The Environmental Kuznets Curve in the 21st Century

Future projections under socioeconomic and climate change scenarios

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Motivation and central question

Starting point

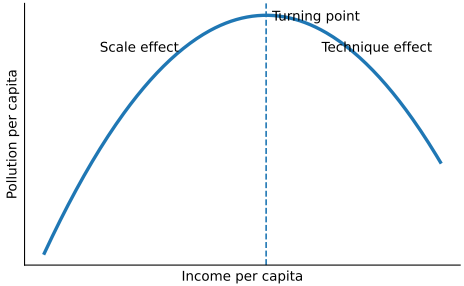
The Environmental Kuznets Curve (EKC) suggests that pollution may first rise with income and then decline after economies become sufficiently developed.

- Most EKC evidence is **historical** and often focuses on CO_2.
- The 21st century will be shaped by very different paths of climate policy, technological change, energy systems, and inequality.
- The key question is therefore forward-looking:

Does the inverted-U EKC persist under alternative socioeconomic and climate change futures?

The EKC intuition

- **Scale effect**: industrialization and output expansion increase emissions.
- **Composition effect**: economies shift toward cleaner sectors as they develop.
- **Technique effect**: richer economies adopt cleaner technologies and regulation.



Interpretation in this paper

The EKC is used as a **diagnostic tool** to summarize the income-pollution path implied by each future scenario.

Literature and gap

- The classical EKC literature documents inverted-U patterns for some pollutants and contexts.
- Other work shows that EKC shapes can be U-shaped, N-shaped, or sensitive to institutions, trade, and empirical specification.
- Recent structural EKC research emphasizes that environmental improvements require policy, technology, and institutional capacity, not growth alone.

Gap addressed here

Existing EKC studies are mainly retrospective. This paper asks how EKC-type relationships may evolve **up to 2100** under structured SSP–RCP futures.

What the paper contributes

1. **Forward-looking EKC analysis**: combines the EKC framework with SSP–RCP projections.
2. **Global pollutant-specific scope**: 193 countries, four future pathways, seven air pollutants.
3. **Robustness and interpretation**: compares quadratic, cubic, trend-adjusted, outlier-adjusted, clustered-SE, and semi-parametric specifications.

The paper does not forecast one future; it compares income-pollution relationships across plausible future worlds.

Scenario framework: four future worlds

Pathway	Short label	Narrative used in the paper
SSP1–2.6	**Sustainability**	Global cooperation, clean energy, strong environmental policy, low population growth.
SSP2–4.5	**Middle of the road**	Historical trends continue, with moderate growth and gradual mitigation.
SSP4–6.0	**Inequality**	Technological and income inequality; cleaner rich regions and constrained poorer regions.
SSP5–8.5	**Fossil fuel development**	Rapid GDP growth with high fossil-fuel reliance and delayed mitigation.

Why this matters for EKC interpretation

Scale, composition, and technique effects are embedded in the scenario assumptions, rather than estimated from random historical variation alone.

Data

- **Countries**: 193 countries and territories
- **Period**: 1980–2100
- **Scenarios**: SSP1–2.6, SSP2–4.5, SSP4–6.0, SSP5–8.5
- **Core variables**: GDP, population, air pollution

Seven pollutants

BC	black carbon
CH_4	methane
CO	carbon monoxide
NH_3	ammonia
NMVOC	non-methane volatile organic compound
NO	nitric oxide
SO_2	sulfur dioxide

GDP and population are from IIASA SSP Scenario Explorer 3.0; emissions are from the IIASA RCP Database.

From scenario data to a balanced panel

- GDP and population are provided in five-year intervals.
- Emissions are provided at ten-year intervals.
- Historical GDP is missing for 53 countries.

Refinement

- **Backward extrapolation** fills missing historical GDP values.
- **Spline interpolation** fills intervening years for GDP, population, and emissions.
- **Visual validation** checks confirm that interpolation does not introduce artificial jumps.

Outcome: balanced annual country-level panel, 1980–2100.

Empirical strategy

Benchmark EKC specification

$$\ln(\text{Pollution pc}_{it}) = \beta_1 \ln(\text{GDPpc}_{it}) + \beta_2[\ln(\text{GDPpc}_{it})]^2 + \gamma_i + \delta_t + u_{it}.$$

- Estimated separately by pollutant and SSP–RCP pathway.
- Country fixed effects control time-invariant cross-country differences.
- Year fixed effects control global shocks and common time patterns.
- Driscoll–Kraay standard errors address cross-sectional dependence, serial correlation, and heteroskedasticity.

