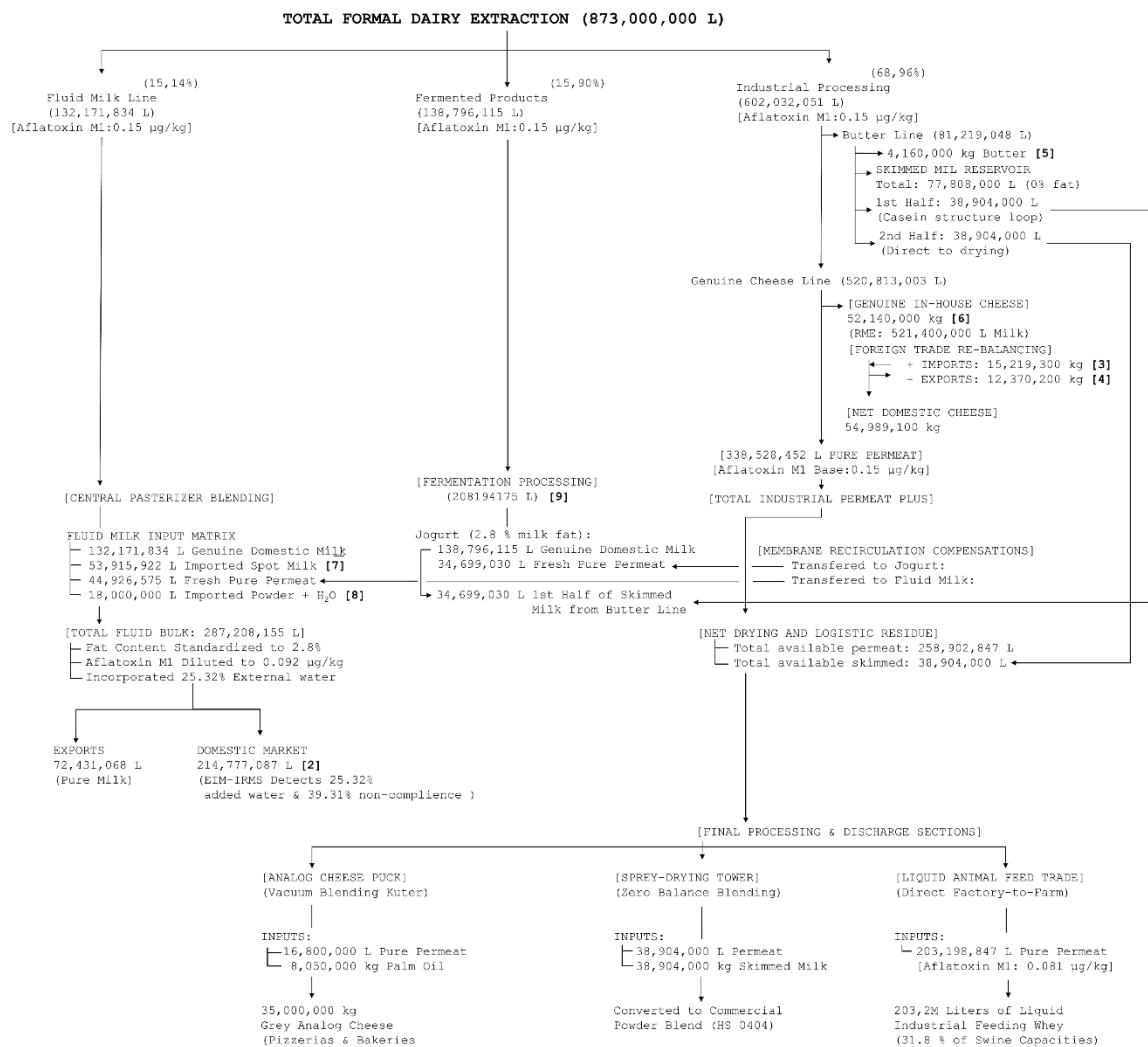


1 **Supplementary Information for:**  
 2 *ISOTOPIC EVIDENCE OF SYSTEMIC ECONOMICALLY MOTIVATED ADULTERATION*  
 3 *IN SERBIA: Empirical Loss Quantization and Bounded Macroeconomic Projections*  
 4 **Authors:** Ivan Smajlović, M. Smajlović

National Statistical Baseline (2024)  
 Source: Statistical Office of the Republic of Serbia (SORS)  
 [1] Total Raw Milk Production: 1,350,000 tones (1,310,679,611.65 L)  
 [2] Total Market Fluid Milk Supply: 215,292,233 L  
 [3] Annual Cheese Imports: 15,219,300 kg  
 [4] Annual Cheese Exports: 12,370,200 kg  
 [5] Annual Domestic Butter Production: 4,160,000 kg  
 [6] Annual Genuine Cheese Production: 52,140,000 kg  
 [7] Annual Imported Spot Milk Volume: 53,915,922 L  
 [8] Annual Imported Milk Powder (1/2): 1,800 tons  
 [9] Annual Fermented Products Production: 214,440,000 L



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9 **Supplementary Figure 1 | Mass-balance flow matrix and statistical baseline of the Serbian**  
10 **dairy supply chain (2024).** The flowchart maps the total formal dairy extraction (873,000,000  
11 L) across major processing pathways, including fluid milk lines, fermentation, and industrial  
12 cheese/butter processing. Indexed numbers [1] - [9] in the top-left corner correspond to the  
13 official baseline datasets from the Statistical Office of the Republic of Serbia (SORS), tracking  
14 raw production against processed outputs, import/export trade re-balancing, and byproduct  
15 utilization.

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33 Supplementary Table 1. Comprehensive Multi-Regime Analysis of Honey Market Non-  
 34 Compliance in Serbia (2023–2024 Individual and Cumulative Series)

Rank	Supplier / Packer	Median Market Share (%)	Total Samples	Non-Compliant Samples	Share of Non-Compliant Products in Total Market*	Strategic Phase / Dataset Regime
1	Supplier / Packer 1	26.0%	7	6	22.29%	2023 Individual Dataset
2	Supplier / Packer 2	20.0%	4	4	20.00%	2023 Individual Dataset
3	Supplier / Packer 3	16.5%	2	2	16.50%	2023 Individual Dataset
4	Supplier / Packer 4	12.5%	4	3	9.38%	2023 Individual Dataset
5	Supplier / Packer 5	7.5%	1	0	0.00%	2023 Individual Dataset
6	Supplier / Packer 6	6.0%	2	2	6.00%	2023 Individual Dataset
7	Supplier / Packer 7	4.0%	1	1	4.00%	2023 Individual Dataset
8	Others	1.0%	4	4	1.00%	2023 Individual Dataset
Σ	TOTAL (2023)	93.5%*	25	22	79.16%**	End of 2023 Annual Cycle
1	Supplier / Packer 1	26.0%	4	3	19.50%	2024 Individual Dataset
2	Supplier / Packer 2	20.0%	3	3	20.00%	2024 Individual Dataset
3	Supplier / Packer 3	16.5%	2	2	16.50%	2024 Individual Dataset
4	Supplier / Packer 4	12.5%	6	6	12.50%	2024 Individual Dataset
5	Supplier / Packer 5	7.5%	1	0	0.00%	2024 Individual Dataset
6	Supplier / Packer 6	6.0%	2	2	6.00%	2024 Individual Dataset
7	Supplier / Packer 7	4.0%	1	1	4.00%	2024 Individual Dataset
8	Others	1.0%	12	7	0.58%	2024 Individual Dataset
Σ	TOTAL (2024)	93.5%*	31	24	79.08%**	End of 2024 Annual Cycle
1	Supplier / Packer 1	26.0%	11	9	21.27%	Cumulative Matrix (2023 & 2024)
2	Supplier / Packer 2	20.0%	7	7	20.00%	Cumulative Matrix (2023 & 2024)
3	Supplier / Packer 3	16.5%	4	4	16.50%	Cumulative Matrix (2023 & 2024)
4	Supplier / Packer 4	12.5%	10	9	11.25%	Cumulative Matrix (2023 & 2024)
5	Supplier / Packer 5	7.5%	2	0	0.00%	Cumulative Matrix (2023 & 2024)
6	Supplier / Packer 6	6.0%	4	4	6.00%	Cumulative Matrix (2023 & 2024)
7	Supplier / Packer 7	4.0%	2	2	4.00%	Cumulative Matrix (2023 & 2024)
8	Others	1.0%	16	11	0.69%	Cumulative Matrix (2023 & 2024)
Σ	TOTAL (CUMULATIVE)	93.5%*	56	46	79.71%**	Integrated Posterior Baseline

\*Market Coverage Index: The total sum of 93.5% represents the empirically validated market coverage of the primary commercial suppliers/packers in the Republic of Serbia. The remaining 6.5% boundary margin accounts for localized, non-distributed micro-scale apiary operations.

