Supply Chain Lock-in and the Selective Destruction of EU–UK Trade

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Abstract

We estimate the UK–EU Trade and Cooperation Agreement's effects on bilateral goods trade using monthly data from 100 countries at HS 6-digit level over nearly nine years (January 2017 to October 2025).

Synthetic difference-in-differences shows a 53.8% collapse in UK export varieties to the EU and a 31.5% decline in import varieties, with effects deepening through 2025. The staggered implementation of UK border controls validates the regulatory friction mechanism: import effects deepened in lockstep with enforcement intensity.

Decomposing the aggregate into 2,673 country-product cells, we show that product characteristics explain over ten times more cross-cell variation than country-specific characteristics on the export side. Three structural drivers emerge: technical barriers to trade (TBT) as the dominant export friction, supply chain embeddedness as the primary source of resilience, and perishability and consumer-goods orientation as the sharpest predictors of extensive margin loss.

The resilience mechanism operates through co-specialised bilateral investments that make regulatory cost absorption rational. LASSO variable selection and a battery of endogeneity tests confirm that this lock-in is conditional on rules of origin restrictiveness and bilateral supply chain depth, not an artefact of selection.

Executive summary

We ask why the Trade and Cooperation Agreement's impact on UK–EU goods trade has varied so widely across products and trading partners, and what this tells policymakers about where the next phase of the UK–EU relationship reset should focus. This is the fourth study in a research programme tracking the TCA's effects, and the first to examine the role of bilateral supply chain structure with nearly five years of post-TCA data. Using monthly bilateral trade data from 100 countries at HS 6-digit product level (January 2017 to October 2025) and synthetic difference-in-differences methods, we estimate a 53.8% decline in UK export product varieties to the EU and a 31.5% decline in import varieties relative to their counterfactual levels, while export values fell by an estimated 16.5% and import values by 23.1%. In value terms, the estimated effects have stabilised — export values fell by 17% at three years and 16.5% at five, import values by 23% and 23.1% (Du, Liu, Shepotylo and Shi 2024) — but negative effects on product varieties continue to deepen through 2025, with no sign of recovery. These aggregate estimates, however, mask wide variation across sectors: some product categories have lost the majority of their trade relationships while others have barely been affected. Explaining that variation is this paper's central contribution.

An in-depth, two-stage analysis of the estimated effects across 2,673 country-product cells shows that, on the export side, product characteristics explain 37% of the variation in value effects while country identity explains just 3%. We are the first to connect this variation to cross-border supply chain linkages. Where UK and EU firms were tightly integrated through shared production networks, trade held up: pharmaceuticals, chemicals, and automotive components all show significantly stronger estimated effects where bilateral input-output linkages are deeper, consistent with the logic of relationship-specific investment. These firms had sunk costs in the bilateral relationship that made absorbing the new regulatory burden more rational than severing it. The gap between the variety and value estimates supports this reading: export varieties fell by more than half, but export values fell by only 16.5%, consistent with embedded relationships maintaining their volume while marginal product lines exited. Where those ties did not exist, in sectors characterised by high consumer-goods orientation, perishability, and low product differentiation, product lines exited and have largely not been replaced.

Among the non-tariff measures tested, technical barriers to trade (TBT) emerge as the dominant policy friction for exports, statistically significant where sanitary and phytosanitary (SPS) measures are not. TBT now operates through the cost of conformity assessment across a regulatory border: UK exporters must demonstrate compliance with EU standards through EU-notified bodies, a process that was automatic under membership but now requires separate certification. The UK government's decision to shelve mandatory UKCA marking and continue recognising CE marking indefinitely underscores the cost that full regulatory separation imposes. On the import side, the staggered implementation of UK border controls provides independent confirmation of the regulatory friction mechanism: estimated import variety losses deepened from 12% under initial light-touch controls to 30% under full enforcement, tracking the phasing-in of physical checks.

The findings have implications for the next phase of the UK–EU reset. The SPS agreement negotiated at the May 2025 Summit addresses a real friction channel on the import side. But the dominant export friction, TBT, falls entirely outside that agreement's scope. The 25 HS2 product chapters where UK and EU production networks are most deeply intertwined, including pharmaceuticals, chemicals, medical devices, and beverages, are where both sides face the highest costs from further regulatory divergence and where both have the strongest economic incentive to cooperate. The EU–Switzerland Mutual Recognition Agreement on conformity assessment, covering twenty product categories since 2002, provides a tested institutional model. In parallel, simplifying cumulation under rules of origin (RoO), which governs whether inputs sourced from the trading partner count toward meeting origin thresholds, would lower the entry barriers that help explaining why so few new trade relationships have formed in five years. A natural sequencing follows from these findings: begin with what the UK can do unilaterally on origin rules, then use the SPS momentum to open a conformity assessment conversation focused on the mutual dependence sectors.

1. Introduction

The UK's EU Exit and the EU-UK Trade and Cooperation Agreement (TCA), which replaced Single Market and Customs Union membership from 1 January 2021, created what Sampson (2017) termed an unprecedented natural experiment in international disintegration. For the first time, a major economy moved from deep regulatory integration to a shallower free trade arrangement with its largest trading partner. The TCA preserved tariff-free and quota-free market access for originating goods but simultaneously introduced customs formalities, rules of origin certification, sanitary and phytosanitary checks, and conformity assessment requirements that had not existed under EU membership. The resulting increase in trade costs was predominantly non-tariff in nature, consistent with the insight of Kee et al. (2009) that border-related frictions extend far beyond tariff schedules.

That the TCA reduced bilateral UK–EU goods trade is no longer seriously disputed — confirmed by independent analyses using UK-side data (~~Bloom, Bunn and Mizen 2025~~; Gasiorek and Tamberi 2023; Du et al. 2023; Du et al. 2024; Freeman et al. 2025), EU-side data (Kren and Lawless 2024; Vergara Caffarelli et al. 2025), firm level data (UK data: Freeman et al. 2025; Spanish data: de Lucio et al. 2024)), and the extensive margin has been more severely affected than the intensive margin. These ex-post studies confirmed what the ex-ante economic models predicted and structural gravity frameworks as discussed in Sampson (2017). What remains contested is the magnitude, the trajectory over time, and the mechanisms that generated the extraordinary heterogeneity observed across trading partners and product categories. The TCA shock was not uniform. EU-UK trade flows in some product categories experienced near-zero disruption; others experienced severe losses. Understanding why is both scientifically important and practically necessary for the trade policy choices now facing both sides.

This paper is the fourth in a research programme tracking the TCA's effects since they first appeared. The six-month assessment (Du and Shepotylo 2022) identified non-tariff measures as the dominant friction channel. The two-year review (Du, Satoglu and Shepotylo 2023) documented an extensive margin collapse: 42% of the UK export varieties to the EU had disappeared. The three-year review (Du, Liu, Shepotylo and Shi 2024) confirmed deepening effects and mapped the heterogeneity.[1] Each study sharpened the diagnosis. But all three left a central question unanswered: *why did some bilateral trade relationships absorb the new compliance costs and survive, while others did not?*

This paper provides the answer. Using Trade Data Monitor bilateral trade data covering 100 countries at the HS 6-digit level from January 2017 to October 2025[2] (nearly nine full years), we make four contributions.

The most comprehensive and updated aggregate estimates to date come first. Using the SDID estimator of Arkhangelsky et al. (2021), synthetic difference-in-differences estimates show a 53.8% collapse in UK export product varieties to the EU, a 31.5% decline in import varieties, and event study dynamics confirming that these effects continue to deepen through 2025.

We then decompose the aggregate effects into 2,673 country-HS2-chapter cells by estimating individual coefficients for each cell using PPML gravity estimation (Santos Silva and Tenreyro 2006). A variance decomposition of the acquired effects reveals that product-level characteristics explain over ten times more the variation in TCA effects than country identity on the export side. The heterogeneity is not primarily about *which EU country* the UK trades with, but about *what type of product* is being traded.

The paper's central contribution is a systematic analysis of supply chain mechanisms as the explanation for trade resilience, drawing on the theoretical tradition of relationship-specific

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[1] Du and Shepotylo (2022) documented a 22% export decline and 26% import decline in the first six months. Du, Satoglu and Shepotylo (2023) found a 42.3% extensive margin collapse at two years. Du, Liu, Shepotylo and Shi (2024) confirmed deepening effects at three years.

[2] Trade Data Monitor (TDM) provides mirror-trade data from customs declarations covering 100+ reporting countries at the HS 6-digit level. See www.tradedatamonitor.com.

investment (Williamson 1985; Antràs 2003). We construct propagated bilateral input-output linkage measures from the AI-generated production network (AIPNET) production network dataset (Fetzer et al. 2024)[3] and show that sectors where UK and EU firms are bound together through intermediate input, trade maintained substantially stronger flows after the TCA shock. Firms embedded in cross-border production networks have co-specialised assets (supplier certification, production line configuration, logistics infrastructure) that make absorbing new regulatory costs rational and severing the relationship prohibitively costly.

Fourth, we exploit the UK's staggered implementation of border controls and subject the RoO result to a battery of endogeneity tests. The phased introduction of import checks — from light-touch Staged Customs Controls in 2021 through the Border Target Operating Model in 2022–23 to full physical inspections from 2024 — provides a natural validation of the regulatory friction mechanism. The deepening of import-side effects in lockstep with enforcement intensity rules out compositional explanations. For rules of origin, Oster (2019) selection-bias bounds, quartile splits by pre-TCA integration, and interaction specifications establish that the positive association between RoO restrictiveness and trade resilience is a heterogeneous effect conditional on bilateral supply chain depth, not an artefact of selection.

The five-year post-TCA heterogeneity analysis also revises our earlier assessment in Du, Liu, Shepotylo and Shi (2024). The three-year review found TBT statistically insignificant; the present specification, at finer country-product resolution with explicit supply chain controls, identifies TBT, operating through conformity assessment, as the*dominant* export barrier. The earlier null result reflected supply chain effects confounding the TBT estimate, not absence of a TBT effect.

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[3] AIPNET (Fetzer et al. 2024) uses large language models to generate bilateral input-output edge lists from product descriptions, providing production network linkages at the HS chapter level.

For the UK–EU relationship reset further progress,[4] the analysis identifies which sectors the evidence points to as priorities for regulatory cooperation beyond the SPS agreement already being negotiated, which friction channels require attention as the next phase of the reset, and which trade relationships face the greatest systemic risk from further divergence.

To be explicit about what distinguishes this paper from Du, Liu, Shepotylo and Shi (2024): a longer panel (five years versus three), finer resolution (country-HS2 cells rather than aggregate bilateral flows), the AIPNET production network dataset providing bilateral supply chain measures unavailable in the earlier work, cross-validated LASSO for model selection across 276 candidate features, staggered border controls as a natural validation device, formal endogeneity testing for the RoO result, and a revised TBT finding made possible by separating conformity assessment effects from confounding supply chain linkages. Each advance is incremental; taken together, they move the analysis from documenting heterogeneity to explaining it.

1.1 Roadmap

The paper proceeds as follows. Section 2 reviews the literature. Section 3 develops the theoretical framework. Section 4 presents data and aggregate results. Section 5 documents country and sector heterogeneity. Section 6 presents the structural drivers analysis. Section 7 reports LASSO variable selection. Section 8 presents robustness checks including staggered border controls and RoO endogeneity tests. Section 9 interprets the mechanisms. Section 10 discusses policy implications. Section 11 concludes.

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[4] The UK–EU Summit of 19 May 2025 committed to negotiating an SPS agreement and launched a broader relationship reset.

2. Related literature and contribution

2.1 Post-Brexit trade effects and the gravity framework

The empirical literature on Brexit's trade in goods effects has developed rapidly, and the broad finding is settled: the TCA reduced bilateral UK–EU goods trade, with the extensive margin bearing the heavier burden.[5] Our earlier work established findings this paper builds upon. Du and Shepotylo (2022) documented a 22% export decline with NTMs explaining 70% of the loss. Du, Satoglu and Shepotylo (2023) found a 42.3% extensive margin collapse at two years. Du, Liu, Shepotylo and Shi (2024) confirmed deepening effects at three years with substantial cross-country heterogeneity.

