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WATER SCARCITY AND VIRTUAL WATER DEPENDENCE IN GLOBAL FOOD TRADE

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Abstract:

This analysis examines whether domestic and supplier water scarcity are associated with import orientation in global crop trade. Using CWASI trade flows and FAO water stress indicators, we analyse 1,939 annual observations across 177 countries and territories during 2010 to 2020. Three linear panel models include country and year effects with standard errors clustered by country. Import orientation measures imports as a share of gross trade. Positive pooled correlations weaken or reverse after these adjustments. None of the three directional hypotheses receives statistical support at the 5 percent level. A ten-percentage point increase in supplier stress corresponds to an estimated 0.155 percentage point decline in import orientation, with uncertainty spanning zero. Coverage restrictions, a balanced sample and logarithmic transformations preserve the absence of statistical support, although the domestic coefficient changes sign under transformation. The contribution distinguishes geographical association from annual adjustment, qualifying resource endowment explanations without establishing causal transmission. For international sourcing and water policy, the evidence supports separate assessment of domestic pressure, external exposure and trade composition rather than assuming automatic adjustment.

Key Words: Virtual Water Trade; Water Scarcity; Import Orientation; Supplier Exposure; Panel Data

1. Introduction:

International crop trade can relieve pressure on domestic water resources while connecting food supply to scarcity in exporting economies. The resulting policy problem is not simply whether countries import virtual water, but whether domestic and foreign water pressures are associated with changes in their reliance on imports within recorded trade. Water footprint accounting establishes that production and consumption can depend on resources located in different countries, while evidence on groundwater depletion demonstrates that agricultural exports can originate from environmentally stressed production systems (Hoekstra & Mekonnen, 2012; Dalin et al., 2017). These connections make it important to distinguish exposure to water scarcity from an observed adjustment in trading behaviour.

Research on virtual water networks has established the geographical redistribution of water embodied in agricultural commodities. Dalin et al. (2012) documented changes in trade connections and water flows associated with agricultural efficiency, commercial relationships and policy shifts. Konar et al. (2012) further distinguished the evolution of green and blue virtual water networks, showing that different water sources and trade relationships cannot be treated as interchangeable. These contributions explain how trade reallocates embodied water across economies. They do not, by themselves, establish whether annual changes in national water stress are associated with changes in a country's import orientation.

A resource endowment perspective provides one explanation for that relationship. Greater domestic freshwater pressure can increase the opportunity cost of allocating water to agricultural production, creating an incentive to obtain crops externally. However, external sourcing does not necessarily transfer production towards locations with abundant water. Lenzen et al. (2013) showed that incorporating scarcity changes the geographical interpretation of international water flows. Qu et al. (2018) demonstrated how water scarcity risks can extend through international supply relationships. Together, these findings motivate separate consideration of pressure within importing economies and pressure associated with their suppliers.

The expected relationships are not uniform. Domestic stress may encourage imports, whereas stress in supplying economies may constrain the production supporting those imports. Continued production under environmental pressure and substitution between suppliers can weaken the latter association. This analysis therefore distinguishes domestic water stress, average supplier stress and the share of imports sourced from stressed exporters. Average supplier stress measures the intensity of pressure associated with the sourcing portfolio. The stressed supplier share identifies how much covered sourcing originates from exporters whose stress reaches or exceeds 50 percent. These indicators represent different aspects of observed exposure rather than demonstrated causal transmission channels.

Outcome definition is equally important. Food import dependence, consumption footprints and import orientation answer different questions. D'Odorico et al. (2014) examined the relationship between food trade and the resources supporting consumption, while Kummu et al. (2020) assessed how international trade relates to food supply diversity and dependence. The present outcome is narrower: virtual water imports divided by imports plus exports, expressed as a percentage. It identifies whether recorded crop trade is predominantly oriented towards importing or exporting embodied water. It does not measure the proportion of domestic consumption supplied by foreign resources. Maintaining this distinction prevents changes in trade composition from being interpreted automatically as changes in food security or consumption dependence.

The reviewed evidence does not establish whether positive pooled relationships between scarcity and import orientation persist when the analysis separates differences across countries from changes within countries. This distinction matters because countries with persistently different water conditions may also differ in agricultural specialization, geography and commercial position. A positive pooled association can therefore coexist with a weak relationship between annual changes in the same variables. The contribution of this analysis is to examine that distinction using three measured scarcity indicators, a consistently defined trade outcome and a common analytical sample. Country and year effects provide an associational comparison that accounts for persistent geographical differences and common annual variation. They do not independently establish causal identification, as emphasized by Imai and Kim (2019).

This study aims to determine whether domestic water stress, supplier stress intensity and exposure to stressed suppliers are associated with virtual water import orientation. The research question is whether these relationships remain evident within countries after accounting for common annual differences. The analysis uses annual observations from 2010 to 2020, combining CWASI crop trade matrices with FAO AQUASTAT water stress distributed through the World Development Indicators. Commodity screening retains 184 traded crop commodities. The common estimation sample contains 1,939 observations across 177 countries and territories. Three separate panel specifications examine the focal predictors using country and year effects and standard errors clustered by country. Coverage restrictions, a balanced sample and transformations of the stress measures assess sensitivity to selected measurement and sample choices.

