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THE LINK BETWEEN ENVIRONMENTAL PRESSURES AND LIFE EXPECTANCY: FROM SPATIAL DEPENDENCE TO INSTITUTIONAL CHALLENGES IN ASIA

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Abstract

Introduction: *Environmental pressures and institutional capacity are increasingly intertwined determinants of population health in Asia. Yet most cross-country life-expectancy studies treat countries as independent units and rarely distinguish own-country effects from spatial spillovers. This study examines the associations of carbon dioxide (CO2), nitrous oxide (N2O), and fine particulate matter (PM2.5) with life expectancy while jointly considering health expenditure, education, government effectiveness, natural-resource rents, spatial dependence, institutional moderation, and a health-expenditure pathway.*

Methods: *The analysis uses a panel of 39 Asian countries comprising 1,014 country-year observations in the supplied analytical results. Country fixed-effects models are estimated separately for CO2, N2O, and PM2.5. Hausman tests support fixed effects. Spatial autoregressive (SAR), spatial error (SEM), and Spatial Durbin Model (SDM) specifications are compared using a row-normalized inverse-distance weights matrix matched to 39 countries. The SDM is used to estimate spatial lags and to decompose pollutant effects into direct, indirect, and total impacts. Government effectiveness is evaluated as a moderator, health expenditure as a potential pathway, and alternative spatial-weight normalization is used for robustness.*

Results: *Life expectancy averages 71.84 years. In fixed-effects models, CO2 (β=0.1644, p<0.01) and N2O (β=0.1490, p<0.01) are positively associated with life expectancy, whereas PM2.5 is negatively associated (β=-0.0504, p<0.01). Health expenditure, education, and government effectiveness are consistently positive. SDM results preserve these signs: CO2 β=0.1566, N2O β=0.1513 and PM2.5 β=-0.0499 (all p<0.01).*

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Spatial lags of life expectancy and pollutants are individually insignificant, and indirect pollutant effects are not statistically distinguishable from zero. However, total effects are significant for N2O (0.2853, p<0.05) and PM2.5 (-0.0909, p<0.05). Government effectiveness attenuates the negative PM2.5 association (PM2.5×GE=0.0196, p<0.05), while the CO2×GE interaction is positive (0.1698, p<0.01). Pollution is negatively associated with health expenditure for CO2 and PM2.5, but the supplied results do not report a bootstrapped indirect effect; therefore, mediation significance is not claimed. Core coefficient signs are preserved under alternative spatial-weight normalization.

Conclusions: *The results show that PM2.5 is the most consistent environmental threat to longevity in the sample, while health expenditure, education, and effective government are robust positive correlates of life expectancy. Positive CO2 and N2O coefficients should not be interpreted as health benefits of emissions; rather, they point to the development-pollution-health bundle and possible residual confounding in macro panels. Spatial spillovers are weaker than direct effects, but the total N2O and PM2.5 impacts indicate that regional externalities cannot be ignored. Health policy in Asia should combine particulate-pollution control with stronger health-system financing, education, and governance capacity.*

INTRODUCTION

The significant indicator of population health is life expectancy, as it summarizes the cumulative impact of disease, the availability of health services, living standards, education, the environment, and institutional performance. The life expectancy is as much a result of medical treatment as part of human capital-healthier populations can be more actively engaged in education, the job market, and society. Recent evidence from Asia also confirms that life expectancy depends not only on healthcare inputs but also on the quality of institutions, health expenditure, economic conditions, and environmental degradation [1-4]

Asia provides a particularly important setting for studying this nexus. The countries of these regions vary in terms of industrial and urban development, demographic transition, health-system development, and institutional capacity [4, 21]. Urbanization and industrialization can result in increased income and fiscal capacity, as well as greater exposure to particulate pollution, greenhouse gas emissions, heat, congestion, and environmental degradation. Even non-economic cities of Southeast Asia suffer from urbanization and land-use change because of its negative impact on environmental health [5]. It is also known from more recent studies that development can sometimes be associated with increased ecological costs, indicating a trade-off between development and sustainability rather than a gradient [6].

Various studies show that the harmful health impacts of air pollution, especially fine particulate matter. The general findings from studies on Asian and emerging economies are that exposure to PM2.5 decreases life expectancy and that investment in health, education, and robust institutions improves population health [1–4, 8-7]. Simultaneously, estimates of CO2 and other macro-level emissions are not necessarily negative nationwide. However, positive relationships have been found in some studies in which emissions are proxies by 'industrialization', 'electricity access', 'transportation intensity' or

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'income growth ' (in conjunction with improvements in 'health and living standards') [3,8,19]. These results do not indicate a positive biological effect of pollution; rather, they suggest that macroeconomic emissions may become entangled with development processes, and that other emissions or factors affecting development processes may not be measured or may be measured imperfectly.

Three gaps are particularly relevant. First, most studies calculate average country effects while acknowledging that pollution, economic activity, health shocks, technologies, and policies can be transnational. Therefore, many studies take the view that pollution, economic activity, health shocks, technologies, and policies can be transnational, but they calculate average country effects anyway. In such a context, the goal of spatial econometrics is to address the fact that those can influence outcomes in a location in neighboring or connected locations [9–12, 18, 20]. Second, institutions can go beyond being merely an additive factor affecting health; regulation, monitoring, health-system responsiveness, and public investment can be influenced by the effectiveness of government institutions, which in turn can affect health outcomes. Third, the role of health expenditure as a pathway through which environmental stress might impact longevity of life also requires care because a strong association between health expenditure and environmental stress, along with a strong association between health expenditure and longevity of life, does not imply a strong indirect association between environmental stress and longevity of life.

This study aims to fill these gaps by applying a panel dataset of 39 Asian countries and three pollutant-specific models to CO2, N2O, and PM2.5. The four main contributions add of this study in existing literature review. The first is the integration of country fixed effects with spatial econometric models to distinguish between within-country relationships and cross-country spatial dependence. Second, it uses the Spatial Durbin Model (SDM) and distinguishes among direct, indirect, and total effects, but not among marginal effects, which are commonly misinterpreted as derived from a spatial model [9]. Third, it tests whether the pollution-life expectancy relationship is modified by government effectiveness. Fourth, it provides a possible pathway test for health expenditure without assuming mediation when the provided results do not provide a bootstrapped or otherwise tested indirect effect.

Literature Review and Conceptual Framework

Environmental Pressures and Life Expectancy

Health is impacted by environmental quality in more than one way. Exposure to PM2.5 is known to reach very deep into the respiratory system and is linked to cardiopulmonary disease and premature death; thus, at the macro level, higher exposure should lead to a decrease in life expectancy. However, recent cross-country studies of the relationship between the length of working life and emerging and high-longevity economies shown that air pollution is a negative determinant of longevity, even after controlling for economic and social characteristics [2–4, 20 17,]. For E7 economies, the link between PM2.5 and life expectancy has been reported as one of the most detrimental environmental factors, and clean energy and green-transition variables are correlated with better health outcomes [3]. These two gases, CO2 and N2O, have to be interpreted differently. They are not direct indicators of local exposure, like PM2.5, but rather indicators of carbon-intensive activity and greenhouse gases. In macro panels, emissions shifted in step with industrial production, electricity consumption, transport activity, urbanization, fiscal revenues, and the found of health services. Previous Asian studies consistently found negative long-run environmental impacts [1, 7, 19]. In contrast, other studies examined positive or ambiguous macro-environmental emission values, which they attribute to the development process rather than to a protective biological mechanism [8].