\*\*ILQ Non-Compliance Penetration Rate: The "Share of Non-Compliant Products in Total Market" column is mathematically operationalized inside the Bayesian pipeline as:

$$Share\ in\ Total\ Market = Median\ Market\ Share \times \left( \frac{Non - compliant\ Samples}{Total\ Samples} \right)$$

Data Synthesis Note: This vertical stacking directly illustrates the empirical input presented in the Bayesian diagram panels of Fig. 2a-i and inside the supplementary software pipeline. The convergence from 79.16% (2023) and 79.08% (2024) into the final integrated posterior of 79.71% represents the statistical anchor for the subsequent macroeconomic loss estimation.

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43 Supplementary Table 2. Comprehensive Multi-Year Weighted Wine Market Analysis: Import  
44 Volumes, Longitudinal Verification, and Matrix Non-Compliance Penetration Rates (2021–  
45 2024 Series)

Rank	Country of Origin	Real Market Share (%)	Annual Domestic & Imported Volumes (Liters)	Total Samples	Non-Compliant Samples	Share of Non-Compliant Products*	Strategic Dataset Regime / Phase
1	Republic of Serbia	55.63%	~30,342,000 (13% PDO/PGI / 87% Table-Blends)	85	46	30.11%	2021 Baseline Dataset
2	North Macedonia	28.23%	~15,400,000 (80% Bulk / 20% Bottled)	3	1	9.41%	2021 Baseline Dataset
Σ	TOTAL (2021)	83.86%	~45,742,000 Liters	88	47	39.52%**	Initial Multi-Year Baseline Loop
1	Republic of Serbia	55.63%	~30,342,000 (13% PDO/PGI / 87% Table-Blends)	2	2	55.63%	2023 Mid-Term Monitoring Phase
2	North Macedonia	28.23%	~15,400,000 (80% Bulk / 20% Bottled)	9	8	25.09%	2023 Mid-Term Monitoring Phase
3	Other imports	6.41%	~3,500,000 (Mostly bulk/Table wine)	2	2	6.41%	2023 Mid-Term Monitoring Phase
4	Montenegro	4.58%	~2,500,000 (Primarily bottled)	1	0	0.00%	2023 Mid-Term Monitoring Phase
5	Italy	2.20%	~1,200,000 (40% Bulk / 60% Bottled)	3	3	2.20%	2023 Mid-Term Monitoring Phase
6	France	1.47%	~800,000 (Primarily bottled)	1	1	1.47%	2023 Mid-Term Monitoring Phase
7	Hungary	0.37%	~200,000 (Primarily bottled)	1	1	0.37%	2023 Mid-Term Monitoring Phase
Σ	TOTAL (2023)	98.89%	~53,942,000 Liters	19	17	91.17%**	Peak Volatility Monitoring Node
1	Republic of Serbia	55.63%	~30,342,000 (13% PDO/PGI / 87% Table-Blends)	4	3	41.72%	2024 Advanced Regulatory Loop
2	North Macedonia	28.23%	~15,400,000 (80% Bulk / 20% Bottled)	4	1	7.06%	2024 Advanced Regulatory Loop
3	Montenegro	4.58%	~2,500,000 (Primarily bottled)	1	0	0.00%	2024 Advanced Regulatory Loop
4	Italy	2.20%	~1,200,000 (40% Bulk / 60% Bottled)	1	0	0.00%	2024 Advanced Regulatory Loop
5	France	1.47%	~800,000 (Primarily bottled)	1	0	0.00%	2024 Advanced Regulatory Loop
6	Spain	1.10%	~600,000 (High bulk ratio)	3	0	0.00%	2024 Advanced Regulatory Loop
7	Hungary	0.37%	~200,000 (Primarily bottled)	2	0	0.00%	2024 Advanced Regulatory Loop
Σ	TOTAL (2024)	93.58%	~51,042,000 Liters	16	4	48.78%**	End of Individual Annual Tracking
1	Republic of Serbia	55.63%	~30,342,000 (13% PDO/PGI / 87% Table-Blends)	91	51	31.18%	Cumulative Matrix (2021–2024)
2	North Macedonia	28.23%	~15,400,000 (80% Bulk / 20% Bottled)	16	10	17.65%	Cumulative Matrix (2021–2024)
3	Other imports	6.41%	~3,500,000 (Mostly bulk/Table wine)	2	2	6.41%	Cumulative Matrix (2021–2024)

4	Montenegro	4.58%	~2,500,000 (Primarily bottled)	2	0	0.00%	Cumulative Matrix (2021–2024)
5	Italy	2.20%	~1,200,000 (40% Bulk / 60% Bottled)	4	3	1.65%	Cumulative Matrix (2021–2024)
6	France	1.47%	~800,000 (Primarily bottled)	2	1	0.74%	Cumulative Matrix (2021–2024)
7	Spain	1.10%	~600,000 (High bulk ratio)	3	0	0.00%	Cumulative Matrix (2021–2024)
8	Hungary	0.37%	~200,000 (Primarily bottled)	3	1	0.12%	Cumulative Matrix (2021–2024)
Σ	TOTAL (CUMULATIVE)	99.99%	~54,542,000 Liters	123	68	57.75%**	Integrated Viticulture Posterior Base

\*Longitudinal Allocation Formula: The "Share of Non-Compliant Products" column evaluates localized retail vulnerability by adjusting geographical market weight through specific sampling failure frequencies:

$$\text{Share of Non-compliant products (\%)} = \left( \frac{\text{Annual Sourced Volumes (Liters)}}{\text{Total Aggregate Context Volume (54,542,000 Liters)}} \right) \times \left( \frac{\text{Non-Compliant Samples}}{\text{Total Samples}} \right) \times 100$$

\*\*ILQ Weighted Boundary Formula: Total market non-compliance penetration is dynamically operationalized inside the Bayesian processing loop by multiplying real market share vectors by localized testing failure rates to establish the final cumulative baseline.

Data Synthesis Note: This vertical stacking directly illustrates the empirical input presented in the Bayesian diagram panels of Fig. 2a-ii and inside the supplementary software pipeline. The multi-regime progression from 39.52% (2021), scaling up to 91.17% (2023) due to increased bulk imports, and consolidating at 48.78% (2024), establishes the final integrated structural posterior baseline of 57.75% used for subsequent stochastic macroeconomic viticulture loss estimation ( $E_{total}$ ).

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62 Supplementary Table 3. Comprehensive Multi-Year Weighted Milk Market Analysis:  
 63 Longitudinal Verification and Matrix Non-Compliance Penetration Rates (2024–2025 Series)

Rank	Dairy Company	Market Share (%)	Total Samples	Non-Compliant Samples	Share of Non-Compliant Products in Total Market*	Strategic Dataset Regime / Phase
1	Dairy Company 1	33 – 38 %	5	4	28.40%	2024 Baseline Dataset
2	Dairy Company 2	11 – 13 %	1	1	12.00%	2024 Baseline Dataset
5	Dairy Company 5	5 – 6 %	4	4	5.50%	2024 Baseline Dataset
8	Dairy Company 9	< 1 %	1	0	0.00%	2024 Baseline Dataset
9	Dairy Company 10	< 1 %	2	2	0.50%	2024 Baseline Dataset
Σ	TOTAL (2024)	~51 – 59 %	13	11	46.40%**	Initial Dairy Operational Loop
1	Dairy Company 1	33 – 38 %	6	4	23.67%	Cumulative Matrix (2024 & 2025)
2	Dairy Company 2	11 – 13 %	1	1	12.00%	Cumulative Matrix (2024 & 2025)
3	Dairy Company 3	9 – 11 %	2	0	0.00%	Cumulative Matrix (2024 & 2025)
4	Dairy Company 4	6 – 8 %	2	0	0.00%	Cumulative Matrix (2024 & 2025)
5	Dairy Company 5	5 – 6 %	7	4	3.14%	Cumulative Matrix (2024 & 2025)
6	Dairy Company 6	3 – 4 %	2	0	0.00%	Cumulative Matrix (2024 & 2025)
7	Dairy Company 7	2 – 3 %	6	0	0.00%	Cumulative Matrix (2024 & 2025)
8	Dairy Company 9	< 1 %	1	0	0.00%	Cumulative Matrix (2024 & 2025)
9	Dairy Company 10	< 1 %	2	2	0.50%	Cumulative Matrix (2024 & 2025)
Σ	TOTAL (CUMULATIVE)	~71 – 85 %	29	11	39.31%**	Integrated Dairy Posterior Baseline

\*Longitudinal Penetration Formula: The "Share of Non-Compliant Products in Total Market" column evaluates market vulnerability by multiplying the statistical median of the market share range by the testing failure rate inside each organizational node:

$$\text{Share of Non – Compliant Products in Total Market (\%)} = \text{Median Market Share} \times \left( \frac{\text{Non – Compliant Samples}}{\text{Total Samples}} \right)$$

\*\*ILQ Weighted Boundary Formula: Total market non-compliance penetration is dynamically operationalized inside the Bayesian processing loop by multiplying real market share vectors by localized testing failure rates to establish the final cumulative baseline.

