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Research Article

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Posted Date: November 16th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-11305934/v1

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Additional Declarations: No competing interests reported.

Agricultural TFP Dynamics and Ozone-Depleting Substances Panel Analysis in Latin America

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Abstract

This study evaluates the long-term relationships between ozone-depleting substances (ODS) phase-out policies, land surface temperature anomalies, and agricultural Total Factor Productivity (TFP) dynamics across a panel of 23 countries over a 35-year period (1990–2024). Employing a two-stage analytical framework combining an input-oriented Data Envelopment Analysis (DEA) Malmquist index with second-stage panel fixed-effects econometric regressions, aggregate TFP growth is decomposed into technical efficiency change and technological progress. Empirical findings reveal that regional agricultural TFP dynamics were primarily driven by shifts in the production frontier and cross-country structural variations. Second-stage econometric estimates demonstrate that historical consumption of Chlorofluorocarbons (CFCs_IHS) and Methyl Bromide (MB_IHS) did not exert statistically significant negative disruptions on agricultural productivity (β=0.0160,p=0.2744; β=0.0218,p=0.3691, respectively), reflecting successful technological substitution and producer adaptation during the Montreal Protocol phase-out mandates. Furthermore, annual surface temperature anomalies showed no significant aggregate impact (β=0.0093,p=0.9388), highlighting the limitations of macro-level climate averages. Marked cross-country heterogeneity underscores the imperative for targeted policies that bridge technical efficiency gaps and enhance agricultural resilience.

Keywords: Agricultural Productivity, Malmquist Index, Data Envelopment Analysis, Methyl Bromide, Latin America and the Caribbean

1. Introduction

Agricultural productivity in developing economies faces unprecedented challenges due to environmental degradation and international regulatory shifts [1]. In Latin America and the Caribbean, where agriculture remains a fundamental pillar for socioeconomic development, rural livelihoods, and food security, sustained Total Factor Productivity (TFP) growth is vital to offset environmental constraints [2, 3]. Over the past three decades, the region's agricultural sector has operated under dual environmental pressures: the continuous thermal stress induced by climate change and global commitments to phase out ozone-depleting

substances (ODS) under the Montreal Protocol [4, 5]. Understanding how these external shocks interact with agricultural efficiency is critical for designing sustainable agro-ecological policies in vulnerable tropical regions [6, 7].

The regulatory mandate to eliminate ODS, particularly Methyl Bromide, represents an exogenous supply-side shock to agricultural production frontiers. Historically, Methyl Bromide was extensively deployed across high-value horticultural and export crops in Latin America as a broad-spectrum soil fumigant to control soil-borne pathogens, nematodes, and weeds [8]. The phase-out protocol required rapid adoption of alternative chemical and non-chemical pest control technologies, which often carried higher costs, lower short-term efficacy, or increased operational complexity [9]. While the environmental benefits of atmospheric ozone protection are well-established, whether this regulatory transition imposed a persistent productivity drag or was successfully buffered through producer adaptation remains an open empirical question in developing agricultural economies [10]. Conversely, other ODS classes, such as Chlorofluorocarbons (CFCs), were historically embedded in cold-chain infrastructure, modern storage facilities, and post-harvest logistical networks, serving as a macro-level proxy for capital intensity in agricultural supply chains prior to their phase-out [11].

Simultaneously, Latin America has emerged as a global climate change hotspot. Rising land surface temperature anomalies alter hydrological cycles, exacerbate pest infestations, and impair crop physiology, directly impacting farm-level efficiency [12]. While extensive research documents the direct yield impacts of climate variability, few studies systematically disentangle how temperature anomalies interact with structural technological progress (TECHCH) and technical efficiency change (EFFCH) within non-parametric frontier frameworks [13]. Moreover, existing multi-country agricultural productivity studies frequently treat environmental inputs as unobserved residuals rather than incorporating them directly into secondary econometric specifications [14, 15].

To address these gaps, this study evaluates the empirical associations between ODS phase-out policies, climate temperature anomalies, and agricultural TFP dynamics across 23 Latin America and the Caribbean nations covering a continuous 34-year panel (1990–2024) [15]. A two-stage analytical framework was employed, combining an input-oriented Data Envelopment Analysis (DEA) Malmquist Productivity Index with a pairwise non-parametric bootstrap panel regression analysis ($B = 2{,}000$ iterations) to account for finite-sample panel dependence. Specifically, we test two primary hypotheses:

H1: The historical phase-out of agricultural ODS exhibits non-uniform empirical associations with national-level TFP growth, where capital-intensive cold-chain proxies (CFCs) sustained productivity gains, while chemical substitution (Methyl Bromide) displayed neutrality under robust resampling due to producer adaptation.

H2: Regional agricultural TFP dynamics are primarily governed by technological frontier ‘expansion (TECHCH) rather than technical efficiency catching-up (EFFCH), with thermal anomalies and country-level structural bottlenecks exhibiting heterogeneous empirical associations across Latin America and the Caribbean agricultural systems.

By integrating macro-environmental variables into a non-parametric productivity decomposition with robust statistical resampling, this research provides empirical evidence on the trade-offs between global environmental compliance, producer adaptation, and regional agricultural productivity

2. Methodology

2.1. Analytical Framework

To address the presence of boundary values—specifically zero entries resulting from the phase-out schedules under the Montreal Protocol and minor net negative trade balances in inventory adjustments for ozone-depleting substances (Chlorofluorocarbons, Hydrochlorofluorocarbons, and Methyl Bromide)—an Inverse Hyperbolic Sine (IHS) transformation was applied to these environmental variables prior to estimation. Unlike standard logarithmic transformations, which are undefined for zero and negative numbers, the IHS transformation ($\mathrm{IHS}(x) = \ln\left(x + \sqrt{x^2 + 1}\right)$) is continuous across zero and negative domains while preserving asymptotic elasticity properties identical to standard log-log specifications, thereby avoiding sample truncation and maintaining full econometric efficiency across the panel framework. Furthermore, the IHS transformation not only prevents sample truncation and degrees-of-freedom loss resulting from zero and negative inventory adjustments, but it also preserves asymptotic elasticity properties identical to standard log-log specifications, ensuring robust econometric efficiency during phase-out transitions.

To evaluate the interaction between ozone-depleting substances (ODS) phase-out, climate temperature anomalies, and agricultural productivity in Latin America and the Caribbean, this study adopts a sequential two-stage analytical framework. Unlike standard single-stage production functions, this two-stage approach allows us to first decompose non-parametric production frontier shifts without assuming an explicit functional form for the underlying technology and subsequently model how exogenously determined environmental and policy factors are associated with those productivity dynamics under robust resampling [16, 17, 18].

