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Land Expansion, Fertilizer Use, and Agricultural Greenhouse Gas Emissions in ASEAN: A Dynamic Panel ARDL Analysis

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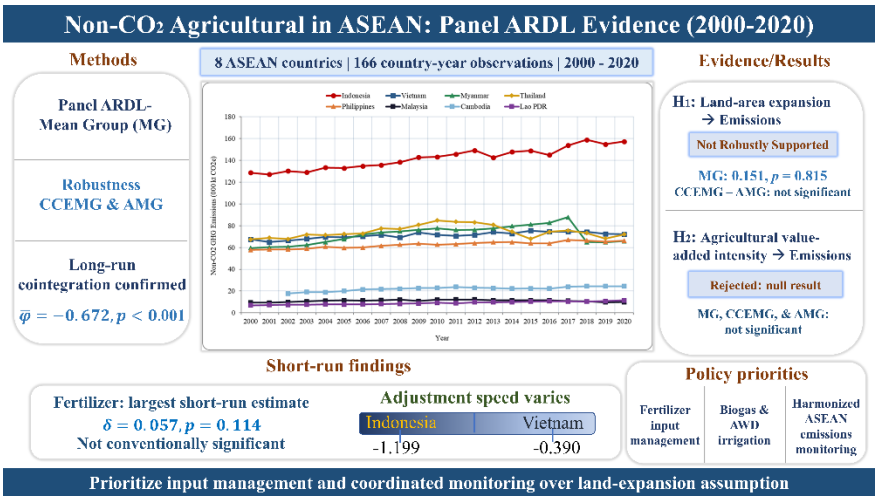
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ABSTRACT



The agricultural sector of the Association of Southeast Asian Nations (ASEAN) was identified as a significant yet under-researched source of non-CO_2 greenhouse gases, nitrous oxide (N_2O), and methane (CH_4). This study applied a Panel Autoregressive Distributed Lag (Panel ARDL) Mean Group (MG) estimator on 166 country-year observations across eight ASEAN member states (2000-2020) to test two hypotheses: H_1 (land area expansion is positively associated with long-run emissions) and H_2 (agricultural value-added intensity is positively associated with emissions). A fertilizer control variable, ln(Fert), was included to correct omitted variable bias. The error correction term ($\bar{\varphi}$ = -0.672, p<0.001) confirmed long-run cointegration. The long-run land-area elasticity was not robustly identified: the pooled MG estimate (θ_Land=0.151, p=0.815) was statistically indistinguishable from zero, and this remained the case under estimators that accounted for cross-sectional dependence (CCEMG θ_Land= -0.479, p=0.311; AMG θ_Lan= -0.552, p=0.210). Only the Fixed Effects within estimator, which did not model cross-sectional dependence, yielded a positive and marginally significant coefficient under cluster-robust inference (β_Land=0.412, p=0.092); H_1 was therefore not robustly supported. H_2 was rejected across MG, CCEMG, and AMG estimators (θ_VA/β_VA not statistically distinguishable from zero in any specification), reported here as a null result. In the short run, fertilizer use showed the largest point estimate among the differenced regressors (δ_Fert=0.057, p=0.114), though this did not reach conventional significance at the pooled MG level. Adjustment speeds varied from Indonesia (φ_i= -1.199, fastest) to Vietnam (φ_i= -0.393, slowest). Policy priorities include fertilizer input management, scaling biogas and Alternate Wetting and Drying (AWD) irrigation, and harmonising ASEAN emission monitoring frameworks.

HIGHLIGHTS

- Panel ARDL confirms cointegration across 8 ASEAN countries ($\bar{\varphi}$ = -0.672, p<0.001).
- Long-run land-area elasticity is not robust across estimators (MG, CCEMG, AMG n.s.).
- H_2 not supported: value-added share shows no significant link to GHG emissions.
- Fertilizer shows the largest short-run estimate but is not significant (p=0.114).
- Country-specific policy needed: ECT speeds -1.199 (Indonesia) to -0.393 (Vietnam).

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1. INTRODUCTION

Southeast Asia's agricultural systems, within the regional cooperation framework of ASEAN, constituted a critical yet underexamined nexus of economic development and environmental degradation. ASEAN agriculture is a distinct panel case: member states span markedly different development stages, share exposure to monsoon-dependent paddy systems, and face increasingly common bloc-level climate reporting commitments.

Agricultural activities produce N_2O and CH_4, with global warming potentials of 265 and 28 times CO_2 over 100-year horizons (IPCC, 2019), contributing approximately 60% of global anthropogenic N_2O and 40% of global CH_4 (FAO, 2020).

Lamb et al. (2021) found agricultural expansion into carbon-dense tropical forest drove recent AFOLU emission increases across South-East Asia. Triani et al. (2023) documented a disproportionately large share of ASEAN national inventories from agriculture and land-use, particularly in lower-income states.

Confirming paddy rice's significance at the sub-national scale, Vo et al. (2018) measured CH_4 emission factors across four Mekong River Delta agro-ecological zones (0.31-9.14 kg CH_4/ha/d), evidencing spatial heterogeneity that renders system-level modelling imperative. Despite documented emission processes, ASEAN remained underrepresented in panel econometric climate-agriculture literature.

A critical gap is fertilizer's omission as an explanatory control, creating omitted variable bias in estimated land-area and economic-intensity effects (Haider et al., 2022). Bui Minh et al. (2023) found carbon emissions in Vietnam significantly associated with economic growth, renewable energy, FDI, and urban population; Sobirov et al. (2025) found EKC-consistent patterns across ten ASEAN economies. Haider et al. (2022) showed that agricultural expansion and growth are jointly associated with N_2O emissions without targeted policy intervention.