How to interpret the coefficients and turning points

- In historical EKC studies, GDP is often interpreted as a driver of emissions.
- In SSP–RCP projections, GDP **co-evolves** with technology, policy, energy systems, land use, and demography.
- Therefore, the estimated EKC summarizes the **income-pollution trajectory implied by a scenario**.

Turning point interpretation

Turning points are **conditional reference points**, not deterministic income thresholds at which pollution will automatically decline.

Main findings

1. **No universal inverted-U**: EKC shapes differ across pollutants and scenarios.
2. **Sustainability matters**: declining paths emerge mainly under SSP1–2.6.
3. **SO_2 is the clearest case**: it shows the most consistent declining pattern across significant scenarios.
4. **Combustion-related pollutants**: BC, NMVOC, and SO_2 display clearer EKC patterns.
5. **Agricultural pollutants**: CH_4 and NH_3 often show rising or weakly declining paths.

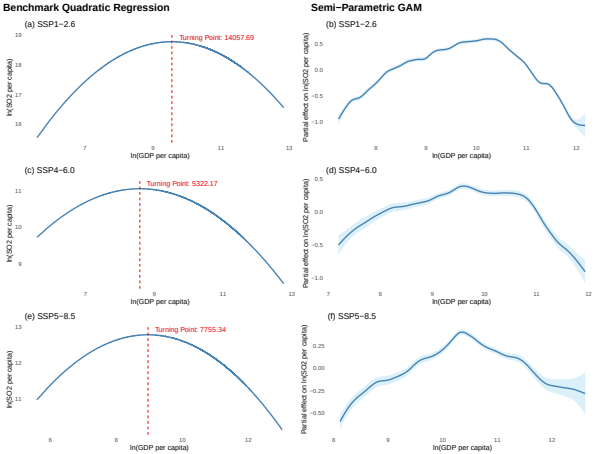
Economic growth alone is not enough to ensure cleaner air.

Results by pollutant and scenario

Pollutant	SSP1–2.6	SSP2–4.5	SSP4–6.0	SSP5–8.5
BC	**inverted-U**	–	–	**inverted-U**
CH_4	**inverted-U**	rising / non-declining	rising / non-declining	rising / non-declining
CO	**inverted-U**	–	mixed / U-shaped	–
NH_3	–	rising / non-declining	mixed / U-shaped	mixed / U-shaped
NMVOC	**inverted-U**	rising / non-declining	rising / non-declining	**inverted-U**
NO	rising / non-declining	rising / non-declining	–	–
SO_2	**inverted-U**	–	**inverted-U**	**inverted-U**

Full estimates and specification-specific details are in the paper and supplement.

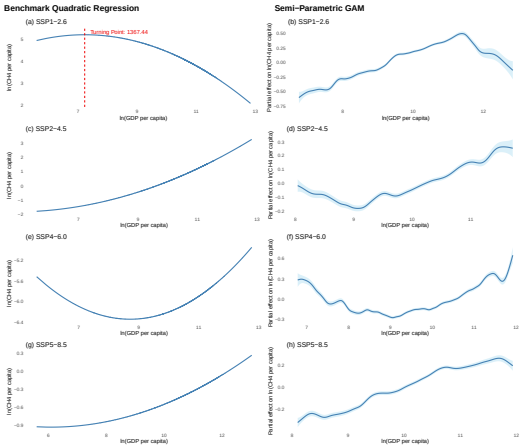
Combustion-related pollutants: the clearest EKC evidence



- SO_2 is closely linked to fossil-fuel combustion and industrial processes.
- It is relatively responsive to policy, fuel switching, desulfurization, and end-of-pipe controls.
- This makes it the pollutant with the most consistent declining EKC pattern.

Agricultural and land-use pollutants: weaker EKC patterns

- CH_4 and NH_3 are linked to livestock, fertilizer, waste, rice cultivation, and land-use practices.
- These sectors have weaker regulatory coverage and slower technological change.
- The classical inverted-U is therefore much less robust.



Policy implication

Energy transition is not enough; agricultural modernization is central.

Turning points and spatial heterogeneity

	SSP1	SSP2	SSP4	SSP5
BC	2.6–2.9	–	–	2.3–2.7
CH_4	0.8–1.4	–	–	–
CO	1.6–1.8	–	0.9–1.3	–
NMVOC	2.7–2.8	–	–	1.6–2.6
SO_2	14.0–25.7	–	2.0–17.1	3.6–7.8

Ranges in thousand US dollars; only statistically significant quadratic models.

