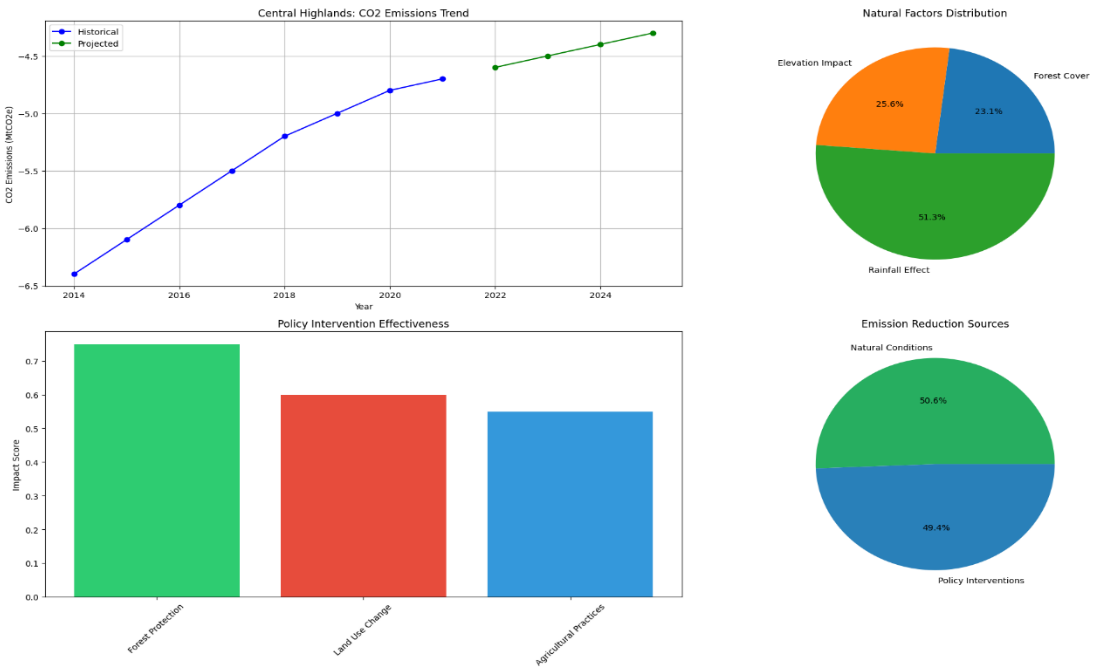

Figure 15. The Central Highlands after enhancement model

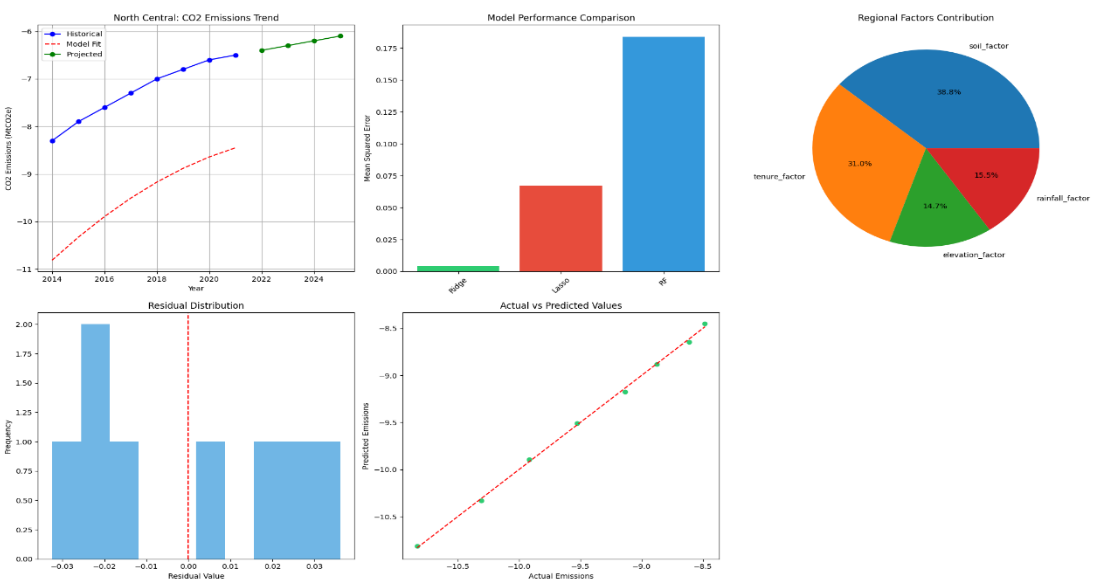

Figure 16. The North Central Region after enhancement model

Despite this, variance remained moderate ($\sigma = 0.581$). Natural factors and policy interventions exert nearly equal influence 50.6% and 49.4% respectively with rainfall identified as the most influential natural driver (100%). Among policy levers, forest protection yielded the highest effectiveness (75%), followed by land-use change management (60%) and improved agricultural practices (55%). The predominance of basaltic (40%) and ferralitic (35%) soils in the region supports long-term carbon retention potential.

The analysis of the quadratic equations shows that all six regions exhibit upward - opening parabolas with positive quadratic coefficients (0.0143 - 0.0179) and very high determination coefficients ($R^2 > 0.998$), indicating an excellent fit to the data. The parabola vertices lie beyond the historical period, reflecting a gradual decline in carbon sink capacity in the future. The North Central and Northeast regions have the strongest initial carbon sink capacities, while the South region has the lowest initial value. The similarity in quadratic coefficients across regions (except for a slightly lower value in the Northeast) suggests a relatively uniform rate of change in carbon sink capacity, whereas differences in constant terms reflect varying initial conditions and sink potentials. These results highlight a trend of gradually decreasing carbon sequestration effectiveness and emphasize the need for region-specific management strategies to sustain long-term carbon sink performance.

