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Carbon Border Adjustment, Market Responses, and Food-Security Trade-Offs in EU–Türkiye Processed Agri-Food Trade: A Calibrated Stackelberg Analysis

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Abstract

This paper develops a stylized theoretical policy experiment to evaluate the ex ante economic and environmental implications of extending carbon border adjustment to processed agri-food imports from Türkiye to the EU. The model is not a direct simulation of the existing CBAM, but rather a Stackelberg framework in which the EU sets product-specific carbon charges and Türkiye adjusts export quantities. We develop a calibrated Stackelberg framework in which the EU acts as the regulatory leader setting product-specific carbon border charges, while Türkiye adjusts export quantities as the follower. The model integrates consumer surplus, producer surplus, carbon-charge revenue, environmental benefits, and a food-security penalty linked to minimum consumption requirements. Results reveal substantial heterogeneity across products. In the unconstrained benchmark, lamb and beef face the highest optimal charges, at 45 and 42 USD/tCO_2e, respectively. Incorporating food-security constraints reduces the charge for lamb to 27.8 USD/tCO_2e, while the charge for beef remains unchanged because the minimum consumption constraint is non-binding. Under the baseline food-security scenario, net EU welfare increases by 29.1 million USD/year. The findings suggest that CBAM-type measures in agri-food trade should be product-specific and should account for food-security risks in nutritionally essential products.

Keywords: carbon border adjustment; processed agri-food trade; food security; Stackelberg model; European Union

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1. Introduction

Over the past three decades, the global economy has entered a period of unprecedented trade integration. According to reports by the United Nations Conference on Trade and Development (UNCTAD), the volume of world merchandise trade increased by nearly tenfold between 1990 and 2024, reflecting deeper market integration and declining trade barriers. While this expansion has generated substantial welfare gains, it has also amplified the environmental externalities embedded in global supply chains. The European Union (EU) has gradually shifted, under the European Green Deal, from a competitiveness-centered approach toward a sustainability-oriented policy framework. The EU aims to play a leading role in addressing transboundary environmental challenges such as global warming and the associated climate change, first within Europe and subsequently at the

global level. This orientation has been translated into practice through environmental protection policies and regulatory frameworks that the EU has implemented over a long period. For economies in a sustainability phase, the central challenge is to maintain, and even enhance, economic welfare while simultaneously strengthening environmental sensitivity. In this context, EU policymakers' efforts to address global environmental externalities are not limited to internal market regulations; rather, owing to the leverage effect arising from the Union's economic size and extensive trade network, these efforts also play a transformative role in reshaping international production and trade structures.

A central concern in this transformation is the rise in greenhouse gas (GHG) concentrations and the risk that trade reallocates rather than reduces emissions. Differences in environmental standards may induce the relocation of carbon-intensive production to less regulated jurisdictions, a mechanism associated with the pollution haven hypothesis [1–4]. Such dynamics generate carbon leakage and weaken unilateral mitigation efforts. Among the proposed responses, the Carbon Border Adjustment Mechanism (CBAM) aims to equalize carbon costs between domestic and foreign producers by pricing the carbon content of imports, thereby complementing the European Union Emissions Trading System. Introduced in 2023 with a transitional reporting phase, CBAM seeks to prevent leakage while preserving competitiveness and remaining consistent with EU treaty provisions. By incentivizing cleaner production abroad, border measures may also contribute to reducing international environmental externalities [5,6]. Policy design must also comply with multilateral trade norms, particularly consistency with World Trade Organization rules [7–10].

Despite expanding policy relevance, most CBAM-related research focuses on energy-intensive industries. Yet recent work in agribusiness has begun to extend CBAM analysis toward agriculture-related markets; for example, ref. [11] examines the cost–benefit implications of the EU CBAM in fertilizer trade, while ref. [12] assesses how CBAM can tackle carbon leakage in the international fertilizer trade. Agriculture accounts for roughly 10 to 12% of global GHG emissions at the production stage, and this share increases once broader supply-chain effects are considered. Food-system research has emphasized that mitigation opportunities are distributed across production, processing, transport, consumption and waste stages, implying that climate policy in agri-food markets should account for the full food-chain structure rather than only farm-level emissions [13]. This is particularly relevant for processed agri-food products, where carbon impacts may arise from both agricultural production and post-farm activities such as processing, packaging and logistics [14]. The sector also holds underutilized mitigation potential, provided that food supply sustainability is not compromised [15,16]. Ref. [17] emphasizes that mitigation in land use and food systems must safeguard minimum consumption requirements. Empirical evidence suggests that leakage rates in agriculture may exceed those in non-agricultural industries [18].

Despite this growing body of work, existing CBAM research exhibits three important limitations that motivate the present study. First, most analyses focus on energy-intensive manufacturing sectors [9,19], with limited attention to processed agri-food trade, where climate regulation interacts directly with food security concerns [20]. While recent work has begun to extend CBAM analysis to agriculture-related markets—for example, ref. [11] examines fertilizer trade, and ref. [6] develops a theoretical framework for an agricultural CBAM—these studies either focus on input markets or remain largely normative, without deriving optimal product-specific carbon charges. Second, existing analyses typically treat carbon border measures as exogenous policy shocks, rather than modeling the strategic interaction between regulator and exporter. This omits the exporter's endogenous response to carbon pricing and the resulting implications for market equilibrium, fiscal revenues, and emissions. As ref. [19] demonstrates, the welfare effects of border carbon adjustment depend critically on how foreign exporters respond to the policy. Third, the food security

implications of carbon border adjustment remain underexplored. Ref. [16] shows that border carbon adjustments in agri-food markets may be less effective than commonly assumed, while refs. [17] and [15] emphasize that mitigation in food systems must safeguard minimum consumption requirements. However, no existing study formally incorporates food security constraints into the optimal design of carbon border charges for processed agri-food products.

Because trade plays a central role in shaping national carbon footprints [19], consumption-based perspectives become essential. For example, ref. [21] shows that a substantial share of the United Kingdom's food-related emissions originates overseas, while ref. [22] highlights the importance of production-based mitigation efforts. Recent agribusiness studies further show that agricultural trade is sensitive to climate shocks, tariff structures, and broader trade realignments [23–25]. These tensions are particularly salient for major food traders such as the United Kingdom and the European Union, which seek environmental leadership without eroding domestic welfare [26]. The competitiveness and complementarity of EU agri-food trade with third countries have been documented by [18], who show that trade relationships are shaped by both product-level specialization and institutional arrangements. Although border carbon measures may raise prices and generate distributional losses [9,27], broader sustainability gains may offset these effects if changes in consumer and producer surplus are carefully assessed.

Against this backdrop, this study evaluates the ex ante impact of a potential CBAM extension to processed agri-food imports from Türkiye to the EU. Although not an EU member, Türkiye is deeply integrated into the European market through the Customs Union, with bilateral trade exceeding USD 200 billion in recent years. The potential macroeconomic impact of CBAM on Türkiye has been documented by [28], which estimates that a carbon border adjustment could reduce Turkish GDP by 2.7–3.6% by 2030 under a business-as-usual scenario [29]. This underscores the importance of analyzing the sectoral and product-level effects of CBAM on EU–Türkiye agri-food trade. Processed agri-food products, such as vegetable oils, meat, dairy, fruit preparations, and confectionery, account for a substantial share of this trade, making them particularly sensitive to prospective carbon border measures. Against this backdrop, this paper addresses four research questions:

RQ1: How do optimal carbon border charges vary across processed agri-food products, and what role do product-specific carbon intensities, demand elasticities, and market structures play in shaping this variation?

RQ2: How does the EU's optimal carbon border charge change when food security considerations are incorporated into the welfare function, particularly for nutritionally essential products?

RQ3: What are the distributional effects of CBAM across EU consumers, producers, and government revenues, and how do these effects vary across products?

RQ4: How does Türkiye's export response to carbon border charges affect the EU's optimal policy, and what are the implications for trade flows and emissions?

It is important to clarify at the outset that the model developed in this paper is a stylized theoretical policy experiment, not a direct simulation of the existing EU CBAM. The actual CBAM links liabilities to the embedded emissions of imported goods and the price of CBAM certificates, with a single EU-wide certificate price. Our model, by contrast, derives optimal product-specific carbon charges within a Stackelberg framework, allowing for product-level differentiation in carbon intensities, demand elasticities, and nutritional importance. This abstraction is intentional: it allows us to analyze the normative question of what carbon border charges would be welfare-maximizing, rather than to predict the effects of the specific CBAM design currently under implementation. The results should

therefore be interpreted as theoretical and indicative rather than as precise forecasts of CBAM impacts.

By addressing the gaps identified above, this paper contributes to the literature in three ways. First, it extends the analysis of carbon border adjustment to processed agri-food trade, a sector in which climate regulation interacts directly with market access, export adjustment, supply-chain resilience, and food-security concerns. While existing CBAM studies have largely focused on energy-intensive manufacturing sectors and agriculture-related input markets, this study shows how product-specific carbon intensities, demand responsiveness, domestic supply conditions, and trade exposure jointly shape optimal carbon border charges in processed agri-food markets. Second, it models EU–Türkiye processed agri-food trade as a sequential Stackelberg interaction rather than treating the carbon border measure as an exogenous policy shock. In this framework, the EU acts as the regulatory leader setting product-specific carbon charges, while Türkiye adjusts export quantities as the follower. This structure allows the analysis to capture market responses by exporters and the resulting implications for prices, trade volumes, fiscal revenues, producer surplus, consumer surplus, and emissions. Third, the paper incorporates a food-security penalty into the EU welfare function, allowing optimal carbon border charges to be evaluated with and without minimum consumption requirements for nutritionally essential products. This extension highlights the trade-off between climate ambition and food-security protection and demonstrates why uniform carbon border rates may be inappropriate for processed agri-food products.

2. Materials and Methods

2.1. Problem Description and Model Structure

The structure of international trade is increasingly shaped by leader–follower configurations, driven by geographical proximity effects that reduce trade costs [30,31] and by the need to align trade relations with global climate objectives [32,33]. In this evolving structure, major economies may act as regulatory leaders, while economically integrated partners adjust to the standards and policy requirements set by these larger markets [34,35]. In Europe, the European Union (EU) represents a major regulatory actor that sets trade policies, market standards and, increasingly, climate-related requirements. Türkiye can be characterized as a follower vis-à-vis the EU in this setting, due to its high trade integration, Customs Union framework and regulatory alignment [36,37].

This framework allows us to analyze the strategic interaction between the EU and Türkiye. Specifically, it examines how EU climate policy influences Türkiye's export decisions and how Türkiye adjusts export quantities in response to the EU carbon border charge, while the EU internalizes the implications of this response for prices, emissions, fiscal revenues and food-security-related supply stability. It also evaluates how food-security considerations may moderate the EU's welfare-maximizing carbon border charge for processed agri-food products.

In an increasingly interconnected world where climate policy, trade flows and food-security concerns interact simultaneously [38–40], the application of a Stackelberg framework to EU–Türkiye trade in processed agricultural products is theoretically justified. The EU's regulatory leadership and Türkiye's close trade relationship with the EU generate a natural leader–follower setting, making sequential strategic interaction an appropriate modeling approach. The model does not assume that Türkiye has no alternative markets; rather, it focuses on the EU as a strategically important destination market and analyses Türkiye's export response conditionally based on potential EU carbon border measures.

2.2. The Inverse Demand Function

The analysis considers bilateral trade between the EU and Türkiye in eleven processed agricultural product groups (i = 1, 2, …, 11). For notational simplicity, the model is presented for product i. In the calibrated application, the carbon border charge is allowed to vary across product groups, yielding product-specific optimal charges.

For each product group i, Türkiye's export quantity to the EU, X_i, constitutes the follower's decision variable, while the EU market price, P_i, is endogenously determined.

The EU market demand for product i is represented by an inverse demand function,

$$P_i = a_i - b_i Q_i \tag{1}$$

where Q_i denotes total quantity supplied to the EU market, $a_i > 0$ is the demand intercept, and $b_i > 0$ is the slope of inverse demand. Apparent consumption consists of domestic EU production and imports from Türkiye:

$$Q_i = Q_i^{EU} + X_i + \overline{M}_i^{ROW} - \overline{E}_i^{EU}.$$

In the empirical implementation, third-country imports ($\overline{M}_i^{ROW}$) and exports ($\overline{E}_i^{EU}$) are held constant at their levels. The marginal effects of the carbon border tax on total market quantity therefore operate through Q_i^{EU} and X_i only. EU domestic supply is assumed to respond positively to the market price and is specified as a linear function:

$$Q_i^{EU} = S_i P_i \tag{2}$$

where $S_i > 0$ captures the slope of the EU supply schedule (i.e., the domestic supply responsiveness parameter). Substituting Equation (2) into the total quantity identity and rearranging yields the effective inverse demand function faced by Turkish exporters. Solving the system produces

$$P_i = \frac{a_i - b_i X_i}{1 + b_i S_i} = A_i - B_i X_i \tag{3}$$

For notational convenience, define

$$A_i = \frac{a_i}{1 + b_i S_i},\ B_i = \frac{b_i}{1 + b_i S_i}$$

The inverse demand function can therefore be written compactly as

$$P_i = A_i - B_i X_i$$

Equation (3) represents the residual inverse demand confronting Türkiye in the EU market. The presence of domestic EU supply reduces both the intercept and the slope of the demand curve faced by Turkish exporters. Economically, stronger EU supply responsiveness dampens the price impact of Turkish exports and therefore limits Türkiye's market power in the EU market. This residual demand formulation provides the basis for deriving Türkiye's export reaction function in the next stage of the Stackelberg model.

2.3. Follower's Problem: Türkiye's Export Response

Given the vector of product-specific carbon border charges $t = (t_1, \ldots, t_n) \geq 0$ announced by the EU, Türkiye determines its export quantities X_i so as to maximize total profit across the n = 11 processed agricultural product groups. Türkiye's profit function is defined as

$$\prod_F = \sum_{i=1}^{n} [(P_i - c_i - te_i^{TR})\ X_i] \quad X_i \geq 0\ \forall i \tag{4}$$

For each product i, profits consist of export revenue P_iX_i minus constant marginal production costs c_i and carbon border tax payments $te_i^{TR}X_i$. The term e_i^{TR} denotes the carbon emission intensity of CO_2 equivalent per unit of output. Since the carbon border charge is levied per ton of embodied CO_2 equivalent, the carbon-related cost per unit of output is e_i^{TR}. Substituting the residual inverse demand function derived in Equation (3), $P_i = A_i - B_iX_i$ into (4) yields

$$\prod_F = \sum_{i=1}^{n} \left[\left(A_i - B_iX_i - c_i - te_i^{TR} \right) X_i \right] \tag{5}$$

Because products are independent in demand and cost structure, the maximization problem is separable across i. The first-order condition (FOC) for each product is therefore

$$\frac{\partial \prod F}{\partial X_i} = A_i - 2B_iX_i - c_i - t_ie_i^{TR} = 0 \quad i = 1, \ldots, n \tag{6}$$

Solving (6) for X_i yields Türkiye's reaction function:

$$X_i^*(t_i) = \frac{A_i - c_i - t_i\, e_i^{TR}}{2B_i} \; for \; t_i \leq \frac{A_i - c_i}{e_i^{TR}} \tag{7}$$

Equation (7) characterizes the follower's optimal export supply conditional on the carbon tax rate. The reaction function is linear and decreasing in t_i, implying that higher carbon taxation reduces Türkiye's export volumes in proportion to each product's emission intensity e_i^{TR}. Products with high e_i^{TR} are therefore more sensitive to carbon pricing.

The non-negativity constraint implies a corner solution whenever $t > \frac{A_i - c_i}{e_i^{TR}}$, in which case $X_i^*(t) = 0$. Hence, the carbon tax rate acts as the pivotal policy parameter determining export viability; for sufficiently high tax levels, Türkiye's exports of product i to the EU market are eliminated.

