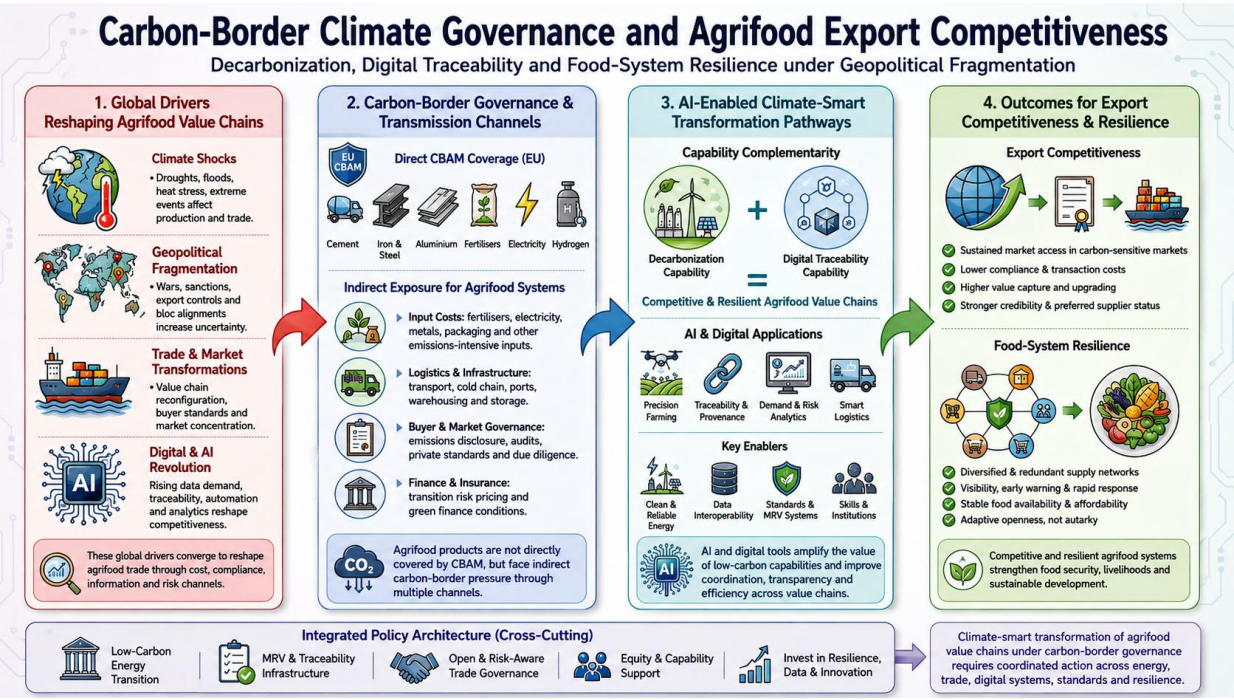
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Carbon Border Climate Governance and Agrifood Export Competitiveness: A Narrative Integrative Review of Decarbonization, Digital Traceability and Food System Resilience Under Geopolitical Fragmentation

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Abstract

Climate policy, carbon-border governance, digital traceability requirements and geopolitical fragmentation are creating new adjustment pressures on agrifood value chains. Yet agrifood products remain largely outside the direct legal scope of the European Union's Carbon Border Adjustment Mechanism (CBAM) at the time of writing, making it necessary to separate formal legal coverage from indirect exposure through inputs, reporting practices, buyer governance and energy systems. This paper develops a narrative integrative review and mechanism-based evidence synthesis of how carbon-border climate governance may affect agrifood export competitiveness and food-system resilience.

The evidence base combines versioned legal and institutional materials, including EUR-Lex, the European Commission, FAO, OECD, WTO, UNCTAD, the World Bank and the IEA, with recent peer-reviewed literature on agrifood value chains, resilience, traceability and sustainable trade. Rather than estimating a common causal effect, the paper identifies recurrent channels and

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the conditions under which competitiveness pressures are more or less likely to emerge. Four synthesis-derived propositions follow. First, current CBAM relevance for agrifood is mainly indirect, especially through fertilizers, electricity, carbon-intensive materials and buyer-side disclosure demands. Second, competitiveness under carbon-sensitive trade increasingly depends on the complementarity between decarbonization capability and digital traceability capability. Third, resilience is better understood as adaptive openness under risk management than as either frictionless globalism or autarky. Fourth, policy responses are strongest when low-carbon energy, measurement-reporting-verification infrastructure, digital interoperability, risk-aware trade governance and support for smaller actors are aligned. The paper contributes a more disciplined analytical framework for studying carbon-sensitive agrifood trade while clarifying legal scope, evidentiary limits and priority areas for future empirical research.

Keywords
carbon border adjustment mechanism; agrifood trade; export competitiveness; decarbonization; digital traceability; food-system resilience; geopolitical fragmentation; narrative integrative review; AI-enabled coordination

1. Introduction

The restructuring of global value chains is occurring through the intersection of climate policy, digital change, and geopolitics. In earlier stages of trade liberalization, companies were able to externalize their carbon intensity, logistics was viewed as a cost management issue, and geopolitics was seen as a backdrop. This assumption has become less valid. Carbon is becoming commodified, disclosed, and audited, digital infrastructure has transitioned from a supporting role to a market access necessity, and war, sanctions, export control, and competition have added political contingency to the location of production and sourcing. These changes are especially consequential for agrifood trade because the sector is simultaneously emissions-relevant, standards-intensive, climate-exposed, and deeply embedded in cross-border networks of inputs, services, processing, transport, and retail coordination (Gereffi, 2014; Taglioni & Winkler, 2016; Barrett et al., 2022).

The agrifood sector is also analytically distinctive because its competitiveness cannot be reduced to border tariffs or farm-gate yields. Modern agrifood exports depend on fertilizers, energy, cold-chain infrastructure, finance, packaging, quality assurance, certification services, data exchange, and logistics reliability. In such a setting, new climate-policy instruments can influence export performance even when they do not directly tax final food products. This observation is central to the present paper. At the manuscript cutoff date, the European Union's CBAM directly covers selected carbon-intensive sectors such as cement, iron and steel, aluminum, fertilizers, electricity, and hydrogen, rather than agrifood products themselves (Regulation (EU) 2023/956; European Commission, 2026a). Yet agrifood production and processing use several of these inputs intensively. The relevant question is therefore not whether food exports are formally listed in Annex I of the regulation, but how carbon-border governance propagates through upstream inputs, buyer requirements, and compliance systems into agrifood competitiveness.

This propagation problem has been obscured by two recurring weaknesses in the literature and policy debate. The first is excessive breadth. The discourse on climate smart value chains often

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blends carbon prices, AI, resilience, food security, industrial policy, and geopolitics into one story without making the primary mechanism, decision makers, and the desired outcome clear. The other problem is exaggeration. Narrative pieces tend to use causation arguments that go beyond the facts presented, particularly where descriptive statistics, legal changes, technological projections, and case studies are combined. A good piece for a journal needs more analytical rigor. The mechanism should be clearly identified, the outcome well-defined, and historical data distinguished from projections and policy prescriptions.

The current paper aims to meet this need by repositioning the initial draft to pose a primary economic question: how is the competitiveness of agrifood exports affected by carbon-border climate governance in conditions of geopolitical fragmentation, and what are the roles played by capabilities for decarbonization and digital traceability? Here, competitiveness is rigorously defined as an ability of firms, industries, and nations to maintain market access and profitability in foreign markets in conditions of increasingly stringent carbon, standards, and logistics requirements. Competitiveness, thus, is not conflated with any of the following indicators: export value, unit value, or revealed comparative advantage. Instead, it is treated as a multidimensional concept that finds expression in terms of market access, cost of compliance, margins, survival, and capability to be a dependable seller in the standards-based market environment.

In addition, food system resilience is treated as an interconnected systems outcome within the context of this study. What is at stake is not the importance of resilience as a concept separate from international trade but whether the skills needed for competitiveness in line with climate goals also impact on the capability of food systems to withstand and adapt to shocks. According to the work of the OECD, international trade can promote the development of resilience because of risk sharing. However, it is worth noting that such an effect can be undermined due to export restrictions and other disruptive policies (OECD, 2023a). According to the work done by the WTO, trade has become more sensitive to geopolitical distance with a clear sign of lower trade growth in hypothetical geopolitical blocs following the war in Ukraine, although there is little evidence of systematic regionalization (Blanga-Gubbay & Rubnov, 2024).

Within this narrowed framework, the paper makes four contributions. First, it provides a transparent synthesis that distinguishes direct legal exposure to CBAM from indirect exposure through input-output and governance channels. Second, it operationalizes otherwise vague concepts, including geopolitical fragmentation, digital traceability capability, decarbonization capability, and resilience. Third, it integrates official evidence from FAO, OECD, WTO, IEA, European Union legal sources, and related scholarly literature into a coherent mechanism-based framework rather than an omnibus narrative. Fourth, it proposes a non-numeric policy architecture for climate-smart agrifood upgrading that avoids unsupported rankings while still identifying actionable complementarities across energy, trade facilitation, standards, traceability, and resilience governance. Such a framing is in line with the existing literature on governance of global value chains, value chain analysis of agribusinesses, sustainability standards and resilience in agrifood systems, all of which have shown how the aforementioned aspects influence inclusion and upgrading processes independent of agricultural production efficiency alone (Gereffi et al., 2005; Mac Clay & Feeney, 2019; Hidayati et al., 2021; Meemken et al., 2021; Stone & Rahimifard, 2018; Stoian et al., 2021; Montanyà & Amat, 2023; Chirombo & Pangapanga-Phiri, 2025; Zhang et al., 2025).