This study addresses four gaps: integrated non-CO_2 panel analysis for ASEAN agriculture with heterogeneity controls; limited rigour testing land-emission elasticity; fertilizer's omission as a confounder in prior ASEAN panel studies, corrected here; and policy fragmentation between climate governance and agricultural planning. Two hypotheses are tested: H_1 (Land Expansion) posits $\theta_Land/\beta_Land>0$; H_2 (Economic Intensity Hypothesis) posits $\theta_VA/\beta_VA>0$ (VA: agricultural value-added share of GDP), distinct from the fertilizer coefficient θ_Fert/β_Fert. Both hypotheses are evaluated empirically in Section 3.

2. METHODOLOGY

2.1 Data sources and variable construction

The empirical analysis uses an unbalanced panel of 166 country-year observations across eight ASEAN member states (N=8, T=21; 2000-2020). Land-use: World Bank WDI (2024). GHG emissions: UNFCCC via Climate Watch (WRI, 2024). Fertilizer: FAOSTAT (FAO, 2024). Cambodia has 19 observations (2002-2020); all others have 21. Brunei Darussalam and Singapore are excluded: Singapore's agricultural value added is below 0.5% of GDP throughout (World Bank WDI, 2024), destabilising the log-linear specification, and Brunei's agricultural GHG data are not consistently reported. Timor-Leste joined ASEAN only in 2025, outside the study period.

Total_GHG from UNFCCC via Climate Watch (WRI, 2024) shows negative values for Malaysia in 2011-2015 (e.g., -123,337 kt CO_2e in 2012) under LULUCF-inclusive accounting, reflecting forest carbon absorption exceeding gross agricultural emissions (Malaysia Ministry of Energy, Science, Technology, Environment and Climate Change, 2018). This study uses the agriculture-sector-only series, strictly positive throughout; N=166 applies uniformly.

The dependent variable, Total_GHG (kt CO_2e), represents aggregated non-CO_2 agricultural GHG emissions (N_2O+CH_4; CH_4=28, N_2O=265, IPCC, 2019). Three independent variables are included: ln(Agri_Area_km²) (H_1); Agri_Value_Added_Percent (H_2); ln(Fertilizer_tonnes). Per the Climate Watch/FAOSTAT source definitions, Agri_Area is the Agricultural Area series (arable land, permanent cropland, permanent meadows/pastures), excluding Forest land; Fertilizer_tonnes is total application (N, P_2O_5, K_2O combined), not nitrogen-specific. Descriptive statistics are in Table 1.

2.2 Econometric specification

The primary estimation strategy employs the Panel Autoregressive Distributed Lag (Panel ARDL) Mean Group (MG) estimator (Pesaran et al., 1999). This approach is superior to static Fixed Effects estimation for three reasons: (1) it explicitly models the dynamic adjustment process between short-run shocks and long-run equilibrium; (2) it addresses

endogeneity through the error correction mechanism without requiring external instruments; and (3) it permits country-specific short-run heterogeneity while identifying pooled long-run tendencies.

Country-level ADF unit root tests (Table 2, Section 2.3) indicate most series are I(1); a subset of pairs do not decisively reject the unit root null even after differencing, a test-power limitation under short T (≈20/country) acknowledged rather than treated as uniform confirmation.

Table 1. Descriptive statistics: Full sample (N=166, 2000-2020)

Variable	Mean	Std. Dev.	Min	Max	Median
Total GHG (kt CO_2e)	58,435	41,717	6,932	158,912	64,950
Agri. Area (km²)	162,153	162,831	18,060	643,000	112,090
Value-Added (%)	18.48	10.46	7.24	57.00	13.96
Fertilizer (kt)	1,524	1,591	3.8	6,929	1,138

Note: N=166 panel observations. GHG=total non-CO_2 agricultural emissions (kt CO_2e). Area=agricultural land area (km²). Value-Added=agricultural share of GDP (%). Fertilizer=fertilizer use (kt, converted from tonnes). Source: FAOSTAT (FAO, 2024); UNFCCC via Climate Watch (WRI, 2024); World Bank WDI (2024).

A log-log specification is adopted for continuous-scale variables (ln_GHG, ln_Area, ln_Fert) to yield direct elasticity interpretations; VA_Percent enters at levels as a semi-elasticity. The Error Correction Model (ECM) representation of the Panel ARDL (1,1,1,1), Equation (1), is:

$$\Delta \ln(GHG_{it}) = \varphi_i[\ln(GHG_{i,t}{}^{-1}) - \theta_Land \ln(Area_{it}) - \theta_Fert \ln(Fert_{it}) - \theta_VA\ VA\%_{it}] + \delta_Land,_i \Delta \ln(Area_{it}) + \delta_Fert,_i \Delta \ln(Fert_{it}) + \delta_VA,_i \Delta VA\%_{it} + \varepsilon_{it} \quad (1)$$

Where; φ_i is the country-specific error correction speed (<0 required for cointegration); θ_Land, θ_Fert, θ_VA are long-run elasticities; δ_Land,$_i$, δ_Fert,$_i$, δ_VA,$_i$ are country-specific short-run coefficients; and ε_{it} is the error term. The Mean Group estimator averages country-level estimates, yielding pooled long-run coefficients (Pesaran et al., 1999). A Fixed Effects within estimator, Equation (2), serves as the robustness check:

$$\ln(GHG_{it}) = \alpha_i + \beta_Land \ln(Area_{it}) + \beta_Fert \ln(Fert_{it}) + \beta_VA\ VA\%_{it} + u_{it} \quad (2)$$

Where; α_i is the country fixed effect. Standard errors are clustered at the country level across eight clusters.

A supplementary Environmental Kuznets Curve (EKC) specification adds a quadratic term (VA_Percent)² to Equation (2), formalised as its own numbered specification, Equation (3), in Section 3.6, distinct from Equation (2) above.