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There are also different environmental-health relationships at the national level. Exposure and vulnerability can be modified by climate, baseline disease burden, health-system capacity, urban form, income and institutions. Climate and health-financing impacts are not equal across all countries or along the entire life-expectancy spectrum, as revealed by recent quantile evidence [13]. This high degree of slope heterogeneity is therefore consistent with the broader literature warning against a uniform response to slopes in Asia.

Health expenditure, education, and institutions

Health expenditure can increase life expectancy when additional resources expand preventive care, primary care, diagnostics, treatment, workforce capacity, and financial protection. Several Asian studies have consistently documented positive health-longevity relationships with health spending [1, 2, 5, 16]. As a health-capital measure, health expenditure is used to sustain and repair health capital. Still, the productivity of health spending depends on governance, allocation, and access to it. In the current context, health expenditure is a direct control and an indirect influence on the population's health, which could be affected by environmental pressures. Education is another constant of life. Educational programs can improve health literacy, preventative behaviors, job options, income, and navigation of the health care system. The evidence for machine learning in high-longevity countries in recent years also shows that education is among the variables important for life expectancy along with GDP and health expenditure [14, 22]. Government effectiveness is a measure of a government's ability to design, implement and enforce policies. Improved public management can improve environmental regulation, pollution monitoring, health care provision, public investment, and crisis response. Earlier studies in Asian countries have identified a positive link between institutional quality and life expectancy [1, 2, 13].

Natural resources, development, and the health-environment trade-off

Natural-resource rents supported public services, but they can also lead to institutional stress, unequal distribution, polluting production, and volatility. Theoretically, the sign of natural-resource rents is uncertain. This is consistent with the resource curse literature and empirical studies showing that the health consequences of resource income vary with governance and development conditions [8, 23]. In general, development increased longevity while also increased ecological pressure. The findings from human development and ecological footprint studies indicate that improvements in health, education, and income can go hand in hand with increased resource consumption, especially in middle- and high-income countries [6, 25]. Such tension in the development-environment can serve as a conceptual lens for explaining the divergence in greenhouse-gas coefficients, where there is no obvious environmental harm.

Spatial dependence and hypotheses

Spatial dependence is plausible because emissions, atmospheric transport, economic activity, healthcare technologies, migration, and policy diffusion are not geographically isolated. Spatial models allow an outcome in one country to respond to conditions in other countries through endogenous interaction (a spatial lag of the dependent variable), exogenous interaction (spatial lags of covariates), or spatially correlated disturbances [10]. The SDM is especially useful because it includes spatial lags of both the dependent and explanatory variables and can encompass simpler SAR-type structures [9, 10].

The analysis assesses the following expectations: PM2.5 is expected to be negatively associated with life expectancy; health expenditure, education and government effectiveness are expected to be positive; the signs of the greenhouse-gas coefficients are treated as empirical, as macro-development confounding can cancel out the environmental-health impacts

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of pollution; spatial dependence can lead to indirect effects across countries; and government effectiveness can condition the magnitude of the pollution-health relationships.

Methods

Study design and analytical sample

The study uses a country-level panel design covering 39 Asian countries and time period 26 years data from 2000 to 2025. The total 1,014 observations in the descriptive dataset, equivalent to 39 countries observed up to 26 times. Life expectancy at birth (LEX) is the dependent variable. The focus environmental variables are CO2 emissions, N2O emissions, and PM2.5 exposure. Health expenditure (HE), education (EDU), government effectiveness (GE), and natural-resource rents (NRR) are the four control variables. The results provided are used to determine the abbreviations and the empirical scales for each variable. The variables details explained in table 1.

Table 1: Variables Description

Variable	Role	Description used in manuscript	Expected direction
LEX	Dependent variable (outcome)	Life expectancy at birth, total (years)	-
CO2	Focal exposure	Carbon dioxide emissions (tCO2e per capita)	Negative (−)
N2O	Focal exposure	Nitrous oxide emissions (tCO2e per capita)	Negative (−)
PM2.5	Focal exposure	PM2.5 air pollution, mean annual exposure (micrograms per cubic meter)	Negative (−)
HE	Control / pathway variable	Current health expenditure (% of GDP)	Positive (+)
EDU	Control variable	Average years of schooling, used as a proxy for education	Positive (+)
GE	Control / moderator variable	Government effectiveness: Estimate	Positive (+)
NRR	Control variable	Total natural resources rents (% of GDP)	Ambiguous (−/+)

Baseline fixed-effects specification

Three pollutant-specific models are estimated to avoid forcing conceptually different environmental indicators into the same equation and to keep interpretation transparent. For pollutant P ∈ {CO2, N2O, and PM2.5}, the baseline model is:

$$LEX_{it} = a_i + \beta_i P_{it+y} + \gamma_1 HE_{it} + \delta_2 EDU_{it} + \sigma_3 GE_{it} + \rho_4 NRR_{it} + e_{it}$$

Where a_i denotes country fixed effects that absorb time-invariant country characteristics. The Hausman specification test is used to compare fixed- and random-effects assumptions. In all three pollutant models the null of systematic coefficient equivalence is rejected, supporting fixed effects.

Spatial weights and Spatial Durbin Model

To use spatial econometric models, a matrix W must be provided to capture pairwise connections between countries explicitly. The results presented in the main specification are the row-normalized inverse-distance matrix. Assigning greater weights to closer locations is done with Inverse-Distance weights, and row-normalization scales the weights so that they sum to 1 per row. Spatial panel applications [11, 12, 15] are also often constructed in such a way. The original

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matrix all reported spatial results are therefore 39-country results. The SDM is written as:

$$LEX_{it} + \rho WLEX_{it} + \beta_i P_{it+y} + \gamma' X_{it} + \theta PWP_{it} + \theta X'WX_{it} + \mu_i + e_{it}$$

Where X_{it} contains HE, EDU, GE, and NRR; ρ is the spatial autoregressive coefficient; WP_{it} and WX_{it} is spatially lagged covariates; μ_i captures country fixed effects; and e_{it} is the idiosyncratic disturbance. SAR, SEM, and SDM specifications are compared using log likelihoods. In the supplied results, SDM has the highest (least negative) log likelihood in each pollutant block, although the size of the gain varies across pollutants. An important point of interpretation is that the SDM coefficients are not marginal effects. A change in one country can be propagated through the spatial system, so the proper effect is given by the partial-derivative matrix $(I-\rho W)^{-1}(\beta I+\theta W)$. The elements on the diagonal represent own-country or direct effects, and the off-diagonal elements represent indirect or spillover effects. Average direct, indirect, and total effects are thus reported, as was done by LeSage and Pace [9, 10] using a spatial-econometric approach.

Moderation by government effectiveness

To evaluate whether institutional capacity conditions environmental-health relationships, pollutant and government-effectiveness variables are mean-centered and interacted. The moderation model includes the centered pollutant, centered GE, their interaction, HE, EDU, and NRR. The interaction coefficient indicates how the marginal association between the pollutant and life expectancy changes as government effectiveness increases. For PM2.5, a positive interaction offsets part of a negative main effect; for a pollutant with a positive main coefficient, a positive interaction strengthens that positive conditional association and should not automatically be described as mitigation.