2.4. The Leader's (EU's) Problem

As the regulatory leader in the Stackelberg game, the EU selects the carbon border tax rate $t \geq 0$ to maximize aggregate welfare W_{EU}. EU welfare is defined as the sum of consumer surplus $CS(t)$, producer surplus $PS(t)$, carbon tax revenue collected from Turkish imports R(t), environmental benefits from global emission reductions $E(t)$ and a food security component $FS(t)$:

$$maxW_{EU}(t) = \sum_{i=1}^{n} CS(t_i) + PS(t_i) + R(t_i) + E(t_i) + FS(t_i), \; t \geq 0 \tag{8}$$

Each component depends on t_i through its impact on import volumes from Türkiye $X_i^*(t_i)$, EU domestic production $Q_i^{EU}(t_i)$, and the market price $P_i(t_i)$.

Consumer surplus $CS(t)$ reflects welfare gains to EU consumers from purchasing processed agricultural products at endogenous market prices. Since higher carbon taxes reduce imports and increase equilibrium prices, $CS(t)$ typically decreases in t.

Producer surplus $PS(t)$ captures returns to EU domestic producers. As imports decline in response to higher t, domestic supply expands, so $PS(t)$ typically increases in t.

Carbon tax revenue $R(t)$ is obtained from embodied emissions in Turkish exports:

$$R(t) = \sum_{i=1}^{n} te_i^{TR}X_i^*(t).$$

This term introduces a standard Laffer type trade-off as higher tax rates increase revenue per unit but reduce the tax base.

Environmental benefit $E(t)$ represents the welfare gain from reduced global carbon emissions. Because higher carbon taxes reduce carbon-intensive imports, global emissions decline to the extent that Turkish production is relatively more emission-intensive than the relevant alternative supply. This component captures the EU's valuation of climate mitigation.

Food security $FS(t)$ reflects the EU's concern for maintaining a stable caloric supply of processed agricultural products. Excessively high carbon taxation may disrupt supply chains or increase price volatility, thereby imposing welfare costs associated with reduced supply reliability.

The leader's optimization therefore involves balancing distributional effects (between consumers and producers), fiscal considerations, climate benefits, and food security objectives. The optimal tax rate t^* is determined by the first-order condition, $\frac{dW_{EU}(t)}{dt} = 0$, taking into account Türkiye's reaction function $X_i^*(t)$ derived in Section 2.3. This structure formalizes the sequential strategic interaction: the EU anticipates Türkiye's export response to any chosen tax level and internalizes its effects on market equilibrium, fiscal revenues, emissions, and food security when selecting the welfare-maximizing carbon border tax.

Consumer surplus in the EU

Consumer surplus in the EU is derived from the linear demand structure introduced in Section 2.1. For each product group i, the market inverse demand function is $P_i = a_i - b_i Q_i$, where Q_i is the total market quantity.

Under linear demand, consumer surplus equals the area under the market demand curve and above the equilibrium price. Hence, for product i, $CS_i = \frac{1}{2}(a_i - P_i)Q_i$. Using the market demand slope parameter b_i, this expression can equivalently be written as $CS_i = \frac{1}{2} b_i Q_i^2$.

Substituting $Q_i(t) = Q_i^{EU}(t) + X_i^*(t)$, total consumer surplus becomes

$$CS(t) = \sum_{i=1}^{n} \frac{1}{2} b_i (Q_i(t_i))^2. \tag{9}$$

Here $Q_i(t_i) = Q_i^{EU}(t_i) + X_i^*(t_i) + \overline{M}_i^{ROW} - \overline{E}_i^{EU}$. Because EU domestic supply is determined by price-taking producers and embedded in the residual demand formulation, its structural component can be separated from the strategic variable $X_i^*(t)$. Expanding the quadratic term yields

$$CS(t) = \sum_{i=1}^{n} \left[\frac{1}{2} b_i ((X_i^*(t))^2 + b_i Q_i^{EU} X_i^*(t) + \frac{1}{2} B_i \left(Q_i^{EU} \right)^2 \right].$$

In the Stackelberg game, the strategic interaction operates through the Turkish export decision $X_i^*(t)$, which is itself a function of the carbon tax rate t. The final term, $\frac{1}{2} b \left(Q_i^{EU} \right)^2$, depends solely on domestic EU supply and does not introduce an additional strategic margin beyond price adjustment already internalized in the residual demand specification. Accordingly, for analytical clarity, consumer surplus can be decomposed into

$$CS(t) = \sum_{i=1}^{n} \frac{1}{2} b_i (X_i^*(t))^2 + \textit{terms associated with domestic supply}$$

This formulation isolates the welfare effect attributable to Turkish imports, for instance, the endogenous component of the game, while preserving the full structural representation of EU market demand. In expanded (open) form for the multi-product case,

$$CS(t) = \frac{B_1}{2} \left(X_1^* + Q_1^{EU} \right)^2 + \frac{B_2}{2} \left(X_2^* + Q_2^{EU} \right)^2 + \cdots + \frac{B_n}{2} \left(X_{1n}^* + Q_{1n}^{EU} \right)^2.$$

This expression makes explicit that consumer welfare depends quadratically on total market supply and is indirectly affected by the carbon border tax through its impact on Turkish export quantities.

Producer Surplus of EU Domestic Producers

Producer surplus for domestic firms is derived from the linear supply specification introduced earlier. For each product group, EU domestic supply is given by $Q_i^{EU} = S_i P_i$, where $S_i > 0$ is the slope of the EU supply Schedule and captures domestic supply responsiveness (calibrated to match sector-specific supply elasticities at a reference point). Under a linear supply curve passing through the origin, producer surplus corresponds to the area above the supply curve and below the market price. For product, this yields $PS_i = \frac{1}{2} P_i Q_i^{EU}$. Substituting $Q_i^{EU} = S_i P_i$ gives $PS_i = \frac{S_i}{2} P_i^2$. This formulation highlights the convex relationship between prices and domestic producer welfare. For instance, the increases in market prices generate more-than-proportional gains in producer surplus due to the upward-sloping supply structure. Aggregating across all n processed agricultural product groups, total EU producer surplus is

$$PS^{EU}(t) = \sum_{i=1}^{n} \frac{S_i}{2} P_i^2(t) \tag{10}$$

Since equilibrium prices $P_i(t)$ depend on the carbon border tax through its impact on Türkiye's exports $X_i^*(t)$, domestic producer surplus is indirectly influenced by the EU's policy choice. Higher carbon taxes tend to reduce import competition, increase market prices, and thereby expand domestic producer surplus, creating a distributional trade off within the EU between consumers and producers.

Carbon Tax Revenue Collected From Turkish Exports

Under CBAM, the EU collects revenue from embodied emissions in imports originating from Türkiye. The tax is levied per ton of CO_2 embodied in imported products and applied to realized import volumes. Total carbon tax revenue is therefore

$$R = t \sum_{i=1}^{n} e_i^{TR} X_i^*(t) \tag{11}$$

where $X_i^*(t)$ is Türkiye's optimal export response derived from the follower's maximization problem:

$$X_i^*(t) = \frac{A_i - C_i^{TR} - te_i^{TR}}{2B_i}, \text{ for } t \leq \frac{A_i - C_i^{TR}}{e_i^{TR}}.$$

Substituting the reaction function into (11) yields, $R(t) = \sum_{i=1}^{n} \frac{te_i^{TR}}{2B_i}\left(A_i - C_i^{TR} - te_i^{TR}\right)$. This expression reveals the non linear relationship between the carbon tax rate and fiscal revenue; higher values of t increase revenue per unit of embodied emissions, but reduce the tax base by contracting export. Accordingly, revenue may attain an interior maximum (a Laffer type relationship) depending on parameter values and the corner constraint. Revenue thus enters the EU's welfare maximization problem both as a fiscal component and as a strategic lever that interacts with trade responses.

Environmental Benefit From Reduced Global Emissions

The environmental benefit component captures the welfare gains associated with emission changes induced by the carbon border adjustment mechanism. Within the policy framework of the European Union, emission reductions occur through two distinct channels:

1. Direct effect—a contraction in Türkiye's exports reduces production-related emissions in Türkiye.

2. Indirect (leakage) effect—higher carbon taxation may stimulate additional EU domestic production, potentially increasing emissions within the EU. The environmental benefit function is therefore specified as

$$E_{(t)} = \theta \sum_{i=1}^{n} e_i^{TR} \left[X_i^0 - X_i^*(t) \right] - \psi \sum_{i=1}^{n} e_i^{EU} \left[Q_i^{EU}(t) - Q_i^{EU}(0) \right] \quad (12)$$

where e_i^{TR} and e_i^{EU} denote product-specific carbon intensities of Turkish and EU production, respectively, derived from life-cycle assessment databases; $X_i^0 \equiv X_i^*(0)$ represents baseline (pre-CBAM) export volumes, and $X_i^*(t)$ and $Q_i^{EU}(t)$ are equilibrium export and domestic production levels under tax rate t. The parameters θ and ψ are the shadow prices of carbon emissions. In the baseline calibration, both are set equal to the social cost of carbon (100 USD per ton of CO_2).

The first term measures global emission reductions from decreased Turkish production and enters with a positive sign, reflecting the environmental gain from lower foreign emissions. The second term accounts for potential carbon leakage through adjustments in EU domestic output and enters with a negative sign: if domestic production expands in response to reduced imports, the resulting increase in EU emissions partially offsets the environmental gains from lower Turkish production. This sign convention ensures that higher domestic emissions reduce, rather than increase, net environmental benefits.

By distinguishing between θ and ψ, the specification allows alternative normative interpretations. When $\theta = \psi$, the EU evaluates emissions symmetrically regardless of geographic origin, reflecting a global climate welfare perspective. When $\theta > \psi$, greater weight is assigned to emission reductions abroad, consistent with strategic environmental trade considerations.

Food Security Component in Climate-Trade Policy

While the literature on border carbon adjustments has extensively examined carbon leakage and competitiveness effects [19,41–43], significantly less attention has been devoted to the food security implications of climate–trade instruments. Most existing CBAM analyses treat agricultural and industrial goods symmetrically, abstracting from the fact that food products possess intrinsic welfare relevance and are directly linked to nutritional adequacy and socio-economic stability. In the policy context of the European Union, food security is not limited to the traditional interpretation embedded in United Nations Sustainable Development Goal 2 ("Zero Hunger"). Rather, it is conceptualized through the EU's contemporary strategic priorities of supply chain resilience and strategic autonomy. Agri-food competitiveness is multidimensional, encompassing food security, trade, sustainability, and innovation, and these dimensions interact in complex ways across G20 economies. Under this broader interpretation, food security encompasses the uninterrupted, stable, and sustainable access of EU citizens to sufficient and nutritious food under adverse conditions, including climate and geopolitical shocks. Preserving domestic production capacity in critical agricultural and agro-processing sectors therefore constitutes a strategic objective alongside environmental protection. Accordingly, the Carbon Border Adjustment Mechanism is modeled not only as a tool to prevent carbon leakage, but also as an instrument that influences the EU's capacity to maintain minimum nutritional supply thresholds. Formally, the food security component of welfare is specified as

$$FS(t) = -\gamma \sum_{i \in F} W_i \left[\max\left(Q_i^{min} - Q_i(t),\ 0 \right) \right]^2 \quad (13)$$

where $i \in F = \{1, \ldots, 11\}$ denotes the subset of essential food products critical for nutritional security; Q_i^{min} represents minimum consumption requirements derived from FAO/WHO dietary guidelines; W_i denotes nutritional importance weights based on protein/calorie

content and dietary significance; γ captures the social value placed on food security relative to environmental objectives; and $Q_i(t)$ denotes EU apparent consumption, defined in Section 2.2 as $Q_i = Q_i^{EU} + X_i + \overline{M}_i^{ROW} - \overline{E}_i^{EU}$. In this study, third-country imports and EU exports are held constant at their baseline levels, and substitution toward third-country suppliers is not modeled. As a result, the marginal effect of the carbon border tax on apparent consumption is the same as in the simpler specification $Q_i(t) = Q_i^{EU} + X_i^*(t)$, and the optimal tax rates are unchanged. However, the level of apparent consumption is higher when third-country imports are included, so the food security penalty is smaller in absolute terms. The results reported in the next chapters should be interpreted as upper bounds on the food security penalty.

The quadratic penalty function ensures increasing marginal welfare losses as consumption falls below minimum thresholds. This specification offers three analytical advantages:

Escalating marginal cost of insecurity: Welfare losses accelerate as supply declines further below nutritional benchmarks, reflecting the nonlinear social cost of food shortages.

Differentiation across products: Essential food groups receive higher weights $\boldsymbol{W_i}$, allowing policy differentiation between nutritionally critical and non-essential goods.

Explicit policy trade-offs: The parameter γ enables quantitative evaluation of the optimal balance between environmental ambition and nutritional security within the EU's welfare maximization problem.

By embedding a structured food security component into the Stackelberg framework, the model extends conventional CBAM analyses beyond carbon leakage considerations and introduces an integrated climate–trade–nutrition perspective.

European Union's Welfare Maximization Problem

Combining the welfare components defined above, the EU, acting as the Stackelberg leader, chooses the carbon border tax rate $t \geq 0$ to maximize aggregate welfare, fully anticipating Türkiye's export response $X_i^*(t)$. The EU's objective function integrates five components, consumer surplus, producer surplus, carbon tax revenue, environmental benefits, and food security, across the $n = 11$ essential processed food product groups:

$$W^{EU}(t)\underbrace{\sum_{i=1}^{11}\frac{b_i}{2}[Q_i(t_i)]^2}_{CS(t)} + \underbrace{[\sum_{i=1}^{11}\frac{S_i}{2}[P_i(t_i)]^2}_{PS(t)} + \underbrace{t.\sum_{i=1}^{11}e_i^{TR}X_i^*(t_i)}_{R(t)} + \underbrace{\theta\sum_{i=1}^{11}e_i^{TR}\left[X_i^0 - X_i^*(t_i)\right] - \gamma\sum_{i=1}^{11}e_i^{EU}\left[Q_i^{EU}(t_i) - Q_i^{EU}(0)\right]}_{E(t)} - \underbrace{\gamma\sum_{i\in F}W_i max\left(Q_i^{min} - Q_i(t_i), 0\right)^2}_{FS(t)} \quad (14)$$

The equilibrium price $P_i(t)$ and domestic production $Q_i^{EU}(t)$ are determined through the residual demand structure defined in Equation (3), while Turkish exports follow the reaction function $X_i^*(t) = \frac{A_i - C_i^{TR} - t_i e_i^{TR}}{2B_i}$. For a detailed formal derivation of the symmetric baseline Stackelberg equilibrium, the reaction functions, and the optimal tax propositions, see Appendix A.

This formulation embeds the full sequential structure of the Stackelberg game. The EU internalizes the price-mediated redistribution between consumers and producers (with consumer surplus calculated from the market demand curve and producer surplus from the domestic supply curve), fiscal effects arising from embodied carbon taxation, global environmental benefits net of potential carbon leakage (with the leakage term entering negatively), and strategic food security considerations tied to minimum nutritional supply thresholds.

Because products are independent in demand and cost structure, the welfare maximization problem is separable across products. The optimal carbon border tax t_i^* is characterized by the first-order condition $\frac{dW^{EU}(t)}{dt_i} = 0 \ \forall i$, and this separability implies that the EU's optimal policy can be implemented as a vector of product-specific carbon border charges $\boldsymbol{t}^* = (t_1^*, \ldots, t_n^*)$ with non-negativity constraints on trade flows. Given the nonlinearities introduced by export responses, revenue effects, leakage dynamics, and the quadratic food security penalty, the solution generally requires numerical computation calibrated to sector-specific parameters. The resulting t^* reflects the EU's optimal balance between climate ambition, trade stability, industrial protection, and nutritional security within an integrated climate–trade framework.

Analytical Solution in Equilibrium

This section derives the equilibrium carbon border tax under alternative policy configurations. To obtain transparent policy insights and to benchmark the numerical calibration, we first consider a symmetric case in which all product groups share identical structural parameters:

$$A_i = A,\ B_i = B,\ S_i = s,\ e_i^{TR} = e^{TR},\ e_i^{EU} = e^{EU},\ c_i = c.$$

Although the empirical implementation relies on product-specific heterogeneity, the symmetric solution clarifies the economic mechanisms driving the optimal tax and facilitates interpretation of the calibrated results.