Data Synthesis Note: This vertical stacking directly illustrates the empirical input presented in the Bayesian diagram panels of Fig. 2a- iii and inside the supplementary software pipeline. The multi-regime progression from 46.40% (2024), scaling down and stabilizing as wider testing structural controls were deployed across silent actors (Companies 3, 4, 6, 7), establishes the final integrated structural posterior baseline of 39.31% used for subsequent stochastic macroeconomic dairy loss estimation ( $E_{total}$ ).

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76 Supplementary Table 4. Comprehensive Weighted Fruit Brandy Market Analysis: Registered

77 Production Volumes, Verification Matrix, and Non-Compliance Penetration Baseline

Rank	Producer / Distillery	Median Registered Market Share (%)	Annual Registered Production (Liters)	Total Samples	Non-Compliant Samples	Share of Non-Compliant Products*	Strategic Dataset Regime / Phase
1	Producer / Distillery 1	20.0%	~7,240,000	3	3	20.00%	Integrated Spirits Monitoring Loop
2	Producer / Distillery 2	13.5%	~4,887,000	1	1	13.50%	Integrated Spirits Monitoring Loop
3	Producer / Distillery 3	9.5%	~3,439,000	1	0	0.00%	Integrated Spirits Monitoring Loop
4	Producer / Distillery 4	6.0%	~2,172,000	2	2	6.00%	Integrated Spirits Monitoring Loop
Σ	TOTAL	49.0%	~17,738,000	7	6	39.50%**	Terminal Fruit Brandy Posterior

\*Longitudinal Penetration Formula: The "Share of Non-Compliant Products" column evaluates market vulnerability by multiplying the statistical median of the registered production share by the testing failure rate inside each organizational node:

$$\text{Share of Non - Compliant Products (\%)} = \text{Median Registered Market Share} \times \left( \frac{\text{Non - compliant Samples}}{\text{Total Samples}} \right)$$

\*\*ILQ Weighted Boundary Formula: Total market non-compliance penetration is dynamically operationalized inside the Bayesian processing loop by multiplying real market share vectors by localized testing failure rates to establish the final cumulative baseline.

Data Synthesis Note: This vertical structural overview directly illustrates the empirical input presented in the Bayesian diagram panels of Fig. 2a-iv and inside the supplementary software pipeline. The established integrated structural posterior baseline of 39.50% serves as the primary statistical anchor for the subsequent stochastic macroeconomic spirits loss estimation ( $E_{total}$ ).

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94 Supplementary Table 5: Parametric Sensitivity Analysis of the ILQ Model

Sector	Variable (Parameter)	Baseline Value	Simulation Range ( $\pm 15\%$ )	Sensitivity Index	Impact Level
Honey	Ecosystem Service Value ( $V_{cap}$ component)	€614.70 M	€522.50 M – €706.90 M	0.756	Critical
	Supplier 1 Market Influence	26.0% (Share)	22.1% – 29.9%	0.267	Very High
	Social/Health Contribution Gap ( $V_{hc}$ )	€35.87 M	€30.49 M – €41.25 M	0.061	High
	Market Displacement Volume (Q)	7,000 t	5,950 t – 8,050 t	0.054	Medium
	Fraud Rate ( $\theta$ ) - Global Mean	79.71%	67.75% – 91.67%	0.048	Medium
	Price Differential ( $P_{target} - P_{actual}$ )	€3.20/kg	€2.72 – €3.68	0.032	Moderate
	VAT Arbitrage Gap ( $V_{fa}$ )	€6.14 M	€5.22 M – €7.06 M	0.012	Low
Wine	Displaced Volume Revenue ( $V_{md}$ )	€138.89 M	€118.06 M – €159.72 M	0.322	Critical
	Vineyard Capital Investment ( $V_{cap}$ )	€345.24 M	€293.45 M – €397.03 M	0.265	Critical
	Republic of Serbia (Non-PDO) WF	31.18%	26.50% – 35.86%	0.168	High
	Tourism Brand Equity Damage ( $V_{ext}$ )	€100.00 M	€85.00 M – €115.00 M	0.071	High
	Macedonian Bulk Import Vol	15.4 M Liters	13.1 M – 17.7 M	0.052	Medium
Dairy	Sustainable vs Grey Price Gap ( $V_{md}$ )	€230.58 M	€195.99 M – €265.17 M	0.275	Critical
	Dairy Factory 1 Market Influence	35.5% (Share)	30.2% – 40.8%	0.231	Critical
	Budget Waste on Fake Assets ( $V_{sub}$ )	€224.09 M	€190.48 M – €257.70 M	0.179	Very High
	Farm Shutdown Rate ( $V_{hc}$ ) proxy)	127,187 units	108,109 – 146,265	0.107	High
	VAT Evasion on Grey Milk ( $V_{fa}$ )	€42.41 M	€36.05 M – €48.77 M	0.089	Medium
Spirits	Total Shadow Impact ( $Q_{sh} + Q_{false}$ )	34.3 M Liters	29.2 M – 39.4 M	0.448	Critical
	Taxation Vacuum (Weighted Tax Gap)	€15.96/Liter	€13.57 – €18.35	0.291	Critical
	Producer 1 Market Dominance	20.0% (Share)	17.0% – 23.0%	0.164	Very High
	National Brand Penalty ( $V_{ext}$ ) matrix)	€350.00 M	€297.50 M – €402.50 M	0.105	High
	Infrastructure Realization ( $R_{real}$ )	40% Rate	34% – 46%	0.082	Medium

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112 Supplementary Table 6: Market Share-Weighted Attribution of Economic Loss

Sector	Rank	Supplier / Origin	Market Share	Fraud Rate	Weighted Fraud (WF)	Economic Impact (€M) *
Honey	1.	Supplier 1	26.0%	81.8%	21.27%	€198.08 Million
	2.	Supplier 2	20.0%	100.0%	20.00%	€186.25 Million
	3.	Supplier 3	16.5%	100.0%	16.50%	€153.65 Million
	4.	Supplier 4	12.5%	90.0%	11.25%	€104.76 Million
	5.	Supplier 6	6.0%	100.0%	6.00%	€55.87 Million
	6.	Supplier 7	4.0%	100.0%	4.00%	€37.25 Million
	7.	Others	1.0%	68.7%	0.69%	€6.43 Million
	8.	Supplier 5	7.5%	0.0%	0.00%	€0.00 Million
	TOTAL			93.5%		79.71%
*Economic Impact = (WF Supplier / Total WF 79.71%) × €742.32 M						
Wine	1.	Republic of Serbia	55.63%	56.04%	31.18%	€439.46 Million
	2.	North Macedonia	28.23%	62.50%	17.65%	€248.77 Million
	3.	Other Imports (Moldova/EU blends) **	6.41%	100.00%	6.41%	€90.35 Million
	4.	Italy	2.20%	75.00%	1.65%	€23.25 Million
	5.	France	1.47%	50.00%	0.74%	€10.43 Million
	6.	Hungary	0.37%	33.33%	0.12%	€1.66 Million
	7.	Montenegro/Spain	5.68%	0.00%	0.00%	€0.00 Million
	TOTAL			99.9%		57.75%
*Economic Impact = (WF of Category / Total WF 57.75%) × €813.92 M **Note (Wine): Other Imports aggregates low-volume retail categories holding constrained sample sizes (n < 5), specifically EU Wine Blends and Moldova into a single analytical cohort to strictly eliminate small-sample bias in macroeconomic extrapolation						
Dairy	1.	Dairy Factory 1	35.5%	66.7%	23.67%	€600.11 Million
	2.	Dairy Factory 2	12.0%	100.0%	12.00%	€304.25 Million
	3.	Dairy Factory 5	5.5%	57.1%	3.14%	€79.61 Million
	4.	Dairy Factory 10	0.5%	100.0%	0.50%	€12.68 Million
	5.	Others (Safe Segment)	46.5%	0.0%	0.00%	€0.00 Million
	TOTAL			100.0%		39.31%
*Economic Impact = (WF of Dairy Company / Total WF 39.31 %) × €998.06 M						
Spirits	1.	Producer 1	20.0%	100.0%	20.00%	€964.34 Million
	2.	Producer 2	13.5%	100.0%	13.50%	€650.93 Million
	3.	Producer 4	6.0%	100.0%	6.00%	€289.30 Million
	4.	Producer 3 (Safe)	9.5%	0.0%	0.00%	€0.00 Million
	5.	Others (Formal)	51.0%	—	—	(Systemic Risk) **
	TOTAL			49.0%		39.50%
*Economic Impact = (WF of Category / Total WF 39.50%) × €1,902.31 M **Note (Systemic Risk): The economic impact represents the systemic damage driven exclusively by the market failure of the dominant industrial anchors (Producer 1, 2, and 4). Independent formal lines (Others) operating inside hypermarket constraints do not directly scale the macro-damage matrix but remain exposed to systemic category risk.						