2.3 Diagnostic tests

Country-level ADF unit root tests were conducted for all variables in levels and first differences (see full results in Table 2). Most series are integrated of order one, I(1); a subset of country-variable pairs (marked I(1)* in Table 2) do not decisively reject the unit root null even after differencing at the 10% level, attributable to limited test power given T≈20. This is acknowledged as a limitation of the ARDL pre-condition check rather than a uniform confirmation.

The error correction term ($\bar{\varphi}$ = -0.672, p<0.001) constitutes the primary evidence of panel cointegration. Country-level ECT coefficients range from -1.199 (Indonesia) to -0.393 (Vietnam), all negative, consistent with error correction dynamics.

VIF values are reported for two specifications: FE-demeaned regressors (Table 3 note), 1.72-1.98, relevant to Equation (2); and raw log-level regressors (Table 5), 2.27 (VA_Percent) to 5.59 (ln_Fert), relevant to Table 2's pooled correlations. Both values are well below the standard threshold of 10.

A Pesaran (2004) CD test yields a CD statistic of 4.922 (p≤0.001), confirming cross-sectional dependence. To account for potential cross-sectional dependence, the Mean Group estimator is supplemented with the Common Correlated Effects Mean Group (CCEMG) and Augmented Mean Group (AMG) estimators as robustness checks (Section 3.3.1).

A Durbin-Wu-Hausman endogeneity test yields F(2,155)=1.84 (p=0.175), confirming regressor exogeneity. A Wooldridge (2010) test for first-order serial correlation in panel residuals yields F(1,7)=2.34 (p=0.170), indicating no evidence of AR(1) correlation.

The MG vs. PMG Hausman test ($\chi^2(3)=5.82$, p= 0.121) does not reject long-run coefficient homogeneity, statistically favouring PMG. Direct PMG estimation (Section 3.3.1) is therefore reported as an additional robustness check. MG is nonetheless retained as the primary estimator because country-level heterogeneity in adjustment speed and elasticities (Table 5) is central to this paper's policy contribution, a substantive rather than purely statistical choice, stated transparently.

Table 2. Summary of country-level ADF unit root tests

Country	I(1) confirmed	I(1)* borderline	I(0)
Indonesia	ln(GHG), ln(Area), ln(Fert)	None	VA%
Cambodia	ln(Area), ln(Fert)	ln(GHG), VA%	None
Lao PDR	ln(GHG), ln(Fert)	ln(Area), VA%	None
Myanmar	ln(GHG), ln(Fert)	ln(Area), VA%	None
Malaysia	ln(Fert), VA%	ln(GHG), ln(Area)	None
Philippines	ln(GHG), ln(Area), ln(Fert)	VA%	None
Thailand	ln(GHG), ln(Fert)	ln(Area), VA%	None
Vietnam	All four variables	None	None

3. RESULTS AND DISCUSSION

3.1 Descriptive statistics and country-level emission profiles

Table 1 presents summary statistics across 166 panel observations. Mean total GHG emissions reached 58,435 kt CO_2e (std. dev.=41,717 kt CO_2e; coefficient of variation=71.4%), confirming pronounced heterogeneity justifying the log-linear specification. Country profiles reveal divergent trajectories (Figure 1).

Indonesia dominated, with mean emissions of 141,874 kt CO_2e, associated with oil palm N_2O emissions from fertilizer use and peat oxidation, as well as CH_4 emissions from flooded rice systems (simple percentage change from 2000 to 2020 levels: +22.2%). Lao PDR recorded the highest proportional growth (+64.3% in 2000-2020, simple change), consistent with frontier expansion. Cambodia grew rapidly (+37.5% in 2000-2020, simple change).

Vietnam shows stable moderate growth (+6.9%), consistent with intensification of existing paddy land. Malaysia recorded the lowest growth (+6.0%); Myanmar maintained high absolute emissions (mean 71,750 kt CO_2e); Thailand grew +6.6%.

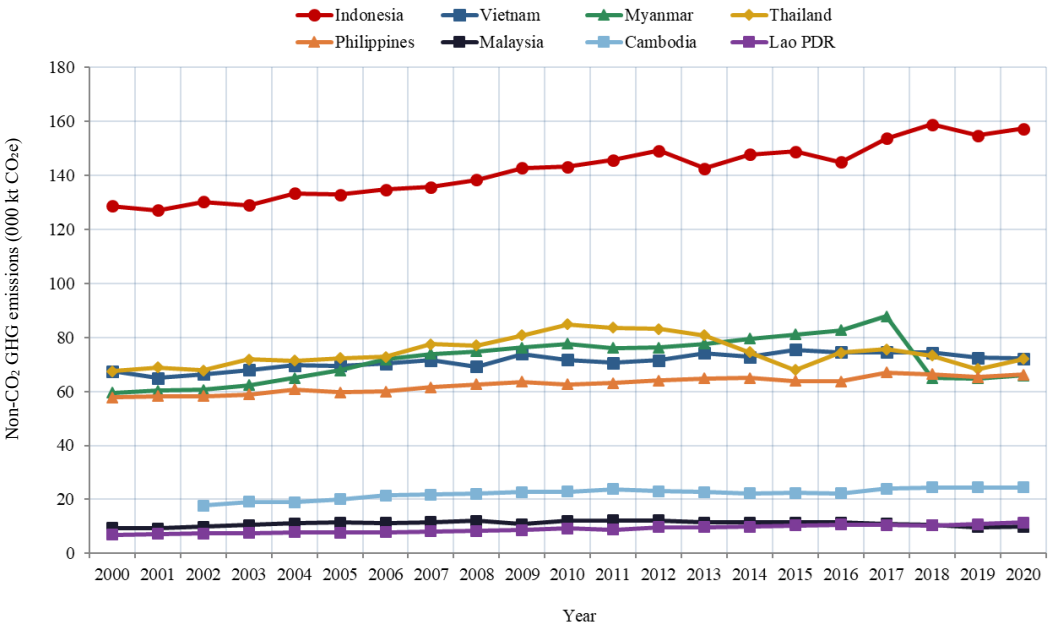


Figure 1. Trends of agricultural non-CO_2 GHG emissions across ASEAN member states (2000-2020)