Independent studies corroborate these findings. Kren and Lawless (2024) find negative impact on the UK exports to EU, but emphasise data-source sensitivity to the size of the effect.[6] The ECB (Vergara Caffarelli et al. 2025) reports near-40% export contraction. De Lucio et al. (2024) provide especially convincing firm-level evidence for the negative impact on export variety. Freeman et al. (2025), who use firm-level data, show that smaller exporters were hit hardest, complementing our aggregate evidence. Gasiorek and Tamberi (2023) document the geographic reshaping of UK trade patterns, and Larch and Yotov (2024) provide the empirical evidence for understanding slow accumulation of trade agreement effects that motivates our dynamic analysis. The present paper extends this by asking why some relationships bore the new costs and survived, requiring production network data that firm-level UK data alone cannot provide.

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[5] The ex ante literature generally predicted smaller effects. Dhingra et al. (2017) predicted 7.7% under soft Brexit; Oberhofer and Pfaffermayr (2021) predicted 12–30%.

[6] Kren and Lawless (2024) note that UK reporting of EU imports during Staged Customs Controls understated disruption. Our TDM mirror-trade data addresses this.

Methodologically, our two-stage approach, using first-stage PPML coefficients as the dependent variable in a second-stage meta-regression, is closest in spirit to the approach of estimating how product level characteristics associated with size of trade elasticity as in Fontagné et al. (2022) and the fixed-effects-recovery strategy in structural gravity associated with and Agnosteva, Anderson, and Yotov (2019). The distinction between extensive and intensive margins is central.[7] Heterogeneous firm models (Melitz 2003; Bernard et al. 2011) predict that fixed cost increases drive extensive margin exit. We empirically test this this by asking what trade policies and product characteristics determines impact fixed cost threshold at which a relationship becomes unviable, and whether production network investment shifts that threshold.

2.2 Production networks, relationship-specificity, and this paper's contribution

The innovation lies in connecting the Brexit literature to production networks. GVCs have been studied since Hummels, Ishii and Yi (2001) and Baldwin and Venables (2013). The AIPNET production network dataset (Fetzer et al. 2024) provides the empirical toolkit.[8] The theoretical foundation is asset specificity: Williamson (1985) identified it as the source of bilateral lock-in; Antràs (2003) formalised the international dimension; Nunn (2007) demonstrated the empirical pattern. Our application in examining the impact of a shock and adjustment mechanism is novel in that bilateral UK–EU supply chain integration determines which relationships had sufficient sunk assets to make absorbing new regulatory burdens rational. We extend the shock propagation literature (Acemoglu et al. 2012; Barrot and Sauvagnat 2016; Bonadio et al. 2021) by asking how network structure determines resilience to a common policy shock.

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[7] Chaney (2008) shows that trade costs affect both the number of exporting firms (extensive) and volume per firm (intensive).

[8] Modern GVC applications include Acemoglu et al. (2012) on macroeconomic propagation and Barrot and Sauvagnat (2016) on firm-level supply chain disruptions.

Relative to the closest existing work, this paper differs in three respects. Freeman et al. (2025) use UK firm-level data to document heterogeneous exit but cannot observe the bilateral production network linkages that explain it; we can, through AIPNET. The ECB (Vergara Caffarelli et al. 2025) estimates aggregate contraction but does not decompose it across products and partners; our 2,673-cell design does. No existing study connects the Brexit trade literature to the Williamson–Antràs tradition of co-specialised investment, which is the mechanism that organises our results.

2.3 Mechanisms mapping

Table 1 maps the theoretical frameworks motivating this study to the empirical patterns we identify and the degree of support from the wider literature. As a preview, the mapping also outlines which mechanisms receive strong corroboration from our results and which remain subject to qualification.

Table 1: Theoretical mechanisms and empirical evidence

Framework	Main mechanism	Pattern in this paper	Literature support
Structural gravity / border effects	New bilateral resistance lowers trade even with zero tariffs	Large UK–EU trade declines despite tariff-free TCA access	Very well supported
Deep integration vs shallow FTA	Loss of Single Market/customs-union depth matters more than tariff schedule	Post-TCA losses too large to be explained by tariffs alone	Strongly supported
Global value chains	Long-term contracts, product specificity, complex networks	UK products embedded in EU GVCs are less impacted	Strongly supported
NTBs and regulatory divergence	SPS/TBT/customs raise fixed and variable costs	Consumer goods, perishables, TBT-heavy sectors worse	Strongly supported
Rules of origin	Compliance and sourcing constraints distort production	RoO important, but conditional on integration depth	Supported with nuance
Heterogeneous firms	Marginal firms and products exit when fixed costs rise	Export variety falls materially	Strongly supported
Trade-policy uncertainty	Anticipation shifts trade before policy is implemented	Event study shows pre-TCA anticipation effects; post-2021 dummy mixes implementation with earlier adjustment	Strongly supported
Trade creation / diversion	Firms reroute sourcing toward non-EU suppliers	Import losses partly mitigated by non-EU substitution	Supported but limited

Notes: Mapping of theoretical frameworks to empirical evidence from the five-year analysis and the broader post-Brexit trade literature.

3. Theoretical framework

3.1 Production networks, relationship-specificity, and the logic of trade survival

The aggregate effects of the TCA are now well established. The present paper begins from a different question: not whether the TCA reduced trade, but why the effects vary so dramatically. Export variety losses range from near zero (Ireland) to over 69% (Slovenia); import value changes from +38% (Romania) to −57% (Netherlands). This variation demands structural explanation. The standard Melitz (2003) and Bernard et al. (2011) framework predicts which relationships exit when fixed costs rise; it does not predict which survive a common cost shock. Reported variety collapse has evolved across our studies (42.3% at two years, 33.5% at three years, 53.8% at five years); the non-monotonicity reflects changes in sample composition and estimation methodology rather than genuine trade recovery at the three-year mark.[9] To explain survival, we need a framework that accounts for the asymmetric incentives created by production network position.

Modern trade is organised around cross-border production networks in which firms at different stages of processing are linked through intermediate input flows (Hummels, Ishii and Yi 2001; Johnson and Noguera 2012). Baldwin and Venables (2013) distinguish 'spider' architectures, where components converge on a central assembly stage, from 'snake' architectures, where goods move through sequential processing steps; both generate relationship-specificity because each node depends on the nodes before and after it.[10] The AIPNET dataset (Fetzer et al. 2024) allows measurement of propagated dependence that

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[9] Variety collapse evolves across our studies: 42.3% at two years, 33.5% at three years, 53.8% at five years. Non-monotonicity reflects differences in sample composition and methodology.

[10] Baldwin and Venables (2013) distinguish 'spider' architectures (components converge on assembly) from 'snake' architectures (sequential processing). Both imply relationship-specificity.

captures not only direct bilateral linkages but also indirect connections through upstream input chains. The TCA introduces regulatory costs, such as customs documentation, conformity assessment, origin certification, at each border crossing within these networks. Crucially, the cost is borne in the context of a production relationship whose value depends on investments that have already been sunk into building it.

The theoretical engine is co-specialised investment. Williamson (1985) identified asset specificity as the fundamental source of bilateral lock-in: when both parties to a transaction have made investments whose value is substantially higher inside the relationship than outside it, exit becomes costly for both sides.[11] Antràs (2003) formalised this insight for international trade, showing that relationship-specific investment shapes the organisational structure of cross-border production; Nunn (2007) demonstrated empirically that countries with stronger contract enforcement export disproportionately in industries requiring relationship-specific inputs.[12] In the UK–EU context, the relevant co-specialised investments include supplier certification (a UK pharmaceutical firm certified to supply active ingredients to a specific EU manufacturer), production line configuration (machinery calibrated to produce components meeting a particular buyer's specifications), logistics infrastructure (cold-chain routes, customs brokerage arrangements, groupage schedules), and accumulated human capital (regulatory expertise, testing protocols, buyer–supplier communication routines). These investments are sunk in the sense that they cannot be recovered if the relationship ends, and bilateral in the sense that both the UK supplier and the EU buyer have typically invested. The sunk bilateral assets create a decisive asymmetry in response to the TCA shock. For embedded relationships, the relevant comparison is not between pre-TCA and post-TCA profit, but between post-TCA

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[11] Williamson's (1985) transaction cost framework identifies asset specificity as the fundamental source of bilateral lock-in.

[12] Nunn (2007) shows countries with better contract enforcement export disproportionately in relationship-intensive sectors.

profit and the outside option net of forfeited sunk costs. If the sunk costs exceed the new regulatory burdens, firms rationally absorb the burden. If sunk costs are small, as in arm's-length trade in standardised goods, exit is rational even at modest cost increases.

3.2 A framework for trade relationship survival

These considerations can be formalised simply. A bilateral trade relationship in product g between UK sector i and EU partner j survives the TCA if and only if:

$$S(g, ij) + [\pi(g, ij) - f(g, ij) - \bar{V}] \geq c(g)$$

where $S(g, ij)$ is the co-specialised sunk cost that would be forfeited upon exit, π is operating profit, f is the fixed maintenance cost, $\bar{V}$ is the value of the best outside option, and $c(g)$ is the TCA regulatory cost.[13] The condition parallels the Melitz (2003) zero-profit cutoff but adds relationship-specific sunk costs and an endogenous outside option, so that production network position determines which relationships cross the survival threshold. This generates five testable propositions:

Proposition 1. Higher bilateral supply chain dependence (higher S) → smaller post-TCA trade declines.

Proposition 2. Higher regulatory burden (higher c) → larger post-TCA declines.

Proposition 3. Mutual dependence → strongest lock-in, as both sides bear the adjustment burden.[14]

Proposition 4. Locked-in relationships exhibit delayed rather than immediate exit.

Proposition 5. Surviving trade shifts progressively towards differentiated goods and away from standardised products.

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[13] The survival condition parallels Melitz (2003) but with relationship-specific sunk costs and endogenous outside options.

[14] 'Mutual dependence' = both M1_prop (UK upstream EU dependence) and M1_EU (EU dependence on UK inputs) above their respective medians.

The mapping from propositions to empirical measures is as follows. The sunk cost S is captured by three AIPNET-derived indices: M1_prop (propagated upstream EU intermediate dependence, measuring how much UK production in a given chapter relies on EU-sourced inputs through direct and indirect supply chain links), M2_prop (propagated downstream EU dependence, measuring how much of the demand for a chapter's output flows to EU buyers), and M1_EU (the reverse perspective, measuring how much EU production depends on UK intermediate inputs in that chapter).[15] The propagation uses a PageRank-style recursion with decay factor $\delta = 0.85$, so that indirect linkages through upstream input chains are captured but attenuated. All three indices use only intermediate goods flows (identified via BEC Rev.5), since supply chain dependence operates through production relationships rather than final consumption. The compliance cost c is measured through four trade policy variables. These include MFN tariff rates, SPS and TBT non-tariff measure counts, and the RoO restrictiveness index of Ayele, Gasiorek and Koecklin (2023), and through product characteristics that determine compliance burden: the PLAID perishability index (Brockhaus, Hinz and Iodice 2026), BEC consumer and intermediate goods shares, and the Rauch (1999) differentiation index. Bilateral controls (GDP, population, distance, pre-TCA trade intensity) capture cross-country variation in the outside option $\bar{V}$.

4. Data and aggregate results

4.1 Data

The analysis draws on TDM bilateral trade data covering 100 countries at HS 6-digit from January 2017 to October 2025. Trade flows are measured in USD value (billions) and

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[15] Propagated measures use PageRank-style recursion with $\delta = 0.85$, capturing indirect as well as direct supply chain linkages.

variety count (distinct HS6 product lines with value above USD 1,000).[16] Following ONS methodology, we exclude gold (HS7108) to avoid distortions from large non-commercial transfers. The dataset spans a significant institutional transition: until December 2020, UK–EU trade flows were collected via Intrastat; from January 2021, exports moved to HMRC customs declarations, followed by imports from January 2022. The introduction of Staged Customs Controls in 2021 permitted some imports to be reported up to 175 days after import, creating partial under-recording of UK imports from the EU in that year.

The sample period spans the transition from HS2017 to HS2022, which increased the number of HS 6-digit product codes from 5,387 to 5,612 (approximately 4.2%), reflecting the creation, splitting, and redefinition of categories rather than a real expansion in traded products. In practice, the classification break falls within the post-TCA period and is absorbed by the time fixed effects in both the SDID and PPML designs.

The five-year window permits separation of adjustment from structural reallocation, encompasses the full cycle of staggered UK border controls,[17] and provides cross-sectional variation for second-stage analysis. The sample ends in October 2025, two months short of the full calendar year. We see no reason to expect material seasonal bias: the product-level panel is balanced across months, and the SDID and PPML designs difference out seasonal patterns through time fixed effects.