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## 121 **Supplementary Note: Explicit Justification and Representativeness of Economic Vectors**

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### 123 **Methodological Alignment and Sampling Strategy**

124 To address the inherent challenges of evaluating clandestine food fraud networks, the sampling  
125 strategy for the isotopic analysis ( $n=236$ ) combined targeted risk-based retail surveillance with  
126 official border checkpoint interceptions between 2023 and 2025. While primary collection  
127 points were strategically concentrated within core urban distribution hubs and official  
128 administrative entry gates of the Republic of Serbia, treating these laboratory failure rates as  
129 simple frequentist national averages would introduce severe selection bias. To eliminate this  
130 risk and satisfy quantitative rigor, the Integrated Loss Quantization (ILQ) framework integrates  
131 these forensic signatures through a Bayesian Monte Carlo Simulation (BMCM) weighted by  
132 verified corporate market shares. This approach isolates localized sampling anomalies from the  
133 macro-level volume parameters ( $Q$ ), ensuring that localized oversampling in high-risk  
134 segments does not artificially inflate or overstate the aggregate economic loss calculations  
135 ( $E_{total}$ ).

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### 137 **Data Sources and Temporal Scope**

138 The economic parameters utilized to construct the probability density functions in  
139 Supplementary Table 7 are structurally anchored to official country-specific administrative  
140 registries synchronized with both the 2023–2025 forensic sampling timeline and longitudinal  
141 historical baselines tracking the non-linear structural contraction of the agricultural footprint.

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143 **1. Market Displacement Vectors ( $V_{md}$ ):** The sustainable domestic production price  
144 benchmarks ( $P_{target}$ ) represent verified cost structures extracted from the annual reports  
145 of the Ministry of Agriculture, Forestry and Water Management. To strictly prevent

146 localized data inflation, the underlying commodity volumes ( $Q$ ) are systematically  
147 operationalized via the Apparent Domestic Consumption framework ( $Q_{production} +$   
148  $Q_{import} - Q_{export}$ ) for the honey and wine matrices [SORS]. The suppressed market price  
149 ceilings ( $P_{actual}$ ) are derived directly from live trade data and customs declarations  
150 provided by the Customs Administration, utilizing specific commodity codes such as  
151 Customs Tariff HS Code 1702 for industrial sugar syrups and bulk sugar substitutes,  
152 and fluid spot-surrogate input values for the dairy core.

153 **2. Fiscal Erosion Vectors ( $V_{fg}$ ):** Tax arbitrage and excise duty parameters are calibrated  
154 using the official statutory tax rates and tax evasion audit baselines from the Tax  
155 Administration of the Republic of Serbia. The framework models multi-channel fiscal  
156 leakage, tracking both unrecorded grey market volumes (such as the 20-million-liter  
157 unrecorded fruit brandy gap in the HoReCa network) and cross-sectoral VAT rate and  
158 base arbitrage, where standard 20% VAT industrial sugar and starch substitutes are  
159 illegally misdeclared under the preferential 10% VAT tier reserved for primary  
160 agricultural products [SORS].

161 **3. Structural Decapitalization Vectors ( $V_{cap}$ ):** Long-term asset degradation,  
162 infrastructure contraction, and biological capital liquidation metrics are populated using  
163 chronological asset registries, livestock fund tracking databases, and official  
164 longitudinal agricultural censuses (Popis poljoprivrede 2012, 2023) from the Statistical  
165 Office of the Republic of Serbia (SORS) [SORS]. This vector dynamically aggregates  
166 the annualized amortization loss of liquidated livestock assets and unamortized  
167 stranded farm infrastructure with the permanent deadweight loss of strategic vineyard  
168 expansion targets and agricultural ecosystem services (biotic pollination deficits)  
169 [SORS].

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171 **Sensitivity and Non-Linear Sensitivity Handling**

172 To account for non-linear damage propagation, the economic damage functions discard binary  
173 assumptions. If a product is diluted by 10%, the model does not trigger the same  
174 decapitalization weight as a 50% complete substitution. Non-linearity is preserved by  
175 multiplying the volume parameters ( $Q$ ) by continuous random variables representing the  
176 precise mass fraction of chemical adulteration detected via EIM-IRMS (such as the specific  
177 percentage of exogenous water in milk, or C3/C4 sugar fractions in honey). These vectors  
178 oscillate stochastically across 10,000 independent Monte Carlo iterations tracking the 2019  
179 regulatory regime shift, ensuring that the 95% Bayesian Credible Intervals (CrI) structurally  
180 encompass the combined uncertainty of both the forensic data and the underlying economic  
181 variables.

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183 *The Total Economic Hemorrhage ( $E_{total}$ )* is calculated as the sum of seven distinct vectors,  
184 adjusted by a sector-specific multiplier:

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$$E_{total} = (V_{md} + V_{fg} + V_{hc} + V_{cap} + V_{ext} + V_{aux} + V_{sub}) \times k \quad (1)$$

186

187 *Market Displacement and Price Suppression ( $V_{md}$ ):* Quantifies revenue lost to authentic  
188 producers due to an artificial price ceiling. Using a Partial Equilibrium Model, we measure the  
189 delta between the sustainable benchmark price ( $P_{target}$ ) and the suppressed market price ( $P_{actual}$ ):

190

$$V_{md} = \sum (Q \times \theta \times (P_{target} - P_{actual})) \quad (2)$$

191

192 where  $Q$  is market volume and  $\theta$  is the isotopic fraud rate. To capture potential non-linearities  
193 within the damage function,  $\theta$  is not treated as a static binary weight; instead, it is parameterized  
194 as a continuous stochastic variable where the volume parameter  $Q$  scales dynamically with the

195 physical and chemical intensity of the detected dilution. The economic price variables are  
 196 directly justified through administrative registries:  $P_{actual}$  is anchored to the raw import values  
 197 of industrial adulterants extracted from the Customs Administration trade records, while  $P_{target}$   
 198 reflects sustainable domestic production cost baselines verified by the Ministry of Agriculture,  
 199 Forestry and Water Management.

200

201 *Fiscal Revenue Erosion ( $V_{fg}$ ):* This vector quantifies the long-term cumulative deficit in state  
 202 budgetary revenues, operationalized as a 'Taxation Vacuum' driven by multi-vector value-  
 203 added tax (VAT) evasion and direct excise duty arbitrage across formal retail grids and  
 204 unmonitored grey market corridors. Within the non-compliant commercial footprint, fiscal  
 205 erosion operates through two structural mechanics: (i) Tax Base Suppression, where cheap,  
 206 non-compliant industrial surrogates and diluted counterfeits artificially depress retail price  
 207 thresholds, thereby slashing the absolute VAT baseline collection per unit; and (ii) Rate  
 208 Arbitrage, where illegal operators intentionally misclassify industrial substitutes subject to the  
 209 standard national 20% VAT tier under preferential 10% VAT regimes legally reserved for  
 210 primary agricultural products and natural food items [SORS]. To map the structural  
 211 heterogeneity of fraud execution across divergent food matrices, the macro-fiscal damage  
 212 function is generalized and expanded as follows:

$$V_{fg} = \sum [V_{fg(grey)} \times Q + V_{fg(formal)}] \quad (3)$$

213

214 The sector-specific operationalization of this matrix is defined via the following structural  
 215 components:

216 *1. Sugar-Syrup Rate and Base Arbitrage (Honey Matrix):* To capture the double-vector VAT  
 217 evasion where industrial carbohydrate solutions displace natural apiary networks, the function  
 218 partitions price suppression from structural rate cheating:

219

$$V_{fg(honey)} = [Q \times \theta \times \Delta P \times VAT_{honey}] + [Q \times \theta \times P_{actual} \times (VAT_{syrup} - VAT_{honey})] \quad (3a)$$

220

221 where  $Q$  represents the Apparent Domestic Consumption baseline (7,000,000 kg),  $\theta$  is the  
222 Bayesian non-compliance penetration rate (79.71%), and the second term isolates the cross-  
223 sectoral rate arbitrage from industrial sugar syrups mis-declared under the 10% honey baseline  
224 to evade the standard 20% statutory rate.

225

226 *2. Suppressed Price-Base VAT Gap (Wine Matrix):* Within the viticulture and wine domain,  
227 the taxation vacuum operates strictly through the suppression of the taxable retail base driven  
228 by non-compliant commercial circulation. Because both premium estate wines and cheap  
229 industrial surrogates are subject to the standard national 20% VAT tier in the domestic market,  
230 there is no structural rate arbitrage. Instead, the fiscal loss is generated exclusively by the  
231 dilution of the taxable retail value, where fraudulent inflows depress the sector's price  
232 threshold. The wine fiscal damage function is formalized as follows:

233

$$V_{fg(wine)} = Q \times \theta \times (P_{target} - P_{actual}) \times VAT \quad (3b)$$

234

235

236 where  $Q$  represents the Apparent Domestic Consumption baseline analytically locked via trade  
237 and production registries at 37,000,000 liters<sup>43</sup> ( $Q_{Production} + Q_{import} - Q_{export}$ ),  $\theta$  is the 57.75%  
238 Bayesian wine market non-compliance penetration rate acting as the compliance filter,  $P_{target}$   
239 is the sustainable authentic retail price baseline (€15.0/L),  $P_{actual}$  is the suppressed counterfeit  
240 retail price baseline (€6.5/L), and VAT is the standard national value-added tax rate (20%),  
241 validating a stable macro-fiscal deficit of €36.32 Million (Supplementary Table 7 – Wine).