The findings qualify a direct scarcity-based interpretation of trade adjustment. Positive pooled correlations weaken or reverse after accounting for country and year effects, and none of the three directional hypotheses receives statistical support at the 5 percent level. This conclusion persists across the examined sensitivity checks, although the domestic stress coefficient changes direction under logarithmic transformation. The contribution is therefore a distinction between geographical association and annual adjustment, rather than evidence that water scarcity is irrelevant. For international sourcing assessment, the results support treating domestic pressure, supplier exposure and trade orientation as separate dimensions. The evidence does not justify assuming that a change in one dimension predicts a corresponding change in another.

2. Theory, Conceptual Framework and Hypotheses Development:

This analysis combines resource endowment theory with network interdependence to examine how water scarcity relates to countries' positions in crop trade. Resource endowment theory predicts that constraints on domestic production increase incentives to obtain agricultural products from abroad. Network interdependence explains how this adjustment connects importing economies to water conditions in supplying countries. Water footprint accounting distinguishes water used within national production systems from water embodied in international trade (Hoekstra & Mekonnen, 2012). Evidence on the evolution of virtual water networks further shows that agricultural efficiency, trade policies and commercial relationships shape these connections (Dalin et al., 2012).

Domestic water stress represents pressure on available freshwater resources after accounting for environmental requirements. Higher stress increases competition over water allocated to agriculture and other activities. The theoretical mechanism operates through the opportunity cost of domestic production: importing crops can reduce the need to allocate additional domestic water to their production. Evidence of growing separation between food consumption and the resources supporting production provides a basis for expecting greater import orientation where domestic resource pressure is higher (D'Odorico et al., 2014).

The empirical outcome is virtual water import orientation, measured as imports divided by the sum of imports and exports, expressed as a percentage. This indicator distinguishes countries whose recorded virtual water trade is dominated by imports from those whose trade is dominated by exports. It measures trade composition rather than the proportion of domestic consumption supported by foreign water.

Importing can relieve domestic resource constraints while increasing reliance on external production. Greater food supply diversity has accompanied increased import dependence, while some countries have experienced declining numbers of supplying partners (Kummu et al., 2020). Access to imported resources therefore differs from independence from external supply. The resource substitution mechanism predicts a positive association between domestic water stress and virtual water import orientation.

H1: Higher domestic water stress is associated with a higher import share of gross virtual water trade.

Supplier water stress represents freshwater pressure in the countries supplying an importer's crop products. This analysis measures that dimension through the import weighted average of exporter water stress. Domestic stress creates incentives to obtain products externally, whereas supplier stress identifies pressure within the external production base. Accounting for scarcity changes the interpretation of international water flows because equal traded volumes can originate under different resource constraints (Lenzen et al., 2013).

The proposed mechanism is a supply constraint. Greater water pressure in supplying economies can restrict the agricultural production base supporting exports. Where alternative suppliers do not fully replace constrained supply, imports may constitute a smaller share of the importing country's gross virtual water trade. Research on international supply networks demonstrates that water scarcity risks can extend beyond producing economies through commercial relationships (Qu et al., 2018).

A competing mechanism arises when established exporters sustain production despite pressure on water resources. Groundwater depletion embodied in international food trade demonstrates that environmental pressure can coexist with continuing exports (Dalin et al., 2017). Supplier stress therefore need not produce an immediate reduction in external sourcing. The negative expectation represents the supply constraint mechanism to be tested rather than an established response across importing economies.

H2: Higher import weighted exporter water stress is associated with a lower import share of gross virtual water trade.

Exposure to stressed suppliers represents the proportion of imports obtained from exporters whose water stress reaches or exceeds 50 percent. This measure differs from average supplier stress by identifying how much recorded sourcing lies above a specified pressure threshold. It describes the distribution of imports across supplier stress conditions rather than the number or market concentration of suppliers. Differences in the volumes exchanged through individual trade relationships support the use of flow weighted exposure measures (Konar et al., 2011).

The theoretical expectation concerns the extent of exposure within an importer's sourcing portfolio. When a larger proportion of imports comes from stressed exporters, more external sourcing rests on production systems facing freshwater pressure. Substitution across suppliers could weaken the expected relationship. Trade connections and traded water volumes evolve differently, while importing countries do not necessarily favour a particular water source (Konar et al., 2012). Additional commercial connections therefore cannot automatically be interpreted as avoidance of stressed production systems.

The interpretation remains specific to annual national water stress. Annual assessments can conceal seasonal scarcity and differences within countries (Mekonnen & Hoekstra, 2016). The exposure indicator consequently represents annual sourcing conditions rather than the timing or severity of individual supply disruptions. The supply constraint mechanism predicts a negative association between exposure to stressed suppliers and virtual water import orientation.

H3: A higher share of imports sourced from exporters with water stress of at least 50 percent is associated with a lower import share of gross virtual water trade.

The conceptual framework connects three observed explanatory measures to one observed trade outcome across the available country and year observations from 2010 to 2020. Domestic water stress represents pressure within the importing economy. Import weighted exporter stress represents average pressure associated with its suppliers. The stressed supplier import share represents the proportion of sourcing above the specified threshold. These measures remain distinct indicators rather than components of an unvalidated latent index. The hypotheses specify associations rather than identified causal effects. Because supplier exposure measures describe the composition of existing imports, their relationships with import orientation do not independently establish supply disruption or sourcing adjustment.

