

SUPPLEMENTARY MATERIAL

Decoupling Economic Growth from CO₂ Emissions in Honduras: A Longitudinal Machine-Learning and Econometric Assessment of Low-Carbon Development, 1990–2023

Dely Ramirez ^{1,2,*}, Jonathan Muñoz Tabora ³ and Ozy D. Melgar-Dominguez ³

Table S1. Unit Root and Cointegration Tests.

Results of unit root tests applied to $\ln(\text{GDP per capita})$ and $\ln(\text{CO}_2 \text{ per capita})$, and cointegration test applied to the residuals of the Environmental Kuznets Curve regression. Panel A series ($n = 34$, 1990–2023).

Series	Test	Statistic	p-value	Conclusion
$\ln(\text{GDP per capita})$	ADF (lag = 1)	-1.616	0.416	I(1) — non-stationary
$\ln(\text{GDP per capita})$	Phillips-Perron	-0.556	0.889	I(1) — non-stationary
$\ln(\text{GDP per capita})$	KPSS (Level)	0.755	< 0.010	I(1) — non-stationary
$\Delta \ln(\text{GDP per capita})$	Phillips-Perron	-6.872	< 0.010	I(0) — stationary
$\ln(\text{CO}_2 \text{ per capita})$	ADF (lag = 1)	-1.208	0.680	I(1) — non-stationary
$\ln(\text{CO}_2 \text{ per capita})$	Phillips-Perron	-0.602	0.869	I(1) — non-stationary
$\ln(\text{CO}_2 \text{ per capita})$	KPSS (Level)	0.838	< 0.010	I(1) — non-stationary
$\Delta \ln(\text{CO}_2 \text{ per capita})$	ADF (lag = 1)	-4.207	< 0.010	I(0) — stationary
$\Delta \ln(\text{CO}_2 \text{ per capita})$	Phillips-Perron	-7.415	< 0.010	I(0) — stationary
EKC residuals	ADF (lag = 1)	-2.454	0.188	Inconclusive
EKC residuals	Phillips-Perron	-3.651	0.022	Cointegrated (5%)

ADF = Augmented Dickey–Fuller [35]; KPSS = Kwiatkowski–Phillips–Schmidt–Shin [37]; PP = Phillips–Perron [36]. Reference numbers correspond to the main text’s Reference list. Ho(ADF/PP): series has a unit root; Ho(KPSS): series is stationary. ADF lag = 1 selected as more appropriate than the automatic lag = 3 for $n = 34$. The PP test is preferred for short samples. EKC residuals refer to residuals from $\ln(\text{CO}_2 \text{ pc}) = \beta_0 + \beta_1 \ln(\text{GDP pc}) + \beta_2 [\ln(\text{GDP pc})]^2$. Cointegration conclusion based on the PP test ($p = 0.022$); the ADF test on residuals is not significant ($p = 0.188$), indicating moderate rather than conclusive evidence.

Table S2. Clustering Robustness: Original vs. Reduced Specification.

Comparison of k-means clustering assignments under the original four-variable specification (GDP per capita, CO₂ per capita, energy intensity, renewable energy share) and a reduced two-variable specification (energy intensity and renewable energy share only), addressing the potential circularity between clustering inputs and the Tapio ratio. Panel B (n = 22, 2000–2021).

Year	Cluster (4 vars, original)	Cluster (EI + Renew. only)	Identical?
2000	2	1	No — only discrepancy
2001	2	2	Yes
2002	2	2	Yes
2003	2	2	Yes
2004	2	2	Yes
2005	2	2	Yes
2006	2	2	Yes
2007	2	2	Yes
2008	2	2	Yes
2009	2	2	Yes
2010	2	2	Yes
2011	2	2	Yes
2012	2	2	Yes
2013	2	2	Yes
2014	2	2	Yes
2015	2	2	Yes
2016	2	2	Yes
2017	1	1	Yes
2018	1	1	Yes
2019	1	1	Yes
2020	1	1	Yes
2021	1	1	Yes

Specification	Variables used	Avg. silhouette	% Agreement with original
Original	GDP pc, CO ₂ pc, EI, Renewables	0.490	— (reference)
Reduced (robustness)	EI + Renewables only	0.697	95.5% (21/22 years)

$k = 2$; $set.seed = 42$; $nstart = 25$ in both specifications. The single discrepant year (2000) has the highest renewable energy share in the dataset (62.28%) and a relatively low energy intensity, characteristics that dominate the clustering when GDP and CO₂ are excluded. The higher silhouette width under the reduced specification (0.697 vs. 0.490) confirms that the structural regimes are more clearly defined by energy-system dynamics than by the composite four-variable space. Source: Own elaboration using R (*kmeans*, *cluster* packages).

Table S3. Tapio Elasticity by Cluster: Robustness Comparison.

Comparison of cluster-level Tapio decoupling elasticities under three calculation methods: the endpoint method (original manuscript), the CAGR-based method (log-linear trend), and descriptive statistics of annual elasticities within each cluster.

Period	Endpoint e (original)	CAGR-based e (robustness)	Classification (endpoint/CAGR)	Mean annual e (SD) [excl. outliers]	Median annual e
Cluster 1 (2000–2016)	1.294	1.253	Expansive Coupling/Expansive Coupling	1.168 (2.787)	0.973
Cluster 2 (2017–2021)	0.621	0.623	Weak Decoupling/Weak Decoupling	-0.102 (1.632)	0.842
Full period (1990–2023)	0.292	—	Weak Decoupling	—	—

Endpoint method: uses GDP per capita and CO₂ per capita at the first and last year of each cluster period. CAGR method: $e = \text{CAGR}(\text{CO}_2) / \text{CAGR}(\text{GDP})$, where CAGR = compound annual growth rate over the cluster period. Annual elasticities: calculated for each year within the cluster range (Panel A); outlier years 2001 ($e = -592.1$) and 2019 ($e = 12.5$) excluded due to near-zero GDP denominators, consistent with Section 3.7 of the main text. The high standard deviations reflect the annual volatility documented in Figure 13. Source: Own elaboration.