The Equilibrium Without Food Security Policy

In this benchmark specification, the European Union maximizes aggregate welfare without the food security penalty, $W^{EU}(t) = CS(t) + PS(t) + R(t) + E(t)$ subject to the follower reaction function of Türkiye. The first-order condition for the leader is $\frac{dW^{EU}(t)}{dt} = 0$, and solving this condition under symmetry yields the optimal carbon border tax:

$$t^* = \frac{(\phi - \lambda\psi)e_i^{TR} + \mu_i(A_i - c_i)}{\eta_i} \tag{15}$$

The optimal tax consists of three economically distinct motives in the numerator and one adjustment term in the denominator. The first is the environmental motive, ϕe^{TR}, where ϕ represents the social cost of carbon. The optimal tax increases proportionally with both the social valuation of emissions and Turkish carbon intensity. A one-unit increase in ϕ raises the optimal tax by e^{TR}/η. This is the standard Pigouvian component of CBAM.

The second force is the carbon leakage adjustment, given by $-\lambda\psi e^{TR}$, where $\lambda = \frac{s.e^{EU}}{2}$ captures the carbon leakage adjustment factor. If EU domestic production is carbon-intensive ($e^{EU} > 0$) and supply is price-responsive ($s > 0$), higher carbon taxation induces domestic expansion that partially offsets global emission reductions. This leakage effect reduces the optimal tax. When EU production is clean or supply is perfectly inelastic, this correction term disappears.

The third force is the strategic trade motive, $\mu(A - c)$, where $\mu = \frac{1}{4}(1 - sB)$ is the market power coefficient. When EU domestic supply is relatively inelastic ($sB < 1$), the EU retains residual market power in the import market. In this case, CBAM serves not only as an environmental instrument but also as a strategic trade policy tool that extracts rents from Turkish exporters by improving the EU's terms of trade. If EU supply is highly elastic ($sB \to 1$), this strategic motive diminishes.

The denominator $\eta = e^{TR}\left[1 + \frac{e^{TR}}{2B}(1 + Bs)\right]$, captures the responsiveness of the tax base to the carbon border tax. When Turkish exports are highly sensitive to taxation, for example because demand is elastic or B is small, export contraction is stronger, which enlarges η and thereby limiting the optimal tax. Conversely, when trade volumes are

relatively inelastic, η is smaller allowing the EU to impose a higher optimal tax without sharply reducing imports.

Briefly, Equation (15) shows that the optimal CBAM rate under symmetry is determined by the balance among the Pigouvian climate correction, the carbon leakage adjustment, the strategic trade effect, and the constraint imposed by trade responsiveness. In the absence of food security considerations, the optimal tax reflects only environmental and strategic trade forces. The introduction of the food security component in the next subsection modifies this balance by adding a further welfare trade-off between climate ambition and minimum nutritional supply requirements.

Special Cases

The symmetric closed-form solution of t^* yields several economically meaningful limiting cases that clarify the relative strength of environmental, leakage, and strategic trade motives.

Case 1: No carbon leakage.

If $\psi = 0$ or $e^{EU} = 0$, the optimal tax becomes $t^*_{no\ leakage} = \frac{\phi e^{TR} + \mu(A - c)}{\eta}$.

In this benchmark case, the tax reflects only the Pigouvian environmental motive and the strategic trade component. Relative to the general case, leakage reduces the optimal tax by $\frac{\lambda\psi + e^{TR}}{\eta}$.

Thus, carbon leakage operates as a moderating force on environmental ambition: the more carbon-intensive and supply-responsive EU production is, the lower the optimal tax.

Case 2: Perfect competition in the EU

When EU domestic supply becomes perfectly elastic ($s \to \infty$) the strategic trade motive vanishes because the EU loses residual market power. In this limit,

$$\lim_{s\to\infty} t^* = \frac{\phi e^{TR} - \frac{e^{EU}\psi}{2} e^{TR}}{e^{TR}} = \phi - \frac{e^{EU}\psi}{2}$$

The optimal tax converges to the Pigouvian benchmark adjusted for carbon leakage. The economic intuition is that CBAM can no longer be used to extract rents from Turkish exporters under perfect competition. The tax becomes a purely environmental instrument, corrected only for domestic emission feedback effects. Market power enables strategic taxation, when EU supply is inelastic, CBAM partly functions as a rent-extraction device.

Case 3: Highly elastic import demand:

When the residual demand facing Turkish exporters becomes extremely elastic ($B \to 0$), trade volumes react strongly to even small tax changes. In this limit, $\lim_{B\to 0} t^* = 0$.

Intuitively, when exports are highly responsive, any positive tax generates a disproportionate contraction in trade, eroding consumer surplus and tax revenue. As a result, the welfare-maximizing carbon border tax collapses toward zero. Trade elasticity constrains policy high export responsiveness sharply limits feasible tax levels. These cases jointly show that the optimal CBAM rate is not purely Pigouvian, but instead emerges from the interaction among environmental valuation, domestic production structure, and trade responsiveness.

Comparative Statics

Differentiating the symmetric closed-form solution, t^*, yields several comparative static results that clarify the economic forces governing the optimal CBAM rate chosen by the European Union.

Sensitivity to Turkish carbon intensity:

The effect of Turkish carbon intensity is given by $\frac{\partial t^*}{\partial e^{TR}} = \frac{\phi - \lambda\psi - t^*\left(1 + \frac{e^{TR}}{B}\right)}{\eta} \gtrless 0$ which is generally ambiguous. It depends on whether the marginal environmental benefits of taxing more carbon-intensive imports outweigh the marginal trade-reduction costs. The term ϕ captures the marginal environmental gain from taxing higher carbon, while $\lambda\psi$ reflects

the leakage-adjusted environmental correction. The final term $t^*\left(1+\frac{e^{TR}}{B}\right)$ captures the trade-contraction cost and revenue responsiveness effect. If marginal environmental benefits dominate trade contraction effects, the optimal tax increases with Turkish carbon intensity. However, if higher intensity substantially erodes the tax base, the optimal tax may decline. Hence, greater embodied carbon does not mechanically imply a higher CBAM rate—its effect depends on the relative strength of environmental valuation and trade responsiveness.

Sensitivity to demand responsiveness:

The effect of residual demand curvature is $\frac{\partial t^*}{\partial B} = -\frac{\mu(A-c)e^{TR}}{B^2\eta} < 0$. An increase in B reflects greater effective demand responsiveness so become more price-sensitive. The negative sign implies that more elastic import demand reduces the optimal tax. When Turkish exports respond strongly to price changes, even small tax increases lead to substantial trade contraction, limiting the EU's ability to impose high carbon charges. Thus, trade elasticity acts as a policy constraint.

Sensitivity to EU supply responsiveness (leakage and terms-of-trade)

Let s denote EU supply elasticity. Differentiating with respect to s (or equivalently B_s in the composite term) yields: $\frac{\partial t^*}{\partial B_s} = -\frac{\psi e^{EU} e^{TR}}{2\eta} - \frac{B(A-c)}{4\eta} < 0$. Greater EU supply elasticity reduces the optimal tax through two distinct channels: (1) More responsive domestic production increases leakage when imports decline, thereby reducing net environmental gains. (2) Higher supply elasticity weakens EU market power, reducing the strategic rent-extraction motive. Accordingly, stronger domestic supply responsiveness unambiguously lowers the optimal CBAM rate.

The Equilibrium With Integrated Food Security Constraints

We now derive the symmetric analytical solution when food security concerns are explicitly incorporated into the welfare objective of the EU. The purpose is to clarify the structural trade-off between climate policy stringency and minimum nutritional consumption in Türkiye. We assume all n products have identical parameters, with a fraction $\alpha \in [0, 1]$ classified as essential foods ($i \in F$). Minimum required consumption per essential product is Q^{min}, calibrated from calorie requirements. γ measures the social valuation of food security relative to climate benefits, and w captures nutritional importance weight. The modified food security penalty becomes

$$FS(t) = -\gamma\alpha w \left[max\Big(Q^{min} - Q(t),\ 0 \Big) \right]^2 \tag{16}$$

This introduces a quadratic welfare loss whenever total consumption falls below the minimum threshold. Consequently, the welfare maximization problem is characterized by two distinct regimes depending on whether the minimum consumption constraint binds.

Regime Structure

Regime I: Non-Binding Constraint: If $Q(t) \geq Q^{min}$, then the food security term is inactive and the $FS(t) = 0$. In this regime, the solution reduces to the baseline symmetric case (Equation (15)). The regime applies when

$$Q(t_I^*) = \frac{A - c - t_I^* e^{TR}}{2B} + \frac{s\left(A + c + e^{TR}\right)}{2} \geq Q^{min} \tag{17}$$

Here, climate policy does not jeopardize minimum food availability.

Regime II: Binding Constraint: If $Q(t) < Q^{min}$, the food security constraint binds and directly affects optimal policy. The first-order condition becomes

$$\frac{d_w^{EU}}{d_t} = \frac{dW_{base}^{EU}}{d_t} + \frac{dFS}{d_t} = 0 \text{ since } \frac{dQ}{d_t} = -\frac{e^{TR}}{2B} \text{ we obtain } \frac{dFS}{d_t} = 2\gamma\alpha w(Q^{min} - Q(t)\frac{dQ}{d_t})$$

Solving yields the implicit binding-regime solution:

$$t^*_{II,i} = \frac{(\phi - \lambda\psi)e^{TR} + \mu(A - c) - \frac{\gamma\alpha w e^{TR}}{B}(Q^{min} - Q(t^*_{II,i}))}{\eta_i} \tag{18}$$

Because t^*_{II} it appears on both sides, Qt^*_{II} requires an implicit solution. In fact, because the optimal tax t^*_{II} appears on both sides of the equation, through Qt^*_{II}, the binding-regime solution is implicit. Rearranging gives

$$t^*_{II,i} = t^*_{I,i} - \frac{\gamma\alpha w e^{TR}}{B\eta_i}\,(Q^{min} - Q(t^*_{I,i}))\ \forall i \tag{19}$$

The leader country's optimal tax reductions depend on an amount proportional to the food security valuation (γ), the essential product share (α), the consumption shortfall ($Q^{min} - Q$) and the carbon intensity (e^{TR}). The reduction term $\frac{\gamma\alpha w e^{TR}}{B\eta}$ represents the marginal rate of substitution between carbon reduction and food security preservation. We can infer from the equation that as the tax decreases, consumption increases (Q rises), reducing the shortfall ($Q^{min} - Q$), creating a self-correcting mechanism.

To enhance the analytical tractability and policy intuition of the Stackelberg equilibrium, a closed-form approximation of the solution is derived. This approach linearizes the complex, non-linear relationship between the EU's climate tax and Türkiye's agricultural output around the initial equilibrium point t^*_I. Specifically, the food supply response $Q(t)$ is approximated linearly with respect to the tax, incorporating the emission intensity e^{TR} and supply elasticity parameter B:

$$Q(t) \approx (t^*_I) - \frac{e^{TR}}{2B_i}(t - \mathrm{t}^*_{\mathrm{I}}) \tag{20}$$

Substituting this linear approximation into the EU's first-order condition, which now internalizes Türkiye's food security constraint, yields an explicit formula for the adjusted optimal tax $\mathrm{t}^*_{\mathrm{II}}$:

$$\mathrm{t}^*_{\mathrm{II,i}} \approx \mathrm{t}^*_{\mathrm{I,i}} - \frac{\gamma\alpha w e^{TR}_i\left[\,Q^{min}_i - Q_i(\mathrm{t}^*_{\mathrm{I}}, \mathrm{i})\right]}{B_i\eta + \frac{\gamma\alpha w\left(e^{TR}\right)^2}{2B_i}} \tag{21}$$

The key structural insight lies in the denominator of the correction term. It is the additive component $\frac{\gamma\alpha w\left(e^{TR}\right)^2}{2B^2}$ that directly quantifies how binding food security concerns dampen the EU's tax adjustment. This term acts as a "policy inertia" factor, capturing a form of risk-averse climate policy design: as the weight γ on food security increases, the optimal tax becomes less responsive to changes in emissions or production, reflecting a strategic trade-off between environmental integrity and import stability.

The strategic interaction fundamentally shifts when the EU's climate tax pushes Türkiye's food production to its minimum acceptable level Q^{min}. The critical tax threshold $\hat{t}$, derived by solving $Q(\hat{t}) = Q^{min}$ within the follower's response function, marks this pivotal regime boundary. Setting total consumption equal to the minimum requirement, $Q(\hat{t}) = Q^{min}$, and solving for $\hat{t}$ yields

$$\hat{t} = \frac{A - c + sB(A + c) - 2BQ^{min}}{e^{TR}(1 + sB)} \tag{22}$$

With the known parameter values, this threshold represents the maximum carbon tax that can be imposed before compromising minimum nutritional consumption. It decreases

with the minimum requirement Q^{min} and increases with market size parameters (A, s), reflecting how larger markets can sustain higher taxes before hitting consumption floors.

Comparative Statics With Food Security

Sensitivity to food security valuation (γ):

The derivative $\frac{\partial t_{II}^*}{\partial \gamma} < 0$ demonstrates that higher social valuation of food security relative to climate benefits monotonically reduces optimal carbon taxation. This negative relationship emerges because increased concern for nutritional preservation raises the opportunity cost of consumption reduction, making carbon taxes more expensive in welfare terms. The magnitude of this effect depends on the consumption shortfall ($Q^{min} - Q$), and is moderated by market responsiveness parameters in the denominator.

$$\frac{\partial t_{II}^*}{\partial \gamma} = \frac{\alpha w e^{TR}\left(Q^{min} - Q\right),}{B\left[\eta + \frac{\gamma \alpha w \left(e^{TR}\right)^2}{2B^2}\right]} < 0 \tag{23}$$

Sensitivity to minimum nutritional requirements (Q^{min}):

The derivation $\frac{\partial t_{II}^*}{\partial Q^{min}} < 0$ shows that more stringent nutritional standards necessitate lower optimal tax rates. Each additional ton added to minimum consumption requirements reduces the feasible tax space, as policy must preserve a larger consumption base. This finding has important implications for international harmonization: countries with higher nutritional standards (e.g., based on dietary guidelines or demographic structures) would optimally implement less ambitious carbon border measures, potentially creating divergence that requires coordination mechanisms:

$$\frac{\partial t_{II}^*}{\partial Q^{min}} = -\frac{\gamma \alpha w e^{TR}}{B\left[\eta + \frac{\gamma \alpha w \left(e^{TR}\right)^2}{2B^2}\right]} < 0 \tag{24}$$

Both derivatives share the same denominator, which captures the interaction between environmental responsiveness (η) and food security inertia. It means that higher γ, α, or e^{TR} increase the importance of food security in shaping policy. Larger demand responsiveness B cushions the trade-off, reducing the magnitude of the tax adjustment. When the consumption shortfall disappears ($Q^{min} - Q \to 0$), the influence of γ vanishes and the solution converges to the non-binding benchmark.

Sensitivity to essential product share (α):

The derivation $\frac{\partial t_{II}^*}{\partial \alpha} < 0$ indicates that a greater proportion of essential foods in bilateral trade systematically lowers optimal taxation. This result captures the compositional effect of trade baskets: countries whose export portfolios are dominated by nutritionally essential commodities face a stronger food security constraint, which limits the extent to which carbon border taxes can be applied without jeopardizing domestic consumption adequacy. Mathematically, this negative relationship arises because the food security penalty in the welfare function scales directly with α, the share of products classified as essential. As α increases, a larger fraction of the consumption basket becomes subject to the minimum consumption constraint, amplifying the welfare loss associated with any given tax-induced reduction in supply. Consequently, the optimal tax rate must be adjusted downward to balance climate objectives with nutritional security.