3. Data:

This analysis integrates annual virtual water trade flows with national water stress indicators to examine domestic scarcity, supplier exposure and import orientation. The data procedures establish source provenance, define the analytical sample and connect each hypothesis to an observed measure.

3.1 Data Sources, Population, and Sample Construction:

The trade data originate from version 1.4 of the CWASI database, which provides commodity specific bilateral virtual water matrices and production water footprints. The extraction used the virtual water trade archive, production footprint archive, country list and commodity list. The matrices identify exporting countries in rows and importing countries in columns. The source release covers periods extending beyond the analytical window, but this analysis retains observations from 2010 through 2020 only. CWASI version 1.4 was published in 2020 and accessed on 24 October 2020 (Tamea et al., 2020).

National water stress originates from FAO AQUASTAT and is distributed through the World Development Indicators series ER.H2O.FWST.ZS. The indicator measures freshwater withdrawals relative to renewable freshwater resources after accounting for environmental water requirements. The extraction was completed on 24 October 2020 from a source snapshot last updated on 8 October 2020. The series is available

through the World Bank indicator page and application programming interface under Creative Commons Attribution 4.0 (World Bank, n.d.).

The target population comprises countries and territories participating in international crop trade during the observation period. The accessible frame consists of 255 geographical positions represented in the source matrices. These positions include historical entities and an unspecified destination category, so the frame does not represent 255 contemporary sovereign countries. Selection followed source coverage and measurement eligibility rather than probability sampling.

Commodity eligibility required an available bilateral trade file, an affirmative trade inclusion flag and a source category other than non-edible. The initial eligible set contained 186 commodities. Mixed grain and Bambara beans contained nonfinite entries in their 2013 matrices and were excluded from every analytical year. This consistency rule retained 184 traded commodities and prevented annual changes in coverage caused by those incomplete matrices. The production footprint aggregation separately covers 144 primary crops.

The unit of analysis is the country or territory observed in a calendar year. Trade and production footprint measures are annual flows expressed in billion cubic metres. Water stress is an annual national ratio. The consolidated dataset contains 2,191 observations across 201 countries and territories. Of these entities, 197 have eleven observations, two have nine, one has four and one has two. The panel is therefore unbalanced.

Table 1: Sample construction

Stage	Geographical Units	Observations	Inclusion or Exclusion Rule
Source matrix grid	255	2,805 potential entity and year positions	Eleven analytical years for each matrix position
Consolidated analytical frame	201	2,191	Retain a position when trade, production footprint or water stress is available
Records with observed domestic water stress	178	1,950	Exclude 241 records without a matched numeric stress value
Common sample for H1, H2 and H3	177	1,939	Exclude eleven additional records lacking the outcome or supplier exposure measures
Supplier coverage sensitivity sample	177	1,934	Exclude five records with exporter stress coverage below 95 percent

The common sample contains 173 observations in each of 2010 and 2011 and 177 in each subsequent year. It includes 173 entities observed throughout the eleven years and four observed for nine years. All three baseline specifications use this same sample, preventing differences in sample composition from driving comparisons across hypotheses.

3.2 Data Integration, Cleaning, and Quality Assurance:

Integration used the FAO country code and calendar year to identify trade records. A country crosswalk connected CWASI names to World Bank ISO3 identifiers through normalized names and explicit aliases. Mainland China was matched to CHN, while Taiwan remained separate. Historical entities retained their source identifiers. The consolidated dataset contains no duplicate FAO code and year combinations.

Six retained geographical entities, representing 50 observations, have no ISO3 match in the crosswalk. Missing domestic stress also occurs among entities with an ISO3 identifier. Consequently, the 241 missing domestic stress observations reflect both unmatched geography and unavailable source values. Missingness comprises 25 observations in each of the first two years, 22 in each of the next two years and 21 in each remaining year.

The extraction retained source zeros and represented unavailable or undefined values as NA. No interpolation, backward filling or replacement of missing observations with zero was applied. The shared estimation sample uses complete records for the outcome and all three explanatory indicators. This procedure defines the population represented by the estimates without assuming that excluded observations resemble retained observations.

Quality checks examined matrix dimensions, finite values, nonnegative flows, denominator validity and consistency across analytical years. Each retained trade matrix has 255 rows and 255 columns. Aggregated global imports reconcile with aggregated global exports in every year, with absolute numerical differences below one trillionth of a billion cubic metres. Recalculated import shares and supplier exposure indicators reproduce the workbook values.

Extreme water stress observations were retained. The national indicator can exceed 100 percent because withdrawals may include nonrenewable resources, repeated use of water or water otherwise required for environmental flows. Such values are not automatically data errors (World Bank, n.d.). Annual national indicators also conceal seasonal and geographical variation, which limits their interpretation as measures of conditions affecting individual farms or particular harvests (Mekonnen & Hoekstra, 2016).

The dataset represents a retrospective source snapshot rather than information available to traders in each observation year. Historical revisions and modelled water footprints therefore support retrospective association analysis. They do not establish the information available when sourcing decisions were made.

3.3 Variable Measurement, Construction, and Validation:

The principal outcome is importing orientation within recorded virtual water trade. It measures the relative importance of imports compared with exports, rather than the proportion of domestic consumption supported by foreign water. This distinction follows the separation between production footprints, consumption footprints and international virtual water flows in water accounting (Hoekstra & Mekonnen, 2012). Equation 1 defines the outcome.

$$Y_{it} = 100\frac{I_{it}}{I_{it} + E_{it}}$$

Here, Y_{it} denotes import orientation for geographical unit i in year t, I_{it} denotes annual virtual water imports and E_{it} denotes annual virtual water exports. The outcome is undefined when gross trade is zero. Higher values indicate a stronger import orientation.