Health-expenditure pathway analysis

The pathway analysis reports two parts: Path A measures the association between each pollutant and health expenditure, and Path B measures the association between health expenditure and life expectancy in the pollutant-outcome model. Typically, an explicit product-of-coefficients test, a bootstrap confidence interval, and/or similar inference would be necessary to establish a statistically significant indirect effect. Such a statistic of indirect effect is not reported in the results provided. Therefore, the analysis is considered to be a plausible pathway analysis rather than a confirmed mediation effect.

Robustness and heterogeneity

Robustness is measured by re-estimating the SDM with alternative spatial-weight normalization. The reported impacts are direct, indirect, and total, compared to the baseline. Further, a Pesaran–Yamagata (PY) slope heterogeneity test is also presented for each pollutant model. In all cases, the null of homogeneous slopes is rejected at the 1% level, suggesting meaningful cross-country variation; therefore, caution is warranted when interpreting whether the estimated coefficients represent a general effect.

Results

Descriptive statistics and correlations

In table 2 described the essential information about of the data. The descriptive sample contains 1,014 observations across 39 Asian countries. Average life expectancy is 71.84 years (SD 5.62), with a range from 55.01 to 85.97. Environmental exposures are highly heterogeneous: CO2 averages 6.36 (SD 7.90), N2O 9.76 (SD 15.54), and PM2.5 32.72 (SD 17.62). Health expenditure averages 4.94, education 75.56, government effectiveness -0.30, and natural-resource rents 13.70. The wide dispersion of the environmental and institutional indicators is consistent with the structural diversity of the 39-country sample. Therefore, the

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outcomes of pairwise correlation are shown in Table A1 (Appendix 1). It show that LEX is strongly correlated with education (r=0.6932) and government effectiveness (r=0.6961). CO2 is also positively correlated with LEX (r=0.5782), while PM2.5 has almost no unconditional correlation with LEX (r=-0.0098). These bivariate relationships are descriptive and should not be read as adjusted or causal effects. Figure 1 display correlation Heat-map results which indicate Life expectancy is positively correlated with education, government effectiveness, and CO_2 emissions, while its correlations with the remaining variables are weak.

Table 2: Descriptive statistics

Variable	N	Mean	SD	Min	Max
LEX	1,014	71.8443	5.6221	55.0050	85.9732
CO2	1,014	6.3642	7.9028	0.1125	29.7041
N2O	1,014	9.7562	15.5365	0.0289	68.8418
PM2.5	1,014	32.7236	17.6181	6.8204	86.0228
HE	1,014	4.9438	2.4775	0.0035	23.0882
EDU	1,014	75.5623	20.0686	13.9595	99.9996
GE	1,014	-0.3025	0.8396	-9.5400	1.6276
NRR	1,014	13.6976	17.5192	0.0000	72.8551

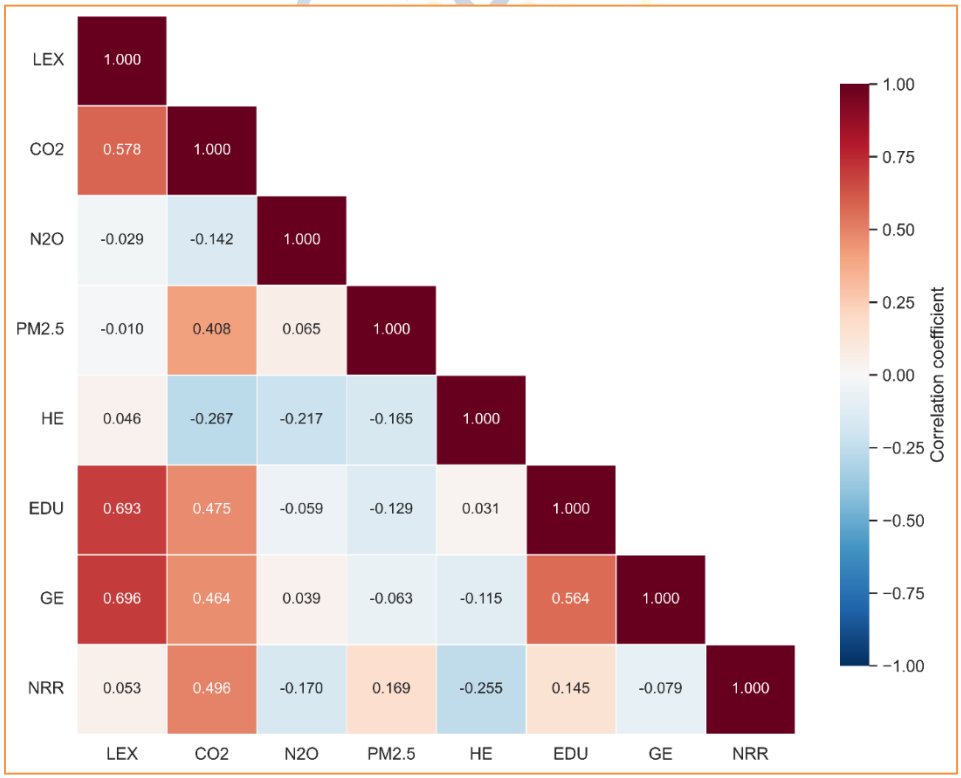


Figure 1: Correlation Heat-map

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Baseline fixed-effects estimates

Table A2 presents the country fixed-effects results. CO2 is positively associated with life expectancy (β=0.1644, p<0.01), as is N2O (β=0.1490, p<0.01). PM2.5 has the opposite sign and is strongly negative (β=-0.0504, p<0.01). The three models explain roughly 46–47% of within-country variation according to the reported within R^2. The control variables are notably stable. Health expenditure ranges from 0.1865 to 0.2474 and is significant at p<0.01 in all models. Education ranges from 0.1292 to 0.1348, also p<0.01. Government effectiveness is positive and large across specifications (0.8003–0.9056, p<0.01). Natural-resource rents have small positive coefficients, statistically significant at conventional levels. These patterns suggest that health-system financing, human capital, and institutional capacity is robust correlates of longevity in the sample.

Hausman tests, Slope of Homogeneity and spatial model comparison

The Hausman tests reject the null that coefficient differences between fixed and random effects are not systematic. The test statistics are 18.37 for CO2 (p=0.0025), 32.36 for N2O (p<0.001), and 28.81 for PM2.5 (p<0.001), supporting the fixed-effects specification. The results are shown in Table A3 (Appendix 1). The Pesaran–Yamagata test rejects slope homogeneity for all three pollutant models. The Δ statistics are 26.347 for CO2, 27.114 for N2O, and 23.984 for PM2.5, with adjusted Δ statistics of 30.827, 31.724, and 28.098, respectively; all p-values are below 0.01. The finding confirms that pollutant-health relationships vary materially across countries and reinforces the need to interpret the reported coefficients as sample-average associations. The outcome of this test described in table A4 and figures A1 to A3 (Appendix 1). Therefore, the comparison of SAR, SEM and SDM specification examined in table 3. The across spatial specifications, focal pollutant coefficients are highly stable. SDM provides the highest log likelihood in each pollutant block: -1882.1314 for CO2, -1871.5583 for N2O, and -1666.1983 for PM2.5. The improvement is modest for CO2 and N2O and more visible for PM2.5 relative to SAR. The stability of the focal coefficients across SAR, SEM, and SDM suggests that the direct pollutant associations are not driven by a single spatial specification.