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This paper does not attempt to provide any causal effect estimates. There are far too many heterogeneities in units of analysis, methods and time span in the evidence base to be able to construct a valid pooled econometric model, and several important channels of policy relevance have not been fully explored in the literature. Therefore, this research can be considered an integrative narrative review with mechanism-based evidence synthesis. The findings of the paper should be interpreted as evidence-driven, evidence-proportional propositions, not point estimates or causal generalizations. The structure of the rest of the paper is as follows. In section 2 we describe the evidence-synthesis methodology, the sources selection procedure, coding scheme and harmonization procedures. In section 3 we present our results, starting with the conceptual baseline and then proceeding to CBAM propagation, export competitiveness, resilience and policy architecture.

2. Materials and Methods

This paper utilizes the narrative integrative review and mechanism-based evidence synthesis approach. There is a reason for this decision. The issue in question falls into the realm of trade laws, agrifood economics, global value chains, and resilience studies and digital governance, and there is no way to find a single database that would cover all these channels at one level of analysis. In such circumstances, a scholarly paper needs to be open about how the evidence was selected and what the concepts mean. For that reason, the literature review is divided into two levels. The first level is made up of primary and quasi-primary sources such as regulations and implementation information from the EU about CBAM; publications from FAO and FAOSTAT on agrifood trade and food prices; reports from the OECD about the resilience of food systems and digital facilitation for trade; the WTO on fragmentation and re-globalization; IEA report on the energy demands related to AI and data centres; and institutional material that served to complement the clarification of definitions, legal timing and mechanisms. The second level is composed of scientific articles published in journals, books or as working papers that are relevant to agrifood value-chain transformation, border carbon adjustment, resilience or digital coordination.

The review methodology was guided by the principles of transparency in reporting of evidence synthesis like those set out by the PRISMA 2020 reporting guideline, but tailored to a multidisciplinary trade policy question involving legal, statistical and conceptual evidence, as opposed to intervention studies (Page et al., 2021). The combination of versioned legal texts, public data sets, institutional briefs, policy analysis and peer-reviewed literature using different units of analysis precludes any claims to the systematic review status of PRISMA compliance with its flow-count precision that is not possible to reconstruct from the available information. In addition, it allows for the reporting of the search terms, source types, inclusion criteria, coding rules and boundaries of inference. In order to broaden the coverage of the analysis of legal spillovers and adjustment issues, the screening procedure also included certain studies on the relevance of CBAM for agriculture and developing countries' exporters, including legal commentaries, policy analysis and scenario work (Matthews, 2022, 2023; Carlson et al., 2023; Del Federico & Giorgi, 2024; Nordin et al., 2025; Bassi et al., 2025; Anh et al., 2025). For the fragmentation and food governance risks, the review also covered studies on sanctions, trade constraints and geopolitical exposures in the World Trade Organization, UNCTAD and applied

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agrifood studies (WTO, 2023; UNCTAD, 2026; Afesorgbor & Santeramo, 2025; Shanoyan et al., 2025; Tsakok, 2026; Emami & Javidan, 2026).

The inclusion criteria are as follows: first, the source must have made a direct contribution to one or more of the six dimensions analyzed in the paper policy exposure, upstream exposure, competitiveness outcome, resilience mechanism, digital capacity, or evidentiary design. Secondly, the source must have been an official publication of an institution, peer-reviewed research, or a recognizable working paper of scholars with clear identification of author and argument. Thirdly, the source must make a definitional, empirical, legal, or mechanism-based contribution to the understanding of agrifood trade. The exclusion criteria include dated commentary, technology promotion, sources without any identifiable authors or institutions, and papers having little relevance to agrifood trade or carbon-border adjustment.

As the subject matter is highly dynamic, unique considerations were applied to time-sensitive information. Legal claims regarding CBAM were sourced using versioned material as well as the manuscript cut-off date. Future forecasts were treated as scenario-driven as opposed to observations for the same, especially in the field of AI-energy. Statements that were statistical in nature were included only when the units used could not be misinterpreted as nominal value, real value, physical volume, or price-related. For instance, the FAO 2025 highlight on agrifood trade was selected due to the distinction it makes between trade growth in real terms until 2020 and subsequent growth in current-value exports beyond 2020 without volume growth (FAO, 2025a).

To improve reproducibility, each retained source was coded into a structured extraction template. The template recorded publication type, jurisdiction or geographic focus, temporal coverage, unit of analysis, outcome domain, evidence type, and relevance to the paper's central question. Two distinctions were especially important. The first was the separation between observed evidence and forecast or scenario material. For instance, IEA estimates of current data-center electricity consumption were treated as observed analytical estimates, whereas 2030 demand pathways were treated as conditional scenarios subject to uncertainty (IEA, 2025). The second was the separation between direct legal coverage and indirect transmission. Sources that described the formal scope of CBAM were not automatically treated as evidence on agrifood outcomes; they first had to be linked to an identified transmission channel such as fertilizer pricing, electricity cost pass-through, packaging material costs, buyer standards, or disclosure obligations.

The unit of analysis for the synthesis exercise thus becomes the evidence claim, rather than the country year observation. This has consequences in terms of how we interpret our sources. A legal document can state formal obligations. An official statistics document can describe a pattern of value or concentration in trade. A review paper can hypothesize about a probable mechanism from various cases. The common feature of all these documents is that they have different estimands. It is for this reason that we did not aggregate our data numerically. We instead sought three types of patterns: convergence, conditional convergence, and contradiction. Convergence would mean several sources agreeing on the directional mechanism. Conditional convergence means that there exists a mechanism that holds good only under specific conditions, such as institutional strength, interoperability, or access to finance.

The quality of the source was judged pragmatically, and not using any universally applicable measure. Legal and statistical documents were seen as authoritative for legal scope, policy timeframes, and descriptive statistics, but not necessarily as comprehensive regarding economic

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impacts. Peer-reviewed literature was deemed valuable for its conceptual insights, case analysis, and specialization within sectors; however, it was not considered to be equivalent and distinct categories were made such as simulations, legal documents, literature review, and observational studies. If a finding was present only in an advocate report or a single technology-promotional literature, then this finding was not relied upon for the core claims. Conflicting claims were adjudicated in favor of those with clear units, methodology, and institutional accountability, as well as the conservative reading of uncertainty.

The paper operationalizes five core concepts. First, geopolitical fragmentation is defined as the growing relevance of geopolitical distance, sanctions, export controls, bloc alignment, and strategic distrust in shaping trade costs, supply-chain choices, and the predictability of cross-border exchange. This definition follows the WTO literature that measures fragmentation through differential trade growth across geopolitically aligned and non-aligned partners rather than treating fragmentation as a rhetorical label (Blanga-Gubbay & Rubnov, 2024). Second, direct CBAM exposure refers only to imports of goods formally covered by Regulation (EU) 2023/956 and subsequent implementation rules. Third, indirect CBAM exposure refers to competitive or cost effects experienced by sectors outside formal legal scope because they rely on covered inputs, sell into buyer systems that impose emissions disclosure, or operate in supply chains where carbon-accounting capability becomes a condition of market participation. Fourth, decarbonization capability refers to the ability of firms, sectors, or countries to reduce emissions intensity, document embedded emissions, and access lower-carbon energy or process technologies at reasonable cost. Fifth, digital traceability capability refers to the ability to collect, verify, exchange, and use transaction- and process-level information relevant to standards compliance, provenance, emissions documentation, logistics coordination, and risk management.

Competitiveness is defined not empirically, but rather as a conceptual measure. Competitiveness outcomes are seen in at least four dimensions that are commonly used in the literature: market access and compliance viability, cost and margin pressures, market share or survival impacts, and upgrading capability into more standard-compliant parts of value chains. Food system resilience is similarly understood as a structured concept rather than an umbrella term for any positive outcome in food policies. Building on the findings of the OECD, resilience is described as the ability of food systems and food chains to anticipate, absorb, adapt to, and recover from shocks while retaining their critical functions regarding food access, affordability, livelihoods, and sustainability (OECD, 2023a).

The time horizon for the study will extend approximately from the period after 1995, but with strict indicator-by-indicator discipline. Globalization and value chains will be assessed on the basis of the literature starting from the late 1990s. Official agrifood trade and price statements will be limited to 2000-2024, as this is the timeframe explicitly provided in the FAO highlight that will be used here. CBAM law analysis will be limited to the 2023 regulation, the transitional phase until 2025, and the definitive phase that will begin in 2026. The AI-energy section will rely on contemporary analytical projections and future scenarios until 2030, although this is clearly noted in the paper as such projections. This rule solves one of the biggest issues of the previous version of the paper, namely the assumption of a unified dataset between 1995 and 2026 when it does not exist. Hence, the paper can be seen as a clear mechanism-oriented

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integrative review rather than an attempt at a comprehensive systematic review in its narrowly defined meta-analytical sense.

Table 1. Evidence-selection and coding protocol

Dimension	Operational definition	Typical source type	Use in analysis
Direct policy exposure	Formal legal coverage under CBAM and implementation rules	EUR-Lex; European Commission	Identify what is directly covered versus not covered
Indirect upstream exposure	Transmission through fertilizers, electricity, materials, finance, and buyer governance	Official policy sources; sector studies	Trace spillovers into agrifood systems
Competitiveness outcome	Market access, cost incidence, value capture, survival, upgrading	Peer-reviewed agrifood/GVC literature	Structure outcome discussion
Resilience mechanism	Diversity, redundancy, visibility, learning, governance	OECD and resilience literature	Differentiate capacities from realized outcomes
Digital capability	Traceability, interoperability, documentation, coordination	OECD digital trade reports; supply-chain literature	Assess conditioning role of data systems
Evidentiary strength	Observed statistics, legal text, simulation, review, scenario	All retained source types	Prevent overstatement and separate scenarios from observations

3. Results

3.1 Secondary-data architecture and conceptual baseline

The first consequence of the synthesis is more conceptual than econometric. Carbon-border climate governance influences agrifood competitiveness in a four-tiered structure of direct regulation, upstream transmission through inputs, buyer governance and capability-based adaptation. Such a structure was present in all retained documents. The definition of CBAM's official legal parameters in the EU comes from EU legal sources. The interconnection and dependency structure, the concentration, and the volatility of the agrifood industry come from official international trade and food systems-related documents produced by FAO, OECD, and WTO. The global value chain theory describes the impact of the standardization and coordination of lead firms on market access. The digital trade in agriculture and food by the OECD illustrates that data management, traceability, and standardization verification play the

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same role as tariff regulation in modern agrifood business (Jouanjean, 2019). The synthesis demonstrates that carbon-border governance cannot be considered solely as a tariff tool.