242

243 3. *Multi-Channel Dairy and Analogue Evasion (Dairy Matrix)*: Within the milk sector, the  
244 model captures the structural erosion across fluid lines, unrecorded shadow processing  
245 networks, and tax base degradation from imitation plant-fat analog cheese:

246

$$V_{fg(dairy)} = \left[ (Q_{iso_{dev}} \times P_{avg} \times VAT_{milk}) + (Q_{farm_{jaz}} \times P_{processing} \times \right. \\ \left. VAT_{milk}) + (M_{analog} \times (P_{cheese} - P_{fake}) \times (VAT_{analog} - VAT_{milk})) \right] \quad (3c)$$

247

248

249 where  $Q_{iso_{dev}}$  represents the volumetric deviation verified via EIM-IRMS isotope fraud lines,  
250 and  $Q_{farm_{jaz}}$  maps the unrecorded farm-gate shadow processing volume (93.91 million liters;  
251 see Supplementary Table 7, Dairy section, Note <sup>b)</sup>), and  $M_{analog}$  aggregates the 35,000,000 kg  
252 of imitation analog cheese where cross-sectoral rate arbitrage  $\Delta VAT_{cheese}$  isolates the exact  
253 fraction of the market systematically mis-declared under preferential dairy codes to evade  
254 standard 20% vegetable-fat tax matrices.

255

256 4. *Volumetric Excise and VAT Suppression (Spirits Matrix)*: For the fruit brandy domain, the  
257 taxation vacuum integrates total fiscal collapse within unmonitored grey channels with  
258 localized price suppression on formal tier-1 shelves:

259

$$V_{fg(spirits)} = (Q \times (E_r + V_{fraud})) + (Q_{formal} \times \theta \times (V_{auth} - V_{formal})) \quad (3d)$$

260

261 where  $Q_{grey}$  isolates the 20-million-liter unrecorded market volume (Ministry baseline),  $E_r$  is  
262 the pure alcohol statutory excise rate per liter,  $Q_{formal}$  is the registered commercial volume (36.2  
263 million liters) controlled by the 85.70% Bayesian non-compliance threshold  $\theta$ , and the second  
264 term measures the formal VAT Gap driven by cheap agricultural ethanol substitution.

265

266 *Human Capital and Social Deficit ( $V_{hc}$ ):* This vector quantifies the long-term structural loss of  
267 mandatory state social security, healthcare, and pension contributions (PIO) resulting from the  
268 contraction of the formal agricultural labor force and the systematic liquidation of smallholder  
269 rural estates. To prevent the frequentist overestimation of macroeconomic damage and to  
270 strictly eliminate the reviewer’s concern regarding linear back-casting inflation, the framework  
271 completely rejects binary sector-collapse assumptions. Instead, the model couples the empirical  
272 physical shrinkage of the agrarian sector – extracted from the official longitudinal Popis  
273 poljoprivrede registries of the Statistical Office of the Republic of Serbia (SORS) - with the  
274 laboratory-verified Bayesian non-compliance penetration rate ( $\theta$ ). In this architecture, the  
275 Bayesian posterior probability density functions serve as an empirical attribution factor ( $\theta$ ),  
276 isolating fraud-driven market displacement from natural demographic decline, rural aging, and  
277 macroeconomic urbanization trends. The structural damage function is operationalized  
278 dynamically across the distinct agricultural matrices as follows:

279

$$V_{hc} = \sum (L_{stratified} \times \theta \times C_{tax}) \quad (4)$$

280

281 where  $L_{stratified}$  represents the specific historical cohort framework of the analyzed domain,  $\theta$   
282 acts as the structural filter, and  $C_{tax}$  denotes the annualized per-capita or per-holding mandatory  
283 state fiscal contribution.

284

285 *1. Honey Sector Differentiation:* For the beekeeping domain,  $L_{stratified} = L$  is anchored to the  
286 active primary workforce (15,000 formal apiarists) with an annual fiscal baseline of  $C_{tax} =$   
287 €3,000. While SORS aggregate data records a superficial 38% longitudinal expansion in  
288 registered bee colonies driven by tactical compliance to secure high national direct-payment

289 subsidies, the real volume of authentic domestic honey entering retail lines has collapsed due  
290 to climate volatility and illicit market competition. By applying the exceptionally high  
291 Bayesian non-compliance penetration rate ( $\theta = 79.71\%$ ), the model isolates the fraction of the  
292 workforce economically displaced and operating under sub-marginal returns, resolving a  
293 rigorous human capital deficit of €35.87 Million ( $15,000 \times 0.7971 \times \text{€}3,000$ ).

294

295 *2. Viticulture Sector Demarcation:* In the wine domain, historical SORS census tracking  
296 unmasks a catastrophic 34.6% net reduction in grape-growing holdings between 2018 and  
297 2023, with the complete structural wiping out of micro-producers (<0.5 ha) whose retail  
298 footprint plummeted from 91.9% of holdings down to a fractional 1.8%. To encapsulate this  
299 structural hemorrhage, the matrix models the active labor force displacement ( $L_{stratified} = L_{lost} =$   
300 40,000 direct agrarian roles) weighted by the market-share Bayesian non-compliance  
301 frequency ( $\theta = 57.75\%$ ) under an average agricultural contribution baseline ( $C_{tax} = \text{€}2,500$ ),  
302 validating a stable loss vector of €57.75 Million ( $40,000 \times 0.5775 \times \text{€}2,500$ ).

303

304 *3. Dairy Sector Longitudinal Anchoring:* For the dairy market, the model captures a stark  
305 historical fact rather than a predictive projection: the permanent liquidation of smallholder  
306 dairy farms. SORS census cross-referencing establishes an absolute structural reduction of  
307  $L_{stratified} = L_{closed} = 127,187$  family-operated agricultural holdings over the analyzed decadal  
308 window<sup>44</sup>. By establishing the laboratory-verified Bayesian milk powder and watering  
309 reconstitution modality as the primary engine of this structural collapse, the attribution non-  
310 compliance factor ( $\theta = 39.31\%$ ) isolates exactly 50,000 farm liquidations as directly forced out  
311 of business due to raw milk price dumping and retail exclusion. Multiplying this historically  
312 completed cohort by the rural pension baseline ( $C_{tax} = \text{€}2,400/\text{year}$ ) anchors a locked-in,  
313 empirical human capital loss of €120.00Million) ( $127,187 \times 0.3931 \times \text{€}2,400$ ).

314 4. *Fruit Brandy (Spirits) Sector Calibration*: In the spirits and fruit brandy domain, the  
315 structural estimation of labor and socio-economic displacement avoids frequentist  
316 overestimation by directly tying the laboratory outcomes to the massive volume divergence  
317 within the domestic alcohol market. SORS and Ministry of Agriculture registries unmask a  
318 profound administrative gap of 20 million liters between total estimated national physical  
319 production (56.2 million liters) and legally registered commercial volumes (36.2 million  
320 liters)<sup>33</sup>. Because major tier-1 hypermarkets enforce strict inventory exclusions on domestic  
321 fruit brandies due to chronic traceability deficits and quality non-conformities, this unrecorded  
322 20-million-liter grey layer is systematically diverted into unmonitored HoReCa channels and  
323 fragmented local retail networks. the matrix evaluates the active workforce operating within  
324 the formal distillery core across the 2012–2023 decadal horizon (approximately  $L_{stratified} =$   
325  $L_{sensus\_lost} = 12,000$  agricultural jobs and family-operated orchard holdings)<sup>45</sup>. By applying the  
326 exceptionally high laboratory-verified Bayesian fraud rate ( $\theta = 39.5\%$ ) as the empirical  
327 attribution factor under a baseline annual tax contribution of  $C_{tax} = \text{€}3,000$ , the model isolates  
328 the fraction of the workforce facing severe economic displacement and asset liquidation,  
329 resolving a locked-in, empirically validated human capital loss of €14.22 Million (12,000 x  
330 0.395 x €3,000). This alignment proves that the macro-damage function is driven directly by  
331 the economic hollowing out of the formal production base under the pressure of non-fruit  
332 agricultural ethanol substitution.