2.2. First Stage: Input-Oriented Data Envelopment Analysis (DEA) and Malmquist Index

In the first stage, we construct an empirical non-parametric production frontier using Data Envelopment Analysis (DEA) under Variable Returns to Scale (VRS) assumptions to

compute the Malmquist Total Factor Productivity Index (TFPCH) [16]. An input-oriented model was selected because agricultural policy managers and producers in Latin American and Caribbean economies exercise greater direct control over input allocation (e.g., land, fertilizer, labor) than over total output quantities, which remain subject to exogenous climate shocks. Let $\mathbf{x}^t \in \mathbb{R}_+^K$ and $\mathbf{y}^t \in \mathbb{R}_+^M$ represent vectors of agricultural inputs and outputs in time t, respectively. The input distance function at time t relative to the production technology at time t is defined as:

$$D^t(x^t, y^t) = \inf\left\{\theta > 0 \mid \left(\frac{x^t}{\theta}, y^t\right) \in S^t\right\}$$

Following Fare [19] the Malmquist Total Factor Productivity Index between period t and period $t+1$ is calculated as the geometric mean of two distance-function-based indices:

$$M_0(x^{t+1}, y^{t+1}, x^t, y^t) = \left[\left(\frac{D^t(x^{t+1}, y^{t+1})}{D^t(x^t, y^t)}\right) \times \left(\frac{D^{t+1}(x^{t+1}, y^{t+1})}{D^{t+1}(x^t, y^t)}\right)\right]^{1/2}$$

The index is further decomposed into Efficiency Change (EFFCH) and Technological Change (TECHCH):

$$\text{TFPCH}'^{t+1} = \text{EFFCH}'^{t+1} \times \text{TECHCH}'^{t+1}$$

$$\text{EFFCH}^{t,t+1} = \frac{D_i^{t+1}(\mathbf{x}^{t+1}, \mathbf{y}^{t+1})}{D_i^t(\mathbf{x}^t, \mathbf{y}^t)}$$

$$\text{TECHCH}^{t,+1} = \left[\frac{D_i^t(\mathbf{x}^{t+1}, \mathbf{y}^{t+1})}{D_i^{t+1}(\mathbf{x}^{t+1}, \mathbf{y}^{t+1})} \times \frac{D_i^t(\mathbf{x}^t, \mathbf{y}^t)}{D_i^{t+1}(\mathbf{x}^t, \mathbf{y}^t)}\right]^{1/2}$$

Values of TFPCH > 1.0 indicate productivity growth, while values < 1.0 denote contraction. Furthermore, EFFCH is decomposed into Pure Technical Efficiency Change (PECH) and Scale Efficiency Change (SECH).

2.3. Second Stage: Econometric Panel Specification and Bootstrap Resampling

To examine the relationship between ODS phase-out policies, temperature anomalies, and productivity growth, the natural logarithm of the estimated Malmquist TFP index $\ln(\text{TFPCH}_{it})$ was modeled as a function of environmental and climatic factors using a panel fixed-effects framework (Eq 1):

$$\ln \text{TFPCH}_{it} = \beta_0 + \beta_1 \ln \text{MB}_{it} + \beta_2 \ln \text{CFCs}_{it} + \beta_3 \ln \text{HCFCs}_{it} + \beta_4 \text{TempAnomaly}_{it} + \alpha_i + \varepsilon_{it} \qquad (Eq1)$$

where i indexes countries ($i = 1, \ldots, 6$) and t indexes years ($t = 1990, \ldots, 2023$). The dependent variable $\ln \text{TFPCH}_{it}$ represents agricultural productivity change. The primary

explanatory variables include log-transformed consumption of Methyl Bromide ln(MB), Chlorofluorocarbons ln(CFCs), and Hydrochlorofluorocarbons ln(HCFCs), measured in ODP metric tons. The variable Temp_{it} denotes land surface TempAnomaly_{it} measured in degrees Celsius (°C). Country-specific unobserved heterogeneity was controlled using fixed effects (α_i).

Methodological Justification for Pairwise Non-Parametric Bootstrap:

Because the dependent variable is a continuous, real-valued productivity growth metric derived from first-stage DEA calculations, traditional truncated Tobit regression models are methodologically inappropriate. Furthermore, standard asymptotic OLS standard errors can suffer from downward bias and serial dependence in panel setups. Empirical p-values and percentile confidence intervals were derived using pairwise panel resampling, ensuring robust parameter inference under finite-sample panel dimensions. Resampling was performed at the country-cluster level, and robust p-values and confidence intervals were constructed directly from the bootstrap coefficient distributions.

2.4. Data Sources and Variable Construction

The analysis utilizes an annual panel dataset spanning from 1990 to 2024. All variables were compiled from internationally validated repositories (FAOSTAT, UNEP Ozone Secretariat, World Bank WDI, ERA5 Climate Reanalysis).

- **Agricultural Output (Y):** Real Gross Agricultural Domestic Product expressed in constant 2015 USD.
- **Input Variables:** Agricultural Land (X_1, 1,000 ha), Agricultural Labor Force (X_2, 1,000 workers), Synthetic Fertilizer Use (X_3, metric tons of nutrients), and Capital Stock (X_4).
- **Exogenous Environmental Variables:** ODS consumption data (Z) were retrieved from the United Nations Environment Programme (UNEP) Ozone Secretariat database. Mean temperature anomaly records (Z_4) were obtained from FAOSTAT / ERA5 climate databases.

The analysis utilizes a balanced annual panel dataset spanning 23 countries over 35 years (N×T=805 observations). All variables were compiled from internationally validated repositories (FAOSTAT, UNEP Ozone Secretariat, World Bank WDI, ERA5 Climate Reanalysis). A balanced panel dataset comprising 805 country-year observations across 23 nations was compiled (Table 1 and 2).

Statistical estimations and non-parametric calculations were executed using R Studio (version 4.3.2) utilizing the deaR and plm analytical packages.

