Supplementary Material: Panel Regression and Spatial Durbin Model Results

Rationale for Reporting These Results as Supplementary Material

Following the reviewer's suggestion, we conducted panel fixed-effects (FE) regression and Spatial Durbin Model (SDM) analyses to examine the relationship between terrain complexity and carbon emissions. However, these models yielded limited results due to fundamental methodological constraints:

1. **Panel FE absorbs TCI.** Because TCI is a time-invariant city characteristic (derived from a single-epoch 2020 DEM), it is perfectly collinear with city fixed effects and cannot be estimated in a two-way FE specification.

2. **Random Effects assumption is questionable.** While RE allows estimation of TCI, it requires the strong assumption that city-specific effects are uncorrelated with regressors. Given that terrain fundamentally shapes economic structure, this assumption is unlikely to hold.

3. **SDM with N=21 is underpowered.** The cross-sectional SDM with only 21 spatial units yields unstable coefficient estimates with wide standard errors, as reflected in the negative R^2 and uniformly insignificant spatial terms.

We therefore adopt group comparison analysis and Geodetector as the primary analytical framework in the main text, which are better suited to our cross-sectional identification strategy with a small number of spatial units.

Table S1: Panel Fixed-Effects Regression

Table S2: Random Effects Regression

Table S3: Spatial Durbin Model (Cross-sectional)

Table S1. Panel two-way fixed-effects regression. Dependent variable: $\ln(CO_2)$.

Variable	**Coef.**	**Std. Err.**	***t*-stat**	***p*-value**
Constant	6.370	0.353	18.054	0.000***
$\ln(\text{INV})$	−0.075	0.033	−2.300	0.022**
$\ln(\text{GDP})$	0.091	0.046	1.984	0.048**
IS (%)	−0.000	0.001	−0.233	0.816
EI	0.045	0.105	0.427	0.670
TCI	*Absorbed by city fixed effects*			
Entity effects: Yes Time effects: Yes				
$N = 462$ Entities = 21 Periods = 22				
Within $R^2 = 0.037$ $F(4, 416) = 4.015$, $p = 0.003$				

Note: Clustered standard errors at the city level. *** $p < 0.01$, ** $p < 0.05$. TCI is time-invariant and perfectly collinear with city fixed effects; its coefficient cannot be identified in this specification.

Table S2. Random effects regression. Dependent variable: $\ln(CO_2)$.

Variable	**Coef.**	**Std. Err.**	***t*-stat**	***p*-value**
Constant	5.529	0.495	11.178	0.000***
$\ln(\text{INV})$	0.218	0.018	12.361	0.000***
$\ln(\text{GDP})$	−0.018	0.007	−2.445	0.015**
IS (%)	0.001	0.001	0.601	0.548
EI	−0.171	0.055	−3.093	0.002***
TCI	−0.516	1.441	−0.358	0.720
$N = 462$ Entities = 21 $R^2 = 0.762$				
$F(5, 456) = 291.73$, $p = 0.000$				

Note: Clustered standard errors at the city level. *** p < 0.01, ** p < 0.05. TCI coefficient is not significant ($p = 0.720$), with a very large standard error relative to the point estimate, indicating that the RE model cannot reliably identify terrain effects. The Hausman test is expected to favor FE over RE, further undermining the validity of TCI estimation under this specification.

Table S3. Spatial Durbin Model (2SLS). Dependent variable: mean $\ln(CO_2)$. $N = 21$ cities.

Variable	**Coef.**	**Std. Err.**	***t*-stat**	***p*-value**
Constant	-13.402	13.598	-0.986	0.340
$\ln(\text{INV})$	1.254	0.533	2.352	0.033**
TCI	-3.778	3.822	-0.989	0.339
$W \cdot \ln(\text{INV})$	-2.309	2.216	-1.042	0.314
$W \cdot \text{TCI}$	6.460	5.963	1.083	0.296
ρ $(W \cdot Y)$	3.983	3.409	1.169	0.261
$R^2 = -0.461$	Spatial weights: K-nearest neighbors (k=4)			

Note: Estimated via spatial 2SLS with instruments $\{X, WX, W^2X\}$. The negative R^2 indicates severe model misspecification, likely due to the extremely small sample size ($N = 21$). All spatial terms (W)$\cdot$ TCI, $W \cdot \ln(\text{INV})$, ρ) are insignificant, confirming that the SDM cannot reliably identify spatial effects with only 21 cross-sectional units. TCI direct effect = -3.778, indirect effect = 6.460, total effect = 2.682 (all insignificant). ** $p < 0.05$.