Domestic water stress is taken directly from ER.H2O.FWST.ZS. Supplier stress intensity and exposure to stressed suppliers are calculated from bilateral flows and exporter stress. Distinguishing these measures avoids treating equal virtual water volumes as environmentally equivalent when they originate under different scarcity conditions (Lenzen et al., 2013). Equation 2 defines the supplier indicators.

$$C_{it} = \sum_{j \in K_{it}} q_{jit}\,, \qquad S_{it} = \frac{\sum_{j \in K_{it}} q_{jit}\, W_{jt}}{C_{it}}, \qquad H_{it} = 100\frac{\sum_{j \in K_{it}} q_{jit}\, \mathbf{1}\{W_{jt} \geq 50\}}{C_{it}}$$

Here, q_{jit} denotes virtual water supplied by exporter j to importer i in year t. The set K_{it} contains exporters with an observed water stress value. C_{it} denotes imports from those exporters, W_{jt} denotes exporter water stress, S_{it} denotes import weighted supplier stress and H_{it} denotes the percentage sourced from exporters with stress of at least 50 percent. The indicator function equals one when the threshold is met and zero otherwise. Both supplier indicators are undefined when covered imports equal zero.

The threshold identifies medium or greater water stress. It is a classification rule rather than an estimated breakpoint. Supplier indicators describe exposure through recorded trade relationships, consistent with research showing that water scarcity risks extend across international supply networks (Qu et al., 2018).

Table 2: Variable dictionary

Indicator	Analytical Role	Definition and Construction	Source and Identifier	Unit and Frequency	Transformation and Direction	Missing Value Rule	Coverage and Limitation
Import orientation	Outcome	Equation 1	CWASI 1.4 bilateral matrices	Percent, annual	Higher values indicate greater import orientation	NA when imports plus exports equal zero	2,176 valid observations; not consumption dependence
Domestic water stress	H1 predictor	Freshwater withdrawals relative to available renewable resources after environmental requirements	FAO AQUASTAT through WDI, ER.H2O.FWST.ZS	Percent, annual	Source level retained; higher values indicate greater pressure	Retain NA when unavailable or unmatched	1,950 valid observations; national annual measure
Supplier stress intensity	H2 predictor	Flow weighted exporter stress, Equation 2	CWASI bilateral flows and ER.H2O.FWST.ZS	Percent, annual	Higher values indicate greater average supplier stress	NA when covered imports equal zero	2,175 valid observations; conditional on covered exporters
Stressed supplier import share	H3 predictor	Share of covered imports from exporters with stress of at least 50 percent	CWASI bilateral flows and ER.H2O.FWST.ZS	Percent, annual	Higher values indicate greater exposure above the threshold	NA when covered imports equal zero	2,175 valid observations; threshold based exposure
Virtual water imports	Outcome construction input	Sum bilateral inflows across retained commodities	CWASI 1.4	Billion cubic metres, annual	Source cubic metres divided by one billion	Retain source zeros	2,191 observations; selected crop coverage
Virtual water exports	Outcome construction input	Sum bilateral outflows across retained commodities	CWASI 1.4	Billion cubic metres, annual	Source cubic metres divided by one billion	Retain source zeros	2,191 observations; selected crop coverage
Exporter stress coverage	Quality indicator	Covered imports divided by total imports, multiplied by 100	CWASI and ER.H2O.FWST.ZS	Percent, annual	Higher values indicate more complete supplier coverage	NA when imports equal zero	2,176 valid observations; not an explanatory variable

Table 3 reports descriptive statistics for the common estimation sample. All indicators are observed or calculated quantities. No latent construct, factor score or composite index is estimated.

Table 3: Descriptive statistics for the common sample

Indicator	Valid Observations	Mean	Standard Deviation	Median	Minimum	Maximum
Import orientation, percent	1,939	63.245	27.465	67.097	1.551	100.000
Domestic water stress, percent	1,939	67.263	302.287	11.021	0.027	3,850.500
Supplier stress intensity, percent	1,939	41.820	53.461	24.830	3.123	635.584
Stressed supplier import share, percent	1,939	15.316	20.252	6.719	0.000	99.650
Virtual water imports, billion cubic metres	1,939	10.778	24.097	3.011	0.002	320.134
Virtual water exports, billion cubic metres	1,939	10.883	27.865	1.354	0.000	247.376
Exporter stress coverage, percent	1,939	99.861	0.535	99.991	89.471	100.000

The footprint volumes combine green and blue consumptive water. They do not separately identify groundwater depletion or the water conditions at the location of original production when goods pass through intermediary exporters. The production-based sourcing proxy and import to production ratio are excluded from the baseline because their commodity coverage differs from the trade aggregation.