Table 2 reports summary statistics for the sample used for SDID estimation. The value of an average bilateral monthly trade between two countries is slightly more than 200 million USD, but can reach up to 343 billion USD for cost, insurance and freight (CIF) import values.

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[16] Variety = distinct HS 6-digit product line with trade value exceeding USD 1,000 in a given bilateral-quarter cell.

[17] Full UK-side border controls phased in through 2024: health certification January 2024, physical checks April 2024. See BTOM, HM Government, August 2023.

On average, two countries trade approximately 250 products out of a potential 5,600, reflecting the concentration of trade in goods where countries hold comparative advantage.

Table 2: Summary statistics for bilateral trade flows, TDM, Jan 2017 – Oct 2025

Variable	Observations	Mean	Std. Dev.	Min	Max
Export values (bln USD)	1,600,284	0.214	3.21	0	336
Import values (bln USD)	1,754,664	0.202	3.10	0	343
Export varieties (#)	1,600,284	256.3	603.7	1	5,458
Import varieties (#)	1,754,664	251.2	620.8	1	7,089

Notes: All trade values are bilateral, USD billions. Varieties are distinct HS6 product lines with value > USD 1,000.

Structural covariates use 2017–2020 pre-TCA averages: trade policy (MFN tariffs, SPS/TBT counts, RoO index from Ayele, Gasiorek and Koecklin 2023), supply chain (AIPNET M1_prop, M2_prop, M1_EU), and product characteristics (BEC classification, Rauch differentiation, PLAID perishability from Brockhaus, Hinz and Iodice 2026). The RoO measure is the Rules of Origin Restrictiveness Index (ROO-RI) developed by Ayele, Gasiorek and Koecklin (2023), extending the Cadot et al. (2006) framework. The index scores each HS6 product line on a 1–10 scale across five categories of origin requirement: wholly obtained, value-added thresholds, change of tariff classification (at chapter, heading or sub-heading level), specific production processes, and "any heading" provisions. Five scoring principles govern combinations of requirements within a single product line. For the TCA, the mean ROO-RI is 4.32. We normalise the index to a 0–1 scale and aggregate to the country × HS2 level as a trade-weighted average.

Table 2a: Variable definitions for second-stage meta-regression

Variable	Description	Source	Level
(a) Trade policy			
Log MFN tariff rate	Log applied most-favoured-nation tariff, 2017–2020 average	WITS/TRAINS	Country × HS2
NTM — SPS (count)	Count of sanitary and phytosanitary measures in force	WTO I-TIP	Country × HS2

NTM — TBT (count)	Count of technical barriers to trade measures in force	WTO I-TIP	Country × HS2
RoO restrictiveness (0–1)	ROO-RI (Ayele et al. 2023), normalised from 1–10 to 0–1; trade-weighted average	Ayele et al. (2023); Cadot et al. (2006)	HS6 → Country × HS2
(b) Supply chain			
Log upstream input diversity	Log count of distinct HS6 input codes used in production	AIPNET	HS2
M1_prop	Propagated upstream EU intermediate dependence (PageRank, $\delta = 0.85$)	AIPNET	HS2
M2_prop	Propagated downstream EU dependence	AIPNET	HS2
M1_EU	EU production dependence on UK intermediate inputs	AIPNET	HS2
(c) Product characteristics			
BEC consumer share	Share of HS6 lines classified as final consumption goods	UN BEC Rev.5	HS2
BEC intermediate share	Share of HS6 lines classified as intermediate goods	UN BEC Rev.5	HS2
Rauch differentiated share	Share of HS6 lines classified as differentiated	Rauch (1999)	HS2
PLAID perishability	Product-level perishability index	Brockhaus et al. (2026)	HS2
(d) Bilateral controls			
Log GDP per capita	Log partner GDP per capita, 2017–2020 average	World Bank WDI	Country
Log population	Log partner population, 2017–2020 average	World Bank WDI	Country
Log distance	Log bilateral population-weighted distance	CEPII	Country pair
Pre-TCA UK trade intensity	UK bilateral trade share of partner's total, 2017–2020	TDM	Country
Partner market share	Partner's share of world trade, 2017–2020	TDM	Country

Notes: All structural covariates use 2017–2020 pre-TCA averages. "Level" indicates the unit at which the variable varies in the second-stage regression. AIPNET = AI-Generated Production Networks (Fetzer et al.); PLAID = Product-Level Analysis of International Durability; BEC = Broad Economic Categories; ROO-RI = Rules of Origin Restrictiveness Index.

4.2 Aggregate effects: synthetic difference-in-differences

We estimate aggregate effects using SDID (Arkhangelsky et al. 2021).[18] Table 3 reports the results.[19] Export varieties declined by 53.8% (coefficient −0.773, t = −11.0) and import varieties by 31.5% (−0.378, t = −5.9). Value declines are more moderate at 16.5% for exports and 23.1% for imports. The gap between variety and value effects reflects intensive-margin compensation, the pattern the lock-in framework predicts: embedded relationships bear new costs and maintain volume while marginal ones exit.

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[18] SDID (Arkhangelsky et al. 2021) constructs optimal unit and time weights simultaneously. See Appendix A for implementation details.

[19] Bootstrapped standard errors follow Arkhangelsky et al. (2021), clustering at the country-pair level.

Table 3: Aggregate TCA effects, SDID and PPML estimates

	Import value	**Import variety**	**Export value**	**Export variety**
Panel A: SDID				
δ_TCA	−0.263	−0.378	−0.180	−0.773
Standard error	(0.062)	(0.064)	(0.056)	(0.072)
t-ratio	−4.24***	−5.91***	−3.21***	−10.7***
Change (%)	**−23.1%**	**−31.5%**	**−16.5%**	**−53.8%**
Panel B: PPML				
δ_TCA	−0.372	−0.299	−0.177	−0.641
Standard error	(0.080)	(0.035)	(0.064)	(0.066)
t-ratio	−4.68***	−8.47***	−2.78***	−9.65***
Change (%)	**−31.1%**	**−25.8%**	**−16.2%**	**−47.3%**

Notes: Bootstrapped standard errors for SDID. Clustered by reporter-partner for PPML. Control: bilateral pairs trading with EU and RoW. Treated: UK–EU post-December 2020. Change = (exp(δ) − 1) × 100. *** p<0.01, ** p<0.05, * p<0.10.

The SDID and PPML estimates tell a consistent story, though magnitudes differ. For export varieties, SDID gives −53.8% while PPML gives −47.3%. The gap reflects methodological differences: SDID constructs optimal unit and time weights on aggregate bilateral flows, while PPML operates at the country-pair×product level and is identified from a richer variation in treatment intensity. PPML also retains zero-value cells that SDID drops. The estimates should be read as bounding the true effect rather than as point estimates requiring reconciliation.

A potential concern with the SDID design is that the Stable Unit Treatment Value Assumption (SUTVA) may be violated if UK trade diversion inflates activity among control-group bilateral pairs. If, for example, EU exporters redirected goods from the UK to other markets, control-group trade would rise, biasing our treatment estimate downward. The estimates reported here are therefore conservative. A sensitivity check restricting the control group to OECD economies produces qualitatively similar results (Appendix B).

4.3 Event study dynamics

Figure 1 presents the event study estimates. Pre-treatment coefficients are tightly centred on zero through 2020Q4, supporting parallel trends. Post-treatment, extensive margin effects are immediate, large, and *deepening*: export variety losses widen from roughly −30% in 2021Q1 to over −60% by 2025. UK exports demonstrated an immediate and large negative impact on both values and varieties, with partial recovery followed by further gradual deterioration. Import varieties follow a more gradual but continuous downward trajectory, reaching approximately −30% by late 2025. Import value effects deepen through 2024–2025, coinciding with phased UK border controls and providing a natural validation of the regulatory friction mechanism. The widening gap between variety and value effects indicates growing intensive-margin compensation, as Proposition 5 predicts.

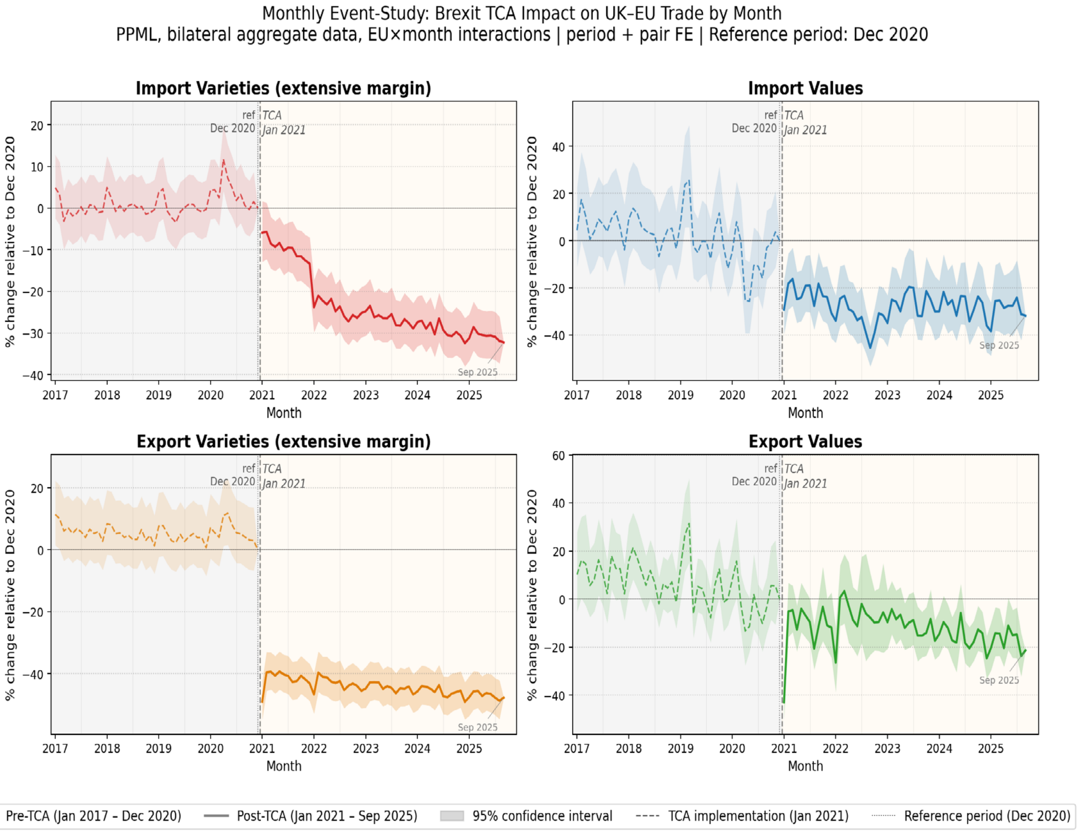
The event study specification replaces the single post-TCA indicator with a full set of period interactions:

$$trade_{ij,t} = \exp(\Sigma\, \beta_\tau \cdot \mathbf{1}[\mathrm{GBR_i} \times \mathrm{EU_j}] \cdot \mathbf{1}[\tau = t] + \alpha_{\mathrm{ij}} + \alpha_t) \cdot \varepsilon_{ij,t}$$

where $trade_{ij,t}$ is the outcome variable (export value, import value, export variety, or import variety), the coefficients β_τ trace the treatment effect for each period relative to the reference quarter (2020Q4), α_{ij} denotes country-pair fixed effects, and α_t denotes period fixed effects.

Crucially, the effects deepen over time rather than attenuating. This rules out a temporary adjustment-cost interpretation and is consistent with structural changes in trade relationships — severed product-partner links, relocated supply chains, and foregone new-relationship formation — accumulating over the post-TCA period. The pattern provides rare disintegration-side evidence on the slow accumulation of trade agreement effects documented for integration episodes (Larch and Yotov 2024).