The important point is that competitiveness needs to be decomposed into its margins. The previous draft switched among export growth, market access, value addition, and resilience too readily, as if they were fungible concepts. They are not. The reviewed literature points to at least four margins. The first is market access in terms of whether the firm remains able to sell in regulated or standards-heavy markets. The second is the incidence of costs, whether compliance, reporting, input, and finance costs are internalized, passed on, or distributed along the chain. The third is strategic position, whether the firm seeks higher-value, standards-laden, or more resilient links in the chain. The fourth is continuity of performance through shock, whether the supplier remains a reliable partner during episodes of climate events, transport disruptions, and geopolitics. A climate-smart competitiveness model that fails to consider any of these margins is either too limited or too broad.

Moreover, the secondary data architecture reveals the gap between the scope and relevance of formal legal scope of regulation and its economic implications. Regulation (EU) 2023/956 creates CBAM only for particular highly emitting sectors but not for the agrifood economy in general. At the same time, the agrifood economy is highly interdependent with some of the regulated sectors, especially with fertilizers and electricity, while it relies upon transport equipment, storage facilities, packaging and industry inputs which can incorporate carbon costs. Therefore, the concept of indirect exposure remains in use in this paper, although it is formulated more precisely than the previous 'shadow CBAM' idea. Indirect exposure is when the competitiveness of the agrifood economy is impacted by the carbon-border governance in some measurable ways (through supply chain and governance channel) despite the fact that no border charge applies to the final product.

Agrifood value chain transformation scholarship reinforces the analytical framework established here. Barrett et al. (2022) demonstrate that value chains in lower and middle-income countries have experienced rapid transformation via supermarket, food service, and midstream 'quiet' revolutions. This was associated with greater coordination, standardization, logistics capabilities, and intermediary involvement by private companies. All of which are relevant to carbon-conscious international trade inasmuch as compliance costs and verification requirements do not pass through anonymous spot markets only. Rather, such processes occur through contract relationships, supplier preferences, auditing, and procurement procedures from the lead firm. Therefore, carbon border governance and standardization are related spheres of analysis.

It also indicates that services are much more important for competitiveness than shown by traditional trade data based on product performance. According to research done by the OECD, limitations in service sectors such as logistics, finance, certification, data processing, and distribution may function as taxes on exporters through reducing the efficiency of the value chain and the country's value added (OECD, 2017a). In the case of carbon-conditional trade, the importance of these services increases significantly as they become necessary for the purpose of reporting on carbon emissions. As a result, agrifood exporters with equally productive farms may experience very different results due to the different services ecosystems surrounding them.

Another baseline finding relates to the distinction between trade growth in nominal terms and systemic resilience. According to FAO, the trade in crops and livestock products grew steadily in

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real terms until 2020, whereas export values continued to grow in nominal terms even without volume growth after 2020 (FAO, 2025a). The importance of this fact is that it makes a fallacy of the usual reasoning about the fact that the growth of nominal trade value is evidence of higher integration or competitiveness. Post-2020 changes in commodity prices, energy prices, and inflation have changed the relationship between value and volume. As a result, the safe conclusion for the paper on agrifood competitiveness is that the agrifood system is large, well connected, and price sensitive, not that nominal growth itself proves competitiveness.

Finally, it becomes evident from the conceptual baseline that resilience needs to be studied as a conditional feature of openness instead of being regarded as self-sufficiency. Resilience framework proposed by the OECD highlights features like diversity, connectiveness, redundancy, visibility, learning, and governance; besides, it also contends that international trade tends to have a positive impact on resilience in most cases by pooling risks (OECD, 2023a). This is not to say that openness tends to stabilize food systems all the time; rather, this is to say that the impact of openness on resilience would be conditioned by factors such as concentrations, policy measures, and avoiding chokepoints. The WTO evidence of fragmentation and the FAO evidence of concentration in commodities like soybean and palm oil make it clear that the issue here is not openness per se, but vulnerable openness.

The framework that emerged out of the synthesis puts forward the following three external drivers as those that exert the most impact on agrifood outcomes and should thus be situated at the top of the analytical architecture: carbon-border climate governance, digitalization and uneven capability distribution, and geopolitical fragmentation. Such drivers affect agrifood outcomes via four different channels: input costs; compliance and verification demand; logistics and coordination; and distribution of risks among the suppliers, firms, and states. Outcomes include competitiveness impacts, distributive impacts, and resilience impacts. Policy interventions come as the moderators.

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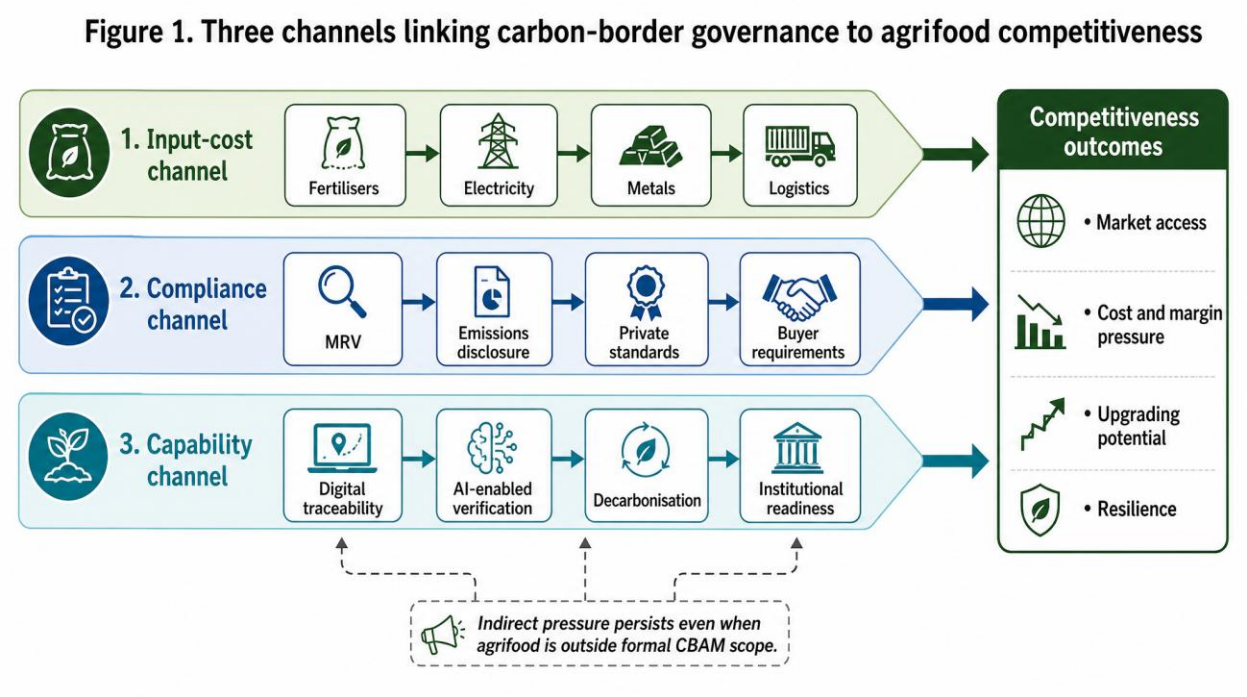


Figure 1. Three channels linking carbon-border governance to agrifood competitiveness: input-cost transmission, compliance pressure and institutional capability formation. Source: author synthesis.

Note: conceptual, synthesis-derived figure; arrows indicate analytically inferred pathways rather than estimated causal effects.

3.2 Carbon border adjustment and transmission into agrifood systems

The second implication of the synthesis is that CBAM should be considered both as a legal instrument as well as a governance signal, though the two should not be confused. In terms of legality, the case for CBAM is clear cut. First, the CBAM Directive is established by Regulation (EU) 2023/956 of 10 May 2023, and the explanation and implementation documents of the European Commission explain the interim reporting system until 2025 and the definitive system after 1 January 2026 (EUR-Lex, 2023; European Commission, 2023, 2026a). The sectors that are explicitly mentioned as being covered are cement, iron and steel, aluminum, fertilizers, electricity and hydrogen. Agrifood sector is not specifically included at the time of writing. Where transmission to agrifoods comes in, however, things become harder to predict. There, the evidence allows for a more nuanced but significant analysis. Fertilizers represent the easiest point of transmission because they are explicitly targeted by CBAM. Fertilizer costs affect the production of agrifoods directly and indirectly, through cropping systems, feed markets, and yield management. Should carbon prices cause an increase in high-emission fertilizer costs within Europe or affect supply chains in related industries, then producers of agrifoods associated with those industries will find themselves affected in terms of their cost structure. It is not a given, however, that those costs will fall where they might. Depending on contract

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arrangements, bargaining power, availability of substitutes, and timing, they could fall anywhere up the line.

The second means of transmission is electricity, although this channel works differently from one location to another. The regulation applies to electricity imports directly, but the economic aspect that affects the agrifood sector is in the importance attached to reliable and low-carbon electricity. Electricity is required for processing, cold storage, milling, irrigation, warehouse operations, refrigerated transportation, and the provision of digital infrastructure. On the other hand, there are concerns related to the rise in demand for electricity for the purposes of AI-based computing. Data centers were estimated to use 415 TWh of electricity in 2024, accounting for 1.5% of total electricity use, while projections for the year 2030 show global electricity consumption at about 945 TWh (IEA, 2025). These figures do not indicate any potential negative impact on the agrifood trade. However, what they indicate is that reliable and low-carbon electricity is turning into an important strategic asset for various sectors. For agrifood exporters, this means that decarbonization and digital upgrade are more challenging in carbon-intensive, unreliable, and expensive electricity systems.