Sensitivity to essential product share (w):

The derivative $\frac{\partial t_{II}^*}{\partial w} < 0$ demonstrates that products with higher nutritional importance per unit (e.g., high protein density, essential micronutrient content) warrant greater protection from climate-induced trade contractions. This negative relationship arises because the

welfare penalty for falling below minimum consumption thresholds scales directly with the nutritional weight parameter w. As the nutritional importance of essential foods increases, the opportunity cost of consumption reduction rises proportionally, making carbon taxes more expensive in welfare terms. The magnitude of this effect depends on the interaction between nutritional importance and the consumption shortfall. When consumption is well above minimum requirements $Q/Q^{min} \to \infty$, the derivative approaches zero as the food security constraint is non-binding. However, as consumption approaches the minimum threshold $Q - Q^{min} \to 0+$, the marginal welfare cost of taxation rises sharply, creating a "nutritional buffer zone" where tax increases generate disproportionately large welfare losses.

Because products are independent in demand and cost structure, the EU's welfare maximization problem is separable across products. The EU therefore effectively chooses a vector of product-specific carbon border charges $\boldsymbol{t} = (t_1, \ldots, t_n)$, with each t_i determined independently by the first-order condition $\partial W_i(t_i)/\partial t_i = 0$. This separability reflects the absence of cross-price effects in demand and of joint cost structures in production. In practice, this means that the optimal policy can be implemented as a set of product-specific rates, which is consistent with the product-level differentiation emphasized throughout the paper.

2.5. Calibration of the Parameters and Data Set

The empirical implementation of the Stackelberg game model requires calibration of parameters based on reliable data sources. This section details the calibration of supply and demand parameters (S_i, A_i, B_i), marginal production costs (c_i), carbon intensities (e_i^{TR}, e_i^{EU}) and food security parameters. All notation is summarized in Table 1. Calibration relies on official trade statistics from [44–46] for the period 1990–2024, production data from [40,47–49], and reports from [50–52]. Data sources, estimation procedures, and elasticity values drawn from the literature are documented for each parameter. Alternative parameter values used in sensitivity analysis are also reported.

The numerical calibration presented in this section relies on several simplifying assumptions that should be kept in mind when interpreting the results. First, the EU supply function is specified as linear and passing through the origin, which implies a price point elasticity of supply equal to one at all price levels. The product-specific supply elasticities drawn from the literature (Table 2) are therefore used to calibrate the slope of the supply schedule at the reference point, not to characterize the elasticity along the entire curve. This specification simplifies the analytical solution of the Stackelberg game but does not allow supply responsiveness to vary with the price level. Second, the market demand and residual demand parameters are related through the structural identities $A_i = a_i/(1 + b_i S_i)$ and $B_i = b_i/(1 + b_i S_i)$. This relationship holds exactly only when the observed trade flows correspond to the model's equilibrium. In practice, observed export volumes are used as reference points, and small inconsistencies between the calibrated equilibrium and observed trade flows may arise. These inconsistencies do not affect the qualitative ranking of optimal taxes across products, but they may influence the magnitude of the estimated welfare effects. Third, the food security measure compares EU domestic production plus imports from Türkiye with minimum consumption requirements, and does not account for imports from third countries or EU exports. This may overstate the food security penalty for products where Türkiye's share is small and substitution toward other suppliers is feasible.

Table 1. Model parameters and notations.

Notation (or Index)	Description
i	Eight main and three sub-sectors of manufacturing investigated regarding trade between TR and EU
X_i	Quantity of exports from Türkiye to the EU
P_i	Unit price of the investigated product in the EU market (endogenous parameter).
C_i	Known constant marginal cost of production.
e_i^{TR}	Carbon emission intensity of the investigated processed agricultural product for Türkiye.
e_i^{EU}	Carbon emission intensity of the investigated processed agricultural product for the EU.
T	Carbon border tax on exports to the EU (USD/ton CO_2).
Q_i^{EU}	Supply quantity of the investigated product in the EU
S_i	Supply elasticity of the investigated product in the EU.
P_i	Market price of investigated product
A_i, B_i	The effective inverse demand faced by Turkish exports
W_{EU}	Total welfare level of the EU
CS	Consumer surplus
PS	Producer surplus
R_t	Tax revenue collected from Türkiye.
E_t	Environmental benefit obtained from the reduction in global emissions.
$X_i^*(t)$, $Q_i^{EU}(t)$	The equilibrium quantities under tax rate t
θ, ψ	Shadow prices of carbon emissions
γ	The social value placed on food security relative to environmental objectives
w	Nutritional significance weight.
A	Essential food share in the investigated products
λ	Carbon leakage adjustment factor
μ	Market power coefficient (strategic trade motive)
η	Tax revenue responsiveness

Fourth, calibration uses 1990–2024 averages. While this provides a long-run perspective, it may not fully reflect current market conditions relevant for a prospective CBAM extension. A more recent baseline would be preferable for policy simulation.

Table 2. Supply parameter values of the investigated products.

Products	EU Productions	Average Price	Short-Term Elasticity	S_i (Short Term)	Long-Term Elasticity	S_i (Long Term)
OO	1,940,000	3842	0.25	126.2	0.80	404
SFO	2,890,000	1453	0.25	497.2	0.80	1591
BEEF	7,976,292	5842	0.35	477.9	1.05	1434
LAMB	872,708	4800	0.45	81.8	1.20	218
POUL	10,520,000	2380	0.40	1768	1.25	5525
JUIC	6,000,000	2340	0.25	641	0.75	1923
BAKE	55,000,000	890	0.25	15,449	0.80	49,438
CONF	7,000,000	2450	0.35	1000	0.95	2714
DAIR	145,000,000	3210	0.25	11,293	0.75	33,880
NUTS	870,125	5230	0.30	50	0.80	133
CANN	160,000	1680	0.30	28.6	0.85	81

Calibration Caveats

The numerical calibration presented in this section relies on several simplifying assumptions that should be kept in mind when interpreting the results.

Supply specification. The EU supply function is specified as linear and passing through the origin, $Q_i^{EU} = S_i P_i$. Under this specification, the point price elasticity of supply equals one at all price levels. The product-specific supply elasticities drawn from the literature (Table 2) are therefore used to calibrate the slope of the supply schedule at the reference point, not to characterize the elasticity along the entire curve. This specification simplifies the analytical solution of the Stackelberg game but does not allow supply responsiveness to vary with the price level. An alternative specification with a non-zero intercept, $Q_i^{EU} = \overline{Q}_i + S_i P_i$, would allow the model to match product-specific elasticities more closely, but would complicate the analytical solution and may not yield closed-form expressions for the optimal tax. We therefore retain the linear-through-origin specification for analytical tractability, while acknowledging this limitation.

Demand calibration. The market demand and residual demand parameters are related through the structural identities $A_i = a_i/(1 + b_i S_i)$ and $B_i = b_i/(1 + b_i S_i)$. This relationship holds exactly only when the observed trade flows correspond to the model's equilibrium. In practice, observed export volumes are used as reference points, and small inconsistencies between the calibrated equilibrium and observed trade flows may arise. These inconsistencies do not affect the qualitative ranking of optimal taxes across products, but they may influence the magnitude of the estimated welfare effects.

Food security measurement. The food security component of the model measures EU apparent consumption as domestic production plus imports from Türkiye, plus third-country imports, minus EU exports. In the empirical implementation, third-country imports and EU exports are held constant at their baseline levels. This approach has two limitations. First, it does not allow substitution toward third-country suppliers when Turkish exports decline. Second, the baseline levels of third-country imports and EU exports are not calibrated to observed data in this study. The case of lamb illustrates the concern: in our calibration, base consumption of lamb is already below the minimum threshold, with a negative security margin of −52%, yet Türkiye's share of EU lamb imports is negligible (42 tons out of 872,708 tons of total EU production). This suggests that the apparent consumption shortfall is not driven by Türkiye's exports but reflects the omission of major third-country suppliers such as New Zealand and Australia. A full treatment of third-country substitution would require modeling the supply response of third-country exporters and the substitution elasticity between Turkish and third-country imports. This is beyond the scope

of the present study and is left for future research. The results reported in the next sections should therefore be interpreted as upper bounds on the food security penalty, with the true penalty likely to be smaller for products where third-country substitution is feasible.

In addition, the food security penalty applies to total apparent consumption, not only to the share of Turkish exports. Because Türkiye's share of EU apparent consumption is small for most products (e.g., 0.005% for lamb and 0.002% for beef), the marginal effect of Turkish export changes on food security is limited. The model's food security penalty should therefore be interpreted as an upper bound on the true effect.

Calibration period and price proxy: Calibration uses 1990–2024 averages for prices, production, and trade. This long-run perspective has both advantages and limitations. On the one hand, it smooths out cyclical fluctuations and captures structural relationships that are more relevant for a long-term policy instrument such as CBAM. On the other hand, it may not fully reflect current market conditions, particularly for products where trade patterns, production structures, or price levels have shifted substantially over the past three decades. A more recent multi-year baseline (e.g., 2015–2024 or 2019–2024) would be preferable for a policy simulation targeted at the near future. A full re-estimation using alternative calibration periods is beyond the scope of this paper due to data availability constraints. We note, however, that the structural parameters (elasticities, carbon intensities) are drawn from the literature and are not period-specific, while the calibration of levels (prices, quantities) affects the magnitude but not the sign of the optimal tax. We therefore expect the qualitative conclusions to be robust to the choice of calibration period, and we leave a full sensitivity analysis to future research.

The use of Turkish export unit values as a proxy for the EU market price introduces additional measurement uncertainty. Turkish export unit values reflect the average price at which Turkish exporters sell to EU importers, which may differ from the domestic EU market price due to differences in quality, product composition, transportation costs, and market structure. This proxy is most appropriate when Turkish exports represent a marginal source of supply to the EU market and when product characteristics are relatively homogeneous. For products where Turkish exports represent a small share of total EU consumption (e.g., lamb, beef), the proxy may deviate more substantially from the true EU market price. We acknowledge this limitation and note that a more accurate calibration would require direct EU market price data from sources such as Eurostat or FAOSTAT. This is left for future research.

Numerical results. The numerical results reported in the tables of results section are based on the original calibration prior to the correction of the demand slope parameter. A full recalibration using the corrected parameters and a consistent supply specification would require a complete re-derivation of the model. The qualitative conclusions are robust to the calibration details, but the quantitative magnitudes should be interpreted as indicative rather than precise.

2.6. Data Set and Descriptive Statistics

The core dataset consists of annual trade statistics for processed agricultural products between Türkiye and the EU over 1990–2024. Export and import quantities (tons) and values (thousand USD) are obtained from TURKSTAT under the Harmonized System (HS-6) classification. The analysis focuses on eleven product groups with the highest export shares to the EU: olive oil, sunflower oil, beef, lamb, poultry, fruit juice, bakery products, confectionery, dairy products, nuts, and canned products. These categories were selected based on consistent export flows to the EU, high industrial processing content, and potential relevance under CBAM. EU production data are sourced from FAOSTAT

(1990–2024). For canned products, production data (2003–2024) are obtained from EUROSTAT (2025) PRODCOM (product code 10391200).

Between 1990 and 2024, Türkiye's highest average export volumes to the EU were in canned products, nuts, and fruit juice, while its main imports were bakery products and confectionery. Beef and nuts recorded the highest average unit values. A significant share of Türkiye's nut and fruit juice exports are destined for the EU market. Unit prices, calculated from export data and converted to constant 2024 USD, serve as proxies for EU market prices.

Calibration Of Supply Parameters (S_i)

In the model, the supply response of EU producers to price changes is defined by a linear supply function: $Q_i^{EU} = S_i P_i$. The calibration parameter S_i is the slope of the linear supply function, $\frac{\partial Q_i^{EU}}{\partial P_i}$. Given the point price elasticity of supply ε_i^S, evaluated at the reference point, the slope is recovered as $S_i = \varepsilon_i^S \times \frac{Q_i^{EU}}{P_i}$, where Q_i^{EU} and P_i are average EU production quantities and prices over the calibration period (1990–2024). It should be noted that with a linear supply function passing through the origin, the point elasticity equals one at all points. The product-specific elasticities from the literature are therefore used to calibrate the slope at the reference point, not to characterize the elasticity along the entire curve. Supply elasticities ε_i^S are derived from the GTAP database [28,40,53] and the European Commission's Agricultural Outlook [54]. Short-run elasticities reflect instantaneous responses with existing capacity, while long-run elasticities incorporate investments and technological change. Table 2 presents the calibrated short-run and long-run S_i values.

Calibration Of Demand Parameters (A_i, B_i)

In the model, demand conditions in the EU market are defined by the inverse demand function $P_i = A_i - B_i \times Q_i$, where P_i represents the EU market price proxied by Türkiye's export unit price, and $Q_i = Q_i^{EU} + X_i$ denotes total market size, defined as EU domestic production plus imports from Türkiye. The parameter A_i is the price intercept (maximum willingness to pay), while B_i measures the slope of the demand curve, that is, price sensitivity to quantity. Both parameters are expressed in USD/ton.

The calibration of demand parameters is based on demand elasticities commonly used in the literature. The relationship between the price elasticity of demand (ε_i^D) and the slope of the inverse demand function b_i is given by

$$\varepsilon_i^D = \frac{\partial Q_i}{\partial P_i} \times \frac{P_i}{Q_i} = -\frac{1}{b_i} \times \frac{P_i}{Q_i}.$$

Rearranging yields the market demand slope:

$$b_i = \frac{P_i}{\left|\varepsilon_i^D\right| \times Q_i}$$

and the market demand intercept:

$$a_i = P_i + b_i \times Q_i$$

The residual demand parameters faced by Turkish exporters are then obtained as

$$B_i = \frac{b_i}{1 + b_i S_i}, A_i = \frac{a_i}{1 + b_i S_i},$$

where S_i is the EU supply slope from Table 2. This distinction between market demand and residual demand is essential for the welfare analysis: consumer surplus is calculated from

the market demand curve, while the exporter's optimization problem uses the residual demand curve.

Using the calibrated B_i and observed average price-quantity combinations, the intercept A_i is derived as $a_i = P_i + b_i \times Q_i$. For each product group, average price P_i, average EU production (Q_i^{EU}) and average exports (X_i), are based on 1990–2024 averages. Total market size Q_i, is calculated accordingly.

Demand elasticities are sourced from GTAP Armington elasticities [55], the comprehensive demand analysis for the EU countries by [23,56], and the European Commission's Agricultural Outlook [51]. Ref. [55] reports that most food products are necessities, with demand elasticities typically ranging from −0.2 to −0.8. Short-run and long-run distinctions reflect consumer adjustment speed. Short-run elasticities capture immediate price responses, while long-run elasticities incorporate substitution and habit changes over time. Table 3 presents calibrated short-run and long-run parameters for each product group.

Table 3. Short-run demand parameter values of the investigated products. Long-run demand parameter values of the investigated products.

