

Unintended consequences of trade in environmental innovation: Agricultural emissions, sectoral leakage, and the Kuznets curve hypothesis

XINYI GU¹, JIANMIN LI^{1*}, FARZAN YAHYA^{2*} , MUHAMMAD WAQAS¹, AMAD RASHID³

¹*School of Economics and Management, Jiangsu University of Science and Technology, Jiangsu, P.R. China*

²*School of Economics and Management, Nanchang Institute of Technology, Jiangxi, P.R. China*

³*School of Management, Forman Christian College University, Lahore, Pakistan*

*Corresponding author: farzan.yahya@yahoo.com; ljm2017@just.edu.cn

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Electronic supplementary material (ESM)

Supplementary Tables S1–10
Exhibit A

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Table S1. Sample countries

Argentina, Australia, Austria, Azerbaijan, Burundi, Belgium, Benin, Burkina Faso, Bulgaria, Bosnia and Herzegovina, Belarus, Belize, Bolivia, Brazil, Brunei Darussalam, Botswana, Chile, China, Congo Rep., Colombia, Comoros, Costa Rica, Cyprus, Czechia, Germany, Denmark, Dominican Republic, Ecuador, Egypt Arab Rep., Spain, Estonia, Finland, Fiji, France, United Kingdom, Georgia, Greece, Grenada, Guatemala, Guyana, Hungary, Indonesia, India, Ireland, Iceland, Israel, Jamaica, Jordan, Japan, Kazakhstan, Kyrgyz Republic, Cambodia, Korea, Rep., Lesotho, Lithuania, Luxembourg, Latvia, Morocco, Moldova, Madagascar, Mexico, North Macedonia, Malta, Myanmar, Montenegro, Mozambique, Mauritius, Malawi, Malaysia, Namibia, Niger, Nigeria, Nicaragua, Netherlands, Norway, Pakistan, Peru, Philippines, Poland, Portugal, Paraguay, Romania, Russian Federation, Senegal, Singapore, El Salvador, Serbia, Sao Tome and Principe, Slovak Republic, Slovenia, Sweden, Eswatini, Seychelles, Togo, Thailand, Turkiye, Tanzania, Uganda, Ukraine, Uruguay, United States, Viet Nam, South Africa, Zambia, and Zimbabwe.

Table S2. Summary of variables

Acronym	Variable	Measurement	Sources
Dependent variables			
<i>AGN₂O</i>	Agricultural nitrous oxide emissions	Agricultural N ₂ O emission (% of total GHGs)	WDI
<i>AGMETH</i>	Agricultural methane emissions	Agricultural CH ₄ emission (% of total GHGs)	WDI
Independent variables			
<i>EEST</i>	Exports of environmentally sound technologies	Exports of ESTs in current USD	OWID
<i>IEST</i>	Imports of environmentally sound technologies	Exports of ESTs in current USD	OWID
<i>AGVA</i>	Agricultural productivity	Agricultural value added (% of <i>GDP</i>)	WDI
Control variables			
<i>GDP</i>	Economic development	Gross domestic product per capita in current USD	WDI
<i>FD</i>	Financial development	Domestic credit to private sector by banks (% of <i>GDP</i>)	WDI
Additional proxies of EST			
<i>AGSEXP</i>	Agricultural sustainable exports	Exports of ESTs in current USD × agricultural raw material exports (% of total merchandise exports)	WDI
<i>AGSIMP</i>	Agricultural sustainable imports	Imports of ESTs in current USD × agricultural raw material imports (% of total merchandise imports)	WDI

EST – environmentally sound technologies; *AGN₂O* – agricultural N₂O emissions; *AGMETH* – agricultural methane emission; *EEST* – exports of environmentally sound technologies; *IEST* – imports of environmentally sound technologies; *AGVA* – agricultural productivity (agricultural value added); *GDP* – gross domestic product; *FD* – financial development; WDI – World Development Indicators; OWID – our world in data

Source: Compiled and calculated by the authors

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Table S3. Slope homogeneity test

Model	Pesaran and Yamagata test	
	Δ	Δ -adjusted
$AGN_2O = f(EEST, AGVA, AGVA_2, X)$	8.618***	14.292***
$AGN_2O = f(IEST, AGVA, AGVA_2, X)$	7.217***	11.968***
$AGMETH = f(EEST, AGVA, AGVA_2, X)$	9.277***	15.383***
$AGMETH = f(IEST, AGVA, AGVA_2, X)$	8.342***	13.834***