Table 3: Comparison of SAR, SEM, and SDM specifications

Pollutant	Spatial model	Focal coefficient	Log likelihood	N
CO2	SAR	0.1564(0.0526)***	-1883.3900	1,014
CO2	SEM	0.1563(0.0526)***	-1883.4134	1,014
CO2	SDM	0.1566(0.0526)***	-1882.1314	1,014
N2O	SAR	0.1508(0.0281)***	-1873.5864	1,014
N2O	SEM	0.1515(0.0281)***	-1873.4875	1,014
N2O	SDM	0.1513(0.0281)***	-1871.5583	1,014
PM2.5	SAR	-0.0487(0.0082)***	-1770.9320	1,014
PM2.5	SEM	-0.0496(0.0082)***	-1667.7383	1,014
PM2.5	SDM	-0.0499 (0.0083)***	-1666.1983	1,014

Note: Standard errors in parentheses and significant are at * p<0.10; ** p<0.05; *** p<0.01.

Spatial Durbin Model estimates

The SDM estimation is the core outcomes of the study and explained in table 4. The SDM preserves the baseline pattern. The own-country coefficients are 0.1566 for CO2, 0.1513 for N2O, and -0.0499 for PM2.5, all significant at

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p<0.01. HE, EDU, GE, and NRR remain positive and statistically significant. Government effectiveness is especially large in the PM2.5 specification (1.7749, SE=0.1992). By contrast, none of the reported spatially lagged pollutant terms is significant, and the spatial lag of life expectancy is also statistically insignificant in all three models. These results indicate that the strongest evidence lies in within-country associations rather than in a single, directly estimated spatial-lag channel. This does not rule out cumulative spillovers, which are assessed using marginal-effect decomposition.

Table 7: Spatial Durbin Model results

Variable	(1) CO2	(2) N2O	(3) PM2.5
CO2	0.1566(0.0526)***		
N2O		0.1513 (0.0281)***	
PM2.5			-0.0499(0.0083)***
HE	0.2855(0.0480)***	0.2637 (0.0472)***	0.1994(0.0462)***
EDU	0.1359(0.0067)***	0.1304(0.0067)***	0.1258(0.0065)***
GE	0.8040(0.1436)***	0.8332(0.1394)***	1.7749(0.1992)***
NRR	0.0174(0.0063)***	0.0199(0.0062)***	0.0189(0.0063)***
W × pollutant	-0.1034 (0.2203)	0.1585 (0.1280)	-0.0450 (0.0377)
W × HE	0.1482 (0.2154)	0.2080 (0.2033)	0.0957 (0.1959)
W × EDU	-0.0206 (0.0345)	-0.0237 (0.0332)	-0.0038 (0.0311)
W × GE	0.7679 (0.6335)	0.7915 (0.6134)	0.6420 (0.9514)
W × NRR	0.0059 (0.0309)	-0.0047 (0.0300)	-0.0256 (0.0309)
Spatial lag of LEX	-0.0426 (0.0994)	-0.0863 (0.1016)	-0.0438 (0.1042)
Observations	1,014	1,014	1,014
Countries	39	39	39
Log likelihood	-1882.1314	-1871.5583	-1666.1983

Note: W denotes the row-normalized inverse-distance spatial weights matrix matched to 39 countries. Standard errors in parentheses and significant * p<0.10; ** p<0.05; *** p<0.01

Direct, indirect, and total spatial effects

The marginal-effect decomposition clarifies the economic meaning of the SDM. Direct effects closely reflect the focal coefficients and are significant for all three pollutants. Indirect effects are not statistically significant. The outcomes shown in table 5 and the total effect of CO2 is small and insignificant (0.0511), whereas N2O has a positive total effect of 0.2853 (p<0.05) and PM2.5 has a negative total effect of -0.0909 (p<0.05). This pattern suggests that the evidence for spatial externalities is cumulative rather than visible in any single spatial-lag coefficient. For PM2.5 in particular, the total negative effect is nearly twice the direct effect in magnitude, although the indirect component itself is imprecisely estimated. The most defensible interpretation is therefore that PM2.5 has a robust own-country association and a negative system-wide total association, while evidence for a separately identified cross-border spillover remains limited. Figure 2 shows significant direct effects for all three pollutants, insignificant indirect effects, and significant total effects only for N_2O (positive) and $PM_{2.5}$ (negative)

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Table 5: Direct, indirect, and total spatial effects of pollution

Effect	(1) CO2	(2) N2O	(3) PM2.5
Direct effect	0.1569(0.0526)***	0.1507(0.0281)***	-0.0498(0.0083)***
Indirect effect	-0.1058 (0.2121)	0.1346 (0.1165)	-0.0411 (0.0346)
Total effect	0.0511 (0.2196)	0.2853(0.1181)**	-0.0909(0.0355)**
Observations	1,014	1,014	1,014

Note: Entries are marginal effects with standard errors in parentheses and significant * p<0.10; ** p<0.05; *** p<0.01.

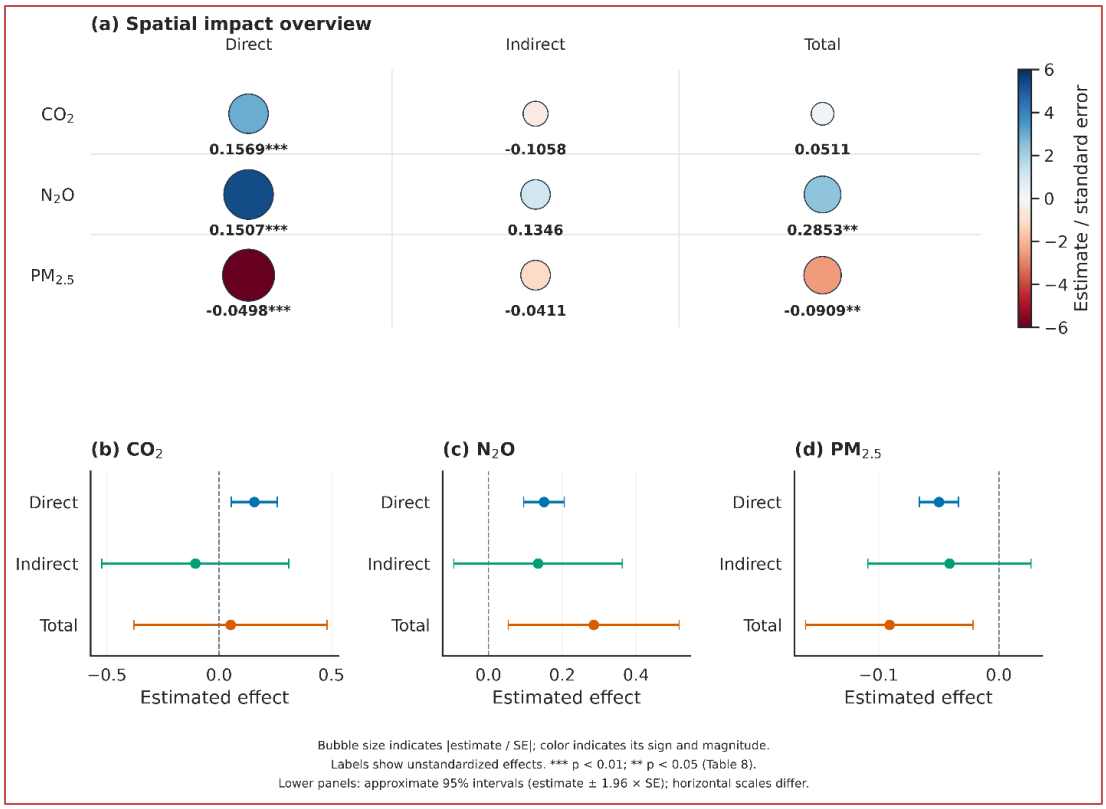


Figure 2. Direct, indirect, and total spatial effects of environmental pressures on life expectancy