- TPs vary substantially across scenarios and pollutants.
- Many low-income countries remain below some TP ranges for longer periods.

Robustness checks

Robustness checks include:

- clustered standard errors at the country level,
- exclusion of outliers,
- cubic specification,
- country-specific linear time trends,
- semi-parametric GAM specification.

Overall

The qualitative EKC patterns are broadly preserved across robustness checks.

Implications for cleaner production

Combustion-related pollutants

BC, CO, NMVOC, NO, SO_2

- fuel switching away from coal and oil,
- electrification and clean public transport,
- vehicle standards and inspection systems,
- flue-gas desulfurization and industrial retrofits.

Agricultural and biogenic pollutants

CH_4, NH_3

- precision fertilization,
- improved manure storage and management,
- biogas and anaerobic digestion,
- methane capture and leakage control.

Main implication: policy must be early, pollutant-specific, and scenario-aware.

Conclusion

1. The inverted-U EKC is **not universal** in the 21st century.
2. Declining income-pollution paths appear mainly under **sustainability-oriented futures**.
3. SO_2 provides the strongest declining pattern; CH_4 and NH_3 require targeted agricultural and land-use policies.
4. The results are **conditional scenario diagnostics**: they show what kind of income-pollution relationship is implied by each future pathway

Thank you

Questions and discussion

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Backup: pollutant sources

Pollutant	Main source profile	Interpretation for EKC patterns
BC	Incomplete combustion of fossil fuels and biomass; wildfires	Combustion-related, but affected by diffuse and natural sources
CO	Incomplete combustion in transport, industry, residential energy, biomass burning	Broad combustion marker; source mix can vary strongly by scenario
NO	Fossil-fuel combustion, transport, power generation, industry	Closely linked to activity growth and combustion technology
NMVOC	Solvents, fuel production, petrochemicals, transport, vegetation	Mixed industrial, transport, and natural sources; less uniform response
SO_2	Coal and oil combustion, power generation, industry, metal smelting	More directly controllable through fuel switching, low-sulfur fuels, desulfurization, and regulation
NH_3	Fertilizer use, livestock, manure management	Agricultural source; weaker automatic response to income growth
CH_4	Livestock, rice cultivation, waste, fossil-fuel extraction	Agricultural and energy-related; requires targeted sectoral policies

Why SO_2 is the clearest case

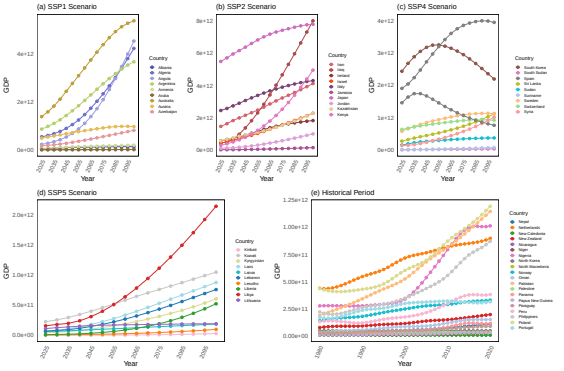
SO_2 is combustion-related, but its main anthropogenic sources are more concentrated and more directly regulated than those of several other pollutants. This makes the **technique effect** more visible: fuel switching, desulfurization, and industrial controls can reduce SO_2 even when economic activity continues to grow.

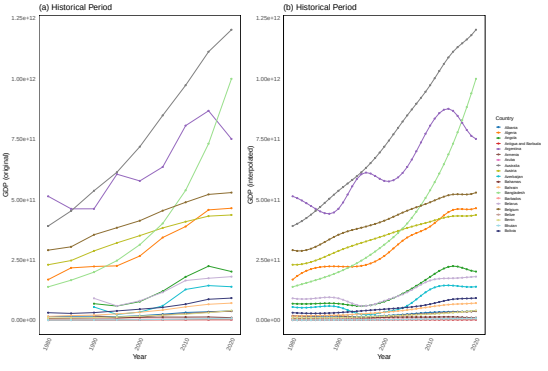
Back

Backup: interpolation and validation

- **Issues**:
  - GDP provided in 5-year intervals, air pollution in 10-year intervals
  - One fourth of the countries were missing historical GDP
- **Solution**:
  - **Backward extrapolation** of GDP using average country-specific growth rates
  - **Spline interpolation** to fill intervening years for GDP, population, and emissions
- **Rationale**:
  - Preserves **non-linear trends**
  - Avoids strong parametric restrictions on dynamics
  - Widely used
  - Visual validation checks show smooth transitions and no artificial breaks.
- **Result**: balanced panel for 1980–2100 enabling **panel regressions** and turning-point analysis.