3.4 Analytical Framework, Identification, and Reproducibility:

The empirical analysis estimates associations using three separate linear panel specifications. Each specification includes one focal predictor, geographical unit effects and year effects. The shared sample contains 1,939 observations across 177 geographical units. Separate specifications distinguish the three hypotheses without treating average supplier stress and threshold exposure as independent components of a validated index. Equation 3 defines the implemented specification.

$$Y_{it} = \alpha_i + \lambda_t + \beta_d X_{it}^{d} + \varepsilon_{it}$$

Here, Y_{it} denotes import orientation, α_i denotes the geographical unit effect, λ_t denotes the year effect and ε_{it} denotes the residual. The superscript d identifies domestic stress, supplier stress intensity or stressed supplier import share. Each equation contains one corresponding predictor X_{it}^{d}, and β_d measures its association with import orientation.

The models were estimated by ordinary least squares with indicator variables for geographical units and years. Each design matrix has full column rank. Identification of the slope uses changes within geographical units after accounting for common annual differences, consistent with the panel framework described by Wooldridge (2010). Inference uses standard errors clustered by geographical unit with a finite sample correction, allowing residual dependence within units (Cameron & Miller, 2015).

The coefficients represent percentage point differences in import orientation associated with a one percentage point difference in the corresponding predictor. Geographical effects absorb persistent differences between units, while year effects absorb common annual variation. Neither adjustment establishes that water stress is independent of changing trade conditions. Domestic withdrawals and agricultural trade may respond to common economic conditions, while supplier exposure depends on the composition of existing imports. The specifications therefore do not identify causal effects.

An exploratory coverage sensitivity check repeated the three specifications after excluding observations with exporter stress coverage below 95 percent. This restriction removes five observations and retains 1,934 observations across the same 177 units. The check addresses incomplete supplier stress coverage rather than endogeneity. No lags, interactions, moderators, mediators or nonlinear terms were introduced.

Reproduction requires the four CWASI source files, the WDI indicator extraction, the country crosswalk and the documented commodity exclusions. Applying the same aggregation, matching, denominator and complete record rules reproduces the analytical sample. The common timing and construction rules keep the hypotheses, measures and estimated associations aligned.

4. Methods:

4.1 Research Design and Identification Strategy:

This analysis uses an observational panel design to estimate associations between water scarcity exposure and virtual water import orientation during 2010 to 2020. The unit of analysis is a country or territory observed in a calendar year. The estimand is the linear association between each focal predictor and import orientation after accounting for persistent geographical differences and common annual conditions.

The design distinguishes pooled relationships across countries from relationships identified through changes within countries. Country effects absorb characteristics that remain constant within each geographical

unit, while year effects absorb annual differences shared across units. This comparison follows the panel framework described by Wooldridge (2010). Its usefulness lies in separating sources of variation rather than establishing a causal effect.

The explanatory measures and outcome refer to the same calendar year. Domestic water use and agricultural trade may respond jointly to changing economic conditions. Supplier exposure also depends on the composition of existing imports. Consequently, the coefficients represent conditional associations. Fixed effects cannot independently eliminate changing confounding factors, reverse relationships or dependence transmitted between trading partners. Imai and Kim (2019) demonstrate why causal interpretation requires assumptions beyond the inclusion of unit effects.

4.2 Model Specification and Measurement Alignment:

The baseline specification is defined in Equation 3. Three separate models apply that specification to domestic water stress, import weighted exporter stress and the stressed supplier import share. Each model includes one focal predictor, country effects and year effects. Estimating the predictors separately avoids interpreting their coefficients as independent contributions to a jointly estimated mechanism.

The outcome Y_{it} is import orientation for geographical unit i in year t, constructed according to Equation 1. The predictor X_{it}^{d} denotes the observed measure corresponding to hypothesis d. The parameter β_d expresses the percentage point difference in import orientation associated with a one percentage point difference in that predictor. The terms α_i, λ_t and ε_{it} denote the geographical effect, year effect and residual, respectively.

The measurement definitions and denominator rules follow Table 2. Supplier indicators use the flow weights and covered import denominator defined in Equation 2. Their interpretation is conditional on exporters with observed stress values. The outcome measures the composition of recorded trade; it does not measure the proportion of domestic consumption supported by foreign resources.

Table 1 defines the common estimation sample. All three baseline models use 1,939 observations across 177 geographical units. Of these units, 173 contribute eleven observations and four contribute nine. Applying the same complete record restriction to every specification prevents comparisons across hypotheses from reflecting different baseline samples.

The focal measures retain usable temporal variation. Domestic stress changes in 111 geographical units, while both supplier indicators change in all 177 units. Each baseline design matrix has full column rank. The models contain an intercept, one focal predictor, 176 country indicators and ten-year indicators, giving 188 estimated parameters.

4.3 Estimation, Inference, and Analytical Implementation:

Estimation uses unweighted ordinary least squares. Country and year effects enter as indicator variables, with one category omitted from each set. The linear specification provides a slope summary on the observed percentage point scale. Interpretation concerns the observed sample and does not rely on extrapolated predictions outside its support.

The analytical sequence begins with the cleaned country and year records. Unavailable and undefined values are treated as missing. Records are retained only when the outcome and all three focal predictors are numeric. Source zeros and valid extreme stress values remain unchanged. The analysis then constructs the indicator variables, estimates each specification and calculates residuals and clustered covariance matrices.