Government effectiveness as a moderator

Government effectiveness is strongly and positively associated with life expectancy in all interaction models. The results explained in table 6 and it shows that the CO2, the centered pollutant main effect is 0.0578 and is no longer statistically significant, while the CO2×GE interaction is positive and significant (0.1698, SE=0.0236, p<0.01). This means that the conditional CO2-life expectancy slope becomes more positive at higher levels of government effectiveness. It should not be interpreted as evidence that effective government makes CO2 biologically beneficial; rather, it is consistent with the possibility that countries with stronger institutions are better able to convert emissions-intensive economic activity into public services or to buffer some co-occurring harms. The primary effect is positive for N2O (0.1592, p<0.01), and the N2O×GE term is negative, but not significant (-0.0133). For PM2.5, the main effect is negative (-0.0436, p<0.01) and the PM2.5×GE interaction

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is positive (0.0196, p<0.05). This is the most direct institutional-buffering effect - that is, the more effective the government, the less negative the relationship between PM2.5 and life expectancy. Figure 3 suggests that government effectiveness weakens the negative $PM_{2.5}$ association and strengthens the positive CO_2 association with life expectancy, while the N_2O interaction is insignificant.

Table 6: Moderating effect of government effectiveness

Variable	(1) CO2 × GE	(2) N2O × GE	(3) PM2.5 × GE
Pollutant (centered)	0.0578 (0.0531)	0.1592(0.0287)***	-0.0436(0.0087)***
GE (centered)	1.3071(0.1564)***	0.7734(0.1466)***	1.9592(0.2144)***
Pollutant × GE	0.1698(0.0236)***	-0.0133(0.0095)	0.0196(0.0088)**
HE	0.2409(0.0472)***	0.2676(0.0472)***	0.1830(0.0467)***
EDU	0.1382(0.0065)***	0.1312(0.0067)***	0.1247(0.0065)***
NRR	0.0218(0.0062)***	0.0195(0.0062)***	0.0206(0.0063)***
Observations	1,014	1,014	1,014
Countries	39	39	39
Log likelihood	-1856.9875	-1870.2140	-1663.5331

Note: Pollutants and GE were mean-centered before constructing interaction terms. Standard errors in parentheses and * p<0.10; ** p<0.05; *** p<0.01.

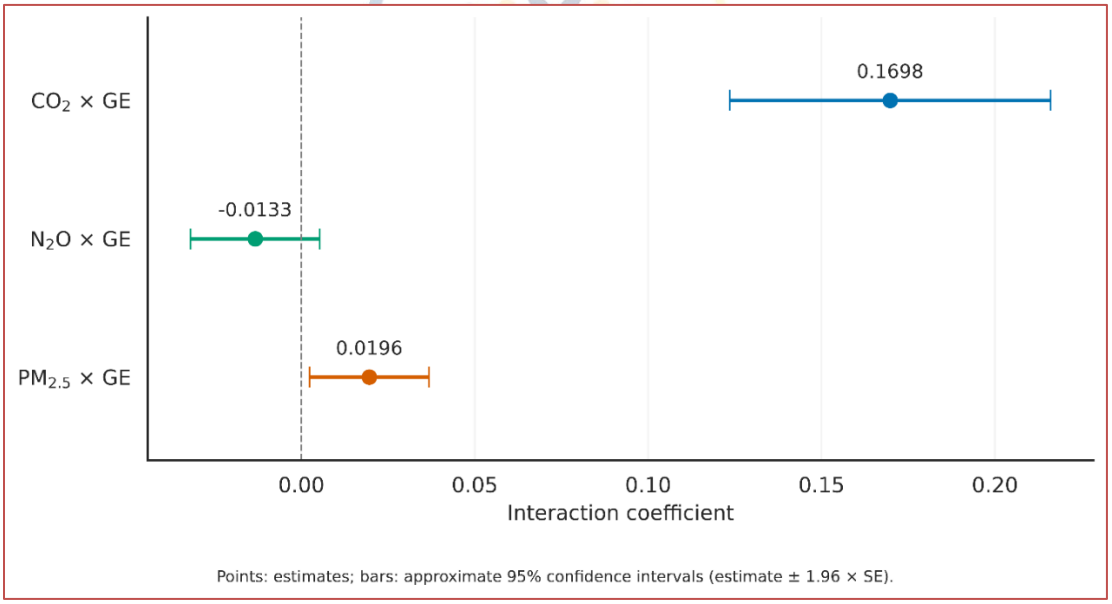


Figure 3. Interaction coefficients between environmental pressures and government effectiveness

Health expenditure as a potential pathway

Path A is negative and significant for CO2 (-0.1199, p<0.01) and PM2.5 (-0.0387, p<0.01), but positive and statistically insignificant for N2O (0.0209). In all outcome models, higher health expenditure is positively and significantly associated with longer life expectancy at a constant level of pollutants (Path B). The direct pollutant coefficients are still important. The polarities of CO2 and PM2.5 are consistent with

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a possible negative relationship between pollution and HE: higher pollution is associated with lower HE, and higher HE with a longer life span. The results provided with the sample data are not based on a bootstrapped indirect-effect estimate and confidence interval, however. The use of formal mediation would, therefore, be statistically inappropriate. The results provide a plausible pathway that can be tested in an indirect-effect test.

Table 7: Health-expenditure pathway analysis

Path/statistic	(1) CO2	(2) N2O	(3) PM2.5
Path A: Pollution → HE	-0.1199 (0.0356)***	0.0209 (0.0194)	-0.0387(0.0058)***
Path B: HE → LEX	0.2855 (0.0480)***	0.2637(0.0472)***	0.1994(0.0462)***
Direct pollutant coefficient	0.1566 (0.0526)***	0.1513 (0.0281)***	-0.0499(0.0083)***
Path A observations	1,014	1,014	1,014
Path B observations	1,014	1,014	1,014

Note: No bootstrapped indirect-effect statistic is reported in the supplied results; formal mediation significance is therefore not asserted.

Robustness to alternative spatial-weight normalization

The alternative weighting specification still keeps the same main signs and significance of the SDM coefficients: CO2 (0.1316, p<0.01); N2O (0.1397, p<0.01); and PM2.5 (-0.0405, p<0.01). The direct effects also remain stable. Indirect effects are small. The overall N2O effects are positive and significant (0.2256, p<0.05), and the overall PM2.5 effects are negative at the 10% level (-0.0608). This pattern also provides qualitative robustness of the central findings to the choice of spatial normalization. The robustness explained in table 7.

Table 8: Robustness test: SDM with alternative spatial-weight normalization

Variable/effect	CO2	N2O	PM2.5
SDM coefficient	0.1316(0.0506)***	0.1397(0.0276)***	-0.0405(0.0080)***
Direct effect	0.1321(0.0506)***	0.1388(0.0277)***	-0.040(0.0080)4***
Indirect effect	-0.0546(0.1806)	0.0868(0.1026)	-0.0204(0.0314)
Total effect	0.0775(0.1868)	0.2256(0.1038)**	-0.0608(0.0321)*
Observations	1,014	1,014	1,014
Countries	39	39	39
Log likelihood	-1695.440	-1685.677	-1516.233
$\chi^2(6)$	11.05	10.56	11.03
Wald test of spatial terms, p-value	0.0869	0.0609	0.0508

*Note: * p<0.10; ** p<0.05; *** p<0.01.*

Discussion

The study has four main findings. First, PM2.5 is consistently associated with reduced life expectancy across fixed-effects, SDM, effect decomposition, and robustness specifications. Second, CO2 and N2O have positive within-country coefficients which remain after spatial modelling. Third, health expenditure, education, and government effectiveness are consistently positive factors for longevity. Fourth, the spatial-

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lag coefficients are not strong; however, the overall impacts of N2O and PM2.5 are statistically significant, meaning that country-level and regional-system interpretations are not the same.