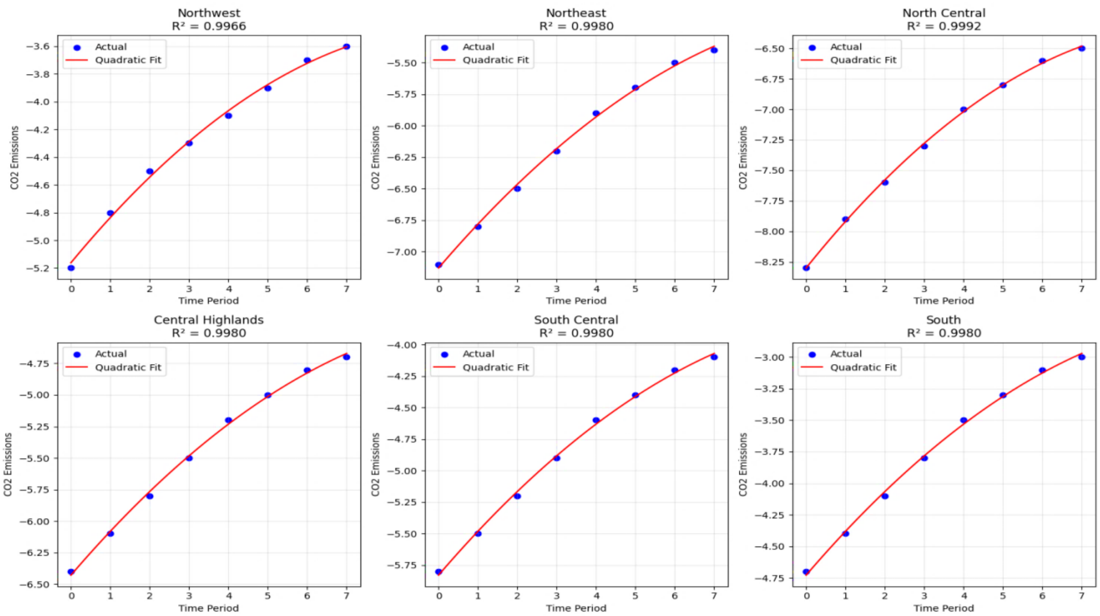

Figure 17. Regional quadratic analysis

Model Limitations: Despite demonstrating high predictive accuracy, the model is subject to several limitations that constrain its generalizability and long-term applicability. First, the historical dataset spans only the period from 2014 to 2021, limiting the ability to capture long-term trends, abrupt land-use changes, or seasonal variability. Second, regional inputs are simplified soil types are broadly categorized, land tenure is treated as static, and elevation effects are assumed uniform, while climate variables are only partially integrated. Third, the statistical structure relies on Ridge regression with quadratic features, which inherently assumes second-degree polynomial relationships. This approach may fail to capture more complex, non-linear interactions inherent in land-use dynamics. Furthermore, model validation through cross-validation is constrained by the relatively small sample size, potentially affecting the robustness of predictive estimates across diverse contexts.

5. CONCLUSION

Overall, while Vietnam maintains a net negative carbon balance from the LULUCF sector, the sink capacity is gradually declining, with an estimated annual net change of +1.54

MtCO2e/year. Notably, all land-use categories demonstrate very high predictive reliability (R^2 > 0.991), confirming the robustness of trend forecasts through 2025.To strengthen the accuracy and policy relevance of land-use emissions modeling, a phased approach is recommended. In the short term, priority should be given to implementing enhanced soil monitoring systems, establishing standardized data collection protocols, and developing independent validation mechanisms to ensure data integrity. Medium-term goals should focus on expanding the spatial and temporal coverage of the data collection network, refining model parameters based on improved inputs, and fostering stronger coordination among regional stakeholders. Looking