There is a third chain of transmission via material inputs and capital goods. Steel, aluminum, and cement are inputs in production of machinery, storage facilities, irrigation, transport, and packaging-related infrastructure. The agrifood industries do not acquire these materials in a similar manner as heavy industries, but their infrastructure investments are certainly not immune to the influence of carbon-sensitive prices. As before, this analysis does not posit any single measurable pass-through coefficient, since there is no empirical basis for doing so. Nevertheless, the principle of upstream exposure holds: industries not directly subject to carbon accounting can be faced with different investment, replacement, or supplier costs as a result of the upstream material becoming carbon-priced.

The other channel is equally vital. Carbon-border control gives rise to incentives for importers, financiers, insurers, and lead companies to ask suppliers for more accurate emission information. Even in cases when food products are not included in CBAM, the diffusion of embedded emissions reporting systems could affect purchasing decisions. While the previous version alluded to this possibility, it did so too vaguely. In the revised synthesis, I identify three possible channels. First, there is due diligence magnification: companies that already have a need for emission data for some of the inputs will logically seek information from a larger set of suppliers. Second, there is portfolio simplification: buyers may benefit from having suppliers who can demonstrate auditable carbon and traceability data on their portfolio, even if regulation applies only to some of its parts. Finally, there is financial conditionality: banks, insurers, and investors may take into account transition risk differently depending on whether or not the firm has emission data and/or carbon-low adjustment strategies. These are quite realistic channels but not quantified estimates yet.

The scholarly debate on whether carbon-border instruments might expand to include agriculture supports the case for being careful. Some legal and modeling approaches suggest that the expansion of CBAM further into agrifood would be an environmentally sensible step or could be carried out effectively under particular circumstances, while others warn against risks in WTO compliance, difficulties in dealing with export rebates, regressivity, and measurement challenges (Del Federico & Giorgi, 2024; Nordin et al., 2025). What is important for the present paper is not

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to make a prediction that such expansion is unavoidable. The significant fact is that even the debate about the possibility of such expansion and existing carbon accounting standards alter the expectation environment for agrifood exporters.

This result is paralleled by another concerning heterogeneity between exporting countries. Those that have substantial sources of renewable energy, established carbon-accounting systems, and relatively advanced customs or standards institutions are better positioned to respond to carbon-sensitive market demands without being subjected to severe exclusion. On the other hand, those for whom agrifood industries rely heavily on emissions-intensive electricity production, imports of high-emission fertilizers, smallholder systems, or lack of capacity for verification incur higher costs of adjustment. However, even such a claim needs to be qualified. Excessive exposure does not mean inevitable loss of competitiveness; it means increased transition risks, particularly in the absence of policy support. Transition strategies remain feasible through targeted energy policy reforms, certification assistance, collective traceability systems, and corridor improvements. Thus, the synthesis justifies a cautious hypothesis: CBAM currently impacts agrifood systems only indirectly, but these impacts are economically significant since they change the cost, information, and governance environment of agrifood exports. This hypothesis is much more robust and justified than the rhetoric of the earlier draft because it is based on scope of legal coverage, credible channels of transmission, and uncertainty about incidence.

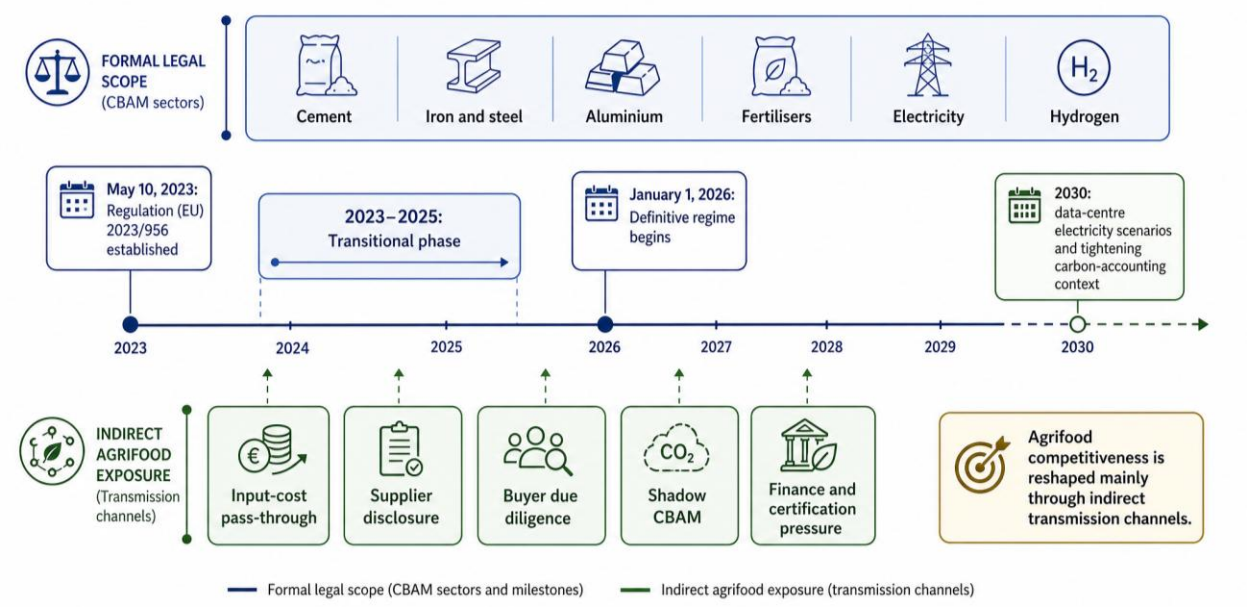


Figure 2. EU CBAM timeline and transmission into agrifood systems, showing the distinction between formal legal scope and indirect agrifood exposure. Source: author synthesis based on Regulation (EU) 2023/956 and European Commission implementation materials.

Note: conceptual legal-timing figure; transmission links are illustrative rather than causal estimates.

Table 2. Direct versus indirect exposure of agrifood systems to carbon-border governance

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Exposure type	Channel	Likely affected agents	Competitiveness implication	Major uncertainty
Direct	Covered imports: fertilizers, electricity, metals, hydrogen, cement	Importers and directly covered sectors	Explicit reporting and certificate obligations	Sector-specific incidence and substitution
Indirect	Fertiliser price transmission	Farmers, processors, feed users	Higher input costs and uneven pass-through	Elasticities and contract structure
Indirect	Electricity and energy-system pressure	Cold chains, processors, irrigation users	Advantage to low-carbon reliable power systems	Local power-market conditions
Indirect	Materials and infrastructure costs	Storage, machinery, logistics operators	Potentially higher capital and replacement costs	Timing and embodied-cost transmission
Indirect	Buyer and finance disclosure demands	Exporters in standards-intensive chains	Greater premium on auditable emissions data	Speed and breadth of private diffusion

3.3 Export competitiveness under decarbonization and digitalization

The third conclusion is that export competitiveness of businesses under carbon-sensitive trade is a function of the interaction of decarbonization capability and traceability capability. Neither alone is enough to enhance competitiveness in trade. Decarbonization without traceability leaves businesses without a means of demonstrating compliance and standing out in standards-heavy markets. Traceability without decarbonization creates informational content about high emissions without addressing competitiveness per se. Thus, the literature review provides a basis for the notion of complementarity as a concept, if not as a universally estimated cross partial effect. The decarbonization dimension of the argument is relatively clear. Carbon-sensitive trade elevates the importance of lower emissions, lower-carbon electricity, efficient processes and credible measurements of embedded carbon emissions. It does not necessarily imply that all low-carbon producers are going to increase their market shares. However, what is certain is that the criteria for competitive comparisons change. Emissions intensity is increasingly important in places where the information on the emissions is translated to costs, favored supplier status and reputation-based selection of the suppliers. In agrifood industries, decarbonization capabilities may include improvements in nutrient efficiency, use of renewable energy in irrigation or cold storage, low-emission production processes, reductions in waste, methane emissions in livestock systems and logistics optimization. What is most important varies from commodity to commodity and location to location, but the pattern is clear – lower emissions and better documentation carry an option value in trade.

However, the digital dimension of the issue is more complex. First, OECD's work on digital trade reveals various ways in which digital technologies could help lower transaction costs related to agriculture and food, including easier access to standards information, electronic certification, enhanced border procedures, traceability, remote advisory services, and better

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coordination of fragmented actors (Jouanjean, 2019). All of these are relevant to climate-conditional trade since emissions accounting and monitoring are essentially problems of information embedded into organizational infrastructure. The less difficult and expensive it is for companies to identify inputs, monitor production process and exchange reliable documents, the easier it will be to ensure compliance. Secondly, recent research on traceability and digital transformation emphasizes the necessity of focusing on real-life interoperability and governance rather than technological showmanship since traceability may increase transparency, safety, and sustainability, but fragmented platform infrastructure and adoption costs might cause new exclusions and asymmetric bargaining power (Kersten et al., 2024; Vasileiou et al., 2025; Vern et al., 2025; Plakantara & Karakitsiou, 2025). Thirdly, export studies also point out that digitalization, AI-based analytics, and transparency technology could ensure market access and coordination only when integrated with skill development, standardization, provision of services and reliable electricity supply (Hye & Rahman, 2023; Gadashov, 2025; Fosu et al., 2025; Phuonga & Nganb, 2024).