The PM2.5 result is the simplest and most consistent with previous evidence. Fine particulate matter is a direct exposure measure that has a clear cardiovascular and respiratory pathway. The negative coefficient is similar to that for particulate pollution and longevity in studies of Asian and emerging-economy countries [2-4,7]. The negative total PM2.5 effect in the Spatial Decomposition introduces a spatial component: although the contribution of the indirect effect is individually unimportant, the system-wide total effect is still negative. This is important from a health economics perspective, since the benefits of pollution control can extend beyond the jurisdiction in which it is regulated, thereby increasing the benefits of regional cooperation.

A greater degree of caution should be used for the positive CO2 and N2O coefficients. These disagree with a straightforward interpretation of environmental damage, but are not new in macroeconomic studies. The links between CO2 and N2O emissions and production, energy use, transport, agriculture, and industrialization are close. These processes can, at the same time, increase emissions and grow income, infrastructure, sanitation, medical technology, and fiscal capacity in a rapidly developing setting. However, if the model cannot fully represent those co-moving development channels, the emissions coefficient can be positive even when the environmental externality remains detrimental. Previous studies have also cautioned that the positive emission-longevity correlation could be driven by development rather than by positive pollution [8]. The present results are thus only macro-associations and should not be regarded as causal toxicological effects.

The control results support this interpretation. The education and effectiveness of government show the strongest and most consistent positive relationships with life expectancy, and health expenditure is positive in all specifications. The results are consistent with Asian evidence which highlights the importance of financing and the quality of health systems for longevity [1,2]. They are also consistent with findings from other high-longevity countries, which found that GDP, health expenditure, and education are all important and leading factors [14]. That is, the data indicate that social and institutional resources are as important as the environmental exposure itself.

This institutional nuance is captured in the moderation results. In the case of PM2.5, the negative correlation to life expectancy is lessened by higher government effectiveness. This is substantively plausible: an adequate government can enforce air-quality standards, control industrial and transport emissions, improve air-pollution monitoring, increase access to care, and respond more quickly to environmental health threats. The PM2.5 interaction therefore aligns with the hypothesis that institutional capacity can help to mitigate the health impacts of environmental stress. The interaction between CO2 and GE should not, however, be referred to as mitigation. This suggests that the positive relationship between the CO2 coefficient and government effectiveness increases as government effectiveness increases. The first potential explanation is that development and carbon-intensive development occur in tandem and strong institutions enable an economy to reap a larger share of the health-enhancing benefits; the latter is residual confounding. The outcome requires additional nonlinear and income-differentiated analysis to make a stronger case.

The health-expenditure pathway results are indicative and incomplete. Path A indicates that CO2 and PM2.5 are negatively associated with HE, whereas Path B indicates that LEX is positively associated with HE. That sign pattern is allowed with a negative indirect pathway. However, since there is no indirect-effect

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standard error or bootstrapped confidence interval, there is no statistical evidence of mediation. This is significant for reporting at the journal level: if two component paths exist, this is not as strong as evidence that their product is different from zero.

Spatial results are also not as straightforward as strong cross-border dependence. None of the spatial lags of the pollutants are individually significant, and the spatial autoregressive coefficient for LEX is not significant. So, there is no clear evidence that a country's life expectancy automatically reflects that of surrounding countries when controlled for. However, the SDM is a marginally better fit than simpler models, and the marginal-effect decomposition identifies the total effects for N2O and PM2.5 as significant. The proper conclusion is that direct country influences predominate, with stronger spatial propagation effects relevant only for some pollutants. This is also in line with spatial-econometric theory, that is, substantive interpretation should be based on the effects rather than the raw coefficients [9,10]. The slope-heterogeneity tests supplement the average results. There are significant disparities among Asian nations in income, urbanization, climate, energy use, prevalent diseases, healthcare coverage, and institutional capacities. It is therefore not surprising that the test for homogeneous slopes is statistically significant. More recent studies on climate-life expectancy associations also reveal country-level differences and differences across outcome quantiles [13]. Future extensions should estimate region- and/or income-specific impacts, non-linearities (where data allow), and, if data allow, dynamic spatial models.

Health-economic and policy implications

There are a number of policy implications. First of all, control of PM2.5 should be given priority, as it is the only pollutant for which the direct coefficient of PM2.5 is consistently negative and the total spatial effect is also negative and significant. Policy measures should focus on combustion sources, transport emissions, industrial controls on particulates, household fuel transition and capacity building for monitoring. Harmonised regional standards and information sharing can yield health benefits that go beyond what national policy will measure, due in part to the fact that air pollution is not national or international property. Second, health-system investments should go hand in hand with environmental policy. All the models have strong associations between health expenditure and life expectancy. This is not to say that spending volume is enough, but efficiency, coverage and primary-care orientation and targeting are still important. However, the uniformity of the HE coefficient suggests that fiscal space for health is a significant addition to pollution control. Third, education and governance should be viewed as health interventions broadly speaking. Education enhances health literacy and socioeconomic capacity, and good government enhances the likelihood that environmental and health spending will result in the provision of services. In particular, the PM2.5 moderation result implies that the quality of institutions may mitigate the risk of exposure to particulate pollution. Fourth, positive CO2 or N2O coefficients do not give the green light to greenhouse-gas growth by the policy makers. The coefficients are probably a development-emissions bundle and should be interpreted in conjunction with the overall evidence of the fact that "growth" causes climate and environmental health costs. The policy goal is to create a separation between health-enhancing development and pollution by reducing the use of polluting energy technologies, transferring non-polluting technologies, and ensuring efficient public investments. This need to gain human-development without a commensurate rise in ecological pressure has gained increasing emphasis in the sustainability literature [6].

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Strengths and limitations

The study has several strengths. It encompasses a wide range of Asian countries, includes environmental, health-system, educational, institutional, and resource factors, and extends beyond non-spatial panel regression. The SDM framework differentiates direct and system-wide effects, and the signs of the focal coefficients are robust to alternative spatial-weight normalization, as demonstrated by the robustness analysis. The moderation analysis also adds an institutional mechanism that is policy relevant. A few caveats must be noted. One, this is an observation-level panel the estimates are associations and not causal effects. There may still be the threat of reverse causality, time-varying omitted variables, measurement error, and policy endogeneity. Second, the CO2 and N2O coefficients are positive, indicating that further development controls (such as GDP per capita, energy structure, urbanization, industrial composition, sanitation, or inequality) could affect the coefficients for greenhouse gases. Third, the results do not include time fixed effects, instrumental variable identification, dynamic adjustment, or the full absorption of common global shocks. Fourth, the single average coefficient does not reflect cross-country differences (slope-heterogeneity tests indicate this). Fifth, pathway analysis was not used to test for an indirect effect; thus, it was not able to conclude whether mediation occurred. Sixth, the actual calendar years and the source/unit definition for the EDU variable are not provided in the supplied results. They will need to be included in the analytic codebook before submission. The bottom value for government-effectiveness, at -9.54, is outside the range of a few commonly used governance indicators and should be compared with the original variable or its transformation. This doesn't affect the value of this manuscript, as it is mentioned in the results provided. Finally, spatial effects are also important for W. The alternative normalization is used to support the main qualitative findings. Yet, distance thresholds, k-nearest-neighbor matrices, trade or migration networks, and pollution-transport matrices may be compared in the future.