***significance at 1% level; X – vector of control variables; AGN_2O – agricultural N_2O emissions; $AGMETH$ – agricultural methane emission; $EEST$ – exports of environmentally sound technologies; $IEST$ – imports of environmentally sound technologies; $AGVA$ – agricultural productivity (agricultural value added)

Source: Compiled and calculated by the authors using data from Our World in Data and World Development Indicators

Table S4. Panel unit root tests

Variables	CADF		CIPS	
	I(0)	I(1)	I(0)	I(1)
AGN_2O	−1.794	−2.247***	−1.889	−3.157***
$AGMETH$	−0.734	−1.993**	−1.184	−2.885***
$EEST$	−1.260	−2.453***	−1.610	−3.088***
$IEST$	−1.713	−2.008***	−1.841	−2.874***
$AGVA$	−1.198	−1.914**	−1.810	−3.406***
GDP	−0.959	−1.407	−1.294	−2.262***
FD	−1.595	−2.146***	−1.629	−2.421***

, *significance at 5 and 1% level, respectively; Cross sectionally augmented Im-Pesaran-Shin; CIPS – Cross-sectionally augmented Dickey-Fuller; AGN_2O – agricultural N_2O emissions; $AGMETH$ – agricultural methane emission; $EEST$ – exports of environmentally sound technologies; $IEST$ – imports of environmentally sound technologies; $AGVA$ – agricultural productivity (agricultural value added); GDP – gross domestic product *per capita*; FD – financial development

Source: Compiled and calculated by the authors using data from Our World in Data and World Development Indicators

Table S5. Westerlund cointegration test

Model	Variance ratio
$AGN_2O = f(EEST, AGVA, AGVA_2, X)$	9.193***
$AGN_2O = f(IEST, AGVA, AGVA_2, X)$	9.292***
$AGMETH = f(EEST, AGVA, AGVA_2, X)$	11.593***
$AGMETH = f(IEST, AGVA, AGVA_2, X)$	11.481***

***significance at 1% level; X – vector of control variables; AGN_2O – agricultural N_2O emissions; $AGMETH$ – agricultural methane emission; $EEST$ – exports of environmentally sound technologies; $IEST$ – imports of environmentally sound technologies; $AGVA$ – agricultural productivity (agricultural value added)

Source: Compiled and calculated by the authors using data from Our World in Data and World Development Indicators

Table S6. Normality tests

Variable	SW	CS	JB
AGN_2O	0.956***	0.980***	152.500***
$AGMETH$	0.949***	0.975***	217.600***
$IEST$	0.988***	0.995***	12.570***
$EEST$	0.979***	0.991***	29.380***
$AGVA$	0.994***	0.998***	0.412
GDP	0.981***	0.992***	28.050***
FD	0.988***	0.995***	24.530***

***significance at 1% level; SW – Shapiro-Wilk, CS – Chen-Shapiro; JB – Jarque-Bera test; AGN_2O – agricultural N_2O emissions; $AGMETH$ – agricultural methane emission; $EEST$ – exports of environmentally sound technologies; $IEST$ – imports of environmentally sound technologies; $AGVA$ – agricultural productivity (agricultural value added); GDP – gross domestic product *per capita*; FD – financial development

Source: Compiled and calculated by the authors using data from Our World in Data and World Development Indicators

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Table S7. MMQR estimations for the relationship between *AGSEXP* and *AGN₂O*

Variables	Quantiles								
	Q10	Q20	Q30	Q40	Q50	Q60	Q70	Q80	Q90
<i>AGSEXP</i>	−0.084*** (0.019)	−0.104*** (0.016)	−0.112*** (0.015)	−0.122*** (0.015)	−0.130*** (0.016)	−0.140*** (0.017)	−0.154*** (0.019)	−0.169*** (0.022)	−0.187*** (0.027)
<i>AGVA</i>	3.329*** (0.271)	2.978*** (0.226)	2.830*** (0.217)	2.664*** (0.216)	2.525*** (0.221)	2.340*** (0.237)	2.099*** (0.267)	1.839*** (0.312)	1.508*** (0.375)
<i>AGVASQ</i>	−0.052*** (0.006)	−0.045*** (0.005)	−0.042*** (0.005)	−0.038*** (0.005)	−0.035*** (0.005)	−0.031*** (0.005)	−0.026*** (0.006)	−0.021*** (0.007)	−0.014* (0.008)
<i>GDP</i>	−0.093*** (0.028)	−0.066*** (0.023)	−0.054** (0.023)	−0.042* (0.022)	−0.031 (0.023)	−0.017 (0.024)	0.002 (0.028)	0.022 (0.032)	0.047 (0.039)
<i>FD</i>	−0.318*** (0.052)	−0.345*** (0.044)	−0.357*** (0.042)	−0.369*** (0.042)	−0.380*** (0.043)	−0.394*** (0.045)	−0.413*** (0.051)	−0.432*** (0.060)	−0.458*** (0.072)
Constant	−38.659*** (3.059)	−34.313*** (2.552)	−32.479*** (2.447)	−30.413*** (2.427)	−28.696*** (2.486)	−26.395*** (2.671)	−23.411*** (3.003)	−20.184*** (3.513)	−16.081*** (4.220)
Observations	1 138	1 138	1 138	1 138	1 138	1 138	1 138	1 138	1 138