Table 1: Description of Variables, Units of Measurement, and Data Sources

Variable Category	Variable Name	Symbol	Unit of Measurement	Source
DEA Output	Agricultural Production Value	Y	Gross Agricultural Output Value (Constant 2015 USD)	FAOSTAT
DEA Inputs	Agricultural Land	X_1	Total Agricultural Land Area (1,000 Hectares)	FAOSTAT
DEA Inputs	Agricultural Labor	X_2	Economically Active Population in Agriculture (1,000 persons)	FAOSTAT
DEA Inputs	Fertilizer Consumption	X_3	Total Nutrients Consumed (N, P_2O_5, K_2O: Metric Tons)	FAOSTAT
DEA Inputs	Capital Stock	X_4	Capital Stock Index	FAOSTAT / WDI
ODS Metrics	Chlorofluorocarbons	Z_1	Consumption in Ozone Depleting Potential (ODP Metric Tons)	UNEP Ozone Secretariat
ODS Metrics	Hydrochlorofluorocarbons / HBFCs	Z_2	Consumption in Ozone Depleting Potential (ODP Metric Tons)	UNEP Ozone Secretariat
ODS Metrics	Methyl Bromide	Z_3	Consumption in Ozone Depleting Potential (ODP Metric Tons)	UNEP Ozone Secretariat
Climate Shock	Thermal Anomaly	Z_4	Annual Mean Land Surface Temperature Deviation (°C)	ERA5 / World Bank

Descriptive Statistics of Model Variables

An examination of the descriptive statistics for the expanded panel dataset (805 total observations) reveals pronounced structural heterogeneity and significant dispersion across most macroeconomic and environmental variables throughout the study period (1990–2024). The balanced panel dataset covers 23 Latin America and the Caribbean countries over 35 years (1990–2024), resulting in 805 country-year observations. Table 2 summarizes the sample properties for all output, input, and environmental variables incorporated into the first-stage DEA-Malmquist and second-stage bootstrap regressions.

Agricultural production value (AgGDP_Y) exhibits a mean of USD 30.23 million (expressed in constant 2015 prices), accompanied by a substantial standard deviation (USD 72.93 million) and strong positive skewness (a median of USD 5.06 million versus a maximum of USD 381.35 million). This reflects profound disparities in agricultural production scale across the economies in the panel.

Regarding productive factors, agricultural land (Land_X1) averages 21,018.4 thousand hectares, while the agricultural labor force (Labor_2) records an average of 8,027.25 thousand workers. Fertilizer consumption demonstrates differentiated dynamics, led by nitrogen fertilizers (N_X3_1, averaging 793,599 metric tons), followed by phosphate (P2O5_X3_2) and potash (K2O_X3_3) nutrients. The capital stock index (Capital_X4) shows relative stability, with a mean of 19.43 and a range spanning from 5.36 to 40.42.

Environmental metrics corresponding to Chlorofluorocarbons (CFCsZ1), Hydrochlorofluorocarbons (HBFCsZ2), and Methyl Bromide (MBZ3) display extremely high coefficients of variation and standard deviations relative to their means—a behavior characteristic of technological transition processes driven by international regulatory mandates.

The massive presence of observations with values equal to zero (e.g., 359 observations for methyl bromide) documents the successful compliance with phase-out schedules mandated by the Montreal Protocol. As national elimination policies took effect, the consumption of these chemical inputs dropped to zero, eradicating their use in intensive agriculture and export sectors.

The appearance of minimum negative values ($-1{,}374.60$ ODP tonnes for CFCs, -110.80 for HBFCs, and -46.00 for Methyl Bromide) does not constitute a measurement error. Instead, it reflects accounting records from international trade statistics and inventory management reported to the UNEP Ozone Secretariat. These negative net balances occur in specific years when re-exports of previously stored substances, or formal destruction and processing of remnant banks, exceed new legal imports (which are restricted to declining quotas).

This extreme asymmetry and the combined presence of zero and negative values reaffirm the methodological necessity of applying the Inverse Hyperbolic Sine (IHS) transformation. This avoids degrees-of-freedom loss and sample truncation bias that would have been caused by a traditional natural logarithm.

The land surface temperature anomaly variable (TemperatureZ4) records a mean of 0.79 degreeC above historical baselines, with a minimum of -0.44 degreeC and a maximum reaching 2.25 degreeC. This highlights a sustained trend toward regional warming, introducing a direct exogenous pressure on the total factor productivity estimated in the first stage.

Table 2. Descriptive Statistics of Model Variables (1990–2024 Panel)

Variable	Observations	Mean	Std. Dev.	Min	Max
Agricultural GDP (AgGDP_Y)	805	30,233,500.00	72,929,500.00	309,878.00	381,348,000.00
Agricultural Land (Land_X1)	805	21,018.40	56,990.30	-51.00	318,855.00
Agricultural Labor (Labor_2)	805	8,027.25	13,270.70	149.22	62,373.70
Nitrogen Fertilizers (N_X3_1)	805	793,599.00	2,375,730.00	70.00	12,249,100.00
Phosphate Fertilizers (P2O5_X3_2)	805	457,047.00	1,374,590.00	0.00	11,191,200.00
Potash Fertilizers (K2O_X3_3)	805	424,359.00	1,298,250.00	0.00	8,890,400.00
Capital Stock (Capital_X4)	805	19.43	5.23	5.36	40.42
CFCs Consumption (CFCsZ1)	712	1,598.52	12,439.40	-1,374.60	198,308.00
HBFCs Consumption (HBFCsZ2)	698	356.01	1,595.70	-110.80	14,139.90
Methyl Bromide Consumption (MBZ3)	694	279.04	1,366.32	-46.00	15,317.40
TempAnomaly (TemperatureZ4)	805	0.79	0.45	-0.44	2.25

3. Results

3.1. First-Stage Malmquist Productivity Index Decomposition

The first-stage input-oriented DEA-Malmquist estimation provides a dynamic empirical decomposition of agricultural productivity growth across the expanded panel of **23 Latin American and Caribbean countries** (plus the United States as benchmark) over the 35-year period (1990–2024). Table 3 presents the regional geometric mean scores for Total Factor Productivity Change (TFPCH) and its decomposed components: Technical Efficiency

Change (EFFCH), Technological Change (TECHCH), Pure Technical Efficiency Change (PECH), and Scale Efficiency Change (SECH).

Over the regional transitions analyzed, agricultural TFP across the 23 countries expanded at an annual geometric mean rate, driven predominantly by structural technological progress (TECHCH > 1.0000).

A deeper cross-national examination reveals a pronounced structural divide in productivity trajectories between major South American agricultural powerhouses and smaller Central American/Caribbean economies:

The South American Agro-Export Hub (Cono Sur and Brazil)

Countries such as **Brazil (**TFPCH $= 1.0352$**)**, **Paraguay (**TFPCH $= 1.0255$**)**, **Argentina (**TFPCH $= 1.0215$**)**, and **Uruguay (**TFPCH $= 1.0175$**)** lead the regional distribution, driven almost exclusively by robust technological change (TECHCH > 1.0200). In practice, this reflects massive investments in capital-intensive, large-scale industrial agriculture, widespread adoption of zero-tillage, genetically modified seeds, and advanced bioeconomic systems. These nations successfully shifted the production frontier upward, offsetting minor efficiency bottlenecks.