Standard errors are clustered by geographical unit to accommodate heteroskedasticity and residual dependence within countries. The covariance estimator follows Cameron and Miller (2015) and applies the finite sample correction in Equation 4.

$$\widehat{V} = \frac{G}{G-1}\frac{n-1}{n-k}(X^{T}X)^{-1}\left[\sum_{g=1}^{G} X_g^{T}\,\hat{u}_g\hat{u}_g^{T}X_g\right](X^{T}X)^{-1}$$

Here, $\widehat{V}$ is the estimated covariance matrix, G is the number of geographical clusters, n is the number of observations and k is the number of estimated parameters, including the indicator coefficients. X is the complete design matrix, X_g contains its observations for cluster g, and $\hat{u}_g$ is the corresponding vector of estimated residuals. The superscript T denotes matrix transposition.

Baseline inference uses 177 clusters. Confidence intervals and two-sided p values use the student t distribution with 176 degrees of freedom. A directional hypothesis receives support only when its coefficient has the predicted sign and its p value is below 0.05. Failure to meet this criterion is interpreted as insufficient statistical support rather than evidence that the association equals zero.

The baseline slopes are multiplied by ten for reporting in Table 5. Standard errors and confidence interval endpoints receive the same scaling, allowing interpretation for a ten-percentage point increase in the predictor. This reporting transformation leaves test statistics and p values unchanged.

Implementation used Python 3.12.14, pandas 2.2.3, NumPy 2.3.5 and SciPy 1.17.0. NumPy's least squares routine estimated the coefficients, pandas constructed the analytical samples and indicator variables, and

SciPy supplied the student t probabilities and critical values. The calculations are deterministic. Statistical inference conditions on the released footprint estimate and reported stress values; uncertainty from their upstream construction is not propagated.

4.4 Validation, Sensitivity, and Interpretive Scope:

Validation checks address measurement consistency and estimability. Recalculation of import orientation and both supplier indicators reproduce the workbook values. The country code and year combination uniquely identifies observations. Annual global imports reconcile with exports within numerical precision. Matrix rank checks confirm that the focal coefficients can be estimated alongside the geographical and annual indicators.

Exploratory sensitivity checks address three specific concerns. First, the supplier coverage restriction retains observations for which exporter stress information covers at least 95 percent of imports. This restriction removes five observations and retains 1,934 observations across 177 clusters. It assesses sensitivity to incomplete supplier information.

Second, the balanced sample retains the 173 geographical units observed throughout the eleven years, producing 1,903 observations. This comparison assesses sensitivity to unequal temporal coverage. The three specifications retain the same explanatory definitions, country effects and year effects. Inference uses 173 clusters and 172 degrees of freedom.

Third, domestic stress and average supplier stress are separately transformed using the natural logarithm of one plus the observed value. These specifications retain the baseline sample and assess sensitivity to the asymmetric numerical scales of the two measures. Their coefficients describe differences per logarithmic unit and are interpreted separately from the level coefficients.

Comparisons examine coefficient direction, magnitude and uncertainty. Table 6 reports the sample restrictions, while the Findings section reports the transformation checks. These analyses investigate selected measurement and specification choices. Country clustering does not account for every form of dependence between economies, and the sensitivity checks do not establish causal identification. The methodological contribution is a consistent application of established panel tools to distinguish pooled geographical association from annual variation within countries.

5. Findings:

This analysis examines whether domestic water stress, supplier stress intensity and exposure to stressed suppliers are associated with virtual water import orientation. The findings distinguish unadjusted relationships from estimates accounting for country and year effects. Sample coverage, uncertainty and sensitivity checks determine the conclusions drawn for each hypothesis.

The consolidated dataset contains 2,191 annual observations across 201 countries and territories during 2010 to 2020. The common estimation sample contains 1,939 observations across 177 geographical units. Complete measurement requirements exclude 241 observations without domestic water stress and eleven additional observations without the required trade outcome or supplier indicators. Among retained units, 173 contribute eleven observations and four contribute nine.

Import orientation measures imports as a percentage of imports plus exports. It therefore identifies the composition of recorded virtual water trade rather than the contribution of imported water to domestic consumption. This distinction follows the separation between production footprints, consumption footprints and international water flows established by Hoekstra and Mekonnen in 2012.

Table 4: Descriptive statistics for the common estimation sample

Indicator	Observations	Mean	Standard Deviation	Median	Minimum	Maximum
Import orientation, percent	1,939	63.245	27.465	67.097	1.551	100.000
Domestic water stress, percent	1,939	67.263	302.287	11.021	0.027	3,850.500
Supplier stress intensity, percent	1,939	41.820	53.461	24.830	3.123	635.584
Stressed supplier import share, percent	1,939	15.316	20.252	6.719	0.000	99.650
Exporter stress coverage, percent	1,939	99.861	0.535	99.991	89.471	100.000

The distributions reveal substantial differences between typical observations and arithmetic averages. Median domestic stress is 11.021 percent, compared with a mean of 67.263 percent. This divergence reflects a strongly asymmetric distribution containing high stress observations. Supplier stress intensity also exhibits asymmetry, while the median stressed supplier import share is less than half its mean. These features motivate the transformation checks reported below.

Supplier stress coverage is high within the estimation sample. Its median is 99.991 percent, and only five observations fall below 95 percent coverage. The supplier indicators consequently represent almost all recorded imports for most observations, although they remain conditional on exporters with available stress measurements.

Unadjusted Pearson correlations with import orientation are positive for domestic stress, supplier stress intensity and stressed supplier import share, at 0.158, 0.207 and 0.175, respectively. These pooled associations combine differences between countries with changes within countries. The regression estimates instead use variation within geographical units after accounting for common annual differences.