*, **, ***significance at 10, 5, and 1% level, respectively; dependent variable is agricultural N₂O emissions; MMQR – Method of Moments Quantile regression; *AGN₂O* – agricultural N₂O emissions; *AGMETH* – agricultural methane emission; *EEST* – exports of environmentally sound technologies; *IEST* – imports of environmentally sound technologies; *AGVA* – agricultural productivity (agricultural value added); *GDP* – gross domestic product *per capita*; *FD* – financial development; *AGVASQ* – squared term of agricultural value added

Source: Compiled and calculated by the authors using data from Our World in Data and World Development Indicators

Table S8. MMQR estimations for the relationship between *AGSIMP* and *AGN₂O*

Variables	Quantiles								
	Q10	Q20	Q30	Q40	Q50	Q60	Q70	Q80	Q90
<i>AGSIMP</i>	−0.072** (0.036)	−0.075** (0.032)	−0.076** (0.030)	−0.078*** (0.030)	−0.079** (0.031)	−0.081** (0.033)	−0.083** (0.037)	−0.085** (0.043)	−0.088* (0.053)
<i>AGVA</i>	4.187*** (0.297)	3.817*** (0.253)	3.586*** (0.243)	3.366*** (0.241)	3.147*** (0.248)	2.895*** (0.266)	2.569*** (0.299)	2.198*** (0.351)	1.669*** (0.427)
<i>AGVASQ</i>	−0.071*** (0.007)	−0.063*** (0.006)	−0.058*** (0.005)	−0.053*** (0.005)	−0.048*** (0.006)	−0.043*** (0.006)	−0.036*** (0.007)	−0.028*** (0.008)	−0.017* (0.010)
<i>GDP</i>	−0.095*** (0.028)	−0.080*** (0.025)	−0.070*** (0.023)	−0.061*** (0.023)	−0.052** (0.024)	−0.042 (0.025)	−0.028 (0.029)	−0.013 (0.033)	0.009 (0.041)
<i>FD</i>	−0.264*** (0.052)	−0.284*** (0.046)	−0.297*** (0.044)	−0.309*** (0.044)	−0.321*** (0.045)	−0.335*** (0.048)	−0.353*** (0.054)	−0.373*** (0.063)	−0.402*** (0.078)
Constant	−48.575*** (3.342)	−44.110*** (2.834)	−41.308*** (2.726)	−38.654*** (2.705)	−35.995*** (2.783)	−32.947*** (2.990)	−29.012*** (3.360)	−24.516*** (3.940)	−18.123*** (4.786)
Observations	1 144	1 144	1 144	1 144	1 144	1 144	1 144	1 144	1 144

*, **, ***significance at 10, 5, and 1% level, respectively; dependent variable is agricultural N₂O emissions; MMQR – Method of Moments Quantile regression; *AGSIMP* – sustainable agriculture imports *AGN₂O* – agricultural N₂O emissions; *AGMETH* – agricultural methane emission; *EEST* – exports of environmentally sound technologies; *IEST* – imports of environmentally sound technologies; *AGVA* – agricultural productivity (agricultural value added); *AGVASQ* – squared term of agricultural value added; *GDP* – gross domestic product *per capita*; *FD* – financial development

Source: Compiled and calculated by the authors using data from Our World in Data and World Development Indicators

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Table 9. MMQR estimations for the relationship between *AGSEXP* and *AGMETH*