Backup: interpolation and validation





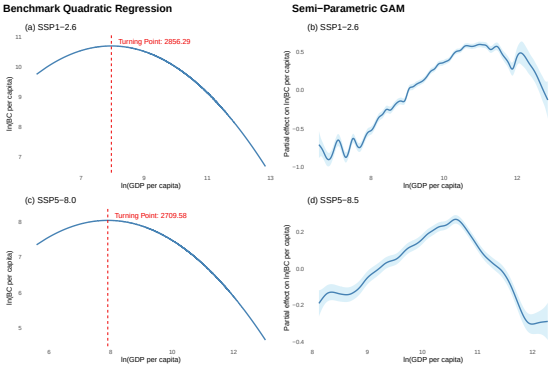
Back

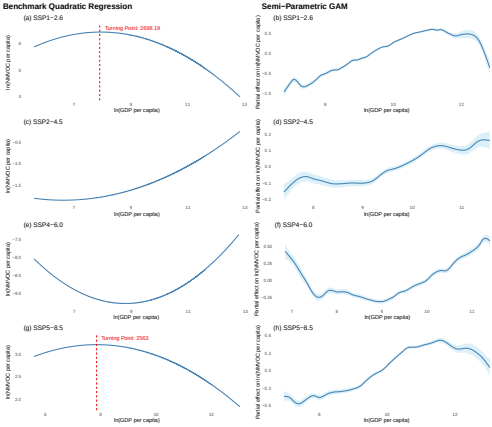
Backup: diagnostic tests

- Cross-sectional dependence: Pesaran CD and Breusch–Pagan LM tests.
- Serial correlation: Breusch–Godfrey, Durbin–Watson, and Wooldridge tests.
- Heteroskedasticity: Breusch–Pagan test.
- Long-run relation: Kao cointegration test.
- Unit-root tests: Augmented Dickey-Fuller, Levin-Lin-Chu, Im-Pesaran-Shin, and Fisher-PP

Back

Backup: alternative pollutant results





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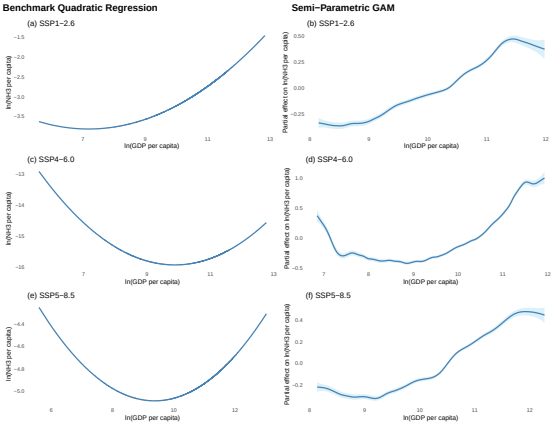

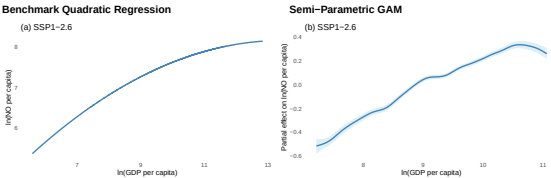

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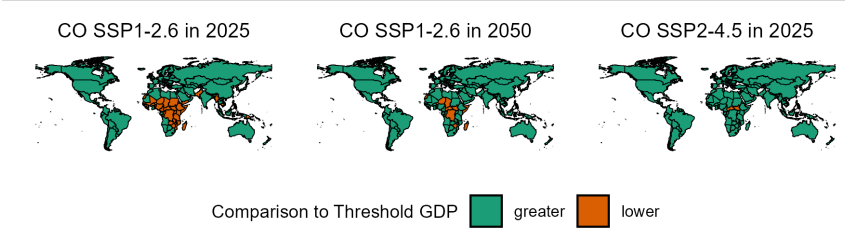
Backup: spatial heterogeneity



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Backup: limitations and future research

- Results are conditional on SSP–RCP assumptions.
- Turning points inherit uncertainty from both the fitted regressions and scenario narratives.
- CO_2 is not included because globally consistent country-level projections are unavailable for this framework.
- Future work can incorporate regional disaggregation, climate damages, tipping points, and transition costs.