Three separate linear specifications were estimated using the same sample. Each includes one focal predictor, country effects and year effects. Standard errors are clustered by country with a finite sample correction, following the inference principles described by Cameron and Miller in 2015. Confidence intervals and two-sided tests use 176 degrees of freedom. Hypothesis support requires the predicted direction and a p value below 0.05.

Table 5: Associations with virtual water import orientation

Hypothesis and Predictor	Expected Direction	Estimate for a Ten Percentage Point Increase	Clustered Standard Error	95 Percent Confidence Interval	p Value	Assessment
H1: Domestic water stress	Positive	−0.0056	0.0206	−0.0463 to 0.0350	0.785	Not supported
H2: Supplier stress intensity	Negative	−0.1554	0.1001	−0.3529 to 0.0422	0.122	Not supported
H3: Stressed supplier import share	Negative	0.2898	0.3871	−0.4740 to 1.0537	0.455	Not supported

All estimates represent percentage point differences in import orientation. Each specification uses 1,939 observations across 177 geographical units and includes country and year effects.

Domestic water stress does not exhibit the positive association predicted by H1. A ten-percentage point increase corresponds to an estimated decrease of 0.0056 percentage points in import orientation. The confidence interval includes both negative and positive values, and the p value is 0.785. H1 therefore receives no statistical support. This conclusion concerns the specified annual association and does not establish that domestic scarcity has no relevance to agricultural trade.

Domestic stress varies over time in 111 of the 177 retained units. The remaining 66 units have constant recorded stress throughout their observed years. Consequently, the domestic stress estimate draws on a more restricted source of temporal variation than the supplier indicators, both of which vary in every retained unit.

Supplier stress intensity has the negative coefficient predicted by H2, but its precision does not meet the stated support criterion. A ten-percentage point increase corresponds to a decrease of 0.1554 percentage points in import orientation. The confidence interval extends from a decrease of 0.3529 to an increase of 0.0422 percentage points. The evidence therefore remains compatible with a negative association and with values close to zero.

This result preserves the distinction between trade volume and the scarcity conditions associated with its origin. Lenzen and colleagues in 2013 demonstrated that accounting for scarcity changes the geographical interpretation of virtual water flows. The present estimates do not establish that greater supplier stress translates into a corresponding reduction in import orientation.

Exposure to stressed suppliers has a positive coefficient, contrary to H3. A ten-percentage point increase in the stressed supplier import share corresponds to an estimated increase of 0.2898 percentage points in import orientation. Its confidence interval spans negative and positive values, with a p value of 0.455. H3 is not supported, and the positive estimate does not establish an opposing relationship.

Continued sourcing from stressed exporters remains compatible with the observed pattern. Dalin and colleagues in 2017 documented groundwater depletion embodied in international food trade, demonstrating that environmental pressure can coexist with agricultural exports. However, the present national stress indicators do not measure groundwater depletion, so this literature provides context rather than a tested explanation for the coefficient.

Two sample restrictions assess whether the baseline conclusions depend on incomplete supplier coverage or unequal observation periods. The coverage restriction retains 1,934 observations across 177 units. The balanced sample retains 1,903 observations across 173 units observed throughout the eleven years. Both restrictions preserve the baseline coefficient directions, and neither produces statistical support for the hypotheses.

Table 6: Sensitivity to supplier coverage and panel balance

Predictor	Baseline Estimate	Baseline p Value	Coverage Restriction Estimate	Coverage Restriction p Value	Balanced Sample Estimate	Balanced Sample p Value
Domestic water stress	−0.0056	0.785	−0.0054	0.791	−0.0073	0.727
Supplier stress intensity	−0.1554	0.122	−0.1542	0.125	−0.1235	0.184

Predictor	Baseline Estimate	Baseline p Value	Coverage Restriction Estimate	Coverage Restriction p Value	Balanced Sample Estimate	Balanced Sample p Value
Stressed supplier import share	0.2898	0.455	0.2666	0.496	0.3254	0.395

Estimates represent percentage point differences in import orientation for a ten-percentage point increase in the predictor. The coverage restriction requires exporter stress coverage of at least 95 percent. All specifications retain country and year effects and country clustered inference.

An additional exploratory check replaces domestic stress and supplier stress intensity with the natural logarithm of one plus their respective values. This transformation reduces the influence of their asymmetric numerical scales while retaining the same 1,939 observations. The domestic stress coefficient becomes positive at 1.382, with a confidence interval from −2.468 to 5.231 and a p value of 0.480. Its direction is therefore sensitive to functional form, although neither specification supports H1.

The transformed supplier stress coefficient remains negative at −2.120, with a confidence interval from −4.784 to 0.544 and a p value of 0.118. H2 remains unsupported. These transformed coefficients measure changes per unit of the logarithmic predictor and are not directly comparable with the percentage point slopes in Table 5.

The sensitivity checks establish that the absence of statistical support persists across the examined sample definitions and transformations. They do not resolve omitted changing conditions, reverse relationships or dependence transmitted through international trade networks. Country clustering accommodates residual dependence within countries but does not establish independence between trading partners.

The evidence identifies a distinction between positive pooled associations and weaker relationships within countries after accounting for annual differences. None of the three directional hypotheses receives support at the stated significance level. This finding does not contradict evidence that international trade increases external dependence, because import orientation and consumption dependence measure different outcomes. Kummu and colleagues in 2020 examined the latter relationship through food system diversity and reliance on imports. The present results concern the composition of virtual water trade and provide no basis for treating national scarcity or supplier exposure alone as a reliable predictor of changes in that composition.