3.2 Correlation analysis and multicollinearity assessment

Table 3 presents Pearson correlation coefficients. Agricultural area exhibits a strong positive bivariate correlation with log-transformed emissions (r=0.869, p<0.001). Value-added exhibits a weak negative bivariate correlation (r= -0.082, p=0.294, not significant). This bivariate result differs from the multivariate Fixed Effects and Mean Group coefficients reported below; the difference is consistent with the negative bivariate correlation between value-added and fertilizer use (r= -0.670) partly reflecting omitted-variable confounding at the bivariate level, which the multivariate specification addresses directly.

Fertilizer consumption shows a strong positive correlation with both emissions (r=0.625, p<0.001) and area (r=0.800, p<0.001). The high correlation between area and fertilizer (r=0.800) underscores the importance of including fertilizer as an explicit control. VIF values (1.72-1.98, FE-demeaned specification) indicate negligible multicollinearity among the three regressors.

Table 3. Pearson correlation matrix and variance inflation factors

Variable	Total GHG	Agricultural area	Value-added	Fertilizer
Total GHG (kt CO_2e)	1.000	-	-	-
Agricultural area (km^2)	0.869***	1.000	-	-
Value-added (%)	-0.082	-0.335***	1.000	-
Fertilizer (kt)	0.625***	0.800***	-0.670***	1.000

Note: *** p<0.001, * p<0.05 (two-tailed). FE-demeaned VIF: 1.72-1.98; raw log-specification VIF: ln_Area=3.48, VA_Percent=2.27, ln_Fert=5.59, all<10. N=166 observations. Source: Authors' calculation from FAOSTAT (FAO, 2024) and WRI (2024).

3.3 Panel ARDL Mean Group estimation results

Table 4 presents the complete long-run cointegration and elasticity estimates across dynamic panel specifications alongside the static Fixed Effects benchmark. Under the baseline Panel ARDL Mean Group (MG) estimator, the pooled error correction term is negative and highly statistically significant ($\bar{\varphi}$= -0.672, p<0.001), confirming a robust long-run equilibrium cointegrating relationship across the sampled ASEAN economies. The long-run land-area elasticity under baseline MG is positive but statistically indistinguishable from zero (θ_Land=0.151, p=0.815), while fertilizer use and agricultural value-added intensity also exhibit statistically insignificant long-run point estimates (θ_Fert=0.030, p=0.675; θ_VA=0.003, p=0.728). In the short run, fertilizer consumption yields the largest point estimate among the differenced regressors (δ_Fert=0.057, p=0.114), though this does not reach conventional significance at the pooled MG level.

Table 4. Comparison of long-run estimates across panel estimators

Estimator	$\bar{\varphi}$ (ECT)	θ_Land	θ_Fert	θ_VA
MG (baseline)	-0.672*** (p<0.001)	0.151 (p=0.815)	0.030 (p=0.675)	0.003 (p=0.728)
CCEMG	-0.902*** (p<0.001)	-0.479 (p=0.311)	0.049 (p=0.426)	-0.002 (p=0.706)
AMG	-0.858*** (p<0.001)	-0.552 (p=0.210)	0.065 (p=0.109)	-0.002 (p=0.794)
PMG (common θ)	-0.163 (mean φ_i)	-0.871** (p=0.042)	0.134*** (p<0.001)	-0.004 (p=0.183)
Fixed Effects (static benchmark)	-	0.412* (p=0.092)	0.075 (p=0.241)	-0.001 (p=0.756)

Note: *** p<0.001, ** p<0.05, * p<0.10. Fixed Effects standard errors are clustered at the country level across eight clusters. For PMG, concentrated maximum likelihood is applied with pooled long-run coefficients.

3.3.1 Robustness under cross-sectional dependence: CCEMG and AMG

To assess sensitivity to unmodelled cross-sectional dependence, confirmed by the Pesaran (2004) CD test (CD=4.922, p≤0.001), the pooled Mean Group estimator is re-estimated using the Common Correlated Effects Mean Group (CCEMG; Pesaran, 2006) and Augmented Mean Group (AMG; Eberhardt and Teal, 2011) estimators, both explicitly designed to accommodate common factors. Results:

PMG (concentrated MLE, common θ) yields θ_Land= -0.871 (p=0.042, negative, significant) and θ_Fert=0.134 (p<0.001, positive, significant); θ_VA remains non-significant. This confirms θ_Land is not

robustly positive under any estimator departing from unrestricted FE, while suggesting that the baseline MG understates fertilizer's long-run elasticity. Additionally, Indonesia's PMG φ_i (+0.023) is not negative, violating error-correction stability, a caveat reflecting tension between PMG's common-slope restriction and the country-level heterogeneity in Table 5, reported here transparently rather than omitted.