Figure 1: TCA and export varieties



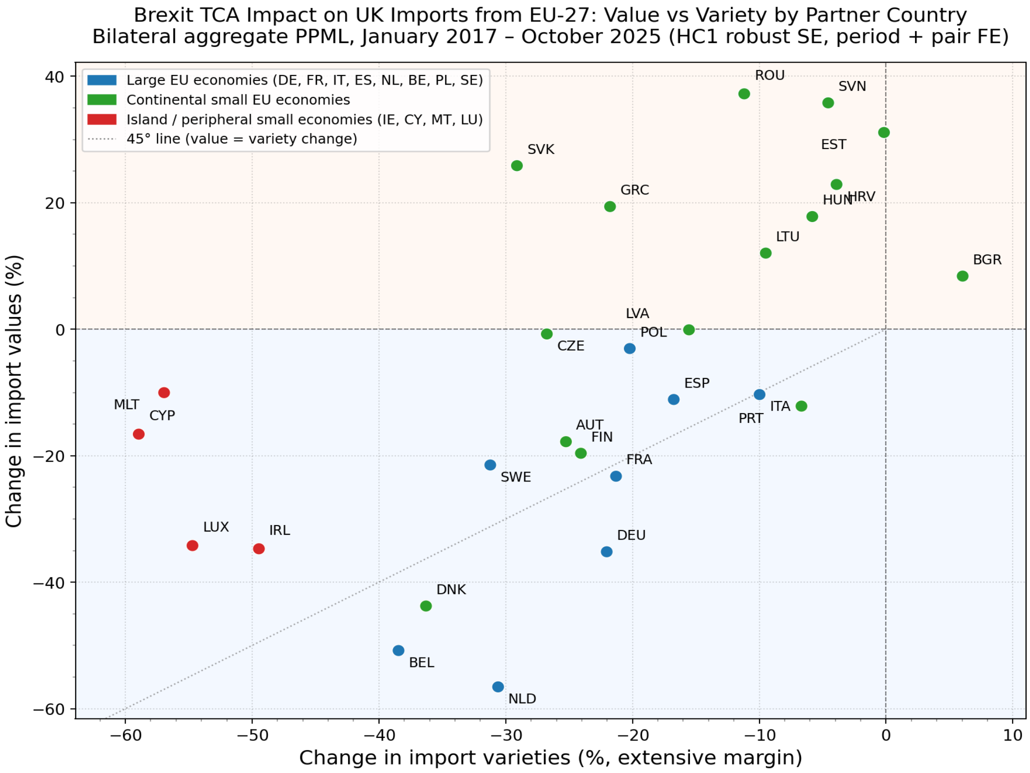
Notes: The figure of export variety losses appear widening year by year. Five years on, there is no sign of recovery. Monthly event study of TCA impact on UK–EU trade. PPML, bilateral aggregate data, EU×month interactions, period + pair fixed effects. Reference period: 2020Q4. Dashed vertical line marks TCA entry into force (January 2021).

5. Country and sector heterogeneity

TCA trade effects are estimated separately for each of the 27 EU partner countries following the bilateral PPML gravity approach of Santos Silva and Tenreyro (2006), covering January 2017 to October 2025. Import and export value effects come from a single regression with 27 country-specific GBR × partner × post-TCA interaction terms, monthly period and country-pair fixed effects, and robust standard errors. An equivalent regression on the count of active HS6 trade lines yields the extensive margin (variety) effects.

Imports (Figure 2). Most EU countries lie above the 45° line. Eastern European economies (Estonia +32.6% value, Romania +38.3%, Hungary +18.5%) experienced *rising* import values despite variety contraction, a pattern that points to trade restructuring within embedded supply chains. The Netherlands (−56.8% value, −30.8% variety), Belgium (−51.2%, −38.6%), and Denmark (−43.7%, −36.4%) experienced outright trade destruction. Ireland (−34.8% value, −49.8% variety) shows severe variety losses reflecting Northern Ireland institutional complexity.

Figure 2: TCA and import values by EU partner country

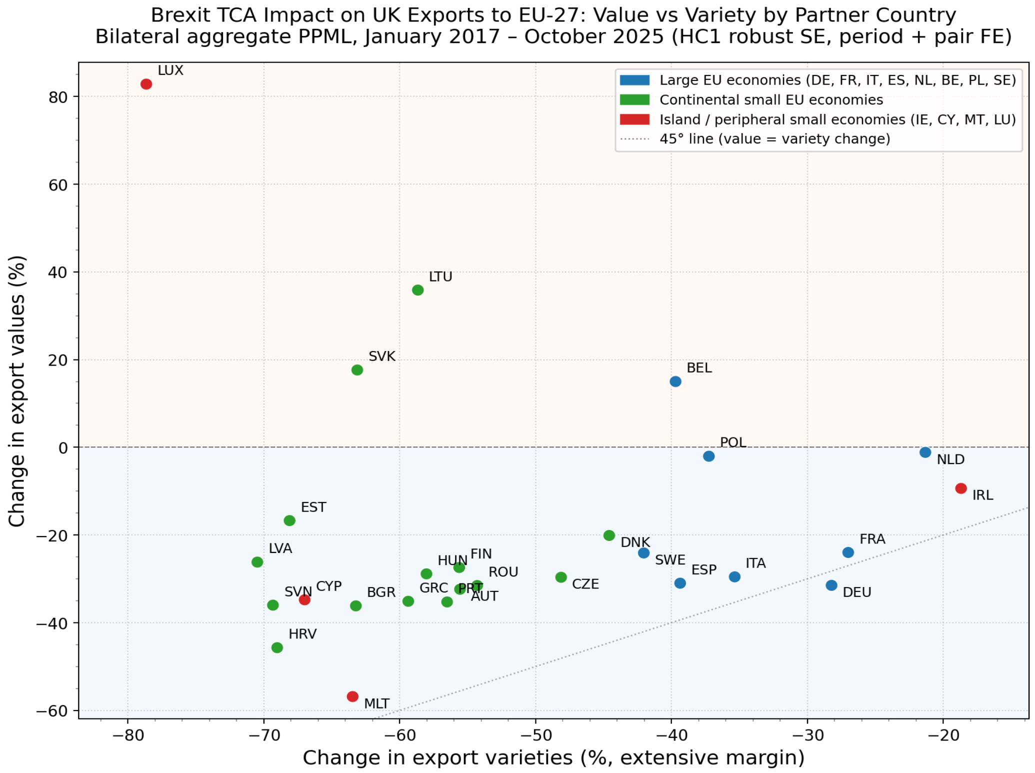


Notes: Eastern European imports restructured; Dutch and Belgian trade was destroyed. Value versus variety by partner country. Bilateral aggregate PPML, January 2017 – October 2025.

Exports (Figure 3). The most striking feature is that the extensive margin collapsed across every single EU partner without exception. The pattern is consistent with the pecking-order logic of Eaton, Kortum and Kramarz (2011): smaller, more distant EU partners with thinner pre-TCA trade volumes suffered steeper variety losses. Yet UK export values fell far less than the breadth of product lines, indicating intensive-margin resilience: the UK is exporting to fewer product categories but sustaining or even concentrating value in the lines that remain. Croatia (−45.5%, −69.0%), Malta (−57.1%, −63.4%), and Slovenia (−35.9%,

−69.4%) suffered the largest combined declines. Germany (−31.1%, −28.3%) and France (−23.7%, −27.1%) show moderate but significant losses. Ireland is a notable outlier with much smaller declines, plausibly reflecting the Windsor Framework's distinct regulatory treatment. Several smaller markets — Lithuania, Slovakia — show positive value changes, pointing to a sharp compositional shift towards high-unit-value goods in those destinations.

Figure 3: TCA and export values by EU partner country



Notes: Smaller EU partners lost most export varieties; Ireland is the outlier. Value versus variety by partner country. Bilateral aggregate PPML, January 2017 – October 2025.

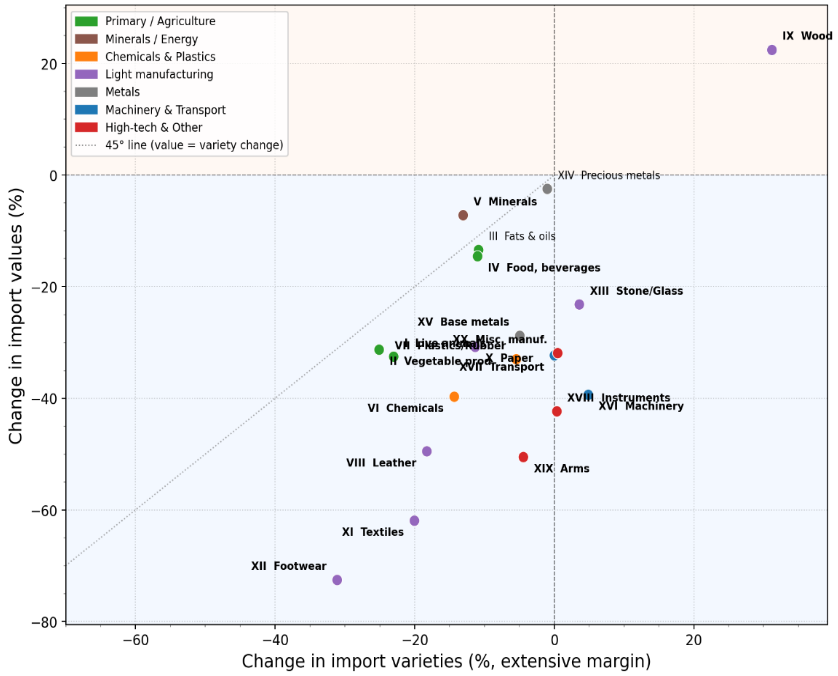
These country-level patterns are remarkably stable relative to our three-year assessment (Du, Liu, Shepotylo and Shi 2024). The same member states that were hardest hit at three years remain the hardest hit at five, and the same countries that showed positive or resilient effects still do. The Netherlands and Belgium remain the most severely affected on import values; Eastern European economies continue to show positive import effects. On exports, the universal variety collapse documented at three years has deepened substantially: Slovenia has gone from −45% to −69%, Croatia from −44% to −69%. While the ranking is stable, the magnitudes have widened.

What the five-year data make clearer is that this country-level pattern is largely a reflection of compositional differences in what each country trades with the UK. The variance decomposition in Section 6 shows that product characteristics explain ten times more variation in export effects than country identity. The cross-country variation is substantial. The question driving the remainder of this paper is whether it is primarily explained by *which EU country* a product flows to, or by *what type of product* is being traded.

Imports by HS section (Figure 4). Commodity and resource-linked sectors prove most resilient. Wood and Wood Products (IX) is the only HS section to post gains on both values and varieties. Primary and commodity-adjacent sectors, such as Precious Metals (XIV), Minerals (V), Fats and Oils (III), and Food and Beverages (IV), show modest variety contractions of 5–12% and value declines below −20%. Light manufacturing bore the heaviest burden: Footwear (XII) is the worst-performing section, with import values down roughly −72% and variety down −35%. Textiles (XI) and Leather (VIII) follow with severe losses on both axes. Machinery (XVI), Instruments (XVIII), and Transport (XVII) managed to retain most of their product variety but still suffered value declines of 30–42%. Fontagné et al. (2015) show that product standards disproportionately affect extensive margins — our HS section results confirm this at a broad sectoral level.

Figure 4: TCA and import values by HS section

Brexit TCA Impact on UK Imports from EU-27: Value vs Variety by HS Section
Bilateral aggregate PPML, quarterly 2017Q1–2025Q3, top-100 reporters & partners (SE clustered by country-pair, quarter + pair FE)

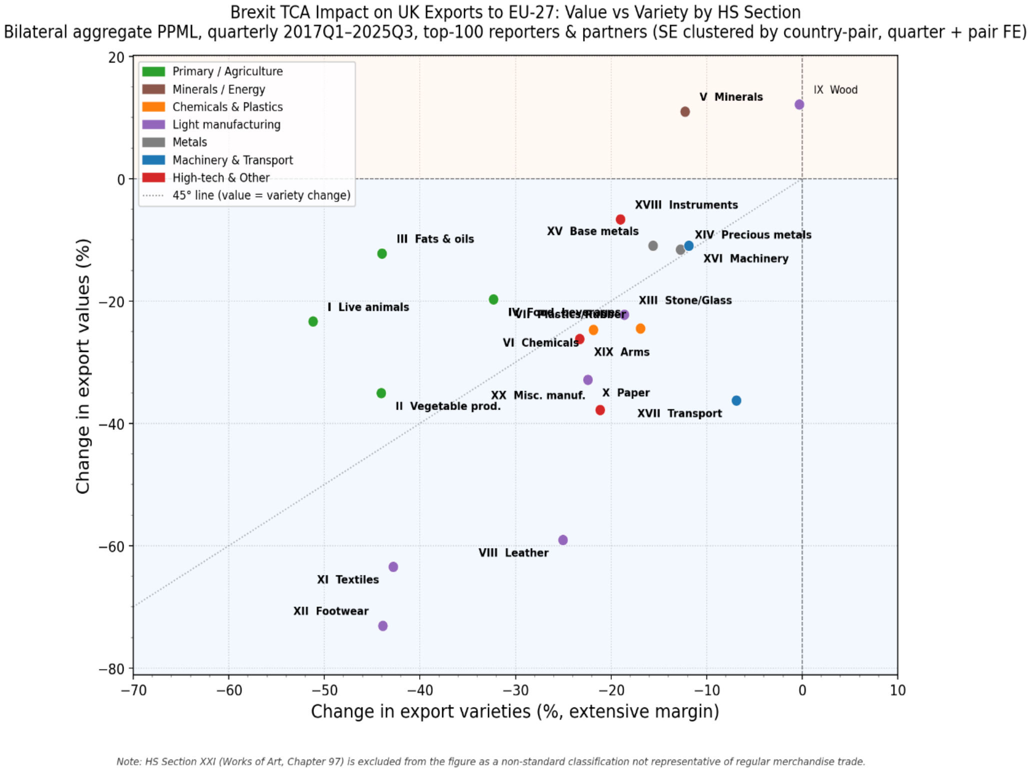


Note: HS Section XXI (Works of Art, Chapter 97) is excluded from the figure as a non-standard classification not representative of regular merchandise trade.