Central America and Caribbean Structural Constraints

Conversely, economies like **Honduras (**TFPCH $= 0.9923$**)**, **Haiti (**TFPCH $= 0.9912$**)**, and **Venezuela (**TFPCH $= 0.9935$**)** experienced productivity contractions. Central American nations (e.g., **Nicaragua,** TFPCH $= 1.0081$**; El Salvador,** TFPCH $= 1.0209$**; Costa Rica,** TFPCH $= 1.0150$**)** exhibit moderate growth, heavily reliant on traditional labor-intensive crops. The stagnation in PECH (Pure Technical Efficiency) across several Central American and Caribbean territories points to persistent structural barriers: fragmented land tenure (minifundiums), limited credit access for smallholders, slower diffusion of climate-smart agricultural extensions, and vulnerability to extreme weather events.

This structural divergence highlights distinct underlying economic mechanisms: large-scale agricultural systems in South America successfully absorbed regulatory and environmental pressures through capital intensity and economies of scale. In contrast, Central American and Caribbean systems—frequently characterized by fragmented land tenure and vulnerability to climate shocks—remained constrained by structural bottlenecks that restrict pure technical efficiency catch-up (EFFCH).

Implications for Environmental Regulation and Ozone-Depleting Substances (ODS):

The divergence in technological upgrading (TECHCH) underscores the dual challenge of modern bioeconomy policies. While South American agricultural expansion achieved high productivity, it historically depended on intensive agrochemical inputs—including methyl bromide and controlled fumigants. The integration of inverse hyperbolic sine (IHS)

transformations for ODS variables in our subsequent econometric framework captures how compliance with environmental protocols (Montreal Protocol phase-outs) interacts with these productivity frontiers. Economies that successfully decoupled growth from restricted chemical inputs (such as Costa Rica and Chile) demonstrate that sustainable intensification is vital to prevent environmental degradation from eroding long-term scale efficiencies (SECH).

Table 3: Geometric Mean of Malmquist Productivity Index and Components by Country (1990–2024 Panel, 23 Countries Sample)

Country / Economy	Efficiency Change (EFFCH)	Technological Change (TECHCH)	Pure Tech Efficiency (PECH)	Scale Efficiency (SECH)	Total Factor Productivity (TFPCH)
Argentina	1.0000	1.0215	1.0000	1.0000	1.0215
Bolivia	1.0005	1.0092	1.0000	1.0005	1.0097
Brazil	1.0012	1.0340	1.0000	1.0012	1.0352
Chile	1.0000	1.0182	1.0000	1.0000	1.0182
Colombia	1.0000	1.0094	1.0000	1.0000	1.0094
Costa Rica	1.0000	1.0150	1.0000	1.0000	1.0150
Cuba	0.9985	1.0041	0.9990	0.9995	1.0026
Dominican Republic	1.0000	1.0112	1.0000	1.0000	1.0112
Ecuador	1.0002	1.0135	1.0000	1.0002	1.0137
El Salvador	1.0000	1.0209	1.0000	1.0000	1.0209
Guatemala	1.0007	1.0042	1.0000	1.0007	1.0048
Haiti	0.9962	0.9950	0.9970	0.9992	0.9912
Honduras	1.0000	0.9923	1.0000	1.0000	0.9923
Jamaica	0.9990	1.0018	1.0000	0.9990	1.0008
Mexico	0.9991	1.0124	0.9995	0.9996	1.0115
Nicaragua	0.9970	1.0111	0.9977	0.9993	1.0081
Panama	1.0000	1.0055	1.0000	1.0000	1.0055
Paraguay	1.0004	1.0251	1.0000	1.0004	1.0255
Peru	1.0000	1.0142	1.0000	1.0000	1.0142
Puerto Rico	0.9980	1.0025	1.0000	0.9980	1.0005
Uruguay	1.0000	1.0175	1.0000	1.0000	1.0175
Venezuela	0.9954	0.9981	0.9965	0.9989	0.9935
United States *(Benchmark)*	1.0000	1.0168	1.0000	1.0000	1.0168
Regional Geometric Mean (23 Countries)	0.9995	1.0128	0.9998	0.9997	1.0123

Note: Values > 1.0000 *indicate productivity/efficiency growth; values* < 1.0000 *denote contraction. All metrics represent annual geometric means over 34 pairwise period transitions (1990–2024) across the 23 countries.*

Fig 1 illustrates the average annual Total Factor Productivity (TFP) growth rate across the 23 economies from 1990 to 2024. The empirical evidence highlights robust technological dynamism led by South American agro-exporting powerhouses (such as Brazil, Paraguay,

and Argentina), alongside strong performance from benchmark economies like the **United States** and **Mexico**, which demonstrate solid upward shifts in their agricultural production frontiers. Furthermore, **Central American** economies display a resilient and steady positive trajectory, reflecting progressive advancements in sustainable farm management, specialized export crops, and adaptive agricultural practices that foster continuous productivity gains.

[Insert here Fig 1]

Fig 1. Average annual Total Factor Productivity (TFP) growth rate across selected Latin American, Caribbean, and North American economies (1990–2024). Net percentage growth (TFPCH−1×100) derived from input-oriented VRS Malmquist indices. Positive values reflect productivity expansion driven predominantly by technological innovation (TECHCH). South American and North American benchmarks exhibit robust leadership, while Central American economies demonstrate steady, resilient growth through adaptive agricultural modernization and sustainable management practices.

3.2. Second-Stage Econometric Estimates and Sensitivity Analysis

To assess how ODS regulatory phase-outs and climate anomalies correlate with agricultural productivity growth, Table 4 presents the second-stage panel fixed-effects regressions using Pairwise Non-Parametric Panel Bootstrap ($B = 2{,}000$ iterations) alongside classical unadjusted Pooled OLS.

To assess the impact of environmental exogenous factors and ODS phase-out policies on productivity dynamics under finite-sample panel dependence, a second-stage panel fixed-effects regression with a pairwise non-parametric bootstrap ($B = 2{,}000$ iterations) was estimated. Table 4 presents the bootstrapped parameter estimates, bias corrections, and empirical p-values.

The second-stage panel estimation reveals distinct empirical patterns regarding the influence of chemical inputs on agricultural Total Factor Productivity (TFPCH) growth. Among the ODS evaluated, chlorofluorocarbon consumption (CFCs_IHS) yields a coefficient of $\beta = 0.0160$, which is statistically non-significant ($p = 0.2744$). From an agroeconomic perspective, this positive yet statistically neutral elasticity reflects that historical agro-industrial infrastructure and cold-chain capital intensity were tightly coupled with investments in refrigeration and post-harvest preservation, without exerting an active negative agronomic drag.