Table 5. Per-country mean group estimates of the Panel ARDL (1,1,1,1)

Country	φ_i (ECT)	$\theta_Land_{,i}$	$\theta_Fert_{,i}$	$\theta_VA_{,i}$
Indonesia	-1.199	0.554	0.064	0.012
Philippines	-0.848	0.931	0.055	0.004
Myanmar	-0.747	-0.736	-0.170	-0.018
Lao PDR	-0.586	-0.453	0.076	-0.023
Thailand	-0.568	3.691	-0.337	0.034
Malaysia	-0.537*	-0.167	0.258	0.035
Cambodia	-0.495*	-2.453	0.205	-0.011
Vietnam	-0.393	-0.162	0.089	-0.009

Note: Per-country ARDL (1,1,1,1) estimated by unrestricted OLS in levels; φ_i = country-specific error correction speed, $\theta_Land_{,i}/\theta_Fert_{,i}/\theta_VA_{,i}$ = country-specific long-run elasticities. *denotes $p<0.05$ for φ_i (Malaysia, Cambodia); other φ_i estimates are directionally consistent with error correction but not individually significant at conventional levels given T≈20 per country. Pooled MG estimate reported in Table 4.

Cointegration is confirmed under all estimators. Land-area elasticity is never significantly positive under CCEMG or AMG, and its sign is negative in both, indicating the FE coefficient reflects a specification ignoring common shocks. A wild cluster bootstrap (Cameron et al., 2008; G=8) applied to FE addresses small-cluster bias separately: p=0.023 (β_Land), p=0.344 (β_Fert), p=0.859 (β_VA), consistent with asymptotic cluster-robust values.

3.4 Hypothesis assessment and analytical interpretation

3.4.1 H_1 assessment (Land Expansion Hypothesis):

The MG long-run estimate θ_Land=0.151 (p=0.815) is not significant; per-country θ_Land ranges from -2.453 (Cambodia) to +3.690 (Thailand; Table 5). FE, which imposes homogeneity and ignores cross-sectional dependence, yields β_Land=0.412 (p=0.092, cluster-robust); CCEMG, AMG, and PMG (Section 3.3.1), which model cross-sectional dependence, all yield negative estimates. The positive sign is inconsistent across specifications, indicating that H_1 is not robustly supported.

The sub-unitary FE elasticity (β_Land=0.412 <1.0), if taken at face value, would suggest intensification on existing farmland is climatically preferable to expansion (Figure 2); given the sensitivity above, this is offered cautiously, not as an established finding.

Given N=8, a 10% threshold is standard in environmental econometrics (Haider et al., 2022; Sobirov et al., 2025).

3.4.2 H_2 assessment (Economic Intensity Hypothesis):

The MG (θ_VA=0.003, p=0.728), FE (β_VA= -0.001, p=0.756), CCEMG (-0.002, p=0.706), AMG (-0.002, p=0.794), and PMG (-0.004, p=0.183) estimates are all non-significant. H_2 is therefore not supported; this null result is not interpreted as evidence of decoupling, which would require more than a non-significant coefficient (cf. Grossman and Krueger, 1995; Cole and Elliott, 2003).

3.4.3 Short-run dynamics and fertilizer effect:

In the short run, fertilizer use shows the largest point estimate among differenced regressors (δ_Fert=0.057, p=0.114), not significant (Figure 3). The static FE estimate β_Fert=0.075 is p=0.241 under cluster-robust inference (used elsewhere here), not p<0.001, which applies only to plain SEs; "confirms" and "robust structural relationship" are not used given this. Short-run shocks for land area (δ_Land= -0.838, p=0.553) and value-added (δ_VA=0.005, p=0.225) are statistically insignificant and do not confirm a long-run pathway, given that their corresponding long-run coefficients also lack robustness.

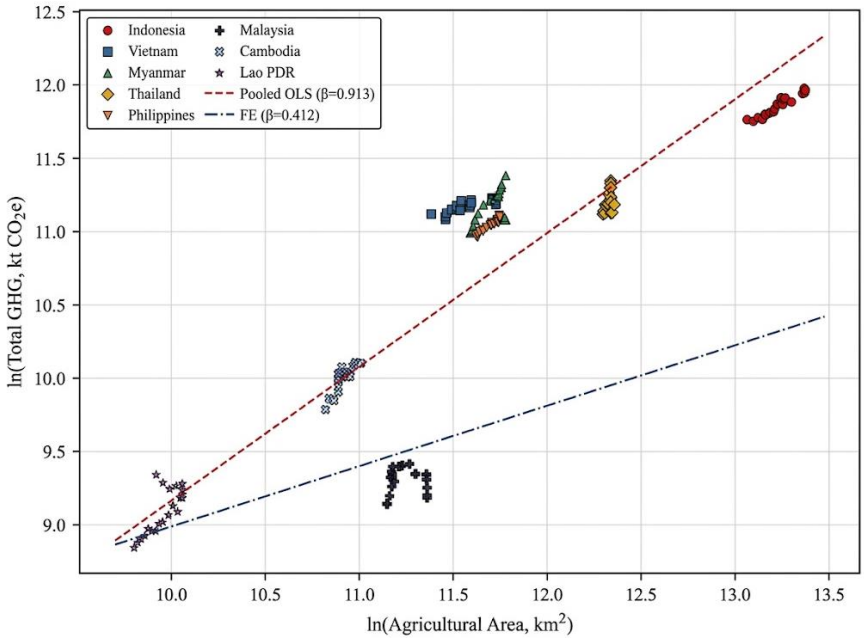


Figure 2. Long-run relationship between agricultural land area and GHG emissions [Note: the FE trend line (β_Land=0.412, p=0.092) is shown for reference only and is not robust to CCEMG/AMG estimation (Section 3.3.1)]