Conclusions

In this study, the relationship between environmental pressures and life expectancy is explored for a panel of 39 Asian countries, with fixed-effects and spatial panel econometric models. The evidence indicates that PM2.5 is the most powerful environmental risk, with a negative coefficient in the baseline and SDM estimates and a negative overall spatial impact. CO2 and N2O are positively associated with life expectancy in the macro panel. Still, the coefficients should not be interpreted as health benefits from CO2 emissions, but rather as conditional associations with the country's development. There is a consistent link between life expectancy and health expenditure, education, and government effectiveness. Health expenditure, education, and government effectiveness are consistently negatively associated with life expectancy. The negative relationship between PM2.5 and government effectiveness also dampens the effect, further highlighting the importance of institutions in translating environmental and fiscal policies into health protection. The spatial spillover is not always significant, but the spatial total effect estimates for N2O and PM2.5 suggest environmental-health relationships can go beyond the own-country coefficient. The message of the policy is therefore embedded: Clean air, good health financing, quality education, and competent public institutions are key enablers of longer, healthier lives in Asia. Environmental and health policy should not be made separately. The empirical findings rather suggest a combined approach that diminishes the impact of particulates and increases the institutional and social capacity that translates economic development into population health.

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Appendix 1

Table A1. Correlation matrix

Variable	LEX	CO2	N2O	PM2.5	HE	EDU	GE	NRR
LEX	1.0000							
CO2	0.5782	1.0000						
N2O	-0.0293	-0.1417	1.0000					
PM2.5	-0.0098	0.4079	0.0653	1.0000				
HE	0.0456	-0.2667	-0.2173	-0.1650	1.0000			
EDU	0.6932	0.4746	-0.0594	-0.1286	0.0307	1.0000		
GE	0.6961	0.4639	0.0391	-0.0626	-0.1150	0.5641	1.0000	
NRR	0.0532	0.4960	-0.1702	0.1691	-0.2551	0.1453	-0.0790	1.0000

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Table A2. Baseline fixed-effects regression results

Variable	(1) CO2	(2) N2O	(3) PM2.5
CO2	0.1644(0.0521)***		
N2O		0.1490(0.0273)***	
PM2.5			-0.0504(0.0082)***
HE	0.2474(0.0457)***	0.2261(0.0450)***	0.1865(0.0462)***
EDU	0.1348(0.0066)***	0.1292(0.0065)***	0.1315(0.0063)***
GE	0.8003(0.1428)***	0.8342(0.1388)***	0.9056(0.1378)***
NRR	0.0173(0.0062)***	0.0204(0.0061)***	0.0153(0.0061)**
Constant	59.3938(0.5241)***	59.4768(0.4941)***	62.7043(0.6506)***
Observations	1,014	1,014	1,014
Countries	39	39	39
Within R^2	0.4621	0.4728	0.4703

Note: Standard errors in parentheses. Therefore, * p<0.10; ** p<0.05; *** p<0.01 and all models use country fixed effects.

Table 3A: Hausman specification tests

Model	χ^2	df	p-value	Indicated specification
CO2	18.37	5	0.0025	Fixed effects
N2O	32.36	5	<0.001	Fixed effects
PM2.5	28.81	5	<0.001	Fixed effects

Note: The null hypothesis is that coefficient differences are not systematic.

Table 4A: Pesaran–Yamagata slope heterogeneity test

Model	Δ statistic	p-value	Adjusted Δ statistic	p-value	Conclusion
CO2	26.347	0.000	30.827	0.000	Heterogeneous
N2O	27.114	0.000	31.724	0.000	Heterogeneous
PM2.5	23.984	0.000	28.098	0.000	Heterogeneous

Note: Null hypothesis: slope coefficients are homogeneous across countries.

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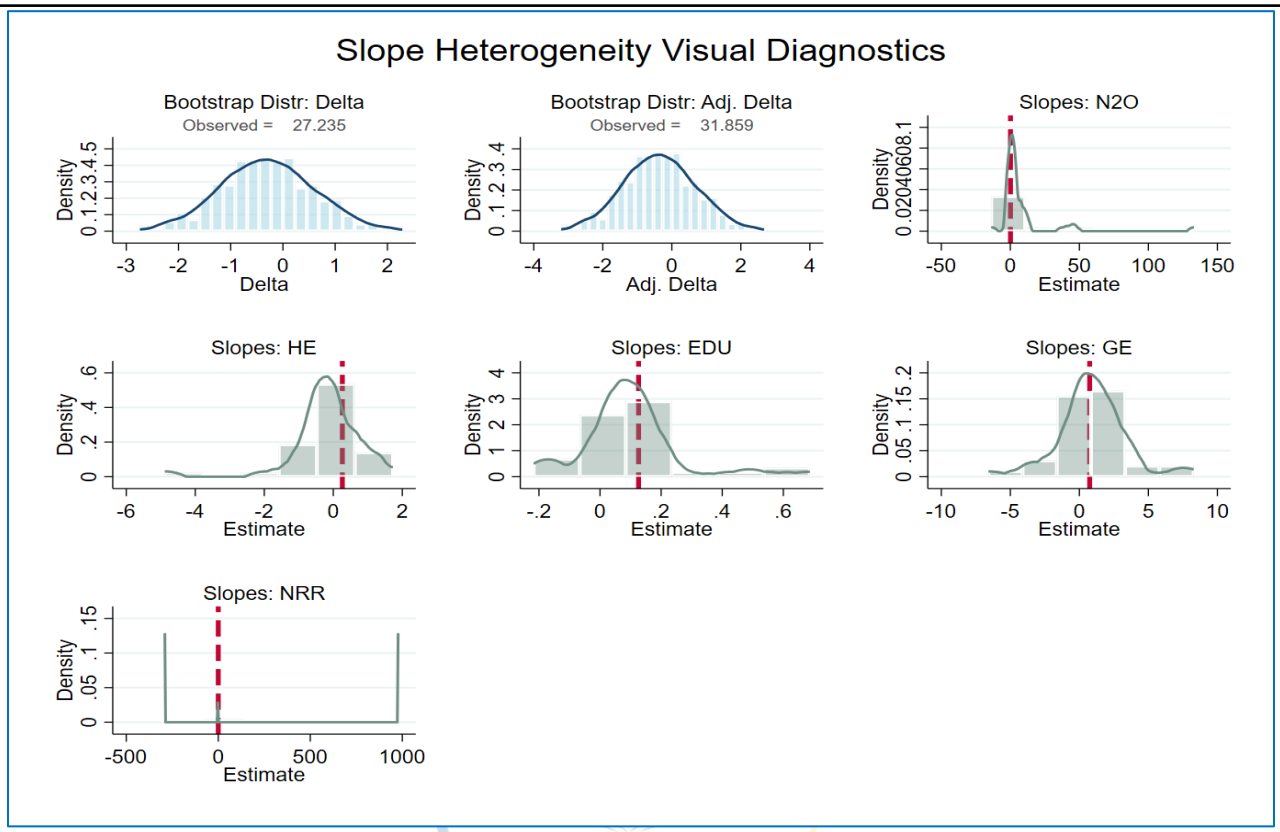