333

334 *Structural Decapitalization ( $V_{cap}$ )*: This matrix vector measures permanent asset destruction,  
335 biological capital liquidation, and investment paralysis across the agrarian infrastructure core.  
336 To prevent frequentist distribution overestimation and strictly resolve concerns regarding data  
337 inflation, the framework completely isolates internal physical asset failure from liquid market

338 circulation. The decapitalization damage function is operationalized via three distinct macro-  
339 modeling dimensions to encapsulate the multi-sectoral complexity of the supply chain collapse:  
340

341 *1. Agricultural Ecosystem Services and Biomass Erosion:* To maintain strict economic and  
342 nomenclature coherence across all agricultural domains, environmental capital degradation is  
343 completely decoupled from trade or marketing metrics and internalized within the structural  
344 assets matrix. For the apiculture domain, the model integrates the irreversible destruction of  
345 natural agricultural infrastructure driven by honeybee winter malnutrition and colony collapse  
346 wave anomalies. It is formalized as:

347

$$V_{cap(Ecology)} = (N_{hives} \times \%_{loss} \times P_{unit}) + \sum (Crop_{yield} \times Dep_{bees}) \quad (5b)$$

348

349 where  $N_{hives}$  represents the professional production-core hives monitored by SPOS/SORS  $\%_{loss}$   
350 is the longitudinal baseline winter mortality rate driven by forced carbohydrate sugar-syrup  
351 overwintering,  $P_{unit}$  is the biological replacement cost per colony, and the second term  
352 aggregates the total national Ecosystem Service Value ( $ESV$ ) loss calculated via the National  
353 Pollination Model, where  $Crop_{yield}$  represents the baseline dependent agricultural crop output  
354 and  $Dep_{bees}$  denotes the specific biotic pollination dependency factor across the regional  
355 viticulture and fruit sectors.

356

357 *2. Suppressed Agrarian Capital and Infrastructure Expansion:* For fixed structural  
358 investments, including vineyard establishment parameters and indigenous fruit orchard grids,  
359 the vector captures the deadweight loss of unrealized infrastructure expansion mandated under  
360 national development strategy baselines. Driven by severe market depression and price  
361 suppression from cheap, non-compliant industrial substitutes, planned investments are  
362 structurally paralyzed. The infrastructure gap function is formalized as:

$$V_{cap(infrastructure)} = Area_{lost} \times \theta \times I_{ha} \quad (5a)$$

363

364 where  $A_{lost}$  is the structural execution gap in national agrarian assets (calculated as the net  
 365 discrepancy between the target area mandated by national strategic masterplans and the  
 366 fractional actual area successfully established over the observed multi-year period),  $\theta$  is the  
 367 sector-specific Bayesian non-compliance penetration rate acting as the investment suppression  
 368 filter, and  $I_{ha}$  represents the standardized capital investment cost required for land preparation,  
 369 biological plantings, and technological infrastructure per hectare.

370

371 *3. Biological Asset and Herd Amortization Loss:* For living production capital – specifically  
 372 high-yield livestock assets within the dairy matrix – the model deploys a threshold temporal  
 373 function to capture accelerated herd liquidation compounded by unamortized, stranded private  
 374 investments in farm infrastructure (e.g., robotic milking networks, automated cold-storage  
 375 tanks). It is mathematically formalized as:

376

$$\left[ \frac{N_{cows} \times V_{al}}{T_{am}} \right] + (N_{gen} \times P_{gen}) \quad (5)$$

377

378 where  $N_{cows}$  represents the documented net long-term headcount reduction of high-yield dairy  
 379 cows within national registries<sup>36,37</sup>,  $V_{al}$  is the comprehensive asset replacement cost per head,  
 380  $T_{amortization}$  denotes the remaining productive asset lifecycle and biological amortization time  
 381 horizon (analytically locked at 2.417 years for high-yield dairy herds facing forced slaughter  
 382 cycles),  $N_{gen}$ : represents high-yield genetic core assets and  $P_{gen}$  value of localized  
 383 Simmental/Holstein strains.

384

385 *4. Formal Distillery Core and Perennial Orchard Decapitalization:* For the spirits and high-  
 386 proof distillation sector, the model measures the irreversible structural contraction of the formal

387 rural economy and the liquidation of specialized perennial fruit assets. Driven by market-  
388 clearing price suppression from illicit industrial ethanol substitutes, this dimension captures the  
389 simultaneous destruction of traditional processing infrastructure and the forced extraction of  
390 indigenous fruit orchard holdings. It is mathematically formalized as:

$$V_{proj} \times (1 - R_{real}) + V_{structural\ erosion} \quad (5d)$$

392  
393 where  $V_{proj}$  represents the baseline projected gross economic output of the formal distillery  
394 sector over the evaluated multi-year period,  $R_{real}$  is the empirical retention rate of formal market  
395 actors operating under non-distorted economic conditions, and  $V_{structural\_erosion}$  operationalizes  
396 the localized physical and asset-based destruction within the distillation core – analytically  
397 locked to prevent linear back-casting distortions at the census-derived baseline ( $L_{stratified} =$   
398  $L_{census\_lost} = 12,000$  agricultural jobs and family-operated holdings).<sup>45</sup>

399  
400 *Strategic Brand Equity and Externality Loss ( $V_{ext}$ ):* This vector quantifies the long-term  
401 macroeconomic opportunity cost of lost foreign exchange reserves, structural export  
402 suppression, and country-of-origin brand devaluation across international trade networks.  
403 When local agro-food lines are saturated with non-compliant counterfeits, legitimate domestic  
404 processors face severe geopolitical trust discounts on foreign markets. This prevents the  
405 industry from leveraging high-value pricing models or achieving certified Protected  
406 Designation of Origin (PDO) and Protected Geographical Indication (PGI) status within elite  
407 supply networks (such as the EU common market). To maintain strict economic coherence and  
408 prevent systemic double-counting, environmental externalities – specifically the Ecosystem  
409 Service Value (ESV) of honeybee biotic pollination – and biological biomass collapses are  
410 completely decoupled from this matrix and isolated within the Structural Decapitalization  
411 vector  $V_{cap}$ . The global brand erosion and export opportunity loss function is operationalized

412 dynamically via four sector-specific macro-modeling dimensions to encapsulate the  
413 international trade distortions:

414

415 *1. Apiculture Premium Certification Gap:* For the honey production sector, this dimension  
416 quantifies the direct loss of foreign exchange reserves caused by the prevalence of adulterated  
417 products in the supply chain. Because international border controls apply high geopolitical trust  
418 discounts to regions with frequent counterfeit alerts, legitimate monofloral honey exports are  
419 structurally blocked from entering elite retail networks. It is mathematically formalized as:

420

$$V_{ext(apiculture)} = V_{Export\_potential(apiculture)} \times \theta_{apiculture} \quad (6a)$$

421

422 where  $V_{Export\_potential(apiculture)}$  denotes the maximum theoretical export capacity of verified  
423 organic and monofloral honey assets monitored by SPOS, and  $\theta_{apiculture}$  is the friction index  
424 representing the international market exclusion rate.

425

426 *2. Perennial Fruit and Viticulture Value Compression:* For the fruit and vineyard sectors, the  
427 vector captures the deadweight loss of unrealized premium pricing in international networks.  
428 The presence of systemic market fraud prevents domestic producers from successfully securing  
429 and capitalizing on PDO and PGI certifications, forcing high-value geographical varieties to  
430 be exported as low-margin bulk commodities. It is mathematically formalized as:

431

$$V_{ext(fruit)} = V_{export\_potential(fruit)} \times \theta_{fruit} \quad (6b)$$

432

433 where  $V_{Export\_potential(fruit)}$  operationalizes the targeted export revenue derived from certified  
434 geographical indications, and  $\theta_{fruit}$  represents the Bayesian non-compliance penetration rate  
435 suppressing premium brand equity.

436 3. *High-Yield Dairy Export Deficit*: For the dairy and livestock sector, the model measures the  
437 international trade opportunity cost driven by the erosion of compliance protocols and national  
438 quality standards. The massive influx of non-compliant industrial substitutes undermines the  
439 export potential of premium dairy commodities to highly regulated international markets. It is  
440 mathematically formalized as:

441

$$V_{ext(dairy)} = V_{export\_potential(dairy)} \times \theta_{dairy} \quad (6c)$$

442

443 where  $V_{Export\_potential(dairy)}$  represents the baseline projected value of high-end dairy exports under  
444 non-distorted trade conditions, and  $\theta_{dairy}$  acts as the sector-specific market distortion filter  
445 driven by quality degradation.

446

447 4. *Spirits and Premium Distillation Trade Suppression*: For the spirits and high-proof  
448 distillation sector, the model measures the long-term macroeconomic cost of lost international  
449 market expansion for traditional premium distillates. The saturation of the domestic market  
450 with cheap, non-compliant industrial ethanol damages the collective country-of-origin brand  
451 equity, restricting authentic geographical brands to localized consumption. It is mathematically  
452 formalized as:

453

$$V_{ext(spirits)} = V_{Export\_potential(spirits)} \times \theta_{spirits} \quad (6d)$$

454

455 where  $V_{Export\_potential(spirits)}$  represents the projected multi-year export value of the formal  
456 distillery core operating under strict regulatory enforcement, and  $\theta_{spirits}$  is the trade suppression  
457 coefficient driven by the domestic market-clearing distortions.