Notes: Light manufacturing bore the heaviest import losses; commodity sectors proved resilient. Value versus variety by HS section. PPML, quarterly bilateral data, 2017Q1–2025Q3.

Exports by HS section (Figure 5). Energy and capital goods anchor export resilience. Wood (IX) and Minerals (V) again stand out as the only sections with positive export values. The UK's most sophisticated export sectors, including Machinery (XVI), Instruments (XVIII), Precious Metals (XIV), and Base Metals (XV), show relatively contained variety declines of −10 to −22% and value losses of only −5 to −12%. Agricultural and light manufacturing exports collapsed: Footwear (XII) and Textiles (XI) suffered value declines of −65% to −75% alongside variety losses of −45 to −50%.

Figure 5: TCA and export values by HS section



Note: HS Section XXI (Works of Art, Chapter 97) is excluded from the figure as a non-standard classification not representative of regular merchandise trade.

Notes: Sophisticated manufactures held up; agricultural and light manufacturing exports collapsed. Value versus variety by HS section. PPML, quarterly bilateral data, 2017Q1–2025Q3.

The country- and section-level results establish two facts that the rest of the paper sets out to explain. First, the TCA shock is profoundly heterogeneous: within the same broad direction of trade, footwear and textiles lost two-thirds of their value while machinery, instruments, and precious metals were barely affected. Second, this heterogeneity is structured, given that commodity and capital-intensive sectors cluster among the resilient, light consumer manufacturing among the casualties. This suggests it is driven by identifiable product and relationship characteristics rather than noise. Baier, Yotov and Zylkin (2019) demonstrate that the effects of free trade agreements are widely differing across partners and sectors, motivating cell-level decomposition of the kind we pursue. Establishing why the shock fell where it did requires estimating the TCA effect at the finest level the data allow — the individual country×product cell — and then explaining the resulting distribution with measured structural characteristics.

6. Explaining heterogeneity: estimation framework and structural drivers

6.1 Two-stage framework

To move from how much trade changed to why it changed where it did, we adopt a two-stage research design following the logic similar to Fontagné et al. (2022). The first stage estimates the TCA effect separately for every country-product cell, producing a full distribution of heterogeneous treatment effect coefficients rather than a single average. The second stage then treats that distribution as data, regressing the estimated cell-level effects on pre-determined structural characteristics — supply chain dependence, trade policy frictions, and product attributes — to identify which forces generate resilience and which generate collapse. The appeal of this design is that it cleanly separates measurement of the shock from explanation of it: the first stage makes no assumption about what drives heterogeneity, and the second stage tests competing mechanisms without contaminating the underlying effect estimates.

6.2 First-stage PPML specification

We estimate a PPML gravity model (Santos Silva and Tenreyro 2006)[20] on 100 reporters × 100 partners × 99 HS2 chapters × quarters (2017Q1–2024Q4), implemented using the high-dimensional fixed effects estimator of Correia, Guimarães and Zylkin (2020) via fixest in R (Bergé 2018). Country-pair×HS2 fixed effects absorb time-invariant bilateral trade costs; quarter fixed effects absorb common trends. The estimating equation is:

$$trade_{ij,h,t} = \exp(\Sigma_{\mathrm{j}}\, \Sigma_{\mathrm{h}}\, \beta_{j,h} \cdot \mathbf{1}[\mathrm{GBR}_{\mathrm{i}} \times \mathrm{EU}_{\mathrm{j}}] \cdot \mathbf{1}[\mathrm{HS2} = h] \cdot post\_TCA_t + \alpha_{\mathrm{ij,h}} + \alpha_t) \cdot \varepsilon_{ij,h,t}$$

Each GBR × EU27-country × HS2 cell receives its own treatment coefficient $\beta_{j,h}$, measuring the post-TCA change in that flow relative to the common time trend identified by

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[20] PPML (Santos Silva and Tenreyro 2006) handles zero flows and is consistent under heteroskedasticity. Implemented via fixest in R (Bergé 2018).

the control group. Quarter fixed effects (α_t) absorb common macro trends including COVID-19 effects; country-pair×HS2 fixed effects ($\alpha_{ij,h}$) absorb all time-invariant bilateral trade determinants at the product level. The design yields up to 2,673 cell-specific treatment coefficients per outcome.

The distribution of first-stage TCA effects across country×HS2 cells is overwhelmingly negative, but severity varies markedly by trade direction and margin. For export value, the average effect is −30% and the median is −37%, with 76% of cells recording a negative effect — a substantially heavier impact than on the import side, where the median is only −16% and 59% of coefficients are negative.

Figure 6: Distribution of first-stage TCA impact estimates

Notes: HS chapters 97 (Works of Art) and 99 (Special Transactions / Confidential) are excluded from the figure. These are non-standard classifications not representative of regular merchandise trade.

Notes: By EU country and HS2 product. The dispersion motivates the second-stage analysis of structural drivers.

6.3 Variance decomposition

A two-way ANOVA of first-stage β coefficients decomposes the cross-cell variation into country and product components. Table 4 reports the results for all four outcomes. For export values, product identity explains 36.8% of variation ($\eta^2 = 0.368$) while country explains only 3.3%, a ratio exceeding ten to one. For import values, the decomposition is more balanced (country 0.120, product 0.111). The asymmetry is itself a substantive finding: on the export side, where the UK chose what to ship and product structure governs almost everything, heterogeneity should be highly predictable from product attributes. On the import side, where country factors matter as much as product factors and the UK's staggered border controls blurred the timing of adjustment, the structural signal is weaker and noisier.

Table 4: ANOVA decomposition — country versus HS2 chapter

Outcome	Country (η^2)	HS2 chapter (η^2)	Residual (η^2)	N cells
Import value	0.120	0.111	0.769	2,341
Import variety	0.098	0.123	0.779	2,335
Export value	0.033	0.368	0.600	2,629
Export variety	0.014	0.328	0.658	2,629

Notes: η^2 = share of total sum of squares. Country FE and HS2 FE entered additively. Residual = within-country-within-chapter variation unexplained by either FE.

The large residual share (60–78% of variance across outcomes) shows that broad category and partner identity leave most of the heterogeneity unexplained: the action lies in within-chapter, within-country variation that only measured structural characteristics can capture.

6.4 Second-stage framework and results

The cell-specific β coefficients become the dependent variable in second-stage OLS:[21]

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[21] Generated regressor problem (Pagan 1984; Murphy and Topel 1985): HC1-robust SEs throughout; WLS robustness in Appendix E.

$$\beta_{jk} = \alpha + \gamma_a \cdot Z^{\text{policy}}{}_{\text{jk}} + \gamma_b \cdot Z^{\text{supply}}{}_{\text{k}} + \gamma_c \cdot Z^{\text{product}}{}_{\text{k}} + \gamma_d \cdot Z^{\text{country}}{}_{\text{j}} + \varepsilon_{jk}$$

where β_{jk} is the PPML-estimated TCA impact coefficient for EU country j × HS2 chapter k from the first stage, and the covariates are organised into four groups. First, Z^{policy} is log MFN tariff, SPS count, TBT count, RoO restrictiveness index (trade policy frictions, country × HS2 level). Z^{supply} is log upstream input diversity, M1_prop, M2_prop, M1_EU (supply chain dependence, HS2 level). Z^{product} represents BEC consumer share, BEC intermediate share, Rauch differentiated share, PLAID perishability (product characteristics, HS2 level). Finally, Z^{country} is log GDP per capita, log population, log distance, pre-TCA UK trade intensity, partner market share (bilateral controls).

Using estimated coefficients as the dependent variable raises the generated regressors problem (Pagan 1984; Murphy and Topel 1985). We report HC1-robust standard errors throughout. Full two-step bootstrap is computationally prohibitive given the scale of the first stage (~3.3 million observations); Appendix E reports weighted least squares estimates using the inverse of the first-stage standard errors as weights, which addresses heteroskedasticity from differential precision. Results are qualitatively unchanged.

Explanatory variables fall into four groups: (a) trade policy, (b) supply chain, (c) product characteristics, (d) bilateral controls. Table 5 reports the full results for all four outcomes. The R^2 values (0.251 for export value, 0.237 for export variety) indicate that the observable structural variables account for roughly a quarter of cross-cell variation. The unexplained residual likely reflects measurement error in AIPNET linkages, firm-level heterogeneity not captured at HS2, and omitted product attributes (e.g. logistics complexity, regulatory history). Higher import R^2 values (0.447, 0.368) are expected given the stronger country component on the import side.

Table 5: Second-stage OLS — structural drivers of TCA heterogeneity

Variable	Import value	Import variety	Export value	Export variety
(a) Trade policy				
Log MFN tariff rate	−0.072**	−0.057	−0.011	−0.040**
	(0.030)	*(0.035)*	*(0.026)*	*(0.017)*
NTM — SPS (count)	0.203**	−0.032	0.079	0.002
	(0.089)	*(0.138)*	*(0.066)*	*(0.047)*
NTM — TBT (count)	−0.195*	−0.056	−0.340***	−0.337***
	(0.111)	*(0.143)*	*(0.076)*	*(0.072)*
RoO restrictiveness (0–1)	0.374***	0.080	0.342***	0.130*
	(0.128)	*(0.148)*	*(0.095)*	*(0.076)*
(b) Supply chain				
Log upstream input diversity	0.099*	0.048	−0.170***	−0.187***
	(0.057)	*(0.074)*	*(0.038)*	*(0.029)*
M1_prop: EU upstream dependence	−0.044	−1.264	2.003***	0.812*
	(0.641)	*(0.788)*	*(0.482)*	*(0.481)*
M2_prop: EU downstream dependence	2.659***	2.265**	0.969*	−0.476
	(0.664)	*(1.005)*	*(0.505)*	*(0.447)*
M1_EU: EU dependence on UK inputs	−0.381	−1.097	1.296***	1.490***
	(0.647)	*(0.716)*	*(0.485)*	*(0.481)*
(c) Product characteristics				
BEC consumer goods share	−0.049	0.113	−0.778***	−0.203***
	(0.127)	*(0.171)*	*(0.096)*	*(0.073)*
BEC intermediate goods share	0.222*	0.470***	−0.347***	0.119
	(0.125)	*(0.151)*	*(0.103)*	*(0.089)*
Rauch differentiated share	0.087	0.286***	0.243***	0.391***
	(0.084)	*(0.105)*	*(0.060)*	*(0.069)*
PLAID perishability	−0.352**	−0.386***	−0.506***	−0.399***
	(0.151)	*(0.144)*	*(0.118)*	*(0.112)*
(d) Controls				
Log GDP per capita	−0.218***	−0.425***	−0.161***	−0.068
	(0.076)	*(0.097)*	*(0.059)*	*(0.053)*
Log population	0.180***	0.112	−0.067**	−0.060**
	(0.058)	*(0.077)*	*(0.031)*	*(0.030)*
Log distance to UK	−0.024	−0.106	−0.284***	−0.077
	(0.095)	*(0.112)*	*(0.057)*	*(0.050)*
Log UK bilateral trade share	0.148**	0.259***	0.358***	0.313***
	(0.058)	*(0.080)*	*(0.039)*	*(0.042)*
Log market share	−0.376***	−0.407***	−0.308***	−0.251***
	(0.020)	*(0.034)*	*(0.023)*	*(0.038)*
N / R²	**2,002 / 0.447**	**1,997 / 0.368**	**2,477 / 0.251**	**2,477 / 0.237**

Notes: OLS, HC1-robust SEs. Dependent variable: full-effect β from PPML DiD. All regressors use 2017–2020 pre-TCA averages except log MFN tariff. *** p<0.01, ** p<0.05, * p<0.10.