Figure A1: Model 1

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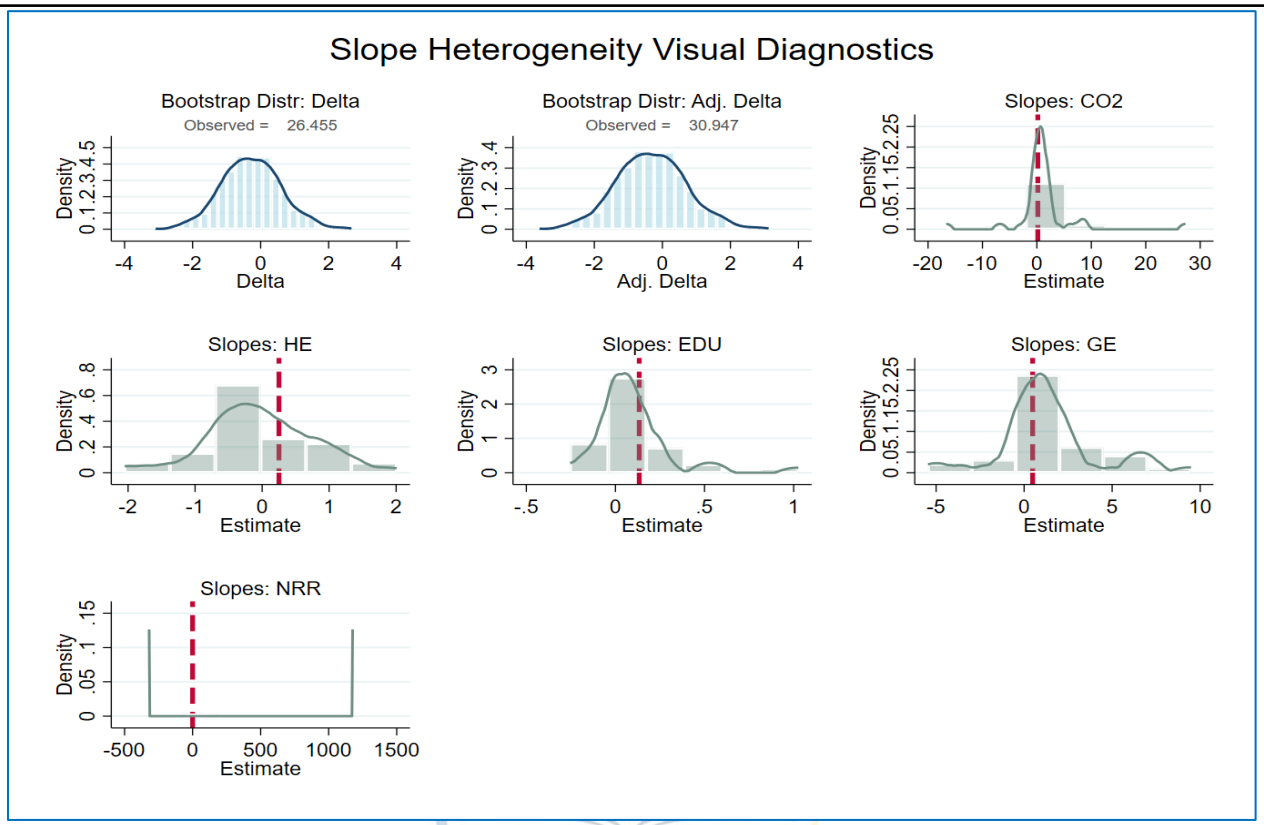


Figure A2: Model 2

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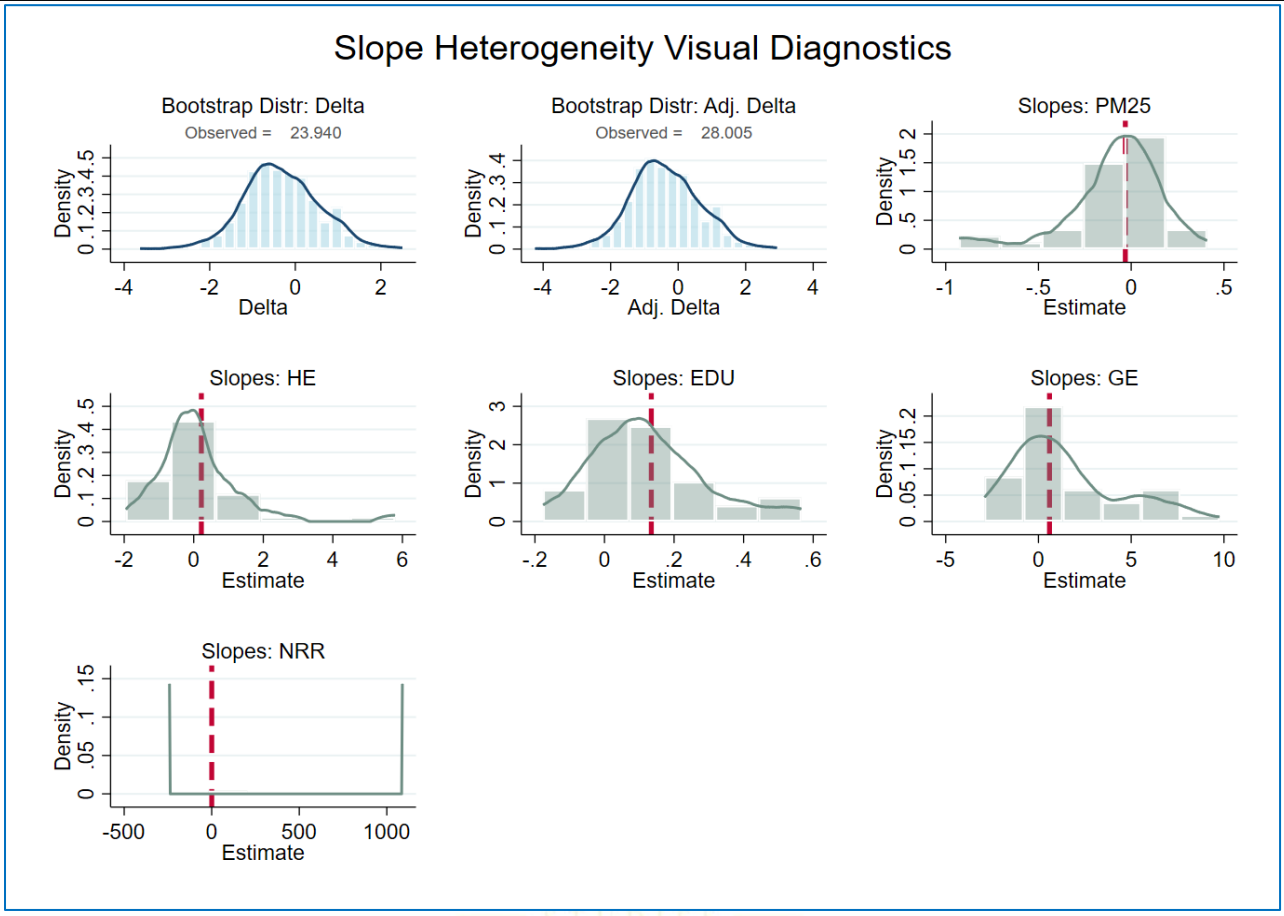


Figure A3: Model 3