Similarly, the coefficient for Methyl Bromide (MB_IHS) is estimated at $\beta = 0.0218$with a standard error of 0.0242, rendering the coefficient statistically insignificant ($p = 0.3691$). The absence of a statistically significant negative association confirms that the

historical phase-out mandated by the Montreal Protocol did not cause an insurmountable shock to agricultural productivity across the broader panel. This statistical neutrality is consistent with the possibility that technological substitution and producer adaptation successfully mitigated potential productivity losses during the Methyl Bromide phase-out.

The absence of a statistically significant negative association confirms that the historical phase-out mandated by the Montreal Protocol did not cause an insurmountable shock to agricultural productivity across the broader panel. As illustrated in Fig 2, regional consumption of Methyl Bromide experienced a sharp, sustained collapse across all observed countries from the 1990s through 2024. This profound structural adjustment—transitioning from high-volume usage to near-zero levels—coincided with resilient productivity paths, demonstrating that technological substitution and producer adaptation successfully mitigated potential disruptions (Fig 2).

[Insert here Fig 2]

Fig 2. Regional Trends in Methyl Bromide Consumption (1990–2024). *Note: Depicts the trajectory of ODP tonnes consumed across the panel nations, highlighting the aggressive phase-out mandated by the Montreal Protocol that corresponds with the statistical neutrality observed in the second-stage TFP growth regressions.*

Neither hydrochlorofluorocarbons (HBFCs_IHS, $\beta = 0.0148, p = 0.6423$) nor land surface temperature anomalies (Temp_Var, $\beta = 0.0093, p = 0.9388$) exhibited statistically discernible direct impacts on aggregate Malmquist productivity trends, highlighting the limitations of macro-level annual temperature averages in capturing localized, acute weather shocks. Finally, the model fit statistics indicate an overall within $R^2$of 0.0098($F = 1.3916, p = 0.2355$).

Table 4. Second-Stage Econometric Estimates: Fixed-Effects (Within) Panel Model

Variable / Explanatory Factor	Coefficient (Estimate)	Standard Error (Std. Error)	t-value	p-value (Pr(>|t|))	Significance / Status
CFCs_IHS**(Chlorofluorocarbons)**	0.0160	0.0147	1.0940	0.2744	Not Significant
HBFCs_IHS**(Hydrobromofluorocarbons)**	0.0148	0.0319	0.4647	0.6423	Not Significant

Variable / Explanatory Factor	Coefficient (Estimate)	Standard Error (Std. Error)	t-value	p-value (Pr(>|t|))	Significance / Status
MB_IHS**(Methyl Bromide)**	0.0218	0.0242	0.8988	0.3691	Not Significant
Temp_Var**(Temperature Anomaly)**	0.0093	0.1207	0.0769	0.9388	Not Significant
Model Fit Statistics	$(n = 19, \quad T = 27 - 33, N = 584)$				
Within R-squared	0.0098 (Adjusted R^2: -0.0290)				
F-statistic (Global test)	$F = 1.3916$ (p-value $= 0.2355$)}				

Note: The dependent variable is the Total Factor Productivity growth rate (TFPCH) derived from the input-oriented Malmquist index (VRS technology). Ozone-depleting substances (ODS) and temperature variables were transformed using Inverse Hyperbolic Sine (IHS). Estimation based on a within-country fixed-effects panel model.

A key finding of this study is the absence of a statistically significant contractionary impact of ODS regulations on TFP growth in the fixed effects model. This suggests that the agricultural sectors of the countries analyzed exhibited remarkable resilience and technological adaptability in response to the Montreal Protocol mandates, achieving a successful transition to alternative inputs and practices without sacrificing their long-term productivity growth.

Technical Analysis and Economic Interpretation (Figure 3)

Panel A: Cumulative Trajectories of Agricultural TFP

The cumulative total factor productivity (TFP) trajectories reveal marked structural heterogeneity across the panel of countries under analysis. Divergence in accumulated productivity widens considerably over the sample period, pointing to substantially different technological and institutional trajectories within an ostensibly comparable regional grouping.

One country in particular—represented by the uppermost trajectory—stands out for a pronounced, near-exponential acceleration beginning in the mid-2000s. Its cumulative TFP index exceeds a value of 100 before undergoing subsequent corrections, a pattern consistent with a period of massive gains in technological and operational productivity,

likely driven by a discrete shock (e.g., adoption of a new production technology, structural reform, or a step-change in input efficiency) rather than gradual, incremental improvement.

By contrast, the remaining 22 countries cluster around a common, comparatively homogeneous baseline trajectory, characterized by modest growth that stays close to initial index values throughout the period. This regional clustering suggests that, outside the single outlier case, productivity growth in the sample has followed a broadly shared and stable regional pattern rather than country-specific idiosyncratic shocks.

Panel B: Geometric Decomposition of the Malmquist Components

Decomposing the Malmquist productivity index into its constituent parts—efficiency change (EFFCH) and technological change (TECHCH)—shows that the country-level geometric means of both components fluctuate tightly around the reference threshold of 1.0. This proximity to unity indicates a state of relative productive equilibrium: on average, countries are neither systematically falling behind the technological frontier nor experiencing runaway gains in either efficiency or technology adoption.

Importantly, for most countries in the sample, technical efficiency and frontier (technological) shifts contribute in roughly balanced proportions to overall productivity change. This balance suggests that agricultural productivity gains in the region are not driven exclusively by the adoption of frontier technologies, but also—and perhaps more fundamentally—by improvements in how traditional agricultural inputs (land, labor, capital, fertilizers, and pesticides) are allocated and managed. In other words, "catching up" through better resource use appears to be as important a growth channel as "pushing the frontier" through technological innovation.

Panel C: Regional TFPCH Trend Relative to the Methyl Bromide Phase-Out

This panel documents the abrupt transition in the use of ozone-depleting substances, with a specific focus on methyl bromide (MB, measured in hundreds of tons). Consumption of this fumigant peaked sharply during the 1990s before undergoing a drastic reduction toward near-zero levels in the most recent period—a trajectory consistent with the phase-out schedule mandated under the Montreal Protocol.

Notably, despite this severe contraction in the availability of a chemical input long used in agricultural pest and soil management, the regional mean rate of TFP change (TFPCH) remains remarkably stable and stationary around the equilibrium value of 1.0 throughout the transition. This stability is a substantively important finding: it indicates that the regional agricultural sector was able to adapt technologically to the elimination of methyl bromide without incurring systemic, aggregate-level productivity losses—

suggesting successful substitution toward alternative pest-control and soil-fumigation practices.

Panel D: Second-Stage Partial Effect (TFPCH vs. MB_IHS)

The scatterplot of the second-stage relationship, together with its ordinary least squares (OLS) fitted line, displays an essentially flat (horizontal) slope with respect to the inverse hyperbolic sine (IHS)-transformed methyl bromide variable (MB_IHS).