Still, the research findings should prevent an unmitigated optimism in regards to the potential of technology to solve problems. In fact, the OECD points out the fact that the use of digital technologies is highly efficient in addressing information bottlenecks while failing to address the bottlenecks which are structural, physical or institutional in nature. The absence of proper connectivity, the lack of interoperability, data management issues, high costs of adoption, fragmentation of farms, uncertainty of the regulation are the factors which may hinder the benefits of the digital transformation process. The digital divide may be created between those enterprises and nations which are able to make use of traceability and automation technologies and those which are not. Such a conditioning effect is even more evident in buyer-driven chains. According to Barrett et al. (2022), agrifood chain reconfiguration in developing countries includes increased vertical integration, enhanced quality and safety criteria, and increased reliance on logistics and services intermediaries. In such chains, suppliers must often comply not only with various regulations but also with documentation standards established by retailers or processors. A carbon management system can simply be added on top of such an existing system. Firms that are used to working within a digitally managed quality management, certification or traceability systems will likely be able to adopt a carbon accounting and sustainability audit system faster than firms that trade via opaque spot markets.

Competitiveness under decarbonization is also found to be affected by the service ecology around production. Services such as logistics reliability, customs effectiveness, testing and certification services, availability of financing and advice will determine whether producers manage to leverage their low-emissions performance in order to export. Previous studies on agro-food value chains conducted by OECD (2017a) indicate that an adverse environment for services could lead to lower domestic value addition and lower export capacity. The very same constraints under carbon-sensitive trade can escalate the costs of compliance. It is possible that the producer will manage to lower emissions at farm/factory level but fail to compete due to lack of interoperable documentation, insufficient verifications services or inability of customs to deal with electronic certificates. Another competitiveness challenge lies in scale and inclusivity. Larger firms involved in exports and being lead firms can bear fixed costs associated with monitoring, reporting and verifying more easily than smaller and medium sized firms who might

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find it costly to comply per unit of their output. In the literature of sustainability governance of agri-food chains, it has been found that the cost burden tends to shift upwards in cases where standards and resilience measures are applied. It has been called a supplier squeeze (Follmann et al., 2024). The implications for carbon sensitive competitiveness is distributional whereby the capacities that look efficiency enhancing at the chain level end up leading to increased exclusion unless there are systems, government involvement and simpler methods to lower entry barriers.

The synthesis also refines the way in which AI ought to be framed with regard to export competitiveness. The technology is pertinent as it will help with forecasting, routing, quality control, predictive maintenance, and anomaly detection. These applications could enhance inventory management, minimize wastage, and enhance coordination in perishable supply chains. However, AI technology is not a determinant of competitiveness; neither should forecasts about its implementation across economies be considered proof of competitiveness in agrifood exports. The more accurate way to frame AI's relationship to competitiveness would be to say that AI-assisted coordination might enhance competitiveness as long as it is implemented within data systems, interoperable traceability frameworks, and low-carbon electricity frameworks. If these conditions are lacking, AI implementation could very well be shallow or make matters worse through increased electricity dependence.

It may still not be possible on the basis of current literature to make a robust comparison and ranking of the country strategies, but it certainly allows us to put forth a very clear-cut proposition related to sequencing. For agrifood exports to carbon-sensitive markets, high-value adjustments will not be made either through digitization alone or through environment-oriented changes alone; rather, these will be more along the lines of credible emissions measurement, availability of low-carbon energy, traceability, and facilitation services for trade.

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Figure 3. Capability complementarity map for low-carbon agrifood competitiveness

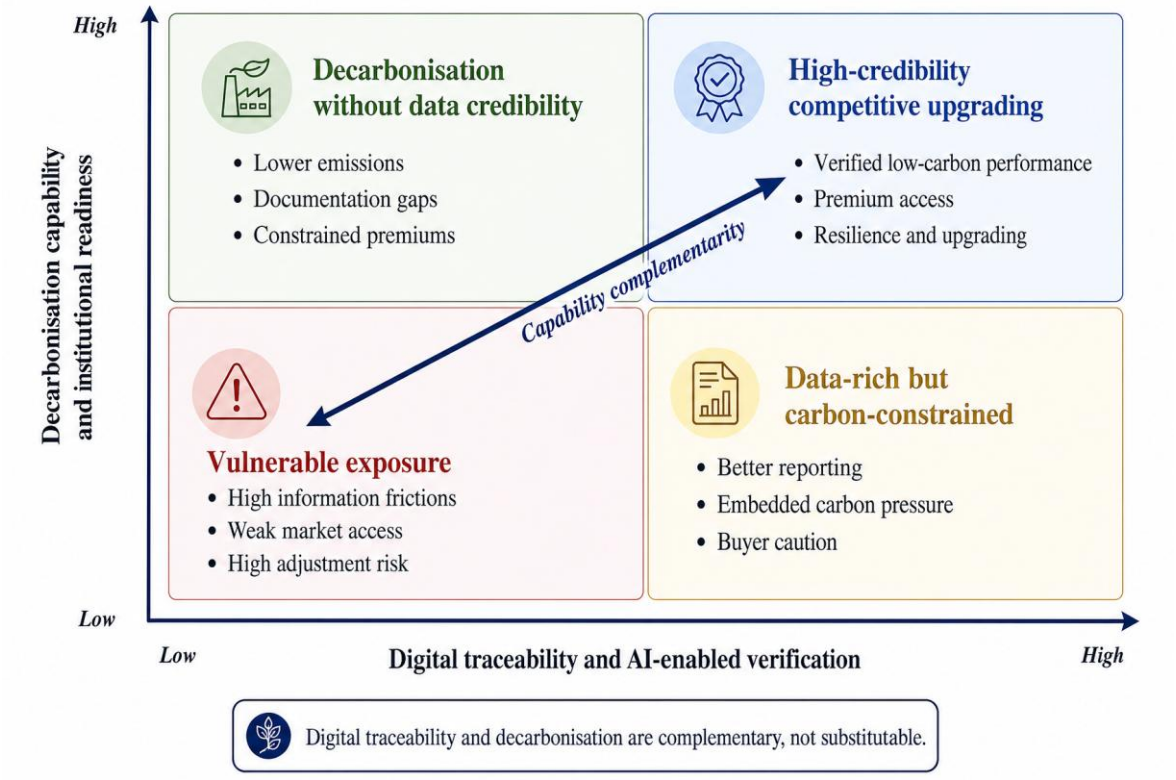


Figure 3. Capability complementarity map showing how digital traceability and decarbonization jointly condition competitiveness under carbon-sensitive trade. Source: author synthesis.
Note: conceptual quadrant; it does not estimate a production frontier or a causal interaction coefficient.

3.4 Food-system resilience under climate shocks and geopolitical fragmentation

A fourth conclusion is that resilience to compound shocks in the food system does not involve reducing exposure to international trade but relies instead on the nature of diversification, transparency, and governance in an open system. This is drawn directly from the OECD's food system resilience assessment, which holds that international trade enhances resilience because trade allows nations to access external resources in the event that production within the country has been disrupted (OECD, 2023a). Trade does not necessarily enhance resilience per se; rather, trade enhances resilience conditionally, depending on factors such as open markets, logistical capacity, information flows, and diversity in supplier dependence. Conditionality is an essential component of agrifood analysis. Climate disruptions tend to be uneven geographically. Droughts, floods, heat waves, diseases, and transport disruption do not hit all producing areas with the same impact at once. In such a scenario, trade will help mitigate any problems in local production. However, if countries resort to restricting exports, if infrastructure constraints prevent substitutes from taking place, or if import systems are overly concentrated, buffering will be impossible.

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The OECD organization directly states that such actions as export restrictions can damage the risk-pooling function of trade because they increase instability in global markets (OECD, 2023a). Therefore, the updated paper does not accept either simplistic cosmopolitanism or simplistic self-sufficiency. The analytically viable approach is adaptive openness.

The idea of geopolitical fragmentation provides further evidence for the point made above. The WTO's research in regard to fragmentation does not imply that there was a mere geographical reorganization of the world economy into clearly defined regional blocs. On the contrary, it indicates a growing sensitivity of the trade flows to the geopolitical distances between trading partners, a smaller increase in trade between hypothetical Eastern and Western blocs compared to intra-bloc trade following the war in Ukraine, and no evidence that near-shoring has reconfigured world trade flows significantly (Blanga-Gubbay & Rubnov, 2024). With regard to agrifood systems, this implies a more complex risk environment rather than an ideal binary division. Some food products will remain globally traded from many different geographies; some will become increasingly vulnerable to the risks of sanctions, financial transactions' difficulties, shipping rerouting, and politically-motivated restrictions. Therefore, the fragmentation is better to be interpreted as an increased political covariance of the trade connections rather than as a simple reduction of the overall level of trade. Finally, even the evidence related to the food security situation generally confirms the conditional approach suggested in this paper. In particular, the long-term food security issues have been discussed well before the debates around carbon border tax (OECD, 2013), whereas existing methods of monitoring stress the significance of trade statistics, quality of logistics infrastructure, commodity prices' observation and public food security indices (FAOSTAT, 2026; World Bank, 2023; World Bank, 2024; FAO, IFAD, UNICEF, WFP, & WHO, 2024).

The FAO evidence about concentration adds to the worries. Its latest trade highlights emphasize that world trade in major agricultural products is extremely concentrated amongst a few major exporting countries, where the two biggest exporters of soybeans and palm oil constituted almost 85% of total exports in 2024 (FAO, 2025a). Concentration does not necessarily mean weakness, but it adds to the cost of any disturbance. If just one or two countries dominate in an important product, disturbances like extreme weather events, policy measures, or logistical issues can quickly spread from the exporting countries to the importing ones. The problem is exacerbated if the importing countries have inadequate storage facilities, lack financial flexibility to absorb prices increases, or are heavily dependent on the product.