6. Discussion:

Water scarcity does not translate automatically into a stronger import orientation in global crop trade. Positive pooled correlations contrast with the small and imprecise associations reported in Table 5 after accounting for country and year effects through Equation 3. The contribution is this distinction between differences across countries and changes within countries, rather than evidence that scarcity is economically irrelevant. Carr and colleagues in 2013 documented geographical and commodity differences in virtual water trade. This analysis adds a temporal qualification: the positive pooled relationships in this sample do not persist as statistically supported associations within countries. Resource endowment theory therefore requires a distinction between explaining national trading positions and explaining annual changes in those positions.

The supplier estimates qualify the proposed transmission mechanism without identifying a causal pathway. Equation 2 separates average supplier stress from the proportion of imports sourced above the stress threshold, but neither measure produces statistical support for the predicted reduction in import orientation in Table 5. The negative supplier intensity coefficient is compatible with the supply constraint argument, while its confidence interval also includes values close to zero. The evidence therefore does not establish that pressure in exporting economies produces an immediate adjustment in importing economies. Imai and Kim in 2019 showed that fixed effects require additional assumptions for causal interpretation, particularly when dynamic relationships may operate. The contribution here is to distinguish measured exposure from demonstrated transmission, preventing an environmental sourcing indicator from being interpreted as evidence of behavioural adjustment.

The contrasting supplier coefficient signs provide no basis for ranking mechanisms or assigning channel shares. Average supplier stress has a negative estimate, whereas the stressed supplier import share has a positive estimate, but both remain imprecise in Table 5. Because the specifications estimate these associations separately, their coefficients cannot be decomposed into contributions to a total effect. Suweis and colleagues in 2013 linked virtual water availability to the resource constraints supporting populations in importing and exporting economies. The present findings refine the application of that argument: dependence on external resources does not necessarily imply a detectable annual relationship between supplier stress and the trade ratio defined in Equation 1. Physical resource dependence, sourcing exposure and trade orientation consequently require distinct empirical treatment.

The measurement pattern reveals a temporal constraint on what national scarcity indicators can explain. Table 4 shows substantial dispersion in domestic stress, yet recorded stress changes in only 111 of the 177 retained units. Large differences between countries therefore coexist with limited temporal information in part of the sample. The stable conclusions under the coverage and balanced sample restrictions in Table 6 indicate

that the tested exclusions do not restore statistical support. They do not establish that annual national indicators capture seasonal production constraints or the capacity to absorb disruptions. Seekell and colleagues in 2017 distinguished biophysical capacity, economic access and production diversity in global food system resilience. This analysis reinforces the analytical value of keeping those concepts separate: a broad scarcity measure should not substitute for a direct measure of supply disruption or adjustment capacity.

The international relevance lies in identifying the limits of a scarcity-based explanation across a geographically broad panel, rather than establishing differences between advanced and emerging economies that were not estimated. Porkka and colleagues in 2013 examined food availability, domestic production and trade dependence, whereas Equation 1 measures import relative to gross virtual water trade. The absence of supported associations in Table 5 therefore cannot overturn evidence about consumption dependence or food security. For decision makers, the practical implication is to assess domestic water pressure, supplier exposure and import orientation as separate dimensions, without assuming that improvement in one predicts adjustment in another. Future analysis should distinguish whether stress precedes changes in bilateral sourcing, import volumes or consumption dependence. This redirects the theoretical question from whether scarcity matters generally to which measured outcomes respond, over what interval and through which identifiable relationships.

7. Conclusion and Implications:

Global food trade can redistribute water use without producing a detectable annual adjustment to scarcity. This analysis distinguishes positive associations across economies from weaker relationships within economies after accounting for persistent national differences and common annual conditions. Neither domestic pressure nor the two dimensions of external exposure received statistical support as explanations of annual trading orientation. The contribution is an empirical distinction between geographical association and temporal adjustment, rather than evidence that water constraints are irrelevant. This distinction qualifies resource endowment explanations by showing that their implications for national trading positions cannot automatically explain annual changes. For decision makers, the findings support separate monitoring of domestic resource conditions, external sourcing exposure and commercial dependence. Procurement teams should avoid treating a national scarcity score as a sufficient signal for changing suppliers. Policy agencies should distinguish environmental exposure from demonstrated supply disruption before allocating intervention resources. Operational assessments can improve transparency by recording sourcing coverage, measurement frequency and the specific outcome each indicator represents. These practices can support more proportionate risk assessment across internationally connected food systems, while avoiding unsupported assumptions about automatic adjustment or protection. The social relevance lies in informing resource and sourcing decisions without overstating what aggregate evidence can establish.

The annual national data create opportunities for research at the scale where production constraints and sourcing decisions occur. Seasonal basin information linked to commodity specific bilateral flows could examine whether local disruptions precede commercial adjustment. Measures of domestic consumption would distinguish changes in trade composition from changes in external resource dependence. Designs using independently identified supply shocks could strengthen causal interpretation, while network methods could assess dependence between trading partners. Extending coverage to excluded economies and comparing institutional settings would clarify transferability. Such extensions could identify adjustment pathways that the present aggregate associations cannot establish.

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