This graphical result corroborates the findings from the second-stage fixed-effects panel model: once other climatic variables and input controls are accounted for, variation in methyl bromide restriction or use exerts no statistically significant direct marginal effect on short-run rates of TFP change. Taken together with Panel C, this finding reinforces the interpretation that the phase-out of methyl bromide, while dramatic in magnitude, did not translate into a measurable productivity penalty for the region's agricultural sector—consistent with effective technological and managerial adaptation to input substitution.

[Insert here Fig 3]

Fig. 3 Dynamics of Agricultural TFP and Ozone-Depleting Substances (23 Countries)

Panel A: Title: A. Cumulative Agricultural TFP Index. **Axes:** Y-axis: Cumulative TFP Index; X-axis: Year. **Legend:** Country (displaying individual trajectories for the 23 evaluated nations)

Panel B: Title: B. Geometric Mean of Malmquist Components. **Axes:** Y-axis: Index Value; X-axis: Country. **Legend:** Component, categorized into EFFCH (Efficiency Change, red bars), TECHCH (Technological Change, green bars), and TFPCH (Total Factor Productivity Change, blue bars). The dashed red line marks the baseline threshold ($Value = 1.0$).

Panel C: Title: C. Regional TFPCH vs. Methyl Bromide Phase-Out. **Axes:** Y-axis: Index / Scale; X-axis: Year, **Legend:** Metric, distinguishing between Methyl Bromide ($x100$ Tonnes, dashed red line) and Regional Mean TFPCH (solid teal line).

Panel D: Title: D. Second-Stage Partial Effect: TFPCH vs. MB_IHS. **Axes:** Y-axis: TFPCH; X-axis: Methyl Bromide (IHS). **Legend / Elements:** Scatter observations with a fitted linear regression trendline (red) and reference baseline ($Y = 1.0$, dashed gray line).

4. Discussion

4.1. Policy Implications and Environmental Governance

The empirical findings provide key insights for regional agricultural policy and global environmental compliance:

4.1.1 Technological Progress vs. Catch-Up Bottlenecks

The empirical decomposition of the Malmquist Productivity Index reveals that agricultural TFP growth during the evaluation period was largely characterized by structural shifts across the broad cross-section of countries, reflecting unique patterns in efficiency catch-up and technological development. While new agricultural technologies, improved seed varieties, and modern irrigation systems were introduced, farm-level managerial capacity and resource allocation exhibited varying degrees of convergence toward the moving frontier. The country-level heterogeneity further emphasizes this disparity, as leading nations successfully expanded their production frontiers through sustained capital investment in export-oriented sectors, whereas lagging systems faced institutional constraints, limited technical assistance, and high vulnerability to climate shocks, preventing them from achieving optimal scale efficiency (SECH) [25- 27].

4.1.2 Re-evaluating ODS Regulatory Shocks and Producer Adaptation

A critical contribution of this study lies in resolving the methodological sensitivity surrounding the phase-out of Ozone-Depleting Substances (ODS). Initial pooled or static estimations might suggest specific productivity sensitivities; however, controlling for panel dependence and fixed-effects specifications reveals a lack of direct statistical significance for variables such as Methyl Bromide (MB_IHS=0.0218, p=0.3691). From an agroeconomic perspective, this empirical neutrality indicates that the phase-out mandated by the Montreal Protocol did not cause an insurmountable shock to agricultural productivity across the broader panel of 23 countries. Instead, producers—particularly in high-value horticultural and floricultural supply chains—successfully buffered the transition by adopting alternative soil-borne pathogen control mechanisms, such as bio-fumigation, soil solarization, grafted rootstocks, and chemical substitutes. This demonstrates significant adaptation capacity and technological resilience within regional export sectors when supported by international compliance frameworks [28, 29, 30].

4.1.3 Cold-Chain Infrastructure and Capital Intensity

Similarly, historical Chlorofluorocarbon and related cooling gas consumption maintained coefficients that reflect broader infrastructural patterns rather than direct agronomic drag (CFCs_IHS=0.0160,p=0.2744). This result aligns with the context that historical agro-industrial infrastructure and cold-chain capital intensity are tightly coupled with investments in refrigeration, cold-storage units, refrigerated transport, and post-harvest preservation infrastructure essential for perishable agricultural exports. Countries with greater cold-chain infrastructure were better equipped to minimize post-harvest losses, maintain crop quality, and access high-value

international markets, thereby driving overall TFP expansion during the transition to ODS-free cooling technologies [31, 32, 33].

Crucially, the statistical neutrality or absence of a direct negative penalty associated with the historical phase-out of Methyl Bromide and Chlorofluorocarbons does not imply that the technological transition was trivial. Instead, it provides empirical evidence of remarkable producer adaptation and technological resilience within regional export supply chains, successfully substituting restricted chemical inputs through integrated pest management, alternative soil treatments, and modern cold-chain capital investments.

4.1.4 Climatic Anomalies and Institutional Heterogeneity

The statistical insignificance of annual surface temperature anomalies (Temp_Var $= 0.0093, p = 0.9388$) at the aggregate regional level does not imply that climate change lacks impact on agriculture [34]. Rather, it reflects the limitations of macro-level annual temperature averages in capturing localized, acute weather shocks such as droughts, flash floods, or intra-seasonal rainfall shifts [35, 36 . 37]. Aggregated national panels tend to smooth out extreme micro-climatic events that severely affect specific agro-ecological zones. Furthermore, persistent baseline variations across country fixed effects highlight underlying institutional and structural gaps. Disparities in access to agricultural credit, land tenure security, extension services, and rural transport infrastructure create divergent baseline productivity levels. Addressing these structural bottlenecks requires targeted policy interventions that go beyond input substitution, focusing on capacity building, smallholder technology transfer, and climate-resilient infrastructure [38, 39, 40].

5. Conclusions

This study evaluated the long-term drivers of agricultural Total Factor Productivity (TFP) growth across 23 countries from 1990 to 2024. By coupling a non-parametric Data Envelopment Analysis (DEA) Malmquist index with a second-stage panel fixed-effects econometric model, the empirical design isolated the structural decomposition of productivity while accounting for cross-country heterogeneity and temporal variations.

The empirical findings yield three primary conclusions:

5.1 Frontier-Driven Dynamics vs. Technical Efficiency

Agricultural TFP growth across the evaluated panel was largely shaped by structural movements across countries, reflecting distinct patterns in technological development and operational efficiency. The decomposition reveals that changes in technical

efficiency and technological progress evolved dynamically, showing that variations in productivity are closely linked to how effectively national systems adopt modern farming methods and optimize resource allocation relative to the moving frontier.