At this juncture, it is important to separate resilience capacity from the performance achieved through that capacity. The earlier draft adopted the resilience dimensions without clarifying if they were measured results or concepts. In the refined version of the synthesis, this gap is explicitly addressed. Diversity, redundancy, visibility, learning, and governance are considered capacities or design attributes, and not results measured in the current study. Diversity denotes the extent of diversification of suppliers, nodes, routes, or geographical locations of sourcing that avoids reliance on singular choke points. Redundancy includes the capacity to cope with the shocks like the spare capacity, inventories, liquidity reserves, backup suppliers, alternative processes, and/or transport methods. Visibility denotes the real-time or near real-time information regarding inventories, shipments, compliance, disruptions, and inputs. Learning pertains to the capacity to adapt one’s practices based on the new information or shocks

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encountered repeatedly. Governance pertains to the institutions, contracts, and coordination systems that permit public and private entities to respond to the information in a timely and credible manner.

This is important because resilience and efficiency can potentially clash. “Just in time” approaches, extreme specialization of sources of supply, and low inventories can minimize costs in “normal times,” but increase vulnerability during disruptions. On the other hand, redundancy and diversification can increase costs but decrease the risk of severe disruptions. As noted by Follmann et al. (2024), “resilience and sustainability need not necessarily go hand in hand. Increased robustness through more transport links or even reshoring could have adverse consequences from an environmental and distributional perspective.” This consideration is particularly salient when discussing the agrifood trade system. A strategy that relies on the uniform regionalization of all operations and the duplication of each link in the supply chain would be inefficient economically and environmentally as well as politically impractical. Digital resilience reenters the discussion as a necessary enabling condition rather than a standalone solution to the problem. It is difficult to ensure visibility without the ability to share data, track shipments, generate alerts, and communicate reliable information among companies and public entities. However, digital solutions may themselves pose new risks if there is reliance on unreliable power supply, non-interoperable platforms, or contested data governance. In the existing literature on transparency and traceability of agrifood systems, both aspects of the question are discussed. Data can help with the improvement of provenance, quality control, efficient recalls, and route selection. However, fragmentary digital architectures can lead to information silos that will not facilitate the coordination of activities at the systemic level.

Price effects are just as important as flow effects in the interaction between climate shocks and fragmentation. A nation might be resilient to one shock but vulnerable to another based on its import portfolio. A nation with varied import sources could still have difficulties with food access if global price surges are rapidly reflected in domestic prices and social safety nets are weak. On the other hand, a nation with some degree of domestic production cushion could still be vulnerable due to increases in production costs brought about by interruptions to fertilizer, feed, or fuel sources. Resilience is therefore a matter not only of tons, but of affordability, finance, and allocation of adjustment burdens among households, farmers, processing firms, and governments. Such an approach is consistent with OECD’s emphasis on resilience that includes livelihoods and sustainability beyond just availability and affordability (OECD, 2023a).

An actor-centric perspective further muddies this water. The literature indicates that resilience is differentially allocated among actors operating in the same value chain. While large lead firms may rely on diversified sourcing and sophisticated monitoring systems as protection measures, small suppliers may be under contractual pressure, have low margins, and limited shock-absorption capacity. While governments may achieve food security in their nation via temporary protectionism which increases volatility in the global market, importers may resort to protecting themselves via dealing mainly with larger and more certified suppliers. This is why resilience is not merely an objective systems feature but a product of power dynamics and policy choices.

Four propositions can be drawn from this review of the evidence concerning resilience in a fragmented world. First, diversified international trade is an essential form of resilience as it enables substitution both geographically and among production systems. Second, concentration

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and opacity are much riskier than openness per se. Third, policy responses such as export controls transform limited shocks into full-fledged crises. And fourth, many capabilities that enhance resilience are very similar to capabilities that enhance competitiveness, especially in visibility, logistics quality, standard harmonization, and low-carbon infrastructure. This list of parallels is far from being exhaustive, however. Some policies that help build resilience, including strategic stockpiling and targeted social protection, do not necessarily increase competitiveness but serve rather for coping with shocks. The challenge for policy-makers lies not in treating resilience as synonymous with competitiveness but in distinguishing between the two.

There are clear implications of such a logic for agrifood value chains under carbon-conscious trade regimes. Insofar as carbon governance leads firms to measure better, have more resilient energy systems, and increase traceability, some benefits related to resilience might ensue. On the other hand, if carbon governance mechanisms become too expensive, fragmented, or exclusive, then resilience will be compromised by the fact that the list of possible suppliers will be reduced. In this sense, the relationship is conditional and political.

Figure 4. Architecture of adaptive openness for food-system resilience

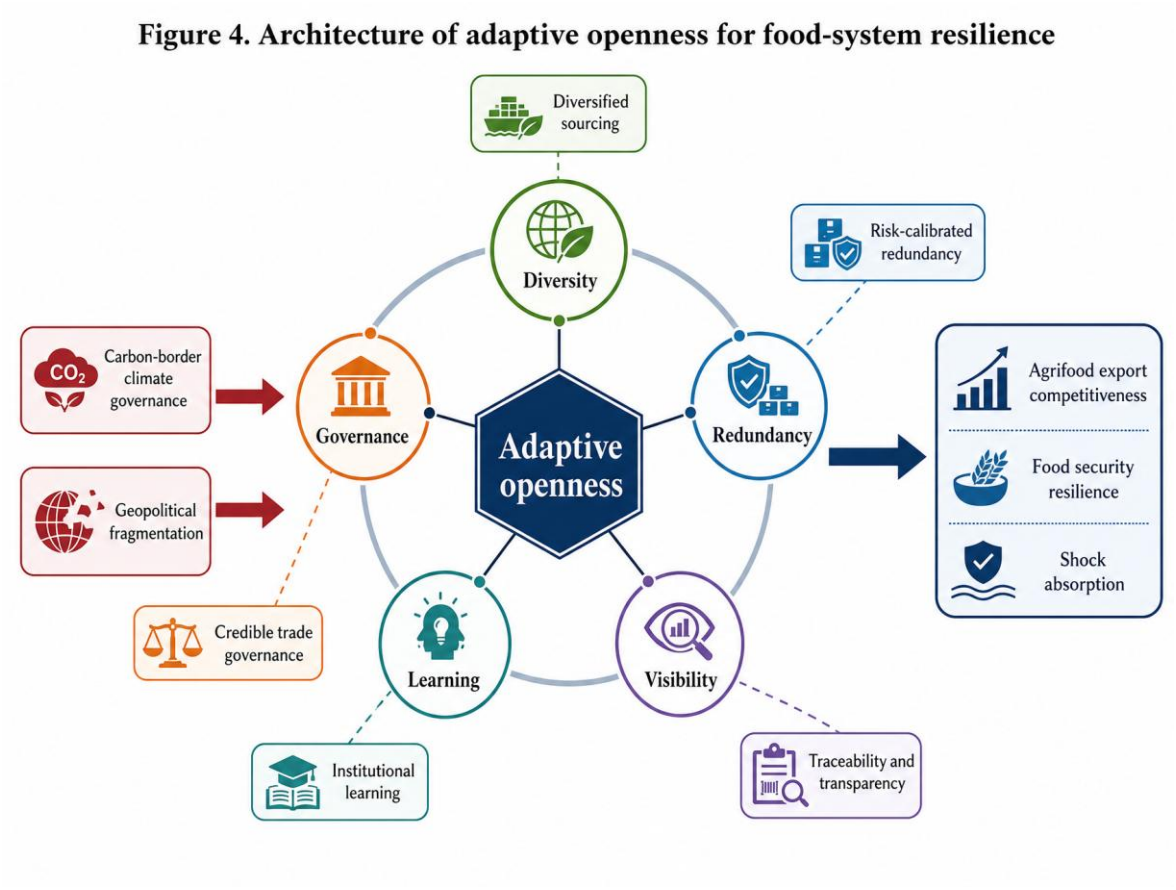


Figure 4. Architecture of adaptive openness for food-system resilience under carbon-border climate governance and geopolitical fragmentation. Source: author synthesis.

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Note: conceptual systems map; arrows indicate synthesis-derived relationships, not estimated causal effects.

3.5 Integrated policy architecture

The fifth conclusion is that the most credible policy approach does not consist of one measure, but rather an architecture, which is the combination of energy transition, traceability capacity, trade facilitation, resilience governance, and distributive cushioning. The original manuscript made an effort to order policy packages numerically in terms of their desirability, lacking any transparent scale for evaluation. Such methodology was not strong in terms of scientific credibility, since it treated judgment as evidence. In contrast, the new manuscript uses the concept of architecture instead of ordering. The key is not the selection of the best policy, but rather interactions of policies.

Pillar one is energy that is both low carbon and reliable. Without such energy, statements about being competitive in light of climate change amount to rhetoric. The agrifood industries will require energy for processing, storing, cold chain logistics, managing transport flows and AI coordination of logistics and production. The markets that pay attention to carbon costs will increasingly value lower embedded emissions, and AI coordination will itself be energy-intensive. The policy implication is clear – energy policy is trade policy. Decarbonization of the grid, renewable energy for cold chain logistics, energy efficiency in processing and energy reliability in industry belong inside competitiveness strategy, not alongside it.

Pillar number two is measurement, reporting, and verification infrastructure. It is not possible to invent carbon-accounting capability just in time for market inspections. Exporters require approaches, registries, testing facilities, certification by accredited verifiers when necessary, and practical reporting templates adjusted to the needs of the sectors concerned. In complex agrifood systems, it would be impractical to expect every small farmer to develop his own approach to measuring his emissions. Institutional systems will make a difference: cooperative traceability systems, sectoral reporting defaults, when necessary, data standards, and reporting tools supported by agricultural extension services can lower fixed costs of compliance. Institutional quality determines this. The same rule can be feasible in one place and prohibitive in another because of reporting infrastructure.