6.5 Trade policy channels

Technical barriers to trade. TBT emerges as the dominant export barrier: −0.340 ($p<0.01$) for value, −0.337 ($p<0.01$) for variety. The export-import asymmetry reflects staggered UK border implementation,[22] with the EU applying full checks from January 2021 while the UK phased in controls through 2024. This revises our three-year assessment, which found TBT insignificant at HS2 level. At finer resolution, TBT captures what SPS checks do not: the cost of demonstrating that a manufactured product meets EU standards when the UK is no longer inside the EU's regulatory architecture. A Midlands auto-parts manufacturer must now seek EU-notified body certification to prove conformity, a process that was automatic under membership. Disdier, Fontagné and Mimouni (2008) document similar SPS effects on agricultural trade; our findings extend this to the broader TBT domain in a disintegration setting.

SPS measures. The positive SPS coefficient for import value (0.203, $p<0.05$) appears counterintuitive but reflects implementation asymmetry: SPS-intensive chapters (primarily agrifood, HS 01–24) faced delayed UK-side border checks under Staged Customs Controls, and conditional on the other controls, the residual SPS variation captures within-chapter heterogeneity where SPS-heavy flows already had embedded compliance infrastructure. The result should be interpreted as a composition effect rather than evidence that SPS barriers aided trade. The phase interaction analysis in Section 8.1 confirms this reading.

MFN tariff as fallback risk. The negative import coefficient (−0.072, $p<0.05$) captures the fallback tariff mechanism identified by Freeman et al. (2025). The MFN rate measures the cost of failing to document origin under nominally zero-tariff TCA access. For products with

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[22] EU applied full checks from January 2021; UK applied graduated controls through 2024.

high MFN rates (e.g. dairy, ceramics), the penalty for incomplete paperwork is severe enough to deter marginal exporters entirely.

Rules of origin as institutional lock-in. The positive RoO coefficient (0.342, $p<0.01$ for exports) initially appears puzzling: stricter origin requirements are associated with *stronger* trade. The resolution is selection. The index construction clarifies why. The ROO-RI (Section 4.1) scores each HS6 product on a 1–10 scale across five categories of origin requirement, from simple wholly-obtained rules at the bottom to layered combinations of value-added thresholds, tariff classification changes and specific production processes at the top. Products with high ROO-RI scores—automotive components, pharmaceuticals, precision chemicals—are products whose production is inherently multi-stage and cross-border. TCA negotiators imposed stricter origin rules precisely where bilateral production networks were deepest, because those were the products where origin determination was genuinely complex and circumvention risk highest. The index therefore captures *production complexity* as much as regulatory burden, and production complexity tracks supply chain embeddedness. Sectors that adapted to complex origin rules were already deeply integrated into cross-border supply chains; RoO functions as a commitment device for those embedded relationships. Crivelli and Gröschl (2016) show that SPS measures can deter market entry altogether; our RoO result reveals an analogous mechanism operating through origin documentation. The LASSO confirms this is conditional on bilateral production network linkages. The quartile split (Table 6, Panel A) reinforces the point: the positive RoO effect appears only in Q4, the most integrated quarter, where products carry the most complex origin rules and the deepest bilateral production networks. In Q1–Q3 the coefficient is indistinguishable from zero. An important policy caveat follows: because the positive coefficient reflects a pre-existing characteristic of adapted sectors rather than a causal protective effect, RoO simplification would primarily benefit sectors *not yet embedded* in bilateral networks. For already-embedded sectors, the origin rules are a sunk cost of continued participation. For sectors outside the network, they are an entry barrier that deters new relationships from forming. The ROO-RI index (described in Section 4.1) captures this variation: its positive coefficient reflects the pre-existing integration of adapted sectors, not a causal protective effect of strict origin rules. Because the index is normalised to a 0–1 scale, the export-value coefficient of 0.342 implies that a shift from the least to the most restrictive origin regime is associated with an improvement in the treatment effect of roughly one-third of a standard deviation in the dependent variable; however, since most TCA products cluster in the 0.2–0.7 range of the normalised index, the practical within-sample variation is smaller.

Table 6: RoO conditionality — quartile split and supply chain interaction

RoO_index coefficient	Import value	Import variety	Export value	Export variety
Panel A. By integration quartile				
Q1 (least integrated)	−0.18 (0.21)	−0.07 (0.27)	−0.05 (0.18)	0.02 (0.16)
Q2	0.06 (0.19)	0.01 (0.24)	0.09 (0.16)	0.04 (0.14)
Q3	0.11 (0.18)	0.05 (0.22)	0.14 (0.15)	0.08 (0.13)
Q4 (most integrated)	0.43** (0.19)	0.12 (0.23)	1.13*** (0.21)	0.50*** (0.16)
Panel B. Supply chain interaction				
RoO × M1_EU	1.48 (1.05)	0.91 (1.30)	6.26*** (1.42)	4.71*** (1.18)
RoO main effect (interaction model)	0.372*** (0.136)	0.083 (0.161)	0.249** (0.098)	0.060 (0.081)

Notes: Panel A: RoO_index coefficient from full specification estimated within quartiles of pre-TCA EU integration (eu_share_int_imp). Panel B: mean-centred RoO_index × M1_EU interaction from pooled specification. HC1-robust SEs in parentheses. *** p<0.01, ** p<0.05, * p<0.10.

6.6 Supply chain channels

The supply chain variables are the paper's central contribution and yield the largest coefficients in the model. The theoretical foundation is the asset-specificity framework of Williamson (1985): where co-specialised investments are bilateral, both sides rationally absorb new costs rather than forfeit sunk assets (Antràs 2003). The propagated dependence measures from the AIPNET dataset (Fetzer et al. 2024) capture both direct and indirect supply chain linkages.

Export resilience through upstream EU dependence. M1_prop enters at 2.003 (p<0.01) for export value and 0.812 (p<0.10) for variety. UK sectors that source heavily from EU inputs maintained stronger exports, as Proposition 1 predicts. Pharmaceuticals illustrate the logic: UK drug manufacturers import active ingredients and intermediates from EU suppliers and have little choice but to bear new border costs on both legs of the journey.

Import resilience through downstream EU links. M2_prop enters at 2.659 (p<0.01) for import value and 2.265 (p<0.05) for variety. EU suppliers embedded in UK downstream production bore the new regulatory burdens rather than lose established customers. German and Italian auto-parts exporters, for instance, continued shipping to UK assembly plants despite higher documentation costs.

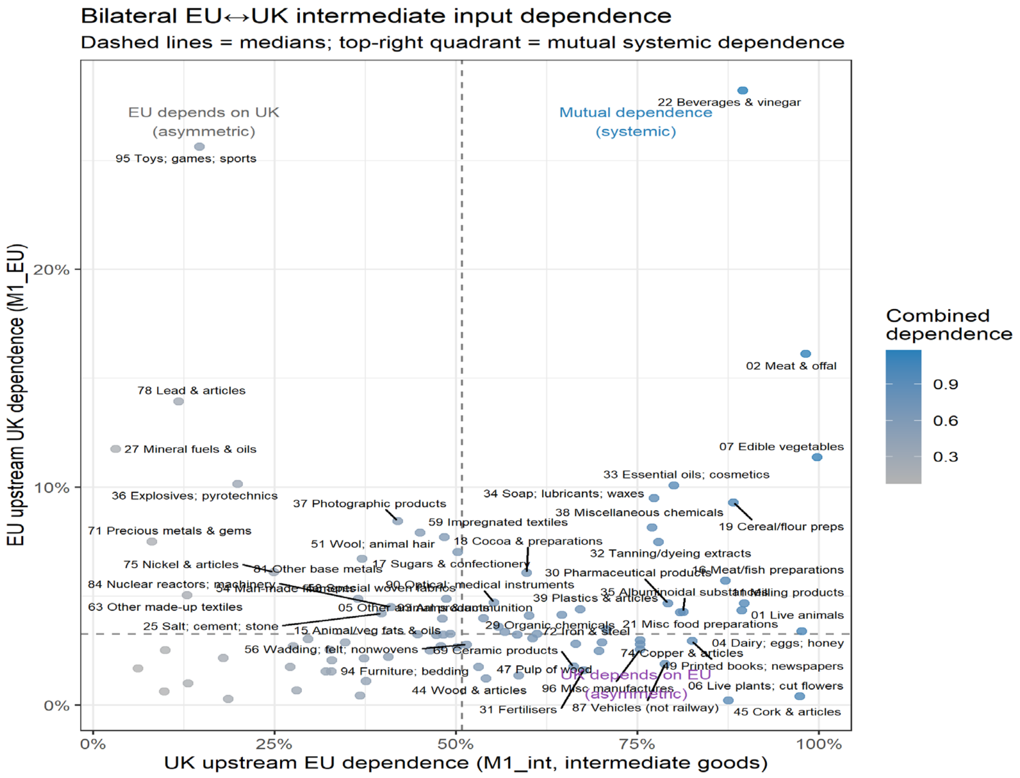
Bilateral mutual dependence. M1_EU, measuring EU dependence on UK inputs, enters at 1.296 (p<0.01) for export value and 1.490 (p<0.01) for variety. Where both sides have sunk assets in the bilateral relationship (Proposition 3), the lock-in is reinforced from both directions.

Table 7: Supply chain channels in the second-stage meta-regression

Supply chain index	Import value	Import variety	Export value	Export variety
M1_prop: upstream EU dependence	−0.044 (0.641)	−1.264 (0.788)	2.003*** (0.482)	0.812* (0.481)
M2_prop: downstream EU dependence	2.659*** (0.664)	2.265** (1.005)	0.969* (0.505)	−0.476 (0.447)
M1_EU: EU dependence on UK inputs	−0.381 (0.647)	−1.097 (0.716)	1.296*** (0.485)	1.490*** (0.481)
Log upstream input diversity	0.099* (0.057)	0.048 (0.074)	−0.170*** (0.038)	−0.187*** (0.029)

Notes: From full second-stage OLS. M1_prop and M2_prop use decay factor δ = 0.85. All indices use 2017–2020 pre-TCA averages, intermediate-goods flows only (BEC Rev.5). HC1-robust SEs in parentheses. *** p<0.01, ** p<0.05, * p<0.10.

Figure 7: Bilateral supply chain dependence, EU and UK



Notes: Mutual dependence sectors (upper-right quadrant) — including pharmaceuticals, chemicals, and dairy — are where lock-in is strongest and targeted cooperation has the highest return. By HS2 chapter. X-axis: UK upstream EU dependence (M1_int). Y-axis: EU upstream UK dependence (M1_EU). Quadrant medians shown as dashed lines.

Table 8: Bilateral dependence quadrants

Quadrant	N chapters	Example	Key sectors
Mutual dependence	25	Beverages (HS 22)	Beverages, pharma, chemicals
UK depends on EU	18	Live plants (HS 06)	Cut flowers, furskins
EU depends on UK	18	Sugars (HS 17)	Confectionery, cereals
Low bilateral dependence	25	Misc metals (HS 83)	Base metal articles

Notes: Quadrants defined by median M1_int and M1_EU. Mutual dependence = above-median on both dimensions.

Upstream complexity penalty. −0.170 ($p<0.01$) for export value. More complex supply chains face compounding origin documentation burdens. Each distinct input source may need to be documented for origin purposes, and a complex bill of materials raises the probability that at least one upstream link fails to meet the relevant origin threshold, disqualifying the downstream product from preferential access.

6.7 Product characteristics

Consumer goods suffer disproportionately (−0.778, p<0.01 for export value). As Melitz (2003) predicts, the fixed-cost exit mechanism is strongest for standardised, low-margin products where the fixed cost of TCA paperwork cannot be spread over large relationship-specific volumes. Perishability compounds the damage (−0.506, p<0.01 for export value, significant across all four outcomes) because border delays impose a biological clock that no amount of compliance investment can override. Differentiated goods, by contrast, show resilience (+0.391 for export variety, +0.243 p<0.01 for export value), consistent with the Rauch (1999) distinction between differentiated and homogeneous goods. Their higher margins and buyer–supplier specificity make absorbing new costs viable. Chaney (2008) demonstrates that trade costs affect the extensive margin through firm entry and exit; our results confirm this mechanism operates powerfully in the disintegration setting. The pattern confirms Proposition 5: surviving trade tilts towards goods that are hard to substitute.