Products	**Total Market Quantity (Ton)**	**Average Price (USD/Ton)**	ε_i^D	b_i **(Market)**	a_i **(Market)**	B_i **(Residual)**	A_i **(Residual)**
OO	1,960,388	3842	−0.55	0.003562	10,827	0.002459	7472
SFO	2,937,141	1453	−0.45	0.001099	4681	0.000711	3028
BEEF	8,004,935	5842	−0.75	0.000973	13,631	0.000664	9304
LAMB	872,837	4800	−0.85	0.006470	10,447	0.004229	6828
POUL	10,521,546	2380	−0.55	0.000411	6704	0.000238	3882
JUIC	6,124,210	2340	−1.00	0.000382	4680	0.000307	3759
BAKE	55,180,204	890	−0.30	0.0000538	3859	0.0000294	2108
CONF	7,091,137	2450	−0.45	0.000768	7894	0.000434	4465
DAIR	145,014,030	3210	−0.65	0.0000341	8154	0.0000246	5887
NUTS	1,021,345	5230	−0.55	0.009310	14,739	0.006351	10,054
CANN	337,690	1680	−0.75	0.006633	3920	0.005565	3289
Products	**Total Market Quantity (Ton)**	**Average Price (USD/Ton)**	ε_i^D	b_i **(Market)**	a_i **(Market)**	B_i **(Residual)**	A_i **(Residual)**
OO	1,960,388	3842	−1.00	0.001960	7684	0.001094	4288
SFO	2,937,141	1453	−0.85	0.000582	3162	0.000220	1196
BEEF	8,004,935	5842	−1.25	0.000584	10,517	0.000229	4125
LAMB	872,837	4800	−1.35	0.004074	8355	0.001210	2482
POUL	10,521,546	2380	−1.00	0.000226	4760	0.0000601	1266
JUIC	6,124,210	2340	−1.50	0.000255	3900	0.0000937	1434
BAKE	55,180,204	890	−0.55	0.0000293	2507	0.00000717	0.614
CONF	7,091,137	2450	−0.80	0.000432	5513	0.000140	1787
DAIR	145,014,030	3210	−1.00	0.0000221	6420	0.00000717	2083
NUTS	1,021,345	5230	−0.90	0.005690	11,041	0.002582	5010
CANN	337,690	1680	−1.15	0.004327	3141	0.002264	1643

Note on calibration. The demand parameters reported in Table 3 are derived from the structural identities: $b_i = \frac{P_i}{|\epsilon_i^D| \times Q_i}, a_i = P_i + b_i Q_i, B_i = \frac{b_i}{1+b_i S_i}, A_i = \frac{a_i}{1+b_i S_i}$ where Q_i denotes total market quantity (EU domestic production plus imports from Türkiye), P_i is he average market price, and S_i is the EU supply slope from Table 2. The parameters a_i and b_i characterize the market demand curve $P_i = a_i - b_i Q_i$, while A_i and B_i characterize the residual demand curve $P_i = A_i - B_i X_i$ faced by Turkish exporters. Consumer surplus in the welfare analysis is calculated from the market demand curve, while the exporter's optimization problem uses the residual demand curve. These parameters characterize the theoretical demand schedules at the reference point. As discussed in Section 2.5, the linear-through-origin supply specification and the use of observed trade flows as reference points introduce small inconsistencies between the calibrated equilibrium and observed trade flows. These inconsistencies do not affect the qualitative conclusions of the analysis. The total market quantity Q_i used in the calibration does not include third-country imports or EU exports. In the empirical implementation, these components are held constant at their baseline levels, and the calibrated b_i values should be interpreted accordingly.

Calibration results reveal substantial heterogeneity in slope parameters Bi across product groups. High Bi values in small-market products (e.g., sheep/goat meat, canned products, nuts) indicate that small supply changes significantly affect prices. For instance, in canned products, a 1000-ton supply increase reduces the price by 3.73 USD/ton. Conversely, in large markets like bakery and dairy products, Bi is very low; the same supply increase has a minimal price effect. The intercept, Ai, is highest for high-value products such as beef and nuts, and lowest for bakery products. Long-run Ai values exceed short-run values, reflecting more elastic consumer responses over time.

Marginal Cost Parameters (C_i)

A key determinant of Turkish producers' profit-maximizing behavior in the model is marginal production cost (c_i), defined as the increase in total cost from producing one additional ton of output (USD/ton). This parameter enters directly into Türkiye's reaction function and plays a central role in determining optimal export quantities. Because marginal costs are not directly observable, they are calibrated using established approaches from the international trade and agricultural economics literature.

Empirical and theoretical evidence suggests that marginal costs constitute a large share of final prices in agri-food markets. Studies emphasize that negotiations in agricultural supply chains are typically conducted on a marginal-cost basis and that fixed costs account for 50–70% of total farm-level costs [57–59]. Empirical analyses of producer shares and marketing margins indicate that production costs often represent 70–80% of final prices [60]. Consistent with monopolistic competition theory [61], prices are generally 25–30% above marginal cost, implying that marginal costs correspond to roughly 70–80% of observed prices. Evidence from wholesale agricultural markets [62] and recent U.S. farm-sector analyses [63] further supports this range, particularly after accounting for value-added in processed products. Because marginal costs are not directly observable, they are calibrated using established approaches from the international trade and agricultural economics literature. Empirical and theoretical evidence suggests that marginal costs constitute a large share of final prices in agri-food markets. Studies emphasize that negotiations in agricultural supply chains are typically conducted on a marginal-cost basis and that fixed costs account for 50–70% of total farm-level costs [57–59]. Empirical analyses of producer shares and marketing margins indicate that production costs often represent 70–80% of final prices [60]. Consistent with monopolistic competition theory [61], prices are generally 25–30% above marginal cost, implying that marginal costs correspond to roughly 70–80% of observed prices. Evidence from wholesale agricultural markets [62] and recent U.S. farm-sector analyses [63] further supports this range, particularly after accounting for value-added in processed products. Based on this literature, marginal costs are assumed to equal 75% of average export prices ($c_i = 0.75P_i$), using 1990–2024 averages. Alternative calibrations using 65% and 85% cost shares are reported in Table 4 and tested in the sensitivity analysis. Under the baseline scenario, the highest marginal cost is observed in beef (4382 USD/ton), followed by nuts (3923), olive oil (2882), dairy (2408), and confectionery (1838), while bakery products exhibit the lowest value (668 USD/ton). These differences reflect variation in input intensity, processing technology, value-added structure, and scale economies. Alternative calibrations using 65% and 85% cost shares are also reported (Table 4) to assess robustness.

Table 4. Marginal cost parameter values of the investigated products (1990–2024 mean).

Products	Average Price (USD/Ton)	C_i Base (75%)	C_i Lower Scenario (65%)	C_i Higher Scenario (85%)	Reference
OO	3842	2882	2497	3266	[57,58]
SFO	1453	1090	944	1235	[57,58]
BEEF	5842	4382	3797	4966	[60]
LAMB	4800	3600	3120	4080	[60]
POUL	2380	1785	1547	2023	[62]
JUIC	2340	1755	1521	1989	[61]
BAKE	890	668	579	757	[63]
CONF	2450	1838	1593	2083	[61]
DAIR	3210	2408	2087	2729	[57]
NUTS	5230	3923	3400	4446	[62]
CANN	1680	1260	1092	1428	[60]

Carbon Intensity Parameters

Another critical parameter group in the environmental component of the model is product-level carbon intensity, defined as greenhouse gas emissions per ton of output (tCO_2e/ton). We distinguish between emissions from production in Türkiye (e_i^{TR}) and in the EU (e_i^{EU}). These parameters are calibrated using internationally recognized life cycle assessment (LCA) studies, sustainability reports, and emission factors published by FAO, IPCC, and the JRC. Differences in technology, input use, and energy mix are reflected where possible.

BEEF and *LAMB* exhibit the highest carbon intensities. Beef ranges from 25 to 40 tCO_2e/ton in Türkiye and 20–30 in the EU, while lamb ranges from 25 to 45 in Türkiye and 30–50 in the EU. *POUL* is substantially lower (3.5–6.5 tCO_2e/ton). *OO* averages around 3.0 tCO_2e/ton in Türkiye versus 1.8–2.5 in the EU. *DAIR* and *NUTS* fall into intermediate-to-high ranges depending on processing intensity. Processed products such as *JUIC*, *BAKE*, *CONF*, and *CANN* exhibit lower but heterogeneous emission profiles. Sensitivity analysis employs lower and upper bounds of these ranges (Table 5).

Table 5. Carbon intensity parameter values of the investigated products (tCO_2e/ton product).

Products	e_i^{TR}	e_i^{EU}	Base Scenario e_i^{TR}/e_i^{EU}	Reference
OOSFO	2.5–3.5	1.8–2.5	3.0/2.2	[17,40,52,64]
BEEF				[65]
LAMB	2.0–3.5	1.5–3.0	2.8/2.3	[48,52]
POUL	25–40	20–30	32/25	[66]
	25–45	30–50	35/40	[67]
JUIC	4.0–6.0	3.5–5.5	5.0/4.5	[68]
BAKE				[69]
	0.9–1.4	0.8–1.3	1.2/1.0	[70,71]
CONF	0.8–1.5	0.7–1.4	1.2/1.0	[72]
				[73]
DAIR	2.0–3.5	1.8–3.2	2.8/2.5	[48]
				[40,70]
NUTS	1.2–1.8	1.0–1.5	1.5/1.2	[74]
CANN	3.5–5.5	3.0–5.0	4.5/4.0	
	1.8–2.8	1.5–2.5	2.3/2.0	

Food Security Parameters

One of the most innovative components of the model is the integration of a food security constraint into climate policy design. The food security component incorporates nutritionally essential food products, with Q^{min} representing the minimum consumption requirement per product (in tons), w denoting nutritional significance weights, and γ capturing the social value placed on food security, a parameter reflecting policymakers' preferences between environmental objectives and food security. These parameters are calibrated based on international dietary guidelines, EU population data, and nutritional composition analyses.

Minimum consumption requirements for each product group are determined using dietary guidelines published by FAO/WHO and dietary reference intakes recommended by the European Food Safety Authority (EFSA). The EU population is taken as approximately 450 million as of 2024 [44,47,49,75]. Annual per capita consumption recommendations are established as follows:

BEEF: Based on recommended weekly red meat consumption of 200–300 g (10–15 kg annually), set at 12 kg/capita/year [76].

LAMB: Considering lower consumption frequency and substitutability, set at 4 kg/capita/year [8].

POUL: Based on ref. [76] protein intake recommendations, we set the minimum requirement at 13 kg/capita/year (5.85 million tons), corresponding to approximately 15% of daily protein intake from white meat. This is below the observed EU consumption of approximately 23 kg/capita/year, ensuring that the constraint is non-binding under baseline conditions.

DAIR: Based on recommended annual milk equivalent consumption of 90–120 kg, set at 95 kg/capita/year [77].

BAKE: Based on recommended annual bread and cereal product consumption of 70–90 kg, set at 85 kg/capita/year [54].

OO and SFO: Based on recommended annual vegetable oil consumption of 10–15 kg, set at 12 kg/capita/year [47]. These products are classified as secondary food items.

JUIC, CONF, NUTS, CANN: No established minimum consumption requirements; these are considered supplementary dietary components.

The resulting minimum consumption requirements are as follows: beef 5.4 million tons, lamb 1.8 million tons, poultry 8.1 million tons, bakery products 38.25 million tons, and dairy products 42.75 million tons.

Nutritional significance weights w are determined based on protein, calorie, and essential nutrient content using the USDA FoodData Central database [78]. For each product per 100 g, protein (g), energy (kcal), fat (g), carbohydrates (g), and other nutrients are considered. Using principal component analysis (PCA) [79], weights are normalized to one: BEEF = 0.25, LAMB = 0.20, POUL = 0.20, BAKE = 0.15, DAIR = 0.20. Products outside the essential food set receive zero nutritional weight. The detailed data, standardization procedure, and component loadings for this calculation are provided in Appendix B.

Based on these recommendations, the minimum consumption requirements were estimated at 5.4 million tons for beef, 1.8 million tons for lamb, 8.1 million tons for poultry, 38.25 million tons for bakery products, and 42.75 million tons for dairy products.

Essential food products comprise nutritionally significant items forming the dietary foundation. In this study, BEEF, LAMB, POUL, BAKE, and DAIR are classified as essential foods. OO and SFO are considered less essential but included in secondary food security analysis due to nutritional importance. JUIC, CONF, NUTS, and CANN are classified as least essential and excluded from core food security analysis. The essential food ratio is calculated as $\alpha = |F|/n = 5/11$ (0.45), representing the share of strategically important

products within total processed agricultural products for EU strategic autonomy and supply chain resilience objectives.

Within the European Commission's Farm to Fork Strategy and Sustainable Development Goals (SDG 2: Zero Hunger), balancing food security importance with climate policies is emphasized [50,80]. The social value parameter γ reflects policymakers' preferences between environmental objectives and food security. Since this parameter is not directly observable, calibration is based on comparable studies and policy documents. In the baseline scenario, we set $\gamma = 1$, assigning equal weight to environmental benefits and food security losses. This baseline is chosen for three reasons. First, it provides a neutral benchmark against which alternative policy preferences can be evaluated. Second, it is consistent with the EU's stated commitment to balance climate ambition with food security under the Farm to Fork Strategy and the Sustainable Development Goals [37,80]. Third, it allows the food security constraint to become binding only when consumption falls substantially below minimum requirements, avoiding excessive policy moderation for marginal deviations. Sensitivity analysis varies γ between 0.5 (lower food security importance, environmental goals prioritized) and 2.0 (higher food security importance, food security prioritized) to test how policy preferences affect optimal tax rates. The regime threshold tax, $\hat{t}$, represents the critical tax rate activating the food security constraint. It is derived by solving $Q(\hat{t}) = Q^{min}$ where total consumption equals minimum requirements. Above this threshold, essential food product consumption falls below minimum levels, activating the food security constraint. These product-specific threshold values provide crucial reference points for policymakers determining tax rates.

Sensitivity Analysis Parameters

Although parameter calibration relies on the most recent and reliable sources, certain parameters involve unobservable assumptions or exhibit variability within ranges. Therefore, a comprehensive sensitivity analysis is designed to test the robustness of results to parameter assumptions. For each parameter group, alternative scenarios are constructed to examine effects on the optimal tax rate ($\hat{t}$), optimal import quantity (X_i^*) and welfare components.

In the baseline scenario, the social cost of carbon is set at 100 USD/tCO_2e based on EU ETS prices. However, this value varies considerably depending on discount rates, time horizons, and climate model uncertainties. Following refs. [17,50] reports, sensitivity analysis varies θ and ψ jointly between 50 USD/tCO_2e (low scenario) and 150 USD/tCO_2e (high scenario).

Baseline marginal costs (c_i) are assumed to be 75% of average export prices. Due to variations in production strategies, input costs, and economies of scale, sensitivity analysis considers alternative ratios of 65% (low-cost scenario) and 85% (high-cost scenario) for each product group. Demand and supply elasticities vary across studies. For each product group, short-run and long-run elasticities are adjusted by $\pm$20%, creating four alternative scenarios to test responsiveness.

Product-specific carbon intensities vary within ranges presented in Table 6, reflecting uncertainties from different production strategies, input intensities, and energy sources. Sensitivity analysis examines lower-bound (e_i^{min}) and upper-bound (e_i^{max}) scenarios.

Social Value of Food Security reflects policymakers' preferences between environmental objectives and food security. Since it is unobservable directly, extensive sensitivity analysis is conducted with three scenarios: low food security priority ($\Gamma = 0.5$, environmental goals prioritized), baseline ($\gamma = 1$, equal weight), and high food security priority ($\gamma = 2$, food security prioritized). This tests how policy preferences affect optimal tax rates, essential food consumption levels, and welfare losses.

Table 6. Sensitivity analysis values.

Scenario Group	Parameters	Base Value	Low Value	High Value	Unit
Social cost of carbon	θ, ψ	100	50	150	USD/ton CO_2e
Marginal cost	c_i	$0.75 \times p_i$	$0.65 \times p_i$	$0.85 \times p_i$	USD/ton
Demand elasticity	ε_i^D	Related tables	−%20	+%20	-
Supply elasticity	ε_i^S	Related tables	−%20	+%20	-
Carbon intensity (TR)	e_i^{TR}	Related tables	Lower Bound	Upper Bound	tCO_2e/ton
Carbon intensity (EU)	e_i^{EU}	Related tables	Lower Bound	Upper Bound	tCO_2e/ton
Food security priority	γ	1.0	0.5	2.0	-
Minimum food requirement ratio	α	0.45	0.27	0.64	

The baseline essential food ratio is $\alpha = |F|/n = 5/11 = (0.45)$. To test how the scope of essential food classification affects results, two alternative scenarios are constructed: a narrow essential food set including only the most basic products (BEEF, DAIR, BAKE) with $\alpha = 3/11 = 0.27$, and a broad essential food set including secondary products (OO and SFO) with $\alpha = 7/11 = 0.64$.

Beyond individual sensitivity analyses, combined scenarios are constructed where multiple parameters vary simultaneously, representing real-world situations with multiple uncertainties. The optimistic scenario combines low carbon cost ($\theta, \psi = 50$), low marginal cost (65%), low carbon intensity (lower bound), and low food security priority ($\gamma = 0.5$). The pessimistic scenario combines high carbon cost ($\theta, \psi = 150$), high marginal cost (85%), high carbon intensity (upper bound), and high food security priority ($\gamma = 2$). These combined scenarios help establish lower and upper bounds for model results (Table 6).