Variables	Quantiles								
	Q10	Q20	Q30	Q40	Q50	Q60	Q70	Q80	Q90
<i>AGSEXP</i>	0.023 (0.029)	−0.023 (0.023)	−0.045** (0.021)	−0.069*** (0.019)	−0.087*** (0.019)	−0.105*** (0.019)	−0.126*** (0.021)	−0.156*** (0.023)	−0.199*** (0.028)
<i>AGVA</i>	4.756*** (0.449)	4.074*** (0.356)	3.756*** (0.328)	3.406*** (0.307)	3.142*** (0.300)	2.888*** (0.305)	2.568*** (0.324)	2.137*** (0.364)	1.512*** (0.446)
<i>AGVASQ</i>	−0.081*** (0.010)	−0.067*** (0.008)	−0.060*** (0.007)	−0.053*** (0.007)	−0.047*** (0.007)	−0.042*** (0.007)	−0.035*** (0.007)	−0.026*** (0.008)	−0.013 (0.010)
<i>GDP</i>	−0.245*** (0.042)	−0.205*** (0.034)	−0.186*** (0.031)	−0.166*** (0.029)	−0.150*** (0.028)	−0.135*** (0.029)	−0.116*** (0.031)	−0.091*** (0.034)	−0.055 (0.042)
<i>FD</i>	−0.394*** (0.076)	−0.382*** (0.061)	−0.376*** (0.056)	−0.370*** (0.053)	−0.365*** (0.052)	−0.360*** (0.052)	−0.354*** (0.055)	−0.347*** (0.062)	−0.335*** (0.076)
Constant	−54.425*** (5.077)	−46.281*** (4.020)	−42.471*** (3.703)	−38.295*** (3.469)	−35.140*** (3.387)	−32.098*** (3.447)	−28.282*** (3.669)	−23.126*** (4.112)	−15.650*** (5.038)
Observations	1 138	1 138	1 138	1 138	1 138	1 138	1 138	1 138	1 138

*, **significance at 5 and 1% level, respectively; dependent variable is agricultural N₂O emissions; MMQR – Method of Moments Quantile regression; *AGSEXP* – sustainable agriculture exports; *AGMETH* – agricultural methane emission; *AGVA* – agricultural productivity (agricultural value added); *AGVASQ* – squared term of agricultural value added; *GDP* – gross domestic product *per capita*; *FD* – financial development

Source: Compiled and calculated by the authors using data from Our World in Data and World Development Indicators

Table S10. MMQR estimations for the relationship between *AGSIMP* and *AGMETH*

Variables	Quantiles								
	Q10	Q20	Q30	Q40	Q50	Q60	Q70	Q80	Q90
<i>AGSIMP</i>	0.236*** (0.056)	0.162*** (0.047)	0.118*** (0.043)	0.068* (0.041)	0.028 (0.040)	−0.009 (0.040)	−0.049 (0.042)	−0.099** (0.047)	−0.203*** (0.059)
<i>AGVA</i>	5.359*** (0.452)	4.759*** (0.378)	4.396*** (0.347)	3.991*** (0.327)	3.660*** (0.318)	3.358*** (0.322)	3.034*** (0.337)	2.627*** (0.381)	1.779*** (0.473)
<i>AGVASQ</i>	−0.095*** (0.010)	−0.082*** (0.008)	−0.074*** (0.008)	−0.066*** (0.007)	−0.058*** (0.007)	−0.052*** (0.007)	−0.045*** (0.007)	−0.036*** (0.008)	−0.018* (0.010)
<i>GDP</i>	−0.242*** (0.041)	−0.213*** (0.034)	−0.196*** (0.032)	−0.177*** (0.030)	−0.161*** (0.029)	−0.147*** (0.029)	−0.132*** (0.031)	−0.113*** (0.034)	−0.072* (0.043)
<i>FD</i>	−0.365*** (0.075)	−0.356*** (0.063)	−0.350*** (0.058)	−0.344*** (0.054)	−0.338*** (0.053)	−0.333*** (0.054)	−0.328*** (0.057)	−0.322*** (0.062)	−0.308*** (0.079)
Constant	−60.981*** (5.107)	−53.939*** (4.260)	−49.685*** (3.912)	−44.939*** (3.690)	−41.056*** (3.586)	−37.513*** (3.633)	−33.704*** (3.806)	−28.936*** (4.300)	−18.990*** (5.334)
Observations	1 144	1 144	1 144	1 144	1 144	1 144	1 144	1 144	1 144

*, **significance at 10 and 1% level, respectively; dependent variable is agricultural N₂O emissions; MMQR – Method of Moments Quantile regression; *AGSIMP* – sustainable agriculture imports; *AGMETH* – agricultural methane emission; *AGVA* – agricultural productivity (agricultural value added); *AGVASQ* – squared term of agricultural value added; *GDP* – gross domestic product *per capita*; *FD* – financial development