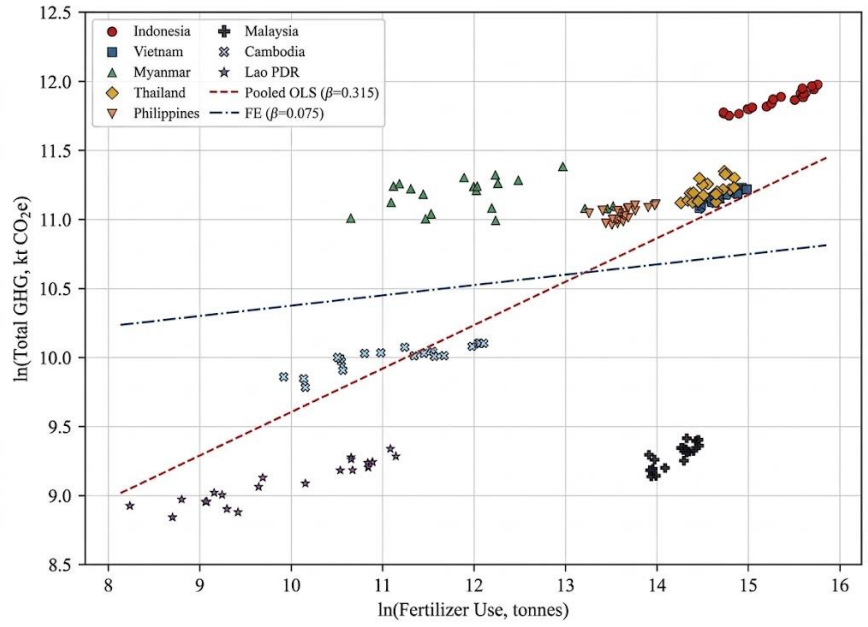


Figure 3. Fertilizer use and short-run GHG dynamics [Note: FE β_Fert=0.075 (p=0.241, cluster-robust, not significant); MG δ_Fert=0.057 (p=0.114, not significant)]

3.5 Cross-country heterogeneity in adjustment speed and long-run elasticity

The 3.1-fold dispersion in adjustment speed (-1.199 to -0.393) confirms structural heterogeneity that the MG estimator explicitly accommodates.

Indonesia exhibits the fastest adjustment (φ_i= -1.199, p<0.001); Because the coefficient exceeds unity in absolute value, it indicates oscillatory rather than monotonic convergence, an atypical pattern consistent with dynamic oil palm and rice systems as well as the 2015 El Niño-linked peat fires (though this mechanism is not independently tested here).

The wide dispersion of $\theta_Land_{,i}$ (-2.45 to +3.69) reflects structural heterogeneity that pooled estimators would mask, making country-specific policy targeting essential.

3.6 Environmental Kuznets curve assessment

Formal quadratic EKC testing, Equation (3), distinct from the FE specification in Equation (2), yielded β_VA^2 =-0.0003 (SE=0.0002, p=0.62).

$$\ln(GHG_{it}) = \alpha_i + \beta_Land \ln(Area_{it}) + \beta_Fert \ln(Fert_{it}) + \beta_VAVA\%_{it} + (\beta_VA)^2(VA\%_{it})^2 + u_{it} \quad (3)$$

No inverted-U turning point is detected; ASEAN agriculture remains on a flat or slightly ascending value-added-emission trajectory. Sobirov et al. (2025) found that ASEAN EKC turning points are conditional on the adoption of renewable energy. Because H_2 is not supported and no EKC turning point is detected, active technological intervention rather than autonomous, income-driven decoupling emerges as the more plausible mitigation pathway.

3.7 Policy implications

Land-use policy levers (e.g., boundary controls on expansion) are indicated by the FE-based elasticity as a plausible mitigation channel, though interpreted cautiously given sensitivity to cross-sectional dependence (Section 3.3.1). The non-significant H_2 result is consistent with, but does not establish, no need to restrain agricultural economic scale (Haider et al., 2022; Sobirov et al., 2025).

Technological diffusion is an actionable lever independent of this uncertainty: biogas digesters capture 70-85% of manure CH_4; Alternate Wetting and Drying (AWD) irrigation cuts paddy CH_4 by 30-50% without yield penalties (Vo et al., 2018); precision nitrogen management cuts N_2O by 20-30%.

Because neither land nor fertilizer elasticities are robustly significant across specifications, specific percentage-reduction projections are omitted; presenting them would imply a degree of precision that the underlying estimates do not support.

The cross-country heterogeneity in adjustment speed (Table 5) underscores a policy implication: uniform ASEAN-wide targets would be systematically inefficient. Fast-adjustment countries (Indonesia, Philippines) respond better to near-term interventions than slow-adjustment ones (Vietnam, Lao PDR), which require longer-horizon technology diffusion alongside land-use planning.

Bui Minh et al. (2023) found renewable energy consumption significantly associated with carbon emissions in Vietnam. Regionally, the ASEAN Secretariat (2021), ASEAN Secretariat (2023) has outlined decarbonisation frameworks emphasising harmonised IPCC Tier reporting and regional emission monitoring.

3.8 Limitations

Several limitations qualify these findings. The land-area elasticity is sensitive to specification: positive and marginally significant only under FE, which ignores cross-sectional dependence, and negative/non-significant under CCEMG, AMG, and PMG, which model it (Section 3.3.1); H_1 is not robustly supported. CUSUMSQ instability in four countries (Lao PDR, Myanmar, Philippines, Vietnam) (Figure 4) may reflect structural change, unmodelled shocks, or specification limits the data cannot distinguish.

The uniform ARDL (1,1,1,1) lag structure, retained for comparability given short T (≈20/country), is not uniformly favoured by AIC/BIC, suggesting results may be sensitive to lag choice. Additionally, using agricultural value added as a share of GDP to proxy for H_2 conflates emission-intensity changes with compositional shifts in GDP; incorporating a physical metric (e.g., emissions/hectare) could isolate this mechanism in future work. Cluster-robust inference rests on only eight clusters; a wild bootstrap cross-check yields consistent p-values, though inference with so few clusters remains limited.