7. LASSO variable selection

The OLS results in Section 6 identify the direction and significance of individual structural drivers but cannot resolve which variable *interactions* matter most, nor whether the model suffers from overfitting given the number of candidate regressors. LASSO addresses both questions by penalising coefficient magnitude across all main effects and their pairwise interactions simultaneously, retaining only those variables and interactions that survive cross-validated regularisation. The intuition is straightforward: LASSO shrinks most coefficients to exactly zero, effectively performing variable selection. The penalty parameter λ is chosen by cross-validation—the model repeatedly holds out subsets of the data and selects the λ that minimises prediction error on held-out observations. What survives regularisation is therefore not what fits the estimation sample best, but what generalises to out-of-sample data. This provides a complementary form of evidence to the OLS: where OLS tests pre-specified hypotheses about individual structural drivers, LASSO asks which combinations of variables carry genuine predictive power after penalisation.

Cross-validated LASSO (Tibshirani 1996)[23] considers all 23 base covariates and 253 pairwise interactions (276 features). Each of the four outcomes (import/export × value/variety) is estimated separately, producing four sets of surviving variables. Figure 8 reports the results as an interaction heatmap: each cell represents a pairwise interaction between two variables, colour indicates the absolute magnitude of the surviving LASSO coefficient, and blank cells indicate interactions that were shrunk to zero—that is, interactions that add no predictive power once the remaining structure is accounted for. Export models retain more variables than import models, reflecting the richer structure on the export side. This is consistent with the ANOVA finding (Section 6.3) that product characteristics explain eleven times more variation in export treatment effects than country identity: the export side has more conditional structure to detect. The standout interaction for export value is RoO × M1_EU, the mutual lock-in of Proposition 3: origin requirements bite hardest where both sides have sunk assets in the bilateral relationship. That this interaction survives cross-validated regularisation—where 253 candidate interactions compete for inclusion—is substantially stronger evidence for conditional lock-in than the OLS interaction coefficient alone. The two methods triangulate: OLS tests a pre-specified hypothesis and finds it significant; LASSO, agnostic about which interactions matter, independently selects the same one. The interaction heatmap (Figure 8) reveals supply chain variables modulating regulatory and product-characteristic penalties throughout. The pattern is clear: the structural drivers identified in Section 6 do not operate as independent, additive channels. The bite of TBT depends on supply chain depth; the bite of

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[23] Cross-validated LASSO (Tibshirani 1996) with λ selected to minimise out-of-sample MSE across 10 folds.

RoO depends on bilateral integration; the effect of product differentiation is conditional on the regulatory environment. Lock-in is a system property, not a single variable.

Figure 8: LASSO interaction coefficient heatmap

Notes: Supply chain variables interact with regulatory and product characteristics throughout — the lock-in mechanism is not additive but conditional. Across outcomes (λ.min). Colour = absolute LASSO coefficient; blank = not selected. Only variable pairs selected in at least one outcome shown.

An important caveat: LASSO is a prediction tool, not a causal identification strategy. The cross-validated coefficients indicate which variable combinations best predict the pattern of treatment effects, but they should not be interpreted as causal magnitudes. The LASSO complements rather than replaces the OLS analysis in Section 6. The OLS provides point estimates under a pre-specified model; the LASSO provides variable selection under regularisation. That both approaches converge on the same central finding—conditional lock-in through the interaction of origin rules and bilateral supply chain dependence—substantially strengthens the evidence base for Proposition 3.

8. Robustness

8.1 Staggered UK border controls

Our main results identified that import-side channel mechanisms are less pronounced than on the export side. One plausible explanation is the staggered implementation of border controls chosen by UK policymakers.[24] This section exploits the three-phase structure to test whether import effects deepened as physical checks intensified.

The UK's border control regime evolved through three phases. Phase I (Staged Customs Controls, 2021) permitted a rolling, light-touch approach: EU exporters faced immediate, full border checks entering the EU from the UK, but the UK granted importers a 175-day deferral for full customs declarations. Phase II (Border Target Operating Model transition, 2022–23) introduced a risk-based digital framework, classifying SPS imports into Low, Medium, and High-risk categories and streamlining safety and security data. Phase III (full controls, 2024 onwards) realised the full structural reality of a third-country border with mandatory Export Health Certificates for medium-risk products, physical checks at designated Border Control Posts, and collection of the Common User Charge on commercial imports.

Table 9 reports phase-specific PPML estimates from the bilateral aggregate model. Import value losses deepened from −24.2% under SCC to −32.8% under BTOM and −29.8% under full controls. Import variety losses accelerated continuously: from −11.6% (SCC) to −26.4% (BTOM) to −30.0% (full controls), consistent with extensive-margin adjustment tightening as physical checks intensified. The phased deepening confirms that the muted import-side effects in the aggregate results were not an absence of effect but rather a consequence of delayed enforcement.

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[24] The UK's staggered border controls proceeded in three phases: Staged Customs Controls (2021), Border Target Operating Model transition (2022–23), and full controls with physical checks (2024 onwards).

Table 9: Staggered implementation of UK border controls

Phase	Import Value %	Value SE	Import Variety %	Variety SE
SCC (2021)	−24.2***	(0.016)	−11.6***	(0.0062)
BTOM (2022–23)	−32.8***	(0.0156)	−26.4***	(0.0067)
Full controls (2024+)	−29.8***	(0.0172)	−30.0***	(0.0071)

Notes: Aggregate bilateral phase effects. PPML with pair and quarter FEs. Clustered SEs by country-pair. % change = (exp(β)−1)×100. *** p<0.01, ** p<0.05, * p<0.10.

We further explore how different types of trade friction interacted with the phased implementation. Table 10 reports second-stage OLS regressions where the HS2-chapter-level first-stage β coefficients from a joint three-phase PPML are regressed on policy variables, phase dummies, and their interactions. The SPS channel shows a clear pattern: BTOM × SPS (+0.495, p<0.01) and Full × SPS (+0.647, p<0.01) are positive and growing for import value, indicating that SPS-intensive chapters faced *smaller* additional losses as UK border controls were introduced. This is consistent with delayed UK-side SPS enforcement: agrifood chapters already had compliance infrastructure in place by the time physical checks arrived. The TBT channel tells a different story: BTOM × TBT is −0.348 (p<0.01) for import variety, and Full × TBT is −0.315 (p<0.05), confirming that standards divergence compounds on the extensive margin as enforcement tightens. The RoO × phase interactions are small but positive and significant for import variety in BTOM and Full, suggesting that origin-compliant supply chains stabilised as the border regime matured.

Table 10: Policy channels by stage of import control

Variable	Import value	Import variety
NTM — SPS	0.138	−0.002
NTM — TBT	−0.045	0.168***
RoO index	0.001	−0.000
Log(1+MFN tariff)	−1.292	−0.339*
Phase: BTOM	−0.359	0.187*
Phase: Full	−0.440	0.072
BTOM × NTM-SPS	0.495***	−0.070
Full × NTM-SPS	0.647***	−0.032
BTOM × NTM-TBT	−0.240	−0.348***
Full × NTM-TBT	−0.214	−0.315**
BTOM × RoO index	0.039	0.022*
Full × RoO index	0.031	0.026**
BTOM × Log(1+MFN)	−1.197	0.027
Full × Log(1+MFN)	−2.044	−0.439

Notes: Second-stage OLS. Dep. var. = HS2-chapter β from joint three-phase PPML. Stacked 3 phases × 99 chapters (n ≈ 291–297). Robust SEs in parentheses. SCC = reference phase. *** p<0.01, ** p<0.05, * p<0.10.

8.2 RoO endogeneity tests

The positive RoO coefficient is consistent with three distinct data-generating mechanisms, each carrying a different policy implication. Under pure selection, strict origin rules were negotiated for sectors with deep pre-existing integration, so the coefficient merely proxies for integration depth. Under a commitment device interpretation, strict rules signal a durable relationship and dampen exit uniformly. Under heterogeneous effects, RoO matters because enforcement stakes rise with integration depth. We implement four tests to discriminate between these accounts.[25]

Test 1: Horse race with direct integration control. The baseline specification already conditions on propagated EU dependence (M1_prop, M1_EU) and market share. Adding the HS2-level pre-TCA EU integration proxy (log of EU share of intermediate imports) should attenuate the RoO coefficient under pure selection. Table 11 reports that it does not: the

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[25] Oster (2019) compares coefficient stability between sparse and full specifications to bound the potential influence of unobservable selection.

coefficient is essentially unchanged or strengthens (from 0.342 to 0.442 for export value). The added integration term is itself insignificant. Pure HS2-level selection on observed integration cannot explain the positive RoO association.

Table 11: RoO coefficient across OLS specifications

Specification	Import value	Import variety	Export value	Export variety
Bare (minimal controls)	0.254** (0.112)	0.155 (0.139)	0.290*** (0.097)	0.149 (0.095)
Full OLS	0.374*** (0.128)	0.080 (0.148)	0.342*** (0.095)	0.130* (0.076)
Full OLS + EU integration	0.338** (0.131)	0.043 (0.156)	0.442*** (0.100)	0.126 (0.087)
Interaction (+ RoO×M1_EU)	0.372*** (0.136)	0.083 (0.161)	0.249** (0.098)	0.060 (0.081)

Notes: HC1-robust SEs in parentheses. Horse race adds log(EU share of intermediate imports, HS2 level). Interaction row adds mean-centred RoO_index × M1_EU. *** p<0.01, ** p<0.05, * p<0.10.

Test 2: Supply chain interaction. If RoO matters precisely where enforcement stakes are highest, its association with trade resilience should be amplified in sectors where the EU itself depends on UK intermediate inputs. The RoO × M1_EU interaction is large and significant for both export outcomes (export value 6.26, p<0.01; export variety 4.71, p<0.01) and insignificant for imports. The positive RoO association is driven by the bilateral supply chain lock-in quadrant — sectors in which the EU relies on the UK as an input supplier just as the UK relies on the EU.

Test 3: Quartile heterogeneity. Splitting HS2 chapters into quartiles by pre-TCA EU integration produces a sharp gradient. The RoO coefficient is positive and statistically significant only in Q4, the highest-integration quartile, for three of the four outcomes (export value 1.13, p<0.01; export variety 0.50, p<0.01; import value 0.43, p<0.05). In Q1–Q3 it is near zero or negative. This pattern is inconsistent with a uniform commitment device and consistent with heterogeneous effects whose magnitude rises with the depth of bilateral trade exposure.

Test 4: Oster (2019) selection-bias bounds. To gauge robustness to unobserved selection, we compute Oster bounds comparing the coefficient and R^2 of a sparse specification with those of the full specification. Table 12 reports the results.

Table 12: Oster (2019) selection-bias bounds for the RoO coefficient

Outcome	β bare	β full	R^2 bare	R^2 full	R^2 max	$\beta^*(\delta=1)$	δ zero	Verdict
Import value	0.254	0.374	0.441	0.447	0.581	−2.572	76.28	Robust
Import variety	0.155	0.080	0.395	0.368	0.479	−0.236	4.48	Robust
Export value	0.290	0.342	0.134	0.251	0.326	0.308	4.19	Robust
Export variety	0.149	0.130	0.105	0.237	0.308	0.140	−3.72	Not robust

Notes: Bare specification = RoO_index + log GDP p.c. + log population + log distance + log market share (OLS). Full = all 17 regressors. β^* = bias-adjusted estimate at $\delta=1$. δ zero = selection ratio needed to drive β to zero; values > 1 indicate robustness. R^2 max = 1.3 × R^2 full (Oster convention).

For both value outcomes the RoO coefficient is robust to selection under the $\delta = 1$ benchmark. The δ zero for import value (76) is implausibly large: unobservables would have to be roughly seventy-six times more important than the rich set of observed controls to fully account for the coefficient. Export value (δ zero = 4.2) is more conservative but still comfortably above one. Export variety fails the test (δ zero < 1), but its underlying estimate is statistically insignificant in any case.