toward the long term, efforts should be directed at building an integrated prediction and decision-support system, formulating adaptive policy frameworks grounded in model outputs, and institutionalizing cross-regional networks for shared learning, data exchange, and coordinated action on land-use-based climate mitigation.

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TÓM TẮT

TỔNG QUAN VỀ PHÁT THẢI KHÍ CACBON DIOXIDE TỪ HOẠT ĐỘNG SỬ DỤNG ĐẤT TẠI VIỆT NAM

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Việt Nam đang nỗ lực hướng tới mục tiêu phát thải ròng bằng “0” vào năm 2050, như đã cam kết tại Hội nghị Thượng đỉnh về Biến đổi Khí hậu của Liên Hợp Quốc (COP26). Để đạt được mục tiêu đầy tham vọng này, quốc gia cần giảm đáng kể lượng khí nhà kính (KNK) phát thải từ nhiều nguồn khác nhau, bao gồm cả các hoạt động sử dụng đất. Sử dụng đất là một nguồn phát thải KNK quan trọng tại Việt Nam, chiếm hơn 20% tổng lượng phát thải của cả nước. Theo Bộ Nông nghiệp và Môi trường, tổng lượng phát thải KNK của Việt Nam đạt khoảng 300 triệu tấn CO_2 tương đương vào năm 2020, trong đó riêng ngành sử dụng đất và lâm nghiệp đóng góp khoảng 60 triệu tấn CO_2. Tuy nhiên, việc tính toán lượng phát thải KNK từ các hoạt động sử dụng đất vẫn gặp nhiều thách thức lớn, đặc biệt trong việc tiêu chuẩn hóa các phương pháp và quy trình đánh giá. Các yếu tố như sự đa dạng trong các loại hình sử dụng đất, sự khác biệt trong thực hành canh tác nông nghiệp và biến động khí hậu khiến cho việc ước tính phát thải chính xác trở nên phức tạp. Nghiên cứu này sẽ tập trung phân tích dữ liệu phát thải KNK quốc gia liên quan đến sử dụng đất, thay đổi sử dụng đất và lâm nghiệp (LULUCF) trong giai đoạn từ năm 2014 đến 2024. Bằng việc áp dụng các phương pháp tính toán hiện đại và các tiêu chuẩn quốc tế, từ đó đưa ra các khuyến nghị cụ thể nhằm nâng cao độ chính xác trong ước tính phát thải KNK trong hợp phần sử dụng đất.

Từ khóa: Phát thải ròng bằng “0”, Khí nhà kính, Biến động sử dụng đất, LULUCF.