Thirdly, interoperable digital data rather than digital spectacle is the way to go. There is no basis for an unfounded zeal regarding blockchain test cases, AI-based data dashboards, or the emergence of platforms in general. The question here is whether the systems can speak to one another in terms of farms, processors, certification authorities, custom agencies, logistics, and buyers. Interoperability eliminates redundancy, facilitates verifications, and lends greater credence to traceability. Further, interoperability avoids creating silos of proprietary data that would trap smaller suppliers in bilateral solutions. Governments have no need to operate all the platforms but certainly should ensure the standards, legal acceptance of documents in a digital form, and a compliance fragmentation that could amount to a non-tariff trade barrier.

Fourthly, there is the issue of open yet risk-aware trade governance. The resilience literature leaves no doubt about the continued importance of market openness, even in the case of shocks. However, openness in the absence of risk management is inadequate in the presence of concentration. What is required is a set of policies that would promote diversification without resorting to isolationism – trade facilitation measures, protection of transit corridors, customs

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cooperation, logistical redundancy arrangements, and, where warranted, strategic stockpiling. There is also the issue of regional cooperation, but the evidence is that regionalization cannot be considered as a substitute for diversification globally. Nearer supplies are not necessarily safer when the region itself is exposed to climatic risks or geopolitical threats.

The fifth pillar is distributive and capability support. Transition policies that do not take into account incidence will be likely to underperform from an economic and political perspective. Small farmers, small processors, and poorer countries that import will bear the greatest relative burden of adjustment and have the fewest buffers. Many different kinds of support are possible: concessional funding for clean equipment, subsidized certification services, shared information infrastructure, assistance with data management, and social protection in cases where food price effects pose affordability problems. These are not secondary additions to the package of welfare programs but shape how adjustment takes place in terms of inclusion or exclusion.

These five pillars also work together through complementarities. Clean energy boosts the credibility and return on investment from measurement. Enhanced data systems boost the utility of logistics and resilience planning. Trade openness and corridor coordination enhance the relevance of diversified sourcing. Capability development means that smaller players can participate in digital and low carbon upgrading pathways rather than being filtered out. The key analytical takeaway here is that the concept of complementarity does not require specifying an exact additive effect. It requires understanding the reasons for underperformance of individual reforms. A country could have good traceability systems in place but be unable to compete due to unreliable power supply. A country could decarbonize specific export enclaves but still find it hard if customs processes are fragmented. A country could maintain open borders but stay vulnerable if supplier diversification and welfare buffers at home are overlooked.

With this view in mind, four figures that have been incorporated into the modified manuscript play certain roles. The graphic abstract has been clearly marked as conceptual and keeps apart drivers, channels, capabilities, and outcomes to prevent implying estimated causality. Figure 1 illustrates the conceptual mechanism by identifying the exogenous drivers, transmission channels, mediators, outcomes, and policy moderators. Figure 2 offers a versioned CBAM timeline based on the regulation of 2023, the transitional period of 2023-2025, and the regime of 2026. Figure 3 displays the complementarity between decarbonization capability and digital traceability capability but does not make any assumptions regarding the measured production frontier. Tables are transparent rather than decorative: the first one presents the evidence-selection and coding framework; the second table identifies the CBAM exposure channels; and the third table connects policy instruments to mechanisms, competitiveness impacts, resilience impacts, and implementation risks.

There is an important relevance of the policy architecture to international cooperation as well. For border carbon governance to maintain its legitimacy, the technical solutions for adapting must go hand in hand with enforcement mechanisms. In case there are no other ways, the border carbon policies could be considered as green conditionality lacking developmental reciprocity. The issue of legitimacy is consistently raised in relation to sustainable trade with developing countries in the scholarly literature. Interoperable standards, mutual learning regarding MRV systems, investments in the low-carbon logistics infrastructure, and the simplification for small

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suppliers can prevent the development of exclusion through carbon-conscious trade administration.

From a strategic perspective, an integrated policy architecture means that states do not need to wonder whether they should prioritize competitiveness or resilience, but rather when these concepts coincide and when there are trade-offs. Clean energy production, increased traceability, improved logistics, and coordination may help in both cases. Strategic reserves, emergency networks, and some aspects of diversification may promote resilience over competitiveness. On the other hand, the elimination of inefficient suppliers will increase competitiveness in the short term, but will undermine resilience and inclusion. An integrated policy architecture is valuable in its ability to highlight such trade-offs, rather than to hide them under the general idea of "smart policies.

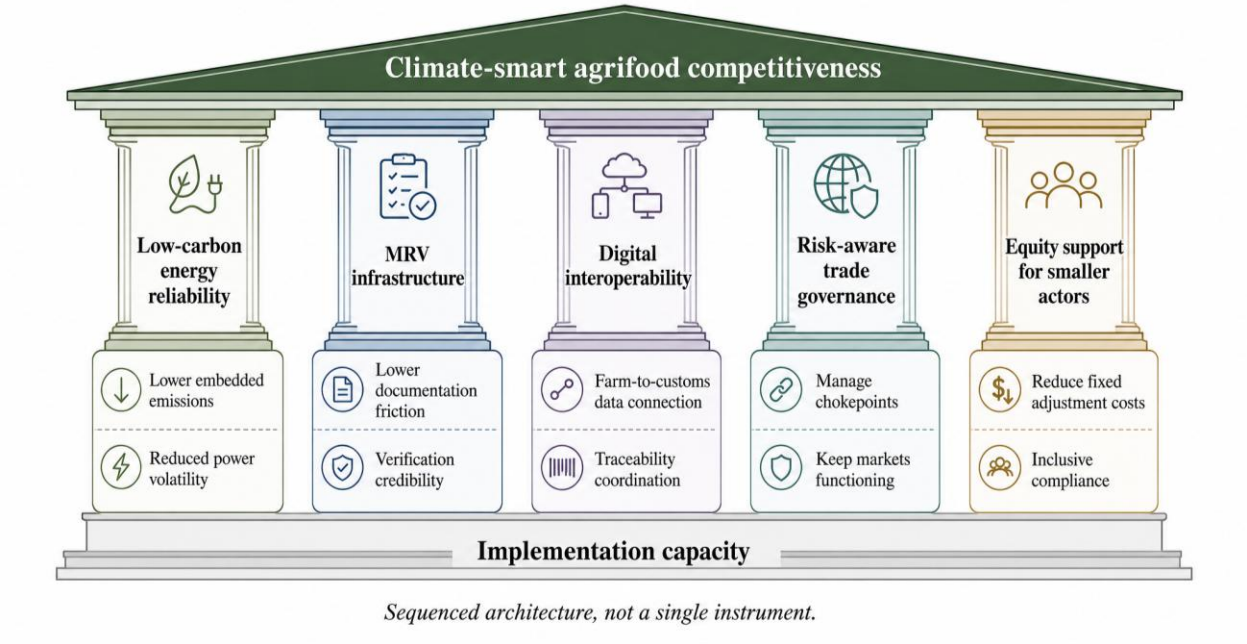


Figure 5. Integrated policy architecture for climate-smart agrifood competitiveness built on five complementary pillars. Source: author synthesis.

Note: conceptual policy architecture; pathway arrows do not imply measured causal magnitudes.

Table 3. Integrated policy architecture for climate-smart agrifood competitiveness

Policy pillar	Primary mechanism	Competitiveness implication	Resilience implication	Implementation risk
Low-carbon reliable energy	Reduces embedded emissions and power volatility	Supports market access and lower operating risk	Improves continuity of processing and cold chains	Capital intensity and grid constraints
MRV infrastructure	Lowers documentation friction and improves proof	Improves credibility in regulated markets	Enhances visibility during disruption	Exclusion of small actors if poorly designed

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	of compliance			
Digital interoperability	Connects farms, processors, logistics, certifiers, customs	Cuts transaction costs and verification delays	Improves coordination and early warning capacity	Fragmented proprietary systems
Open but risk-aware trade governance	Keeps markets functioning while managing chokepoints	Preserves sourcing flexibility and corridor access	Strengthens diversification and risk pooling	Political resort to export restrictions
Equity and capability support	Reduces fixed adjustment costs for weaker actors	Prevents exclusion and supports upgrading	Maintains supplier diversity and social stability	Fiscal burden and weak targeting

4. Discussion

The implications for a revised understanding of agrifood globalization from this new synthesis suggest the need for a much more fundamental theoretical shift in our understanding of agrifood globalization. The previous rounds of research on value chain analysis had a strong focus on governance, upgrading, and value capture when these concepts could be understood to function against a backdrop in which carbon, digital connectivity, and geopolitics were relatively exogenous. This conceptual foundation is no longer sufficient. Carbon accounting is getting closer to the border. Information systems are coming to matter in questions of market access rather than just internal management. Geopolitical alignment is starting to make a difference to the trustworthiness of trade corridors, technology transfer, and regulation. Under these conditions, the theory of agrifood competitiveness needs to become infrastructural and political.

The first issue discussed in this paper regards the definition of carbon border governance. The dilemma presented by this issue has been seen in terms of either being environmentally necessary or trade protectionist. This paper indicates that this dilemma is simplistic. CBAM is clearly an environmental tool; however, it is also a competitiveness tool in the sense that it creates a new context under which foreign and local producers enter the EU market. In the sectors where it applies, this implication is direct; for the agrifood supply chain, it is more indirect in the sense of input sourcing, information needs, and anticipation. The critical analytical task is thus not to reject either, but to determine how one becomes the other through legal reach, upstream dependency, and private governance.

It follows from the above that the second observation is becoming increasingly inseparable governance standards and climate governance. Agri-food trade has always had an element of quality, safety and traceability standards in it, often involving governance beyond public regulation and relying on private governance. Carbon data requests and sustainability audits could be superimposed upon those existing frameworks. Consequently, competitiveness pressure related to climate issues is going to be mediated not so much by carbon prices, but rather by administration capabilities to meet the bundle of requirements. It accounts for the relevance of the revised version focusing on digital capability for traceability. The matter is not that

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traceability substitutes decarbonization, but that without proper information framework, the former would not necessarily yield any advantage at all.