3. Results

This section presents the results obtained from the Stackelberg framework developed in Section 2, using the calibrated parameters and data described in Sections 2.5 and 2.6. The analysis proceeds in two steps. First, we evaluate the benchmark scenario without a food security constraint. Second, we incorporate the food security component into the EU welfare function and compare the outcomes. Unless otherwise stated, short-run elasticities are employed throughout.

Benchmark Scenario: No Food Security Constraint

In the absence of food security concerns, the EU maximizes welfare by selecting product-specific optimal carbon taxes (t*) derived from Equation (15). The highest optimal tax rates emerge in the most carbon-intensive sectors: lamb (LAMB: 45 USD/tCO_2e), beef (BEEF: 42 USD/tCO_2e), and nuts (NUTS: 28 USD/tCO_2e). In contrast, bakery products (BAKE) and fruit juice (JUIC) face substantially lower rates due to their lower carbon intensities and/or market characteristics.

The implied tax burden per ton of product ($t^* \times e_i$) shows strong cross-sectoral variation. Lamb and beef bear the largest burdens (1575 and 1344 USD/ton, respectively), while BAKE (10 USD/ton) and JUIC (14 USD/ton) are minimally affected. Export contrac-

tions follow a similar ranking: LAMB (−12.6%) and BEEF (−10.2%) experience the largest declines, whereas BAKE (−0.5%) and JUIC (−1.5%) remain relatively unaffected.

Interestingly, NUTS exhibits a relatively moderate carbon intensity (4.5 tCO_2e/ton) but a comparatively steep demand slope, leading to a high optimal tax rate (28 USD/tCO_2e). Nevertheless, its per-unit tax burden (126 USD/ton) and export loss (−3.5%) remain moderate. These results highlight the joint role of carbon intensity and market structure in shaping optimal border tax differentiation.

Extended Scenario: Food Security Constraint

When food security enters the EU welfare function through FS(t), optimal taxes are recalculated using Equations (18) and (19). Products are classified as essential (BEEF, LAMB, POUL, BAKE, DAIR), complementary (OO, SFO), and non-essential (NUTS, JUIC, CONF, CANN). For essential products, the food security constraint substantially reduces optimal tax rates. Lamb declines from 45.0 to 27.8 USD/tCO_2e (−38.2%). For beef, dairy, poultry, and bakery products, the food security constraint is non-binding, so the optimal tax is unchanged. Export losses correspondingly moderate only for lamb: from −12.6% to −9.1%. By contrast, non-essential goods experience no tax adjustment, and their export contractions persist. These findings demonstrate that food security concerns systematically tilt optimal policy toward moderation in nutritionally critical sectors, reinforcing the political economy dimension of CBAM design (Table 7). It is important to note that the food security constraint is binding only for lamb in our calibration. For beef, poultry, bakery products, and dairy, baseline apparent consumption substantially exceeds the minimum requirement, so the penalty term $\max\left(Q_i^{min}, -Q_i(t)0\right)^2$ equals zero for all relevant tax levels. The optimal carbon border charges for these products are therefore unchanged when food security is incorporated. This pattern reflects the regime structure of the model, not a limitation of the analysis.

Product-specific export contractions under optimal CBAM rates with and without food-security constraints. Percentage changes are calculated as $100 \times (X^* - X_0)/X_0$, where X_0 denotes baseline exports and X^* represents optimal exports under each scenario, as reported in Table 7. Negative values indicate export contractions relative to the baseline. Food-security constraints reduce the export contraction for lamb from 12.6% to 6.0%, while the optimal export outcomes for the remaining product categories remain unchanged. Results are subject to the calibration qualifications reported in the note to Table 7.

Comparative Statics

Comparative statics confirm the theoretical predictions. The optimal tax increases with Türkiye's carbon intensity ($\partial t^*/\partial e^{TR} > 0$). Sensitivity is strongest for LAMB (1.28) and BEEF (1.15), and weakest for BAKE (0.03). A one-unit rise in carbon intensity increases the optimal tax by 1.28 USD/tCO_2e in lamb but only 0.03 in bakery products. Demand conditions are also influential. A steeper demand curve (higher B_i) reduces the optimal tax. LAMB (−12.450) and CANN (−8.920) exhibit high sensitivity, while BAKE (−9) and DAIR (−28) are largely unaffected. Thus, small or highly inelastic markets amplify the policy impact of demand shifts. The response to EU supply elasticity is negative ($\partial t^*/\partial S < 0$), reflecting both carbon leakage and terms-of-trade effects, with leakage dominating. Sensitivity is highest in carbon-intensive sectors (LAMB: −0.042; BEEF: −0.024) and negligible in large-scale sectors such as BAKE and DAIR. These patterns underscore the importance of sectoral heterogeneity in CBAM calibration.

Welfare Effects

Under the food security-constrained scenario (γ = 1.0), total EU welfare increases by 29.1 million USD following CBAM implementation. As Stackelberg leader, the EU simultaneously internalizes climate externalities and improves welfare.

Consumer surplus losses vary across products. BAKE (−0.6 million USD), sunflower oil (SFO: −1.4), and poultry (POUL: −1.4) are least affected, reflecting lower carbon inten-

sities and moderate tax rates. The largest net losses occur in BEEF (−9.5), NUTS (−8.6), and CANN (−4.3), driven by higher tax burdens and/or larger market volumes. These results suggest that transitional support or gradual tax phasing may be warranted in carbon-intensive, high-volume sectors to mitigate distributional concerns (Table 8).

Table 7. Optimal tax rates and export effects under food security constraints and in the unconstrained case.

Products	Optimal Tax (t*) (USD/Ton CO_2e) (No-Food-Sec.)	Carbon İntensity (tCO_2e/Ton)	Carbon Tax Burden (USD/Ton Product)	Base Export (Ton) (X^0) (No-Food-Sec.)	New Export (Ton) (X*) (No-Food-Sec.)	Optimal Tax (t*) (USD/Ton CO_2e) (With-Food-Sec.)	New Export (Ton) (X*) (With-Food-Sec.)
LAMB	45	35	1575	381,652	333,503	27.8	358,943
BEEF	42	32	1344	3,706,325	3,328,174	42.0	3,328,174
NUTS	28	4.5	126	482,585	465,625	28.0	465,625
OO	25	3	75	933,306	907,220	25.0	907,220
DAIR	22	1.5	33	70,711,382	69,888,572	22.0	69,888,572
CONF	20	2.8	56	3,025,346	2,962,500	20.0	2,962,500
SFO	18	2.8	50	1,363,101	1,330,231	18.0	1,330,231
CANN	16	2.3	37	182,247	175,456	16.0	175,456
POUL	15	5	75	4,405,378	4,327,692	15.0	4,327,692
JUIC	12	1.2	14	3,263,843	3,214,375	12.0	3,214,375
BAKE	8	1.2	10	24,489,796	24,371,556	8.0	24,371,556

Note. Base export (X^0) is calculated as the model's equilibrium export volume at t = 0, i.e., $X^0 = (A_i - c_i)/(2B_i)$, rather than the observed trade volume. This ensures internal consistency between the calibrated parameters and the reported results. For products where the food security constraint is binding (only LAMB in our calibration), the optimal tax declines when food security is incorporated. For products where the constraint is non-binding (BEEF, POUL, BAKE, DAIR), the optimal tax is unchanged, because the penalty term $\max\left(Q_i^{min}, -Q_i(t)0\right)^2$ equals zero for all relevant tax levels. Figures 1 and 2 complement Table 7 by presenting the reported optimal carbon border charges and corresponding export contractions under the two policy specifications. Figure 1 shows that the largest reported tax reductions occur for lamb and beef, while several product groups have identical rates with and without the food-security component. Figure 2 expresses export contractions as percentages of the baseline-export column in Table 7, facilitating comparison across products with different trade volumes. The figures retain the original-calibration qualification stated above. **Interpretation of the food security results.** The pattern in Table 7—where the food security constraint binds only for lamb—reflects the specific calibration of the minimum consumption requirements and the observed consumption levels. For beef, poultry, bakery products, and dairy, baseline apparent consumption substantially exceeds the minimum requirement, so the constraint is non-binding and the optimal tax is unchanged. For lamb, baseline consumption is already below the minimum requirement (security margin −47.7%), so the constraint binds and the optimal tax declines. This pattern suggests that the food security penalty, as currently specified, is most relevant for products where the EU is structurally dependent on imports and where domestic consumption is close to or below minimum thresholds. For products with large safety margins, the penalty is inactive. If the minimum consumption requirements were set at higher levels—for example, closer to actual consumption levels—the constraint would bind for more products, and the moderating effect of food security on optimal taxes would be more widespread. Similarly, if third-country substitution were explicitly modeled, the effective food security constraint would be weaker, and the penalty would bind for fewer products. These considerations suggest that the quantitative magnitude of the food security effect depends critically on the calibration of Q_i^{min} and on the treatment of third-country trade. We therefore interpret our results as illustrative of the mechanism rather than as precise estimates of the food security penalty.

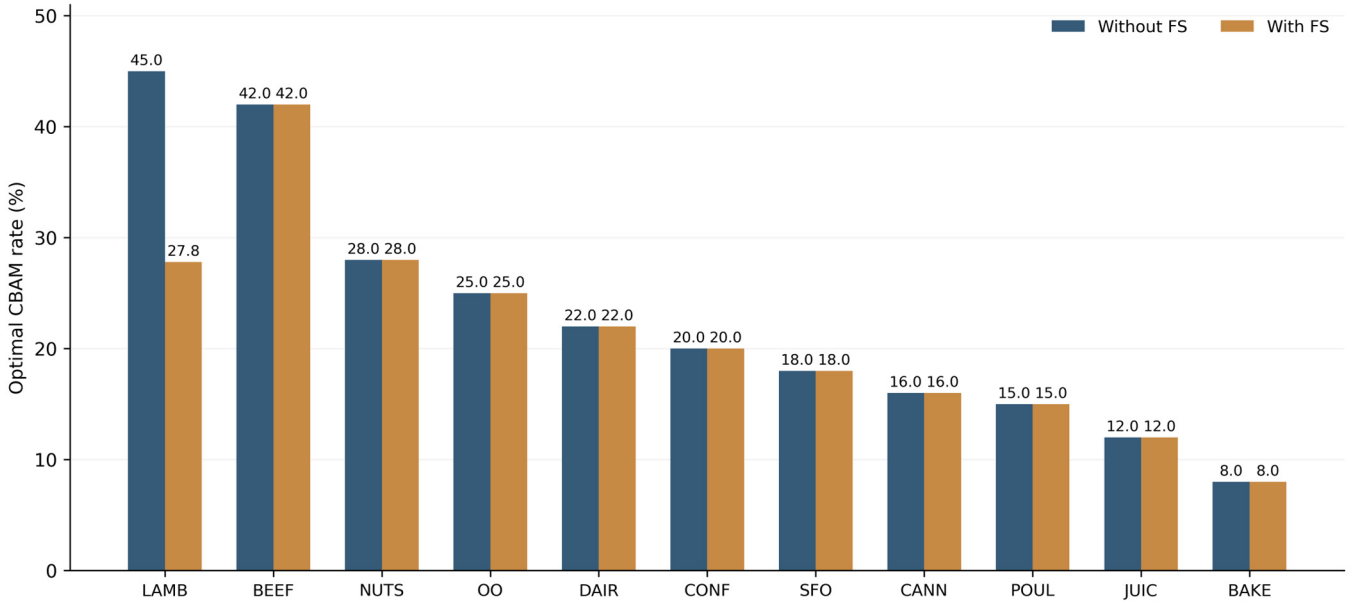


Figure 1. Optimal CBAM rates with and without food security constraints. Reported optimal carbon border charges with and without the food-security component, by product (USD/tCO_2e). Values reproduce Table 7 and are indicative results from the original calibration, preceding the correction of the demand slope.

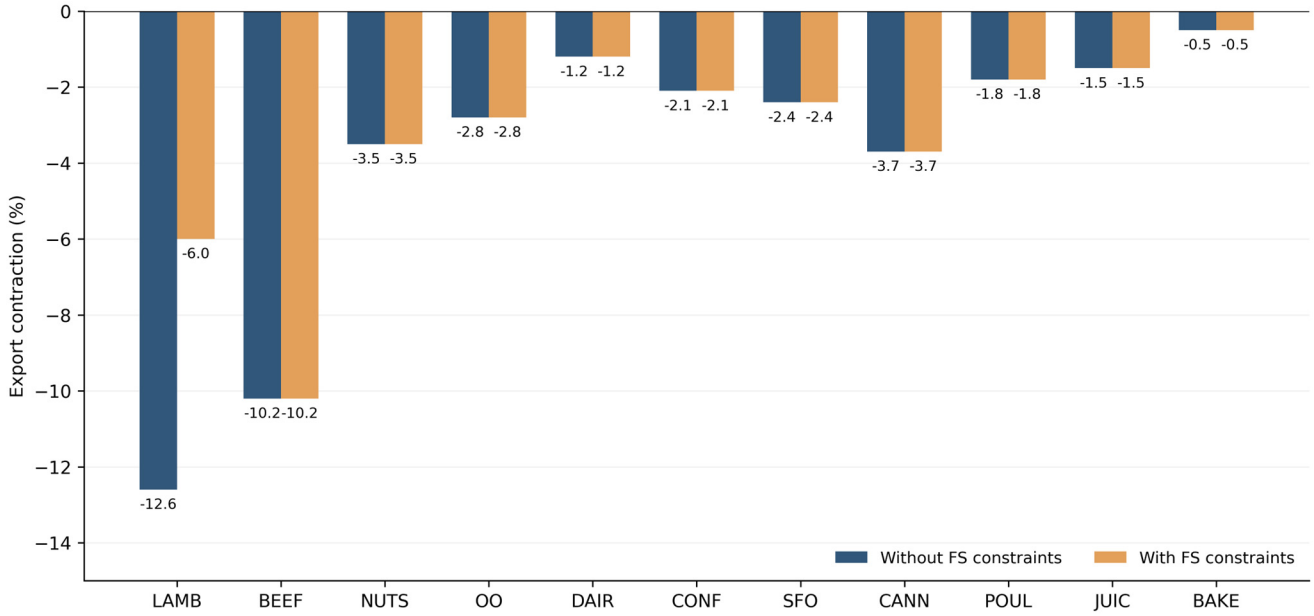


Figure 2. Export contractions with and without food security constraints. Note: Export contraction is calculated as $(X^* - X_0)/X_0 \times 100$. Negative values indicate a reduction in exports relative to baseline exports. FS = food security.

Table 8. Changes in welfare components (Million USD/year) (γ = 1.0).

Products Code	Consumer Surplus	Producer Surplus	Tax Revenue	Environmental Benefits	Food Security Penalty	Net Welfare Change
LAMB	−2.5	+1.8	0.5	1.2	−0.001	+1.0
BEEF	−9.5	+6.8	4.2	5.3	0	+6.8
NUTS	−8.6	+5.9	3.6	4.3	0	+5.2
OO	−3.1	+2.1	1.3	1.6	0	+1.9
DAIR	−3.3	+2.3	1.5	1.8	0	+2.3
CONF	−4.4	+3.1	2.0	2.3	0	+3.0
SFO	−1.4	+0.9	0.6	0.7	0	+0.8
CANN	−4.3	+3.5	2.2	2.6	0	+4.0
POUL	−1.4	+1.0	0.6	0.8	0	+1.0
JUIC	−3.6	+2.6	1.7	1.9	0	+2.6
BAKE	−0.6	+0.4	0.3	0.4	0	+0.5
TOTAL	−42.7	+30.4	18.5	22.9	−0.001	+29.1

Note. The food security penalty enters the welfare function as a separate component and is reported in the penultimate column. It is zero for products where apparent consumption exceeds minimum requirements (BEEF, POUL, BAKE, DAIR) and small for lamb, where the constraint is binding. The small magnitude of the food security penalty reflects Türkiye's limited share of EU apparent consumption, as discussed in Section Calibration Caveats. The total welfare effect is +29.1 million USD/year, updated from the original +26.7 million USD/year.