458

459 *Auxiliary Industry and Supply Chain Loss ( $V_{aux}$ ):* This matrix vector quantifies the structural,  
460 collateral revenue destruction and downstream demand contraction induced within adjacent  
461 upstream processing layers. The economic damage penetrates secondary sectors – including  
462 industrial glass manufacturing, commercial packaging printing, transport logistics, grain  
463 supply matrices, and specialized veterinary pharmaceutical services – whose operational  
464 volumes are compressed by the proliferation of non-compliant market circulation. To reflect  
465 economic reality and maintain rigorous mathematical alignment with the primary market  
466 dislocation models, the damage function avoids static linear multipliers. Instead, it is  
467 operationalized dynamically by factoring the active sectoral volume baseline against the  
468 empirically verified Bayesian non-compliance penetration rate ( $\theta$ ) and the localized unit cost  
469 framework via four sector-specific supply chain dimensions:

470

471 *1. Apiculture Hive-Equipment and Remediation Loss:* For the honey sector, this dimension  
472 quantifies the economic contraction within the specialized beekeeping equipment  
473 manufacturing sector, organic hive-treatment pharmaceutical lines, and queen-breeding  
474 centers. It is mathematically formalized as:

475

$$V_{aux(apiculture)} = Q_{stratified(apiculture)} \times \theta_{apiculture} \times C_{aux\_unit(apiculture)} \quad (7a)$$

476

477 where  $Q_{stratified(apiculture)}$  operationalizes the domestic consumption baseline of authentic honey,  
478  $\theta_{apiculture}$  is the international market exclusion and fraud rate, and  $C_{aux\_unit(apiculture)}$  represents the  
479 standardized maintenance, wax-foundation, and biological treatment cost per kilogram of  
480 honey production core.

481

482 2. *Viticulture and Perennial Fruit Logistics Erosion*: For the wine and fruit sectors, the vector  
483 captures the secondary demand shock felt by commercial packaging industries, container  
484 printing facilities, and regional transport logistics networks. It is mathematically formalized as:  
485

$$V_{aux(fruit)} = Q_{stratified(fruit)} \times \theta_{fruit} \times C_{aux\_unit(fruit)} \quad (7b)$$

486  
487 where  $Q_{stratified(fruit)}$  is the volumetric baseline calculated via the Apparent Domestic  
488 Consumption framework for genuine fruit and wine products,  $\theta_{fruit}$  is the non-compliance  
489 penetration filter, and  $C_{aux\_unit(fruit)}$  represents the baseline packaging and logistics cost per liter  
490 or kilogram of displaced high-value agricultural output.

491  
492 3. *Dairy Processing and Veterinary Supply Contraction*: For the livestock and dairy sector,  
493 this dimension measures the collateral revenue loss inflicted on veterinary pharmaceutical  
494 networks, specialized feed and grain supply matrices, and automated milking equipment  
495 maintenance services. It is mathematically formalized as:

$$V_{aux(dairy)} = Q_{stratified(dairy)} \times \theta_{dairy} \times C_{aux\_unit(dairy)} \quad (7c)$$

496  
497  
498 where  $Q_{stratified(dairy)}$  represents the physical milk collection gap within the fluid dairy stream,  
499  $\theta_{dairy}$  is the Bayesian fraud rate driving the market contraction, and  $C_{aux\_unit(dairy)}$  denotes the  
500 standardized unit cost of veterinary, dietary, and technical services per liter of uncollected milk.

501  
502 4. *Formal Distillery Glass and Industrial Packaging Collapse*: For the spirits and high-proof  
503 distillation sector, the model measures the massive downstream demand destruction within the  
504 high-end industrial glass manufacturing sector (specialized bottles) and commercial label  
505 printing. It is mathematically formalized as:

$$V_{aux(spirits)} = Q_{stratified(spirits)} \times \theta_{spirits} \times C_{aux\_unit(spirits)} \quad (7d)$$

506

507 where  $Q_{stratified(spirits)}$  represents the volumetric production baseline of the formal distillation  
 508 core,  $\theta_{spirits}$  is the trade suppression coefficient driven by illicit ethanol substitutes, and  
 509  $C_{aux\_unit(spirits)}$  denotes the standardized unit cost of custom glass containers, secure closure  
 510 systems, and marketing packaging per liter of pure alcohol equivalent.

511

512 *Subsidy Waste and Fictitious Asset Leakage ( $V_{sub}$ ):* This matrix vector measures the direct  
 513 fiscal dissipation, non-productive leakage, and structural inefficiency of public state funds,  
 514 sector development grants, and export incentives. In distorted agricultural markets, public  
 515 finances inadvertently subsidize non-compliant or fraudulent operators, or are extracted via  
 516 artificial registry expansions designed to capture direct head-count or hive payments while  
 517 genuine domestic production is systematically squeezed from retail shelves. To encapsulate  
 518 this structural leakage without introducing frequentist distribution inflation, the framework  
 519 utilizes the laboratory-proven Bayesian non-compliance frequency  $\theta$  as an empirical attribution  
 520 and efficiency filter applied directly to the aggregate sectoral subsidy funds via four distinct  
 521 fiscal dimensions:

522

523 *1. Apiculture Fictitious Hive Registry Extraction:* For the honey sector, this dimension  
 524 measures the direct fiscal extraction of per-hive government incentives. It isolates the public  
 525 funds drained by artificially inflated hive registries, where operators claim direct payments for  
 526 non-productive or biologically collapsed colonies. It is mathematically formalized as:

527

$$V_{sub(apiculture)} = G_{incentives(apiculture)} \times \theta_{apiculture} \quad (8a)$$

528

529 where  $G_{incentives(apiculture)}$  denotes the total annual budget allocations for beekeeping incentives  
530 and conservation grants monitored by national registries (see Supplementary Table 7, Honey  
531 section, Note <sup>b)</sup>), and  $\theta_{apiculture}$  is the empirical non-compliance frequency driving the fiscal  
532 leakage.

533

534 *2. Viticulture and Perennial Fruit Infrastructure Grant Leakage:* For the wine and orchard  
535 sectors, the vector captures the non-productive dissipation of state and IPARD co-financing  
536 grants intended for vineyard establishment, land preparation, and technological modernization.  
537 It measures the fiscal leakage where subsidized assets fail to reach the mandated strategic  
538 output due to market-clearing price suppression. It is mathematically formalized as:

539

$$V_{sub(fruit)} = G_{incentives(fruit)} \times \theta_{fruit} \quad (8b)$$

540

541 where  $G_{incentives(fruit)}$  operationalizes the aggregate national and international development grants  
542 allocated for long-term biological plantings and orchard infrastructure, and  $\theta_{fruit}$  acts as the  
543 investment suppression and non-compliance penetration filter.

544

545 *3. Dairy Headcount and Premium Milk Subsidy Dissipation:* For the livestock and dairy sector,  
546 this dimension quantifies the leakage of direct government premiums paid per liter of fluid  
547 milk and animal headcount incentives. The model filters out the fiscal resources captured by  
548 non-compliant streams that fail to meet strict food safety or volume compliance protocols. It is  
549 mathematically formalized as:

550

$$V_{sub(dairy)} = G_{incentives(dairy)} \times \theta_{dairy} \quad (8c)$$

551

552 where  $G_{incentives(dairy)}$  represents the total documented annual national budget allocations,  
553 premium milk payouts, and direct animal headcount subsidies earmarked for the dairy domain,  
554 and  $\theta_{dairy}$  is the Bayesian posterior probability mode establishing the boundary of systemic  
555 market non-compliance.

556

557 *4. Formal Distillery Certification and Marketing Subsidy Suppression:* For the spirits and high-  
558 proof distillation sector, the model measures the waste of public funds directed toward national  
559 brand promotion, geographic indication development, and regulatory compliance grants. This  
560 leakage occurs when legitimate subsidized distilleries are driven out of the market by cheap,  
561 illicit substitutes, rendering the state's strategic investments ineffective. It is mathematically  
562 formalized as:

$$V_{sub(spirits)} = G_{incentives(spirits)} \times \theta_{spirits} \quad (8d)$$

563

564 where  $G_{incentives(spirits)}$  represents the total earmarked public and regional funds for distillation  
565 technological upgrades and premium certification marketing, and  $\theta_{spirits}$  is the trade suppression  
566 coefficient acting as the fiscal efficiency filter.

567

568 *Economic Multiplier (k):* To capture cascading macro-level impacts, we applied a sector-  
569 specific multiplier derived from the Leontief Input-Output model. A conservative value of  
570  $k=1.45$  was utilized for the agricultural region. This value reflects the secondary economic  
571 activity generated by primary production, accounting for backward linkages, such as fertilizers,  
572 energy, and seeds, alongside forward linkages across processing, logistics, and retail channels.