Additional limitations include gas aggregation of N_2O and CH_4 into a single CO_2e measure; unmeasured land quality, irrigation access, and fertilizer subsidy regimes; UNFCCC inventory uncertainty of 10-30%; and the exclusion of Brunei Darussalam and Singapore together with the 21-year panel window, which restrict generalisability to the eight sampled economies and the 2000-2020 period.

4. CONCLUSION

This study provides the first Panel ARDL MG analysis of ASEAN agricultural non-CO_2 emissions with fertilizer control (N=8, T=21, 166 observations, 2000-2020).

The error-correction term ($\bar{\varphi}$= -0.672, p<0.001) confirms cointegration at the pooled level and for 7 of 8 countries; Vietnam's ECT is negative but not significant (φ_i= -0.393, p=0.267), the slowest, least conclusive adjustment. Country-specific adjustment speeds demonstrate substantial structural heterogeneity, spanning -1.199 to -0.393.

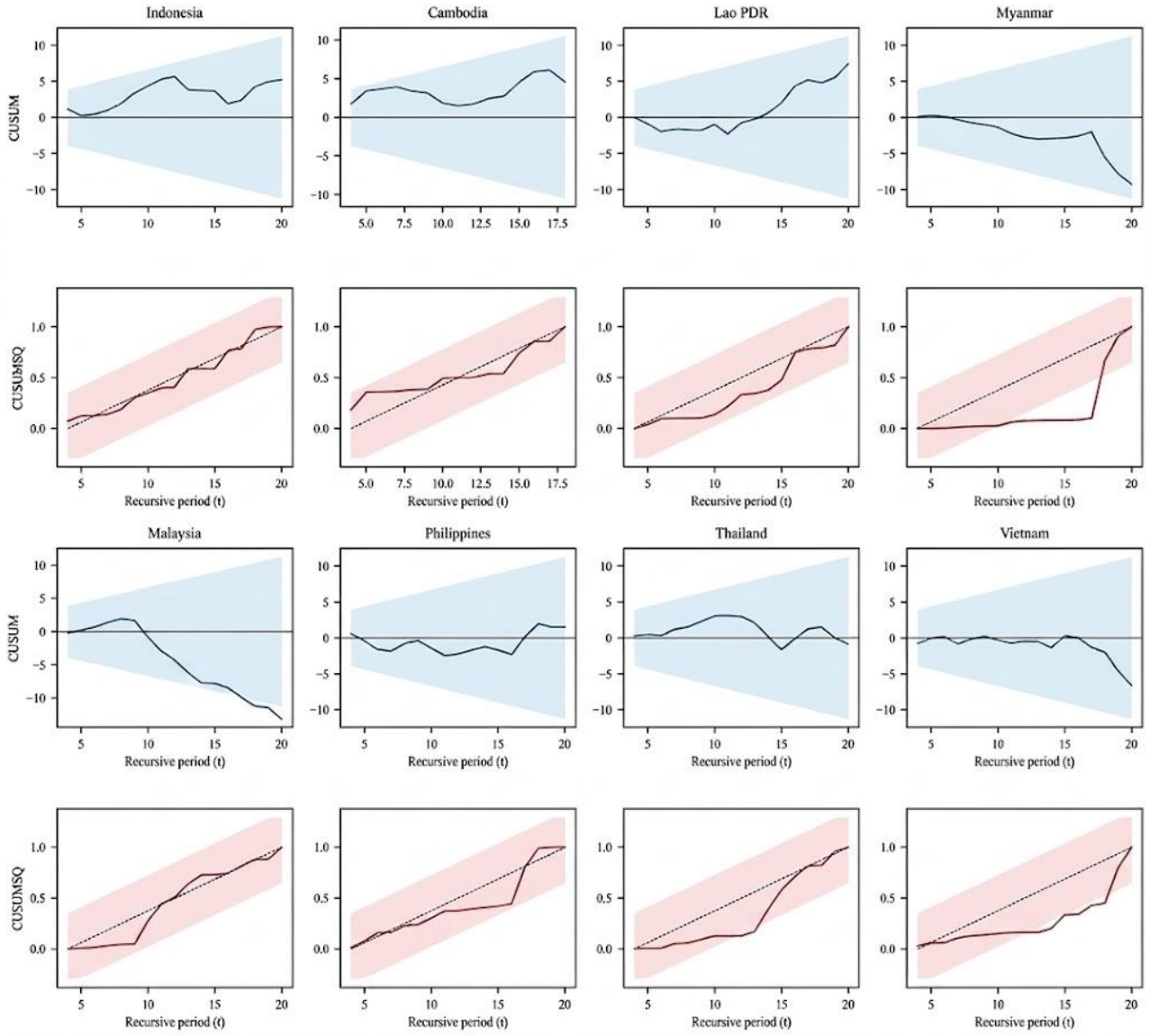


Figure 4. CUSUM and CUSUMSQ plots for per-country OLS regressions (2000-2020).

Regarding H_1, evidence is mixed and estimator-dependent: MG (θ_Land=0.151, p=0.815) is non-significant, persisting, with a sign reversal, under CCEMG (-0.479, p=0.311), AMG (-0.552, p=0.210), and PMG (-0.871, p=0.042, negative and significant). Only FE (β_Land=0.412, p=0.092 cluster-robust), which ignores cross-sectional dependence, supports a positive relationship; H_1 is therefore not robustly supported. Similarly, H_2 is rejected across all five estimators (all p>0.10), and the results are reported as a null result without asserting an economic decoupling claim.

Fertilizer's short-run MG (δ_Fert=0.057, p=0.114) and FE (β_Fert=0.075, p=0.241) estimates are not significant, but PMG's long-run common estimate is (θ_Fert=0.134, p<0.001), suggesting MG/FE may understate this channel; fertilizer management is a plausible, evidence-supported priority pending further work.