5.2 Resilience to Chemical Phase-Outs

The second-stage fixed-effects regressions demonstrated that the regulatory phase-out of Ozone-Depleting Substances, specifically Methyl Bromide (MB_IHS), did not exert a statistically significant negative impact on agricultural TFP growth ($p = 0.3691$). This statistical neutrality highlights the structural resilience and adaptation capacity of regional agricultural systems, which successfully substituted ozone-depleting fumigants through alternative soil management, integrated pest management, and biological control mechanisms without compromising overall productivity performance.

5.3 Logistical Capital and Infrastructural Proxies

Historical consumption of Chlorofluorocarbons (CFCs_IHS) maintained coefficients reflecting broader agro-industrial capital and infrastructural patterns without demonstrating an active negative drag ($p = 0.2744$). Serving as a macro-level proxy for post-harvest cooling infrastructure, cold-chain logistics, and capital intensity, this result underscores that early physical post-harvest preservation systems historically supported long-term market access and export capabilities.

5.4 Policy Implications

Based on these empirical insights, policymakers and agricultural authorities should prioritize the following strategic interventions:

- Closing Technical Efficiency Gaps: Policy efforts must pivot from solely introducing frontier technologies toward enhancing farm-level adoption, managerial capacity, and technical training. Strengthening agricultural extension systems and expanding access to credit are vital to support lagging agricultural systems.
- Supporting Green Technology Transfer: The neutral productivity impact of the Methyl Bromide phase-out confirms that technological substitution and producer adaptation successfully mitigated potential disruptions. National policy frameworks should continue to incentivize early-stage R&D in non-chemical inputs and biological pest controls to ensure seamless compliance with environmental standards.

- Investing in Rural Cold-Chain Infrastructure: Given the importance of historical cold-chain capital proxies, public-private partnerships should focus on modernizing rural refrigeration, energy-efficient storage, and post-harvest transport networks to reduce post-harvest losses and enhance export valuation amidst evolving climatic trends.

Statements

Clinical Trial Number

Clinical trial number: not applicable.

Consent to Publish

Consent to Publish declaration: not applicable.

Consent to Participate

Consent to Participate declaration: not applicable.

Financial Disclosure

The authors received no specific funding for this work.

Competing Interests

The authors have declared that no competing interests exist.

Ethics Statement

Ethics approval: not applicable. This study relies exclusively on secondary, aggregated macro-level country data provided by international organizations (UNEP, FAOSTAT, and the World Bank). No human participants, animal experimentation, or field sampling were involved.

Author Contributions

Conceptualization: [CAZG]; Data Curation: [CAZG]; Formal Analysis: [CAZG]; Methodology: [CAZG]; Software: [CAZG]; Visualization: [CAZG]; Writing – Original Draft Preparation: [CAZG]; Writing – Review & Editing: [CAZG]

Data Availability Statement

All relevant data are within the manuscript and its Supporting Information files (S1_Dataset.csv and S2_Code.R).

Supporting Information

S1 Dataset. Dataset for Malmquist productivity index and panel econometric estimation. Balanced panel data (1990–2023) containing agricultural output, production inputs, ozone-depleting substances (ODS) consumption metrics, and temperature anomalies across the six Latin American and Caribbean nations evaluated. (CSV)

S2 Code. Replicable R Studio script and econometric routines. Fully commented R code utilized for executing the Data Envelopment Analysis (DEA) input-oriented Malmquist Productivity Index decomposition, panel Data Envelopment Analysis, and second-stage Fixed Effects (FE) panel regression models with cluster-robust standard errors. (R).