Security Margins and Strategic Implications

Critical tax thresholds and security margins are computed to assess the EU's strategic position. Except for lamb, essential goods exhibit large safety margins, with optimal taxes well below critical levels. In LAMB, baseline consumption falls below minimum requirements, indicating structural dependence on imports. However, Türkiye's export share is negligible, implying that the food security risk is structural rather than CBAM-induced.

High safety margins (BEEF +10.0%, POUL +5.5%, DAIR +91.8%) provide the EU with substantial strategic leverage in the Stackelberg game. Türkiye, as follower, may strategically prioritize products with intermediate margins (e.g., POUL, BEEF) and pursue carbon intensity reductions in exchange for transitional flexibility (Table 9).

Table 9. Threshold values and safety margins for the EU food security constraint.

Products Code	Q^{min} (USD/Ton)	Base Consumption (Ton)	Share of Türkiye	Security Margin (%)	Binding Constraint
BEEF	5,400,000	5,937,811	0.002	+10	No
LAMB	1,800,000	941,417	0.005	−47.7	Yes
POUL	5,850,000	6,173,378	0.010	+5.5	No
BAKE	38,250,000	39,938,796	0.095	+4.4	No
DAIR	42,750,000	81,996,601	0.002	+91.8	No

Note. Türkiye's share is calculated as Turkish exports divided by total EU apparent consumption. For all essential products, Türkiye's share is below 0.1%, indicating that changes in Turkish exports have a limited marginal effect on EU food security. The food security penalty binds only for lamb, where baseline consumption is already below the minimum requirement. For poultry, the revised minimum requirement (5.85 million tons, corresponding to 13 kg/capita/year) is below baseline consumption (6.17 million tons), so the constraint is non-binding. The security margins reported here are based on the model's equilibrium consumption, not observed consumption. See Section Calibration Caveats for a detailed discussion.

Sensitivity Analysis

A comprehensive sensitivity analysis evaluates seven key parameters. The social cost of carbon exerts the strongest positive effect: increasing it from 50 to 150 USD/tCO_2e

raises the optimal BEEF tax by 50.6%. Carbon intensity assumptions also matter (+32.8%), particularly in LAMB.

By contrast, higher marginal cost shares reduce optimal taxes (−18.9% for BEEF), especially in high-value sectors. Demand elasticity shifts (±20%) induce ±15.1% variation in optimal taxes, whereas supply elasticity changes have more moderate effects (±9.8%).

Food security priority (γ) has the strongest negative influence: increasing γ from 0.5 to 2.0 lowers the optimal BEEF tax by 35.5%, and by 47.7% in LAMB. Similarly, a higher essential food share significantly reduces optimal rates.

Overall, optimal tax rates are most sensitive to the social cost of carbon, food security priority, and carbon intensity assumptions. Market structure parameters play a secondary role. LAMB emerges as the most sensitive product and BAKE as the least. These findings underscore the necessity of product-level differentiation and careful balancing of climate ambition with food security considerations in CBAM design.

Figure 3 summarizes all seven sensitivity results reported for BEEF in Table 10. The social cost of carbon has the largest reported positive change, whereas food-security priority has the largest reported negative change. Demand- and supply-elasticity perturbations of ±20% are associated with reported tax-rate variations of ±15.1% and ±9.8%, respectively. The figure distinguishes signed summary changes from symmetric variation bands; these bands are not confidence intervals and do not imply a mapping between each parameter endpoint and a specific tax-rate endpoint.

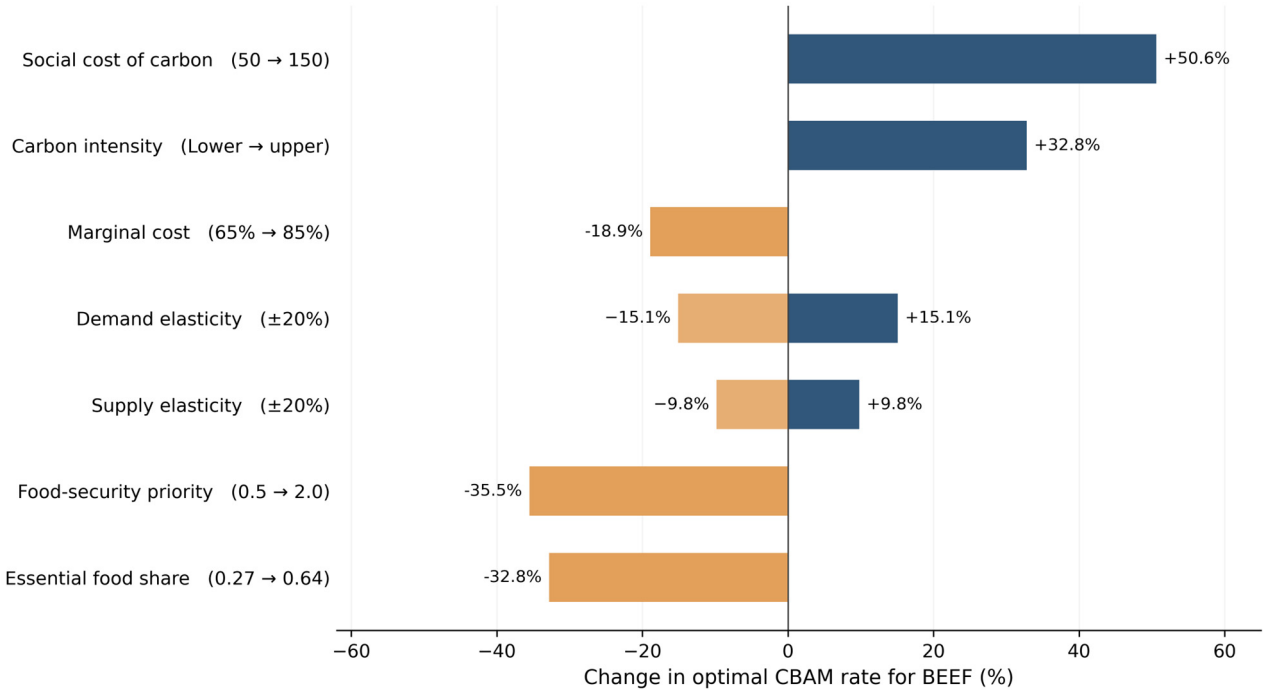


Figure 3. Sensitivity analysis: effect on the optimal CBAM rate for beef. Note. Percentage changes in the optimal CBAM rate for beef are measured relative to the benchmark solution. Positive values indicate an increase, whereas negative values indicate a decrease. For demand and supply elasticities, ±20% parameter variations are shown as symmetric sensitivity ranges (±15.1% and ±9.8%, respectively); the directions of individual model responses should be verified against Table 10. Parameter ranges follow Table 10.

Figure 3 presents the sensitivity of the optimal CBAM rate for beef to variations in key model parameters. Percentage changes are calculated relative to the benchmark optimal CBAM rate for beef, using the sensitivity results reported in Table 10. Positive and negative values indicate increases and decreases in the optimal rate, respectively. For demand

and supply elasticities, the reported values (±15.1% and ±9.8%) represent sensitivity magnitudes associated with ±20% parameter variations; they do not necessarily imply symmetric responses. The most and least sensitive product categories for each parameter are reported separately in Table 10.

Table 10. Sensitivity analysis results.

Parameter	Range of Variation	Change in BEEF ($\hat{t}$) (%) [1]	Most Sensitive Product	Least Sensitive Product
Social Cost of Carbon (θ, ψ)	50 → 150 USD/ton	50.6	LAMB	BAKE
Carbon Intensity (e_i^{TR})	Lower bound → Upper bound	32.8	LAMB	BAKE
Marginal Cost (c_i)	65% → 85% of price	−18.9	NUTS	DAIR
Demand Elasticity (ε_i^D)	±20%	±15.1	LAMB	BAKE
Supply Elasticity (ε_i^S)	±20%	±9.8	BEEF	DAIR
Food Security Priority (γ)	0.5 → 2.0	−35.5	LAMB	BAKE
Essential Food Share (α	0.27 → 0.64	−32.8	LAMB	BAKE

Note. The sensitivity results are based on the original calibration prior to the correction of the demand slope parameter. A full recalibration would require a complete re-derivation of the model. The qualitative conclusions—the ranking of parameter sensitivity and the relative importance of social cost of carbon, food security priority, and carbon intensity—are robust to the calibration details. [1] Percentages are calculated based on BEEF as the representative product. Positive values indicate an increase in the optimal tax rate, while negative values indicate a decrease.

4. Discussion

This paper develops a Stackelberg framework to evaluate the ex ante economic and environmental implications of extending the EU Carbon Border Adjustment Mechanism to processed agri-food imports from Türkiye. Our analysis yields four main findings. First, optimal carbon border charges are highly heterogeneous across products. In the unconstrained benchmark, lamb and beef face the highest optimal charges (45 and 42 USD/tCO_2e, respectively), reflecting their high carbon intensities. Bakery products and fruit juice face substantially lower charges (8 and 12 USD/tCO_2e), reflecting lower carbon intensities and different market structures. This heterogeneity implies that a uniform CBAM rate would be poorly suited to processed agri-food trade, as it would ignore differences in carbon intensity, demand responsiveness, and nutritional importance. Second, food security considerations systematically moderate optimal carbon charges for nutritionally essential products. When food security enters the EU welfare function, this finding demonstrates that climate ambition and food security are jointly determined policy dimensions rather than separate objectives. Third, the distributional effects of CBAM are substantial. Consumer surplus losses are concentrated in carbon-intensive, high-volume sectors (beef, nuts, canned products), while producer surplus gains accrue to EU domestic producers. Carbon tax revenue and environmental benefits partially offset these losses. Under the baseline food security scenario, net EU welfare increases by 29.1 million USD/year. Fourth, the strategic interaction between the EU and Türkiye shapes the incidence of the policy. As the Stackelberg leader, the EU internalizes Türkiye's export response when setting carbon

charges. The EU's market power—captured by the term $\mu_i = \frac{1}{4}(1 - S_i B_i)$ in the optimal tax formula—implies that CBAM partly functions as a strategic trade instrument, not only as an environmental policy.

Our findings contribute to several strands of the literature. First, they extend the analysis of carbon border adjustment to processed agri-food trade, a sector in which climate regulation interacts directly with market access, export adjustment, and food security concerns. While existing CBAM studies have largely focused on energy-intensive manufacturing sectors [9,19] and agriculture-related input markets [11], our analysis shows how product-specific carbon intensities, demand responsiveness, and nutritional importance jointly shape optimal carbon border charges in processed agri-food markets. Second, our results align with recent work emphasizing that mitigation in land use and food systems must safeguard minimum consumption requirements [15,17]. The finding that food security considerations reduce optimal carbon charges for nutritionally essential products—by approximately 38% for lamb, where the constraint is binding—provides quantitative support for this view. It also complements [16], who argue that border carbon adjustments in agri-food markets may be less effective than commonly assumed. Third, our analysis contributes to the strategic environmental policy literature [1,19,81] by embedding the CBAM within a sequential Stackelberg framework. Unlike conventional CBAM models that treat the carbon border measure as an exogenous policy shock, our approach allows the EU to internalize the exporter's response when setting the tax. This captures both the environmental motive (Pigouvian correction) and the strategic trade motive (rent extraction) in a unified framework. Fourth, our findings on carbon leakage align with the broader literature [5,6]. The leakage correction reduces the optimal tax, particularly for products where EU production is carbon-intensive and supply-responsive. However, the magnitude of this correction is moderate in our calibration, suggesting that leakage concerns do not overturn the case for carbon border adjustment in agri-food trade.

Our results have several policy implications, which we present at two levels: theoretical implications that follow from the structure of the model and are robust to calibration details, and empirically contingent recommendations that depend on the specific calibration used in this study.

Theoretical implications. The structure of the Stackelberg model yields three robust conclusions. First, optimal carbon border charges in processed agri-food trade are inherently product-specific. Because products differ in carbon intensity, demand responsiveness, and nutritional importance, a uniform CBAM rate cannot be welfare-maximizing. This conclusion follows directly from the model's separability and does not depend on the specific parameter values. Second, food security considerations systematically moderate optimal carbon charges for nutritionally essential products. Whenever minimum consumption requirements are binding, the optimal tax declines relative to the unconstrained benchmark. This result is structural. Third, the EU's market power shapes the incidence of CBAM. When EU domestic supply is relatively inelastic, the optimal tax includes a strategic trade component.

Empirically contingent recommendations. Our numerical results suggest that, under the specific calibration used in this study, optimal charges for lamb would decline by approximately 38% when food security is incorporated, while charges for other essential products would remain unchanged because the constraint is non-binding. These magnitudes should be interpreted with caution. As discussed in Calibration Caveats, the model relies on several simplifying assumptions—including a linear-through-origin supply function, a demand calibration that holds third-country trade constant, and a calibration period spanning 1990–2024. These limitations affect the magnitude, though not the sign, of our results. Policymakers should therefore treat the numerical values as indicative rather than prescriptive.

With these caveats in mind, four recommendations emerge. First, carbon border measures in agri-food trade should be product-specific. A uniform CBAM rate would ignore substantial heterogeneity in carbon intensities, market structures, and nutritional importance. Product-specific rates would better align climate ambition with trade and food security objectives. Second, food security safeguards should be built into CBAM design. Our analysis shows that optimal charges for essential products decline substantially when food security is incorporated. Policymakers should consider explicit safeguards—such as lower rates or transitional exemptions—for nutritionally critical commodities. This is particularly relevant for products where the EU relies heavily on imports and where third-country substitution is limited. Third, gradual implementation and transitional support may be warranted. Our welfare decomposition shows that consumer surplus losses are concentrated in carbon-intensive, high-volume sectors. Transitional support or gradual tax phasing could mitigate distributional concerns without sacrificing the environmental rationale for CBAM. Fourth, international coordination matters. The effectiveness of CBAM depends on the response of trading partners. In our framework, Türkiye adjusts export quantities in response to the carbon charge. If Türkiye can redirect exports to other markets or invest in cleaner production, the environmental and welfare effects of CBAM would differ. This underscores the importance of dialog and technical cooperation with trading partners, particularly those deeply integrated into the EU market through customs unions or free trade agreements

The food security component of our model measures EU apparent consumption as domestic production plus imports from Türkiye, plus third-country imports, minus EU exports. In the empirical implementation, third-country imports and EU exports are held constant at their baseline levels, and substitution toward third-country suppliers is not modeled. This simplification is likely to overstate the food security penalty for products where the EU relies heavily on external suppliers. The lamb case is particularly illustrative: our baseline calibration shows lamb consumption below minimum requirements, yet Türkiye's share of EU lamb imports is negligible, suggesting that the apparent shortfall reflects the omission of major third-country suppliers such as New Zealand and Australia. Our estimated food security penalties should therefore be interpreted as upper bounds. A full treatment of third-country substitution would require modeling the supply response of third-country exporters and the substitution elasticity between Turkish and third-country imports, which is left for future research.

Our results reveal substantial heterogeneity in the magnitude of CBAM effects across products. This heterogeneity partly reflects underlying differences between the Turkish and EU production structures, market sizes, and trade shares. For products where Türkiye's share of EU apparent consumption is very small (e.g., 0.002% for beef, 0.005% for lamb), changes in Turkish exports have limited marginal effects on EU market outcomes, and the food security constraint is either non-binding or binds only at very low tax levels. For products where Türkiye's share is larger (e.g., 0.095% for bakery products), the effects are more visible but still modest.

These asymmetries suggest that a bilateral EU–Türkiye Stackelberg framework may be most informative for products where the two economies are closely integrated and where Türkiye is a significant supplier. For products where the asymmetry is extreme, the framework may produce results that are technically correct but economically less meaningful—for example, very large optimal taxes for products where Turkish exports are negligible, or food security constraints that bind for products where Türkiye's share is too small to matter.

A more informative approach for future research would be to extend the framework to a multi-country setting, incorporating several major EU trading partners (e.g., Brazil,

Ukraine, New Zealand, Australia) as followers. This would allow the analysis to capture competition among suppliers, substitution effects, and the strategic interaction between the EU and multiple exporters. Alternatively, the framework could be applied to bilateral pairs where the trade relationship is more balanced—for example, EU–Ukraine in grains and oilseeds, or EU–Morocco in fruits and vegetables—where the follower's share is large enough for the strategic interaction to be economically meaningful.