Source: Compiled and calculated by the authors using data from Our World in Data and World Development Indicators

Exhibit A

Cross-sectional dependence and slope heterogeneity. Cross-sectional dependence (CD) in panel data refers to the correlation between different cross-sectional units, which can lead to biased estimators and reduced efficiency of statistical tests if not properly addressed (Pesaran 2015). Concurrently, slope heterogeneity represents the variation in the relationship between variables across units, and accounting for it is crucial for accurate modeling and relevant policy recommendations (Blomquist and Westerlund 2013). To detect CD, we implement the method developed by Pesaran (2021), which involves calculating pair-wise correlation coefficients of the Ordinary Least Squares (OLS) residuals for each variable in the panel. These residuals are derived from standard augmented Dickey-Fuller regressions. Since we have balanced data, CD can be estimated as follows:

$$CD = \sqrt{[(2T / N(N-1)) \sum_{i=1}^{N-1} \sum_{j=i+1}^N \rho_{ij}] \quad (7)$$

To address slope heterogeneity, we apply Swamy's test for slope homogeneity, as presented by Pesaran and Yamagata (2008). This test allows us to evaluate whether the relationships between variables are consistent across different cross-sectional units or if they vary significantly, necessitating the use of heterogeneous panel estimation techniques. By addressing both cross-sectional dependence and slope heterogeneity, we ensure a more robust and accurate analysis of our panel data, leading to more reliable results and policy implications.

Panel unit-root tests. First-generation panel unit root tests do not account for cross-sectional dependence, causing biased estimations of long-run cointegration (Bai and Kao 2006; De Silva et al. 2009). The interconnectedness among major agricultural production countries through integrated financial systems, capital mobility, and agricultural trade likely causes simultaneous effects from common shocks, rendering the assumption of cross-sectional independence problematic (Haider et al. 2020; Yahya and Lee 2023a).

To mitigate these concerns, we implement the second-generation panel unit root tests developed by Pesaran (2007). We utilise the Cross-sectionally augmented Im-Pesaran-Shin (CIPS) and Cross-sectionally

augmented Dickey-Fuller (CADF) tests. These methods extend the traditional IPS and ADF regressions by integrating cross-section averages of lagged levels and first differences of the individual series. This methodology offers a more robust assessment of unit roots when cross-sectional dependence is present, thereby enhancing the reliability of our panel data analysis results. CIPS can be estimated using Equation (3):

$$\Delta W_{i,t} = \phi_i + \phi_i Z_{i,t-1} + \phi_i \bar{Z}_{t-1} + \sum_{l=0}^p \phi_{il} \Delta \bar{W}_{t-1} + \sum_{l=0}^p \phi_{il} \Delta \bar{W}_{i,t-1} + \mu_{it} \quad (8)$$

where: $\bar{W}$ indicates the average cross-sections; by incorporating our target variables, it can be further reformulated as:

$$W^{i,t} = \phi^1 \overline{AGEM}^{i,t} + \phi^2 \overline{EST}^{i,t} + \phi^3 \overline{AGVA}^{i,t} + \phi^4 \overline{GDP}^{i,t} + \phi^5 \overline{FD}^{i,t} \quad (9)$$

The test statistics of CIPS are specified in Equation (10):

$$\widehat{CIPS} = N^{-1} \sum_{i=1}^n CADF_i \quad (10)$$

Cointegration tests. The second-generation panel cointegration tests, such as Westerlund (2005) provide robust estimates compared to first-generation techniques (Kao 1999, Pedroni 2004) in the presence of CD. The variance ratio (VR) test statistics for the model are obtained by estimating a unit root in the predicted residuals using the Dickey-Fuller (DF) regression. The panel-specific augmented regression (AR) test statistic is calculated using Equation (5), which accounts for individual heterogeneity across panel units.

$$VR = \sum_{i=1}^N \sum_{t=1}^T \hat{E}_{it}^2 \hat{R}_i^{-1} \quad (11)$$

where: $\hat{E}_{it} = \sum_{j=1}^t \hat{e}_{ij}$, $\hat{R}_{it} = \sum_{t=1}^T \hat{e}_{it}^2$ and $\hat{e}_{it}$ – residuals from the panel-data regression model; following appropriate standardisation procedures, the asymptotic distributions of all test statistics converge to a standard normal distribution; $N(0, 1)$; this convergence property allows for straightforward interpretation of the test results and facilitates statistical inference across different panel units.