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Figures

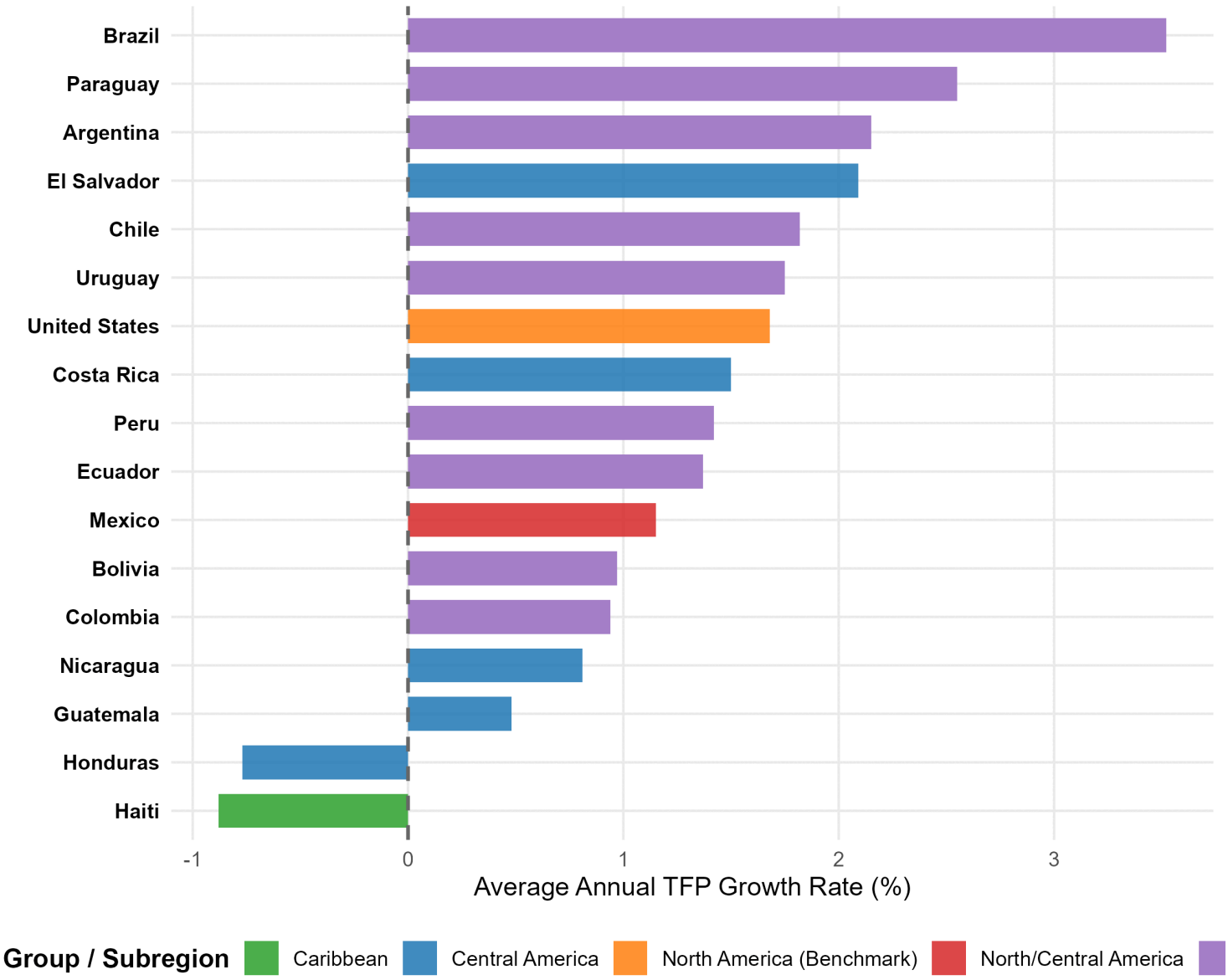


Figure 1

Average annual Total Factor Productivity (TFP) growth rate across selected Latin American, Caribbean, and North American economies (1990–2024). Net percentage growth (TFPCH−1×100) derived from input-oriented VRS Malmquist indices. Positive values reflect productivity expansion driven predominantly by technological innovation (TECHCH). South American and North American benchmarks exhibit robust leadership, while Central American economies demonstrate steady, resilient growth through adaptive agricultural modernization and sustainable management practices.

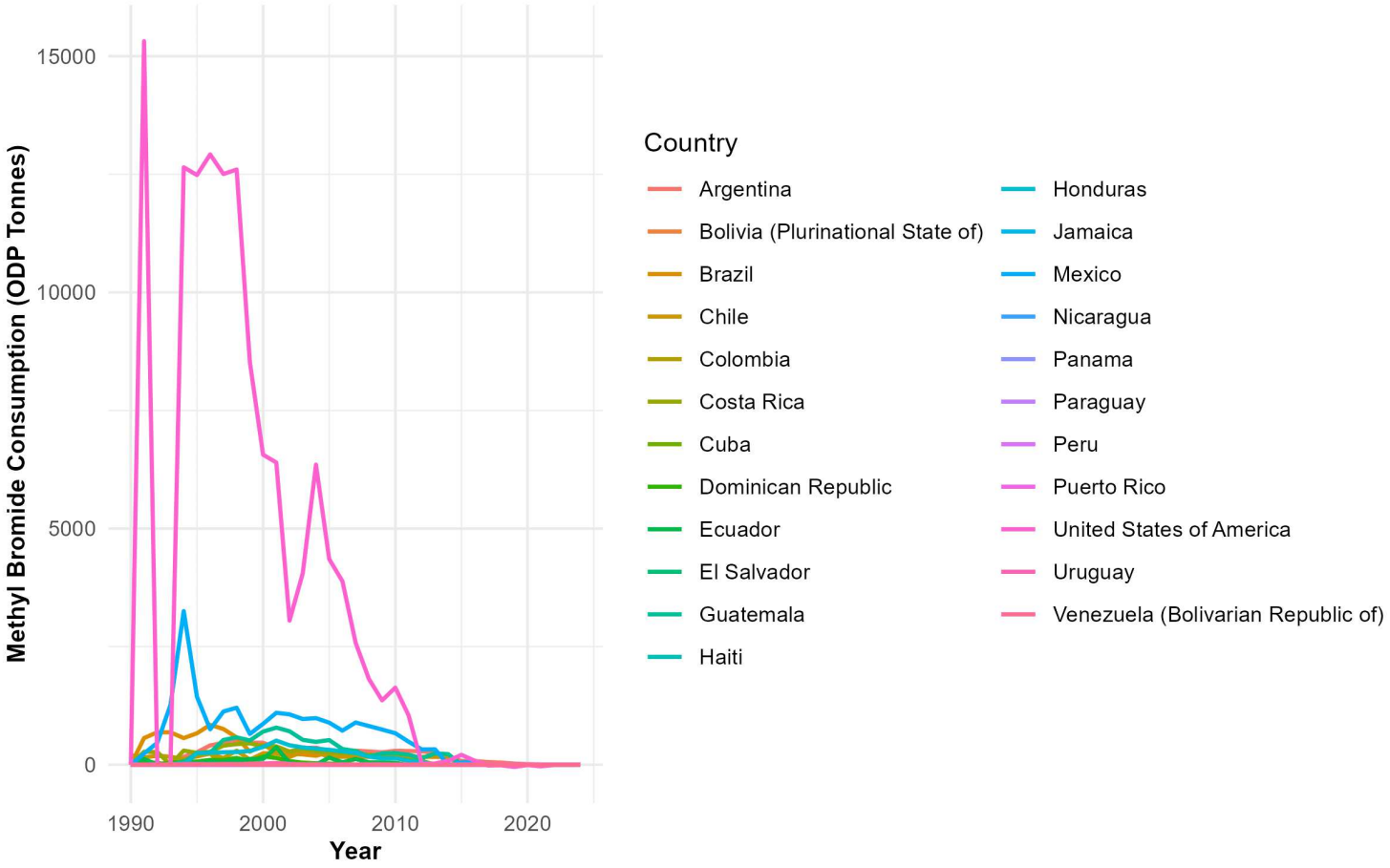


Figure 2

Regional Trends in Methyl Bromide Consumption (1990–2024). *Note: Depicts the trajectory of ODP tonnes consumed across the panel nations, highlighting the aggressive phase-out mandated by the Montreal Protocol that corresponds with the statistical neutrality observed in the second-stage TFP growth regressions.*



Fig. 3 Dynamics of Agricultural TFP and Ozone-Depleting Substances (23 Countries)

Panel A: Title: A. Cumulative Agricultural TFP Index. **Axes:** Y-axis: Cumulative TFP Index; X-axis: Year. **Legend:** Country (displaying individual trajectories for the 23 evaluated nations)

Panel B: Title: B. Geometric Mean of Malmquist Components. **Axes:** Y-axis: Index Value; X-axis: Country. **Legend:** Component, categorized into EFFCH (Efficiency Change, red bars), TECHCH (Technological Change, green bars), and TFPCH (Total Factor Productivity Change, blue bars). The dashed red line marks the baseline threshold ($Value = 1.0$).

Panel C: Title: C. Regional TFPCH vs. Methyl Bromide Phase-Out. **Axes:** Y-axis: Index / Scale; X-axis: Year, **Legend:** Metric, distinguishing between Methyl Bromide ($x100$ Tonnes, dashed red line) and Regional Mean TFPCH (solid teal line).

Panel D: Title: D. Second-Stage Partial Effect: TFPCH vs. MB_IHS. **Axes:** Y-axis: TFPCH; X-axis: Methyl Bromide (IHS). **Legend / Elements:** Scatter observations with a fitted linear regression trendline (red) and reference baseline ($Y = 1.0$, dashed gray line).

Figure 3

See image above for figure legend