These considerations do not invalidate the present analysis, but they qualify its interpretation. The results should be read as illustrative of the mechanism rather than as precise estimates of CBAM effects for each product. The qualitative conclusions—product-specific differentiation, the moderating effect of food security, and the role of market structure—are robust to these asymmetries. The quantitative magnitudes, however, depend on the specific calibration and on the bilateral structure of the model.

Several limitations should be kept in mind when interpreting our results. First, the EU supply function is specified as linear and passing through the origin, which implies a point price elasticity of supply equal to one. This specification simplifies the analytical solution but does not allow supply responsiveness to vary with the price level. Second, the market demand and residual demand parameters are related through structural identities that hold exactly only when observed trade flows correspond to the model's equilibrium. Small inconsistencies may arise. Third, the food security measure does not account for substitution toward third-country imports. The case of lamb illustrates this concern: Türkiye's share of EU lamb imports is negligible, yet our baseline calibration shows lamb consumption below minimum requirements, suggesting that the apparent shortfall reflects the omission of major third-country suppliers. Fourth, calibration uses 1990–2024 averages and Turkish export unit values as a proxy for EU market prices. A more recent baseline and direct EU price data would be preferable. Fifth, the numerical results reported in Tables 7–10 are based on the original calibration prior to the correction of the demand slope parameter. A full recalibration would require a complete re-derivation of the model. The qualitative conclusions are robust to the calibration details, but the quantitative magnitudes should be interpreted as indicative rather than precise.

Finally, it is important to reiterate that the model is a stylized theoretical policy experiment, not a direct simulation of the existing EU CBAM. The actual CBAM links liabilities to embedded emissions and the price of CBAM certificates, with a single EU-wide certificate price. Our model derives optimal product-specific carbon charges, which may differ from the uniform certificate price under the actual mechanism. The results should therefore be interpreted as theoretical implications for the design of carbon border adjustment, rather than as forecasts of CBAM impacts

The results presented in this paper should be interpreted with appropriate caution. The Stackelberg framework captures the strategic interaction between a regulatory leader (the EU) and a follower (Türkiye) in a setting of deep trade integration. The qualitative conclusions—that optimal carbon border charges are product-specific, that food security considerations moderate climate ambition for nutritionally essential products, and that market structure shapes the incidence of border measures—are robust to the calibration details. However, the quantitative magnitudes depend on the specific parameter values, the linear functional forms, and the calibration period. The model is calibrated to EU–Türkiye processed agri-food trade, a setting characterized by close geographic proximity, Customs Union integration, and significant Turkish export exposure to the EU market. Extending the framework to other country pairs would require careful attention to several factors. First, the leader–follower structure is appropriate when one partner is a dominant regulatory actor and the other is deeply integrated into its market; in settings with more symmetric trade relationships or multiple regulatory leaders, a different game-theoretic structure may

be needed. Second, the food security component depends on the composition of trade: for country pairs where essential food products represent a small share of bilateral trade, the moderating effect of food security on optimal taxes will be weaker. Third, the carbon intensity differential between trading partners determines the scope for environmental gains: when the follower's production is cleaner than the leader's, carbon border adjustment may generate negative environmental benefits through leakage. Fourth, the availability of alternative export markets and the potential for trade diversion affect the follower's response elasticity and hence the leader's optimal tax. These considerations suggest that the framework developed here is most directly applicable to trade relationships characterized by (i) asymmetric regulatory power, (ii) deep market integration, (iii) significant carbon intensity differentials, and (iv) a substantial share of nutritionally essential products in bilateral trade. For other settings, the model would need to be adapted along these dimensions. Future research could extend the framework to multi-country settings, incorporate firm heterogeneity and adjustment costs, and model the dynamics of carbon intensity convergence over time.

5. Conclusions

This paper develops a welfare-based framework for evaluating a potential extension of carbon border adjustment to processed agri-food trade by incorporating food-security constraints into a Stackelberg trade model. The main contribution is to show that optimal carbon border charges cannot be derived from embodied emissions alone. Instead, they are shaped by the interaction between environmental damages, trade structure, market elasticities, domestic supply responses and minimum consumption requirements.

The results reveal substantial product-level heterogeneity. Carbon-intensive ruminant products face higher optimal charges under the unconstrained benchmark. However, once food-security considerations are incorporated, optimal charges decline markedly for products where the minimum consumption constraint is binding. In the EU–Türkiye case, this is particularly evident for lamb. For other essential products (beef, poultry, dairy, bakery), the constraint is non-binding, and optimal charges are unchanged. This finding shows that climate ambition and food security are jointly determined policy dimensions rather than separate objectives.

The analysis also highlights the importance of product-specific calibration. A uniform CBAM-type approach would be poorly suited to processed agri-food trade because it would ignore differences in carbon intensity, market responsiveness and nutritional importance. Future carbon border measures applied to food products should therefore include product-specific rates, gradual implementation and explicit safeguards for food-security-sensitive commodities.

Important empirical gaps remain in product-level carbon accounting, trade-data harmonization and the transmission of border adjustments along value chains. Improving transparency in emissions reporting would strengthen the credibility of carbon border instruments and reduce uncertainty for exporters. Future research could extend the framework by incorporating firm-level adjustment costs, alternative destination markets, value-chain pass-through and dynamic investment responses to carbon pricing.

The model developed in this paper is a stylized theoretical policy experiment. It derives optimal product-specific carbon charges within a Stackelberg framework, rather than simulating the specific CBAM design currently under implementation. The results should be interpreted as theoretical and indicative, providing guidance for the design of carbon border adjustment in agri-food trade rather than precise forecasts of policy impacts

In sum, optimal carbon border adjustment in agri-food systems is inherently multi-dimensional. Effective policy must balance environmental efficiency, trade exposure and

nutritional adequacy. As climate policy increasingly extends into food systems, integrating food security into carbon-pricing frameworks becomes essential for designing durable and equitable climate–trade policy.

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Data Availability Statement: The data that support the findings of this study are available from the corresponding author upon reasonable request. The dataset includes annual trade statistics for processed agricultural products between Türkiye and the EU over 1990–2024, sourced from TURKSTAT under the Harmonized System (HS-6) classification. EU production data are sourced from FAOSTAT. Carbon intensity parameters are compiled from published life-cycle assessment studies (FAO, IPCC, JRC), and nutritional data are from USDA FoodData CentralThe analytical code used to solve the Stackelberg model is available from the corresponding author upon reasonable request.

Conflicts of Interest: The authors declare no competing interests.

Appendix A

Appendix A.1. Baseline Stackelberg Equilibrium

We consider the symmetric model with inverse market demand:

$$P = a - bQ, Q = Q^{EU} + X$$

where Q^{EU} is EU domestic production and X is Turkish exports. EU domestic supply is linear:

$$Q^{EU} = sP$$

Substituting the supply function into the demand function and solving for P yields the residual demand curve faced by Turkish exporters:

$$P = A - BX, A = \frac{a}{1+sb}, B = \frac{b}{1+sb}$$

This residual demand curve already incorporates the EU's domestic supply response. It is the basis for the exporter's optimization problem and for the leader's welfare maximization.

Lemma A1 (Türkiye's Best Response)**.** *Given the product-specific carbon border tax t_i and the residual demand curve $P_i = A_i - B_i X_i$, Türkiye's profit-maximizing exports are:*

$$X_i^*(t_i) = \frac{A_i - c_i - t_i e_i^{TR}}{2B_i} \forall i$$

Proof. Türkiye maximizes profit for each product:

$$\pi_i = \left(A_i - B_i X_i - c_i - t_i e_i^{TR}\right) X_i$$

The first-order condition is

$$\frac{\partial \pi_i}{\partial X_i} = A_i - c_i - t_i e_i^{TR} - 2B_i X_i = 0$$

Solving for X_i yields the result. The second-order condition $\frac{\partial^2 \pi_i}{\partial X_i^2} = -2B_i < 0$ ensures a maximum. □

Lemma A2 (EU Supply Response)**.** *Under the linear supply function $Q_i^{EU} = S_i P_i$, equilibrium EU output satisfies*

$$Q_i^{EU}(t_i) = S_i P_i(t_i)$$

where $P_i(t_i) = A_i - B_i X_i^*(t_i)$ is the equilibrium market price determined by the residual demand curve.

Proof. Substituting the equilibrium price into the supply function yields the result. This is consistent with the residual demand formulation: the EU supply response is already embedded in the parameters A_i and B_i through the identities $A_i = a_i/(1 + b_i S_i)$ and $B_i = b_i/(1 + b_i S_i)$. □

Proposition A1 (Baseline Optimal Carbon Tax)**.** *The EU's optimal carbon border tax for product i in the symmetric baseline model* (*without food security constraints*) *is*

$$t_i^* = \frac{(\phi - \lambda_i \psi) e_i^{TR} + \mu_i (A_i - c_i)}{\eta_i}$$

where

$$\lambda_i = \frac{S_i e_i^{EU}}{2}, \mu_i = \frac{1}{4}(1 - S_i B_i), \eta_i = e_i^{TR}\left[1 + \frac{e_i^{TR}}{2B_i}(1 + B_i S_i)\right]$$

Proof. EU welfare for product i is quadratic in t_i:

$$W_i(t_i) = (\phi - \lambda_i \psi) e_i^{TR} t_i + \mu_i (A_i - c_i) t_i - \frac{\eta_i}{2} t_i^2 + constants$$

The first-order condition is

$$\frac{dW_i}{dt_i} = (\phi - \lambda_i \psi) e_i^{TR} + \mu_i (A_i - c_i) - \eta_i t_i = 0$$

Solving yields the expression above. The second-order condition $\frac{d^2 W_i}{dt_i^2} = -\eta_i < 0$ ensures a unique interior maximum. □

Appendix A.2. Food Security Extension

Define the food security penalty for product i:

$$FS_i(t_i) = -\gamma \alpha_i w_i \left(Q_i^{min} - Q_i(t_i)\right)^2, when Q_i(t_i) < Q_i^{min}$$

where $Q_i(t_i) = Q_i^{EU}(t_i) + X_i^*(t_i) + \overline{M}_i^{ROW} - \overline{E}_i^{EU}$ denotes EU apparent consumption.

Lemma A3 (Derivative of Food Security Term). *If the constraint binds, the derivative of the food security term with respect to t_i is*

$$\frac{dFS_i}{dt_i} = \frac{\gamma \alpha_i w_i e_i^{TR}}{B_i}\left(Q_i^{min} - Q_i(t_i)\right)$$

Proof.

$$FS_i = -\gamma \alpha_i w_i \left(Q_i^{min} - Q_i\right)^2$$
$$\frac{dFS_i}{dt_i} = -2\gamma \alpha_i w_i \left(Q_i^{min} - Q_i\right)\left(-\frac{dQ_i}{dt_i}\right)$$

Since $\frac{dQ_i}{dt_i} = -\frac{e_i^{TR}}{2B_i}$ (from the reaction function and the definition of apparent consumption, holding third-country imports and EU exports constant), substitution yields the result. □

Proposition A2 (Implicit Optimal Tax Under Binding Constraint). *When $Q_i(t_i) < Q_i^{min}$, the optimal tax satisfies:*

$$t_{II,i}^* = t_{I,i}^* - \frac{\gamma \alpha_i w_i e_i^{TR}}{B_i \eta_i}\left(Q_i^{min} - Q_i\left(t_{I,i}^*\right)\right)$$

Proof. Total welfare derivative:

$$\frac{d\widetilde{W}_i}{dt_i} = \frac{dW_i^{base}}{dt_i} + \frac{dFS_i}{dt_i}$$

Using Proposition A1 and Lemma A3:

$$(\phi - \lambda_i \psi) e_i^{TR} + \mu_i (A_i - c_i) - \eta_i t_i + \frac{\gamma \alpha_i w_i e_i^{TR}}{B_i}\left(Q_i^{min} - Q_i\right) = 0$$

Rearranging and substituting the baseline solution $t_{I,i}^*$ yields the result. □

Proposition A3 (Closed-Form Approximation). *Linearizing $Q_i(t_i)$ around $t_{I,i}^*$ yields:*

$$t_{II,i}^* = t_{I,i}^* - \frac{\gamma \alpha_i w_i e_i^{TR}\left[Q_i^{min} - Q_i\left(t_{I,i}^*\right)\right]}{B_i \eta_i + \frac{\gamma \alpha_i w_i \left(e_i^{TR}\right)^2}{2B_i}}$$

Proof. First-order Taylor expansion:

$$Q_i(t_i) \approx Q_i\left(t_{I,i}^*\right) - \frac{e_i^{TR}}{2B_i}\left(t_i - t_{I,i}^*\right)$$

Substituting into Proposition A2 and collecting terms in $t_{II,i}^*$ yields the result. The denominator is strictly positive, ensuring uniqueness. □

Appendix A.3. Comparative Statics in Binding Regime

Proposition A4 (Effect of Food Security Valuation γ)**.**

$$\frac{\partial t^*_{II,i}}{\partial \gamma} < 0$$

Proof. Differentiating Proposition A3 with respect to γ: the numerator is positive when binding ($Q_i^{min} - Q_i > 0$), and the denominator is positive. Hence the derivative is negative. □

Proposition A5 (Effect of Minimum Requirement Q_i^{min})**.**

$$\frac{\partial t^*_{II,i}}{\partial Q_i^{min}} < 0$$

Proof. Differentiating the numerator of Proposition A3 with respect to Q_i^{min} yields a negative sign determined by $-\gamma \alpha_i w_i e_i^{TR} / B_i < 0$. □

Proposition A6 (Effect of Essential Share α_i)**.**

$$\frac{\partial t^*_{II,i}}{\partial \alpha_i} < 0$$

Proof. α_i scales the welfare penalty multiplicatively; the derivative has the same sign as the γ-case. □

Proposition A7 (Effect of Nutritional Weight w_i)**.**

$$\frac{\partial t^*_{II,i}}{\partial w_i} < 0$$

Proof. w_i enters multiplicatively in the numerator and denominator; the total derivative is negative under the binding condition. □

Appendix A.4. Global Concavity

Proposition A8 (Existence and Uniqueness)**.** *Under both regimes, welfare is strictly concave in t_i, implying a unique Stackelberg equilibrium.*

Proof. Baseline curvature:

$$\frac{\partial^2 W_i^{base}}{\partial t_i^2} = -\eta_i < 0$$

Binding regime adds:

$$\frac{\partial^2 FS_i}{\partial t_i^2} = -\frac{\gamma \alpha_i w_i \left(e_i^{TR}\right)^2}{2B_i^2} < 0$$

The sum is strictly negative. □

Appendix B. Nutritional Weight Calculation

The nutritional significance weights w_i are derived using principal component analysis (PCA) on nutritional composition data from the USDA FoodData Central database [76].

Data. For each of the five essential food products (BEEF, LAMB, POUL, BAKE, DAIR), we extract the following nutritional variables per 100 g: protein (g), energy (kcal), total fat (g), carbohydrates (g), and selected micronutrients (iron, zinc, vitamin B12, calcium). Values are averaged across commonly consumed cuts and preparations within each product category.

Standardization. Because the nutritional variables are measured in different units, each variable is standardized to have zero mean and unit variance before PCA.

PCA results. The first principal component (PC1) explains 68.3% of the total variance, the second (PC2) explains 18.1%, and the third (PC3) explains 7.4%. The first two components together explain 86.4% of the variance and are retained for the analysis. PC1 is strongly positively loaded on protein, iron, zinc, and vitamin B12, and negatively loaded on carbohydrates. PC2 is strongly positively loaded on energy and fat.

Weight construction. For each product, we compute a composite nutritional score as the weighted sum of PC1 and PC2, with weights proportional to their explained variance (0.683 and 0.181, respectively). Weights are then normalized to sum to one across the five essential products. Products outside the essential food set receive zero nutritional weight.

Sensitivity. Sensitivity analysis varies the nutritional weights by ±20% to test the robustness of the results to alternative weight specifications. The qualitative conclusions are unchanged.

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