A third area for debate is the link between upgrading and distributive justice in the context of the environment. Transition costs are not impartial. Large businesses that have greater access to funding, technology, and verification have the means to cope more effectively with market access standards that are complex. Smaller producers in more fragmented agrifood industries in less-developed countries may face higher per-unit cost of reporting and certification. In discussions about value chain sustainability, the risk has been emphasized time and again that pressure for upgrading can be passed up the supply chain and thus increase asymmetry between the leading firms and the suppliers. This same risk is present in the case of carbon-sensitive trade, where transition to market entry increasingly becomes contingent on reporting, digitization, and low-carbon processes.

The fourth point of discussion focuses on resilience and openness politics. In the recent crises, public discourse has swung from one extreme to the other – from the praise of the international markets to self-reliant policies. The synthesis proposes that both positions are analytically flawed. International trade in agrifood may provide stability through the risk pooling effect across geography. However, international trade systems may quickly transmit the shocks where concentration is significant, informational problems exist, and states apply beggar-thy-neighbour policy. Hence, the conclusion is not that there should be less trade, but well-governed trade. This means that governments need to keep the channels open during the crises, build redundant corridors, and avoid the temptation to use every shock as the evidence of the fact that the only resilient strategy is domestic self-sufficiency. Such a strategy is hardly feasible for low-income food importers.

The connection between AI and agrifood competitiveness leads us to the fifth discussion topic. Most current discourse views AI as a universal accelerator and its benefits are supposed to extend to all industries. The evidence discussed above does not support such a generalization. While AI could potentially enhance demand forecasting, routing, anomaly detection, and quality management, the positive impacts of such an approach depend on the availability of good data, interoperability, energy security, and managerial abilities. Another challenge related to the potential use of AI in agriculture concerns energy use. According to IEA research, the electricity demand of data centers is high and is projected with large uncertainties in future scenarios (IEA, 2025). Thus, in systems with constraints in terms of energy, an uncontrolled growth of digital infrastructure might compete with other energy demands or lead to the lock-in of carbon-intensive energy sources without proper energy planning.

This paper also holds some lessons on how empirical work in this space could move forward. One of the reasons why the initial paper received such harsh critiques was because it spoke at the same time the languages of econometric analysis, policy synthesis, and theoretical framework but did not make clear what approach it followed. The present revision adopts the evidence synthesis approach, which is justified by the current level of the existing evidence base, but it also shows where additional empirical work is needed. First, there are still no comprehensive studies regarding the indirect exposure of agrifood sectors to the carbon borders, the cost distribution among firms of different sizes, buyer sourcing decision elasticity concerning emission disclosure, and the effect of traceability improvement on firm resilience to compound

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shocks. These are issues that require additional empirical study rather than statements included in the narrative review.

There are several agendas that emerge in a targeted manner. The first agenda is to conduct input-output and cost-pass-through analysis at the level of individual sectors in order to estimate the exposure of agrifood commodities through fertilizers, electricity, metals, and packaging. Secondly, firm- or shipment-level analysis may help to establish whether carbon tracking impacts export survival, unit prices, or preferred supplier status in regulated countries. Thirdly, comparison of digital traceability systems can be conducted in order to determine whether or not interoperability brings down compliance costs and proprietary systems lead to exclusion. Fourthly, resilience literature needs to expand from making general arguments about openness in trade and consider the role of diversification, inventory, corridor dependency, and social protection in actual shock scenarios. Fifthly, political economy analysis is required.

Limitations of the paper must be explicitly recognized. Even with the use of a stricter methodology compared to its previous version, the research is limited by heterogeneity of the evidence base. It fails to create one homogeneous quantitative database; it does not identify one common causal effect and does not undertake any formal welfare calculation for different countries and different goods. There are some sources that are of legal nature, some that are based on statistics, some that are conceptual, and even some based on simulations. Different time periods are used. Certain effects are under-measured in the available scientific literature, especially those related to consumer behavior and compliance costs of firms. That is why the synthesis allows us to identify the direction of explanation and policymaking, but not measure the magnitude of impact.

Tensions that no amount of evidence synthesis can ever dispel also exist on a normative plane. Carbon-border governance will help avoid leakage incentives and provide rewards for decarbonization, but it may also impose administration costs on the more vulnerable supplier parties. Digital traceability will increase transparency and coordination, but it may generate new forms of exclusion due to skill differentials, privately owned platforms, and costs of compliance. Redundancy will enhance resilience, but it will also be associated with short-term costs or have other implications for the environment. Open trading will combine risks, but it may still generate shocks and expose households to the fluctuations of world prices. The point of a Q1-style paper is to spell out the nature of these tensions rather than ignore them.

On the whole, the above discussion implies that the transformation of agrifood value chains in line with climate considerations is best characterized not as a search for an optimal model but rather as a case of constrained coordination in light of shifting carbon regulations, fragmented geopolitics, and variable digital capabilities. Divergent conditions at play for countries and firms, yet the nature of the problem is largely uniform – it involves decreasing the emissions intensity whenever feasible, reporting what cannot be decreased in the near term, building up credibility among suppliers, and maintaining resilience to shocks which become increasingly systemic in nature. Policies that fail to address all these issues concurrently are likely to underperform. Perhaps, the main implication emerging from the above revision lies in the institutional dimension of the problem.

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5. Conclusion and Policy Recommendations

The purpose of this paper is to reframe the original manuscript into an evidence-based secondary data analysis around one primary question, which is concerned with the impact that carbon border climate governance has on the competitiveness of agrifood exports through cost, compliance, and capability considerations under conditions of geopolitical fragmentation. It was felt to be essential to undertake such a reframing process as the original paper made claims that were beyond the scope of the evidence provided and tried to cover too many issues without a unifying core analytical thread.

The five key conclusions that can be drawn are as follows. First, the agrifood products are not subject to CBAM as of the manuscript date, and this must be said in any reasonable analysis. In other words, the legal framework still rests with Regulation (EU) 2023/956, and the corresponding implementation sequence of measures, including the transitional period and the definite regime starting in 2026 (EUR-Lex, 2023; European Commission, 2026a). Second, the lack of direct legal coverage does not mean that there is no relevance for the agrifood exporters. The indirect coverage may occur through the use of covered inputs (such as fertilizers and electricity), carbon-sensitive materials and infrastructures, and the diffusion of emissions reporting through the buyer-led supply chains. Third, the competitiveness of exports in carbon-sensitive trade is increasingly determined by the joint capability of decarbonization and digital traceability. Fourth, the resilience of the food system requires adaptive openness rather than naive autarky if the concentration, transparency and discipline are managed well. Fifth, the policy answer has to be architectural rather than fragmentary.

First, we recommend that the energy transition be made an integral part of the export strategy. For government and sector planners to do this, they need to recognize those areas along the agrifood value chain where energy and carbon matter in terms of competitiveness, including processing, refrigeration, irrigation, storage, and data systems. Investment in renewable energy, grid resilience, and energy efficient cold chain should be explicitly tied to export and food system goals and not confined to climate policy alone.

Second, MRV systems need to be developed ahead of time as a means of avoiding a crisis situation. Relevant government departments, business organizations, and big customers can collaborate to develop standardized reporting formats, data interoperability standards, verification procedures recognized as legitimate or any other form of verification, and mechanisms to lower the fixed cost of compliance for smaller players. Reporting systems for sectors where producers are widely scattered may be easier to develop in agrifood systems than reporting systems that only rely on firms. Default values must be clear and should not disadvantage efficient producers.

The third suggestion would be to emphasize digital interoperability over stand-alone technology initiatives. Countries and companies must spend their resources on traceability and information systems only if those information systems have the capacity to share their information along the chain and serve the purposes of compliance or logistics. Pilots that create proprietary information systems that are not recognized by any regulatory agency will find it difficult to ensure competitiveness in the long run. Hence, policymakers must emphasize digital public goods, data standards, recognition of electronic certificates if relevant, and interoperability of private systems.

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Fourthly, maintaining open trade without exposing oneself to concentration risks should be encouraged. It entails improving cooperation within customs, ensuring that vital corridors are protected in times of crisis, enhancing logistics resilience, and avoiding the practice of placing export bans on goods except in the rarest of cases. The importing country should identify the concentration risks of critical products while the exporting country should consider its reliance on specific corridors and infrastructure vulnerability.

Fifthly, equity considerations must be built into transition designs. Small-scale farmers, small processors, and smaller export economies must have access to finance, technical support, and compliance infrastructure if carbon-sensitive trade is to not become an exclusive club. International cooperation on climate and trade should encompass support for measuring emissions, digital verification, and low-carbon logistics. In-country social protection and transition aid will also be necessary if either food price transmission or compliance costs put livelihoods and affordability at risk.

The sixth recommendation is methodological and targeted toward the research community as well as policymakers. Studies going forward need to be careful not to equate narrative convergence with causal inference. Units of analysis need to be stated, legal reach distinguished from economic reach, history distinguished from scenarios, and the process by which evidence was collected and coded described clearly. Empirical studies that provide more credibility in terms of indirect exposure to CBAMs, compliance cost incidence, buyer behavior, and the interplay of traceability and resilience under shocks are sorely needed.

What emerges from the paper is the wider implication that climate-smart competitiveness in agrifood systems in the age of artificial intelligence is not really an issue of simply adding yet another list to trade policies. Rather, it is one of restructuring the material and informational conditions of participation in international markets such that carbon intensity, data authenticity, and supply chain robustness all become pertinent issues for being able to sell and under what conditions and how robustly against shocks. Thus, future agrifood value chains will have to rely not only on comparative advantage based on land, labor, or location but also on institutional competence to do low-carbon, authentic, and shock-resilient production.

However, the current study does not end the discussion. Neither does it try to suggest an optimal policy package that would work in all situations. It only manages to create a more robust framework for the analysis of an ever-evolving policy field. The study achieves this through limiting the main discussion point and giving precise definitions of some concepts, as well as matching claims with evidence.

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