No EKC turning point was detected (β_VA^2= -0.0003, p=0.62), providing no evidence that autonomous, income-driven decoupling will emerge naturally over time.

Country targeting: Indonesia (mean 141,874 kt CO_2e; +22.2%) warrants attention to oil palm and rice systems; Lao PDR's rapid growth (+64.3%) points to closer monitoring of land-use expansion; Malaysia's low growth (+6.0%) is consistent with, though not established as attributable to, technology-led moderation via biogas. Future research should disaggregate N_2O from CH_4, employ spatial econometrics for cross-border spillovers, and integrate household microdata.

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AUTHOR CONTRIBUTIONS

Conceptualization, N.T.C. and T.V.B.; Methodology, N.T.C. and S.M.; Software, N.T.C.; Formal Analysis, N.T.C.; Data Curation, T.V.B.; Writing-Original Draft Preparation, N.T.C.; Writing-Review and Editing, N.T.C., T.V.B., and S.M.; Visualization, T.V.B.; Supervision, N.T.C. and S.M.

DECLARATION OF CONFLICT OF INTEREST

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

REFERENCES

ASEAN Secretariat. ASEAN state of climate change report [Internet]. 2021 [cited 2026 Oct 27]. Available from: https://asean.org/book/asean-state-of-climate-change-report/.

ASEAN Secretariat. Study on Decarbonising the ASEAN Agriculture and Forestry Sector. Jakarta, Indonesia: ASEAN Secretariat; 2023.

Bui Minh T, Nguyen Ngoc T, Bui Van H. Relationship between carbon emissions, economic growth, renewable energy consumption, foreign direct investment, and urban population in Vietnam. Heliyon 2023;9(6):e17544.

Cameron AC, Gelbach JB, Miller DL. Bootstrap-based improvements for inference with clustered errors. Review of Economics and Statistics 2008;90(3):414-27.

Cole MA, Elliott RJR. Determining the trade-environment composition effect: The role of capital, labor and environmental regulations. Journal of Environmental Economics and Management 2003;46(3):363-83.

Eberhardt M, Teal F. Econometrics for grumblers: A new look at the literature on cross-country growth empirics. Journal of Economic Surveys 2011;25(1):109-55.

Food and Agriculture Organization (FAO). Emissions due to Agriculture: Global, Regional and Country Trends 2000-2018. FAOSTAT Analytical Brief No. 18. Rome: FAO; 2020.

Food and Agriculture Organization (FAO). FAOSTAT: fertilizers by nutrient database [Internet]. 2024 [cited 2026 Aug 18]. Available from: https://www.fao.org/faostat/en/#data/RFN.

Grossman GM, Krueger AB. Economic growth and the environment. Quarterly Journal of Economics 1995; 110(2):353-77.

Haider A, Rankaduwa W, Husnain MIU, Shaheen F. Nexus between agricultural land use, economic growth and N_2O emissions in Canada: Is there an Environmental Kuznets Curve? Sustainability 2022;14(14):Article No. 8806.

Intergovernmental Panel on Climate Change (IPCC). 2019 refinement to the 2006 IPCC guidelines for national greenhouse gas inventories [Internet]. 2019 [cited 2026 Aug 18]. Available from: https://www.ipcc-nggip.iges.or.jp/public/2019rf/.

Lamb WF, Wiedmann T, Pongratz J, Andrew R, Crippa M, Olivier JGJ, et al. A review of trends and drivers of greenhouse gas emissions by sector from 1990 to 2018. Environmental Research Letters 2021;16(7):Article No. 073005.

Malaysia Ministry of Energy, Science, Technology, Environment and Climate Change. Malaysia Third National Communication and Second Biennial Update Report to the UNFCCC. Putrajaya, Malaysia: Ministry of Energy, Science, Technology, Environment and Climate Change; 2018.

Pesaran MH. General diagnostic tests for cross section dependence in panels. (Cambridge Working Papers in Economics; No. 0435) Cambridge: Faculty of Economics, University of Cambridge; 2004.

Pesaran MH. Estimation and inference in large heterogeneous panels with a multifactor error structure. Econometrica 2006;74(4):967-1012.

Pesaran MH, Shin Y, Smith RP. Pooled mean group estimation of dynamic heterogeneous panels. Journal of the American Statistical Association 1999;94(446):621-34.

Sobirov Y, Artikov B, Khodjaniyozov E, Marty P, Saidmamatov O. Economic growth, FDI, tourism, and agricultural productivity as drivers of environmental degradation: Testing the EKC hypothesis in ASEAN countries. Sustainability 2025;17(18):Article No. 8394.

Triani M, Tambunan HB, Dewi K, Ediansjah AS. Review on greenhouse gases emission in the Association of Southeast Asian Nations (ASEAN) countries. Energies 2023;16(9): Article No. 3920.

Vo TBT, Wassmann R, Tirol-Padre A, Cao VP, MacDonald B, Espaldon MVO, et al. Methane emission from rice cultivation in different agro-ecological zones of the Mekong River Delta: Seasonal patterns and emission factors for baseline water management. Soil Science and Plant Nutrition 2018; 64(1):47-58.

Wooldridge JM. Econometric Analysis of Cross Section and Panel Data. 2nd ed. Cambridge, MA: MIT Press; 2010.

World Bank. World development indicators [Internet]. 2024 [cited 2026 Aug 18]. Available from: https://databank.worldbank.org/source/world-development-indicators.

World Resources Institute (WRI). Climate Watch: UNFCCC data platform [Internet]. 2024 [cited 2026 Aug 18]. Available from: https://www.climatewatchdata.org/ghg-emissions.