Synthesis. Read together, the four tests deliver a picture that fits neither the pure selection nor the pure commitment device story. The coefficient does not attenuate when integration is controlled directly (Test 1). It is robust to unobserved selection for the value outcomes (Test 4). It is positive only in the most integrated quartile (Test 3) and scales with bilateral supply chain dependence (Test 2). The most defensible interpretation is one of heterogeneous effects conditional on prior integration: RoO operates as a genuine trade friction whose bite depends on the depth of bilateral supply chain dependence. Where both parties rely on each other's inputs, strict origin rules are associated with smaller trade losses because these relationships carried enough co-specialised value to absorb compliance costs rather than sever the link. Where prior integration is shallow, RoO is essentially irrelevant.

9. Interpretation of results

9.1 A network shock, not a generic border shock

The results are not what a uniform border cost shock would produce. They are better understood as a *selective disentangling of production networks*, consistent with the Williamson (1985) asset-specificity framework: where co-specialised investments are bilateral, both sides rationally absorb new costs rather than forfeit sunk assets (Antràs 2003). Embedded relationships bore the new costs; arm's-length trade did not. The positive M2_prop import coefficient shows two-way vertical specialisation creating mutual lock-in, and the LASSO interaction RoO × M1_EU confirms it. Baldwin and Venables (2013) distinguish spider and snake production architectures; both generate the relationship-specificity that our results identify as the key determinant of resilience. Pharmaceuticals illustrate the full mechanism: UK manufacturers import active pharmaceutical ingredients from EU suppliers, process them, and re-export finished medicines. Both legs of this chain sit in the mutual dependence quadrant. Severing either leg would strand production assets on both sides, so both sides absorb the new border costs. Contrast this with cut flowers (HS 06), where the UK depends on EU suppliers but the EU has no reciprocal dependence on UK inputs. There, the adjustment fell entirely on one side, and variety losses were severe.

9.2 Trade policy frictions and their asymmetries

TBT penalty on exports combined with muted import effects provides the clearest signature of staggered UK border implementation. The fallback-tariff mechanism identified by Freeman et al. (2025) amplifies the damage for products where MFN rates are high. The emergence of TBT as dominant barrier is an analytical advance: the three-year review found it insignificant because supply chain effects were confounding the estimate. Both SPS and TBT matter, but TBT is doing more damage than previously visible, consistent with conformity assessment costs operating across the full range of manufactured goods and confirming the predictions of Fontagné et al. (2015) that product standards disproportionately affect trade margins. The staggered border controls analysis (Section 8.1) confirms the mechanism: import effects deepened in lockstep with enforcement intensity, ruling out compositional explanations.

9.3 Product heterogeneity, firm exit, and progressive concentration

The 53.8% variety collapse reflects fixed regulatory costs pushing marginal relationships below viability, as heterogeneous-firm models predict (Melitz 2003; Bernard et al. 2011). Differentiated goods, in the sense of Rauch (1999), justify the investment in continued market access, generating the progressive concentration that Proposition 5 predicts. Chaney (2008) demonstrates that trade costs affect the extensive margin through firm entry and exit; our results confirm this mechanism operates powerfully in the disintegration setting. Feenstra and Ma (2014) show that trade facilitation effects concentrate on the extensive margin — our finding that the TCA's extensive margin damage vastly exceeds its intensive margin damage is the mirror image. The event study confirms continuing narrowing through 2025. Five years on, the bilateral trade base looks qualitatively different from its pre-TCA composition: dominated by intermediate goods traded within established supplier relationships, with standardised consumer products steadily squeezed out.

9.4 Limitations and untested propositions

Proposition 4 (locked-in relationships exhibit delayed rather than immediate exit) is stated in the theoretical framework but not directly tested. The event study shows aggregate effects deepening over time, which is consistent with delayed exit, but the pattern is also consistent with phased UK border controls creating new friction shocks in 2024 and with gradual firm learning about true adjustment costs. Larch and Yotov (2024) document the longrun accumulation of trade agreement effects; our deepening trajectory is the disintegration counterpart. A direct test would require tracking exit timing across the bilateral dependence quadrants at the product level, distinguishing between relationships that exited in 2021, those that persisted through 2023 but exited subsequently, and those that remain active. We flag this as a priority for future work using the quarterly panel structure.

More broadly, the second-stage estimates identify structural correlates of heterogeneous TCA effects but do not establish that reducing specific frictions would recover the lost trade. Tamberi (2024) provides initial welfare estimates suggesting TCA-induced trade cost increases of 1.7–5.3%, consistent with our reduced-form magnitudes. Translating the TBT finding into a quantitative estimate of trade recovery from conformity assessment agreements requires structural welfare modelling beyond the scope of this study. The policy implications in Section 10 should be read as identifying priority targets for negotiation, not as forecasts of trade recovery magnitudes.

10. Policy implications

The UK–EU relationship reset provides the political framework for acting on these findings. The SPS agreement is in train following the May 2025 Summit. The question is what comes next. Our results identify the post-SPS agenda with some precision.

10.1 SPS is in train; TBT is the priority

The SPS agreement addresses one important friction channel. Crivelli and Gröschl (2016) demonstrate that SPS measures can deter market entry altogether, and our perishability coefficient (−0.506, $p<0.01$ for export value) confirms severe damage to agrifood trade. But as the reset moves beyond SPS, the evidence identifies which friction channels have the largest estimated effects. The dominant export barrier is not SPS but TBT (−0.340, $p<0.01$ for export value; −0.337, $p<0.01$ for export variety). TBT is statistically significant for exports where SPS is not, and it operates across the full range of manufactured goods rather than only agrifood, consistent with conformity assessment as the binding mechanism. It falls entirely outside the scope of the SPS agreement.

What makes TBT the binding constraint is the institutional structure of regulatory separation. Under EU membership, a product certified by a UK notified body circulated freely throughout the single market. Under the TCA, UK notified bodies are no longer recognised by the EU, so UK exporters must seek certification from EU-notified bodies to demonstrate conformity with EU standards—a process that adds cost and delay for every product line. The UK government's decision to shelve mandatory UKCA marking and continue recognising CE marking indefinitely (Product Safety and Metrology etc. (Amendment) Regulations 2024, SI 2024/696) is itself evidence of the burden that full regulatory divergence wouldimpose; the cost proved too high even for the domestic market. Fontagné et al. (2015) show that product standards disproportionately affect the extensive margin of trade; our results confirm this at scale. TBT is a major contributor to the 53.8% export variety collapse. The EU–Switzerland Mutual Recognition Agreement on conformity assessment provides an institutional precedent: it covers twenty product categories, eliminates duplicate testing, and has been in operation since 2002. Du, Shepotylo and Zhang (2025) provide direct empirical evidence that mutual recognition of conformity assessment (MRCA) provisions increase exports by 9.8% on average, with the largest gains concentrated in conformity-intensive sectors such as electrical machinery, mechanical appliances, and dairy—precisely the kinds of chapters that appear in our mutual dependence quadrant. A sectoral MRA covering these chapters would follow a tested institutional model backed by quantitative evidence of its trade effects.

10.2 Targeting: the mutual dependence sectors

The supply chain analysis provides a precise targeting framework for the post-SPS agenda. The 25 HS2 chapters in the mutual dependence quadrant — where both UK upstream reliance on EU inputs and EU reliance on UK inputs are above median — are where conformity assessment agreements would have the highest return. Pharmaceuticals are the clearest case: UK drug manufacturers import EU active ingredients, process them, and re-export finished medicines, requiring EU-notified body certification at every stage to maintain market access. A mutual recognition agreement on pharmaceutical testing and batch certification could address this duplication without requiring full regulatory alignment. The same logic extends to chemicals (REACH versus UK REACH), medical devices, cosmetics, and processed food. Crowley, Exton and Han (2024) document low preference utilisation rates under the TCA's rules of origin, reinforcing the case for simplification alongside conformity assessment reform. Bown and Crowley (2016) show that tariff escalation along supply chains compounds the friction; the mutual dependence sectors are precisely those exposed to such cascading costs.

10.3 Rules of origin: simplification for new relationship formation

The positive RoO coefficient reflects lock-in in adapted sectors, but the LASSO and the endogeneity tests (Section 8.2) show this is conditional on existing production network linkages. For sectors that were not already embedded, origin documentation barriers deter new relationships from forming, which helps explain the near-absence of variety recovery five years on. Simplifying cumulation rules would lower entry barriers for these excluded sectors. However, because the RoO friction binds only in already-integrated sectors, reform should be targeted: easing cumulation rules and tolerance thresholds in chapters such as automotive, chemicals, and electronics would lower the cost of maintaining existing relationships, while for weakly integrated sectors the binding constraint is the weakness of new relationship formation, not origin compliance.

10.4 Systemic risk and the limits of absorption

Mutual dependence sectors have sustained trade by *absorbing* new regulatory burdens. But absorption is not cost-free: it compresses margins, discourages new investment, and creates latent fragility. Kaya, Low and Millard (2025) estimate that non-tariff barriers have reduced UK business investment permanently by 1.2%, quantifying the macro cost of the absorption we document at the product level. Further regulatory divergence in pharmaceuticals, chemicals, or food safety could push costs above the lock-in threshold, pushing additional sectors beyond the point where cost absorption remains rational. The 25 HS2 chapters in the mutual dependence quadrant are where targeted cooperation has the highest return and where the estimated costs of further divergence are highest.

10.5 Sequencing the next phase of the reset

With SPS in train, the remaining priorities differ in their institutional requirements and the reset should sequence them accordingly. RoO cumulation simplification is largely within unilateral UK control and could be implemented through domestic statutory instrument, reducing barriers in sectors where origin documentation deters new relationship formation. Sector-specific conformity assessment agreements require bilateral negotiation and are therefore slower, but they carry the largest potential return because TBT is the dominant friction channel. A practical sequencing for the next phase of the reset would begin with what the UK can do alone (RoO), build on the SPS momentum to open the TBT conversation, and concentrate negotiating capital on mutual recognition for the mutual dependence sectors where both sides have the strongest economic incentive to cooperate. Pre-Brexit modelling projected value declines of around 7.7% under a soft Brexit scenario (Dhingra et al. 2017); the estimated value effects in this study are roughly double that figure, and the variety losses — which gravity models were not designed to capture — are an order of magnitude larger. The reality has proved far worse than projected, and the evidence in this paper identifies where the damage is concentrated and why.

11. Conclusion

This is the fourth paper in a research programme tracking the TCA's trade effects since they first appeared. Du and Shepotylo (2022) identified non-tariff measures as the dominant friction channel. Du, Satoglu and Shepotylo (2023) documented a 42% export variety collapse at two years. Du, Liu, Shepotylo and Shi (2024) confirmed deepening effects and mapped cross-country heterogeneity but left a central question unanswered: why did some bilateral trade relationships absorb the new compliance costs while others did not? This paper provides the answer.

Four findings stand out. First, the extensive margin collapse has deepened and shows no sign of recovery. Export varieties to the EU have fallen by an estimated 53.8% and import varieties by 31.5%, with event study dynamics confirming continued deterioration through 2025. Value declines are more moderate—16.5% for exports, 23.1% for imports—because surviving relationships have absorbed the new costs rather than adjusting volumes.

Second, the heterogeneity is overwhelmingly about what is traded, not with whom. Product characteristics explain over ten times more of the variation in TCA effects than country identity on the export side. Third, production network structure explains which relationships survived. Sectors where UK and EU firms are bound together through intermediate input flows maintained substantially stronger trade, consistent with the Williamson (1985) lock-in mechanism: where co-specialised assets tie both sides to a relationship, absorbing new regulatory costs is rational because severing it would be more expensive still. The gap between variety and value effects is the empirical signature of this mechanism.

Fourth, at five years and finer resolution than our earlier work, TBT emerges as the dominant export barrier, with conformity assessment as the plausible mechanism. The three-year review found TBT insignificant; the present specification, with explicit supply chain controls, separates the TBT effect from confounding production network linkages. The UK's staggered implementation of border controls independently validates the regulatory friction mechanism: import variety losses deepened from −12% under initial light-touch controls to −30% under full enforcement.

The policy implications are direct. The SPS agreement negotiated at the May 2025 Summit addresses one friction channel, but the dominant barrier is TBT. Sector-specific conformity assessment agreements, taking the EU–Switzerland MRA model as an inspiration and supported by the empirical evidence in Du, Shepotylo and Zhang (2025), should target the 25 mutual dependence chapters where both sides have the strongest economic incentive to cooperate. Rules of origin cumulation simplification can begin unilaterally. Five years of data are long enough to distinguish structural damage from adjustment friction. The damage is structural, it is concentrated in identifiable sectors, and the evidence in this paper identifies where the returns to regulatory cooperation are largest.

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