Table S4. Sensitivity of Cluster 2 Decoupling Classification to the COVID-19 Shock.

Comparison of Cluster 2 (2017–2021) decoupling elasticity computed over the full period (as reported in Table 9) versus the pre-pandemic sub-trend only (2017–2019), excluding the exogenous COVID-19 shock of 2020.

Version	Period	ΔGDP (%)	ΔCO_2 (%)	e	Decoupling type
Original (includes COVID)	2017–2021	1.70	1.05	0.621	Weak Decoupling
Sensitivity (pre-COVID, excludes 2020)	2017–2019	2.70	3.66	1.357	Expansive Coupling

Elasticity computed as $e = \% \Delta \text{CO}_2 / \% \Delta \text{GDP}$ using GDP and CO₂ per capita at the first and last year of each period. The 2020 COVID-19 shock produced a simultaneous, exogenous contraction in both GDP and CO₂ emissions, qualitatively distinct from the endogenous energy-system transition that the clustering procedure is designed to capture. When this year is excluded, the classification reverses from weak decoupling to expansive coupling, indicating that the full-period (2017–2021) classification for

Cluster 2 should be treated as provisional. This sensitivity does not affect the study’s central, full-period (1990–2023) conclusion of weak decoupling ($e = 0.292$, Table 9), which is not driven by any single annual observation. Source: Own elaboration.

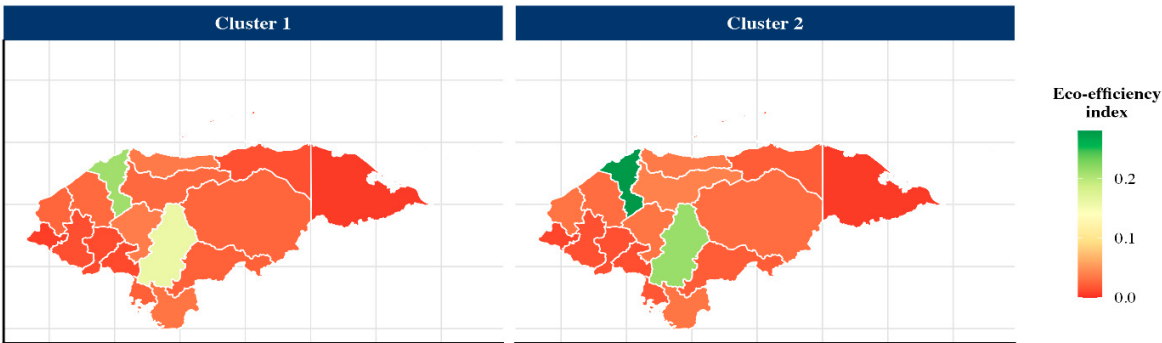
Table S5. Random Forest Variable Importance: Rolling-Origin CV vs. 5-Fold CV.

Complete permutation-based variable importance (%IncMSE) for all four predictors under the rolling-origin cross-validation robustness check, compared with the 5-fold CV results already reported in Table 8 of the main text.

Variable	Rank	%IncMSE (rolling-origin)	%IncMSE (5-fold, Table 8)
GDP per capita	1st	28.71	31.47
Energy intensity	2nd	3.56	3.35
Carbon intensity	3rd	2.65	2.06
Renewable energy share	4th	0.94	0.16

Rolling-origin CV: caret timeslice (initial Window = 14, horizon = 2, expanding window); $R^2(\text{OOB}) = 0.400$, $\text{RMSE} = 0.073$ (pooled out-of-fold predictions). 5-fold CV: $R^2(\text{OOB}) = 0.644$, $\text{RMSE} = 0.056$ (see Section 2.2 and Table 8 of the main text). The relative ranking of predictors is identical under both schemes, with GDP per capita dominant by a wide margin in both cases. Source: Own elaboration.

Figure S1. Departmental Eco-Efficiency (Exploratory)



Departmental eco-efficiency proxy by k-means cluster, Honduras. Values represent estimated eco-efficiency indices scaled by approximate departmental GDP shares and cluster-level mean GDP per capita. Because Honduras does not publish official departmental GDP or CO₂ emissions inventories, all values are estimated proxies and not official statistics. Cluster 1 corresponds to 2000–2016; Cluster 2 corresponds to 2017–2021. Spatial data: GADM v4.1 (gadm.org). Source: Own elaboration.

SENSITIVITY NOTE: The departmental GDP shares used in this exercise are approximate proxies derived from INE (Instituto Nacional de Estadística) population-weighted estimates and ENEE (Empresa Nacional de Energía Eléctrica) electricity consumption data, and do not constitute official published statistics. A sensitivity analysis was conducted using alternative share

assumptions ($\pm 15\%$ uniform adjustment to shares of the two highest-GDP departments, Cortés and Francisco Morazán). Under all tested scenarios, Cortés and Francisco Morazán retain the highest eco-efficiency values, and the spatial ranking of departments is qualitatively unchanged. Full results are available from the corresponding author upon request. This figure should not be used for subnational policy targeting without validation against official departmental data.