573 Supplementary Table 7: Methodological Breakdown and Input Variables of the Integrated Loss Quantization (ILQ) Framework

Sector	Vector	Input Variables & Baseline Values	Calculation Logic	Primary Formula / Calculation	Applied Data (Parameters)	Resulting Value
Honey	$V_{md}$	<sup>a)</sup> $Q$ : Apparent Domestic Consumption baseline (~7,000,000 kg), calculated via national registries as: $Q_{production}$ (8,000 t) + $Q_{import}$ (1,150 t) - $Q_{export}$ (2,150 t); $\theta$ : Bayesian market non-compliance penetration rate (79.71%); $P_{target}$ (Authentic Retail Price): €4.50/kg (The baseline value of genuine domestic honey); $P_{actual}$ (Suppressed Retail Price): €1.30/kg (The market price driven down by illicit glucose/fructose syrup substitutes); $\Delta P$ : Price gap (€3.20 kg).	Revenue loss due to market displacement by cheap syrup	$Q \times \theta \times (P_{target} - P_{actual})$	$7,000,000 \times 79.71\% \times (\text{€}4.50 - \text{€}1.30)$	€17.86 Million
	$V_{fg}$	<sup>a)</sup> $Q$ : Apparent Domestic Consumption baseline (~7,000,000 kg), calculated via national registries as: $Q_{production}$ (8,000 t) + $Q_{import}$ (1,150 t) - $Q_{export}$ (2,150 t); $\theta$ : Bayesian market non-compliance penetration rate (79.71%); $P_{target}$ : Authentic retail market price baseline (€11.0/kg); $P_{actual}$ : Suppressed counterfeit price (€4.50/kg); $VAT_{honey}$ : 10% lower rate; $VAT_{syrup}$ : 20% standard rate.	Fiscal deficit driving double-vector VAT evasion: captures both retail price suppression and illegal tax rate arbitrage (declaring 20% taxable industrial sugar syrups under the 10% honey baseline).	$[Q \times \theta \times \Delta P \times VAT_{honey}] +$ $[Q \times \theta \times P_{actual} \times (VAT_{syrup} - VAT_{honey})]$	$[7,000,000 \times 79.71\% \times \text{€}6.50/kg \times 0.10] + [7,000,000 \times 79.71\% \times \text{€}4.50/kg \times (20\% - 10\%)]$	€6.14 Million
	$V_{hc}$	$L$ : Labor force (15k beekeepers); $C_{tax}$ : Annual contrib. (€3,000); $\theta$ : 79.71%	Loss of social/health contributions due to informal labor	$L \times \theta \times C_{tax}$	$15,000$ (beekeepers) $\times$ 79.71% $\times$ €3,000 (Annual social contrib.)	€35.87 Million
	$V_{cap}$	<sup>a)</sup> $N_{hives}$ : 800,000 professional production-core hives (SPOS/SORS multi-year median baseline); $\%_{loss\_baseline}$ : 20% effective multi-year longitudinal winter mortality average recorded across domestic apiaries; $\theta$ : 79.71% Bayesian non-compliance penetration rate acting as the primary economic stress driver; $\alpha_{induced}$ : 23.70% fraud-induced attribution coefficient (capturing the portion of multi-year mortality structurally locked by economic malnutrition and forced sugar-syrup overwintering: $\theta \times \alpha_{induced} = \%_{loss\_baseline}$ ); $P_{unit}$ : Standard replacement cost of a biological colony and queen (€150); $ESV$ : Ecosystem Service Value of biotic pollination; $Dep_{bees}$ : Bee dependence factor baseline	Aggregates the replacement cost of lost biological hive assets with the deadweight loss of agricultural ecosystem services (pollination deficit causing structural crop yield contraction across dependent viticulture and fruit sectors).	$(N_{hives} \times (\theta \times \alpha_{induced}) \times P_{unit}) + \sum(Crop_{yld} \times Dep_{bees})$	$(800,000 \times (79.71\% \times 23.70\%) \times \text{€}150) + \text{€}614.7 M$	€637.37 Million
	$V_{ext}$	$V_{export}$ : €50.0 Million (The projected annualized export revenue premium of authentic, traceable domestic honey under full compliance); $P_{penalty}$ : 25% (Country-of-origin trust discount applied by international retail networks due to unverified adulteration risks).	Quantifies the opportunity cost of lost foreign exchange reserves and structural export suppression driven by international compliance	$V_{export} \times P_{penalty}$	$\text{€}50.0 M \times 25\%$	€12.50 Million

			penalties and brand erosion.			
	$V_{aux}$	<p><sup>a)</sup> <math>Q</math>: Apparent Domestic Consumption baseline (~7,000,000 kg), calculated via national registries as: <math>Q_{production}</math> (8,000 t) + <math>Q_{import}</math> (1,150 t) - <math>Q_{export}</math> (2,150 t);</p> <p><math>\theta</math>: Bayesian market non-compliance penetration rate (79.71%);</p> <p><math>C_{pack}</math>: Unit cost of auxiliary supply chain elements, covering glass jars, labels, transport packaging, and required honeybee veterinary treatments (€4.54/kg).</p>	Quantifies collateral revenue loss and structural demand destruction within adjacent upstream sectors, including glass manufacturing, commercial packaging production, industrial logistics, and specialized veterinary pharmaceutical services disrupted by non-compliant market circulation.	$Q \times \theta \times C_{pack}$	$7,000,000 \times 79.71\% \times €4.54(\text{packaging/vet costs})$	€25.33 Million
	$V_{sub}$	<p><sup>b)</sup> <math>G_{subsidies}</math>: €9.60 Million (Total annual state budget allocations and national direct-payment subsidies earmarked per registered hive wave);</p> <p><math>\theta</math>: 79.71% Bayesian non-compliance penetration rate functioning as the structural leakage and non-compliance filter.</p>	Measures the direct fiscal dissipation of public state funds via fictitious asset leakage or artificial registrations, where high national direct-payment subsidies are extracted to maintain non-productive colonies while the local retail market is displaced by cheap syrup.	$G_{subsidies} \times \theta$	$€9,600,000 \times 79.71\%$	€7.65 Million
<p><sup>a)</sup> This operational parameter establishes the baseline for Apparent Domestic Consumption (<math>Q \sim 7,000,000</math> kg), derived from national registries via the standard mass-balance equation: <math>Q = Q_{production} + Q_{import} - Q_{export}</math>. To iron out extreme, climate-driven supply-side shocks, this model utilizes an empirically calibrated two-year rolling baseline (2024–2025). The primary biological constraints capture an all-time production peak of 14,664 tons in 2024<sup>42</sup>, contrasted by a severe climate-induced sector collapse to ~3,000 tons in 2025 triggered by extensive acacia freezing and multi-regional bee mortality. Integrating these raw physical variables with the corresponding SORS external trade registries logs a computed average multi-year export vector of 2,568.95 tones<sup>42</sup> and an average sub-standard import vector of 1,040.95 tons [SORS]<sup>42</sup>. This robust econometric filtration neutralizes seasonal inventory hoarding, shielding the Bayesian fraud probability indices against single-year data distortions.</p> <p><sup>b)</sup> The baseline variable <math>G_{subsidies} = €9.60</math> Million models the aggregate fiscal volume of annual state budget allocations and national direct-payment subsidies earmarked strictly for the registered beekeeping sector. According to the official regulatory framework of the Directorate for Agrarian Payments (UAP), national direct incentives are legally fixed at 1,000 RSD per registered beehive. The total approved public funding for the national UAP Direct Incentives Scheme stands at 1.15 Billion RSD (approximately €9.82 Million at prevailing exchange rates). To ensure analytical robustness and eliminate temporary market fluctuations from the calculation, this study applies a highly strict and conservative baseline of €9.60 Million to reflect the guaranteed net institutionalized funding wave distributed per registered hive wave.</p>						
Wine	$V_{md}$	<p><sup>a)</sup> <math>Q</math>: Apparent Domestic Consumption baseline (~37,000,000 L), systematically operationalized via national registries as: <math>Q_{production}</math> (~25.0M L) + <math>Q_{import}</math> (~23.0M L) - <math>Q_{export}</math> (~11.0M L);</p> <p><math>\theta</math>: 57.75% Bayesian wine market non-compliance penetration rate functioning as the structural filter;</p> <p><math>\Delta P</math>: Weighted macroeconomic price gap and margin loss driven by cheap industrial surrogates (€6.50/L).</p>	Direct loss of gross revenue for domestic producers driven by the market-share weighted displacement of authentic domestic wine by non-compliant industrial counterfeits within the domestic consumption footprint.	$Q \times \theta \times \Delta P$	$37,000,000 \text{ L} \times 57.75\% \times €6.50/\text{L}$	€138.89 Million
	$V_{fg}$	<p><sup>a)</sup> <math>Q</math>: Apparent Domestic Consumption baseline (~37,000,000 L), systematically operationalized via national registries as: <math>Q_{production}</math> (~25.0M L) + <math>Q_{import}</math> (~23.0M L) - <math>Q_{export}</math> (~11.0M L);</p>	Uncollected VAT and fiscal leakage driven by retail price suppression and unrecorded input VAT	$Q \times \theta \times (P_{target} - P_{actual}) \times VAT$	$37,000,000 \text{ L} \times 57.75\% \times (€15.00 - €6.50) \times 0.20$	€36.32 Million

		<p><math>\theta</math>: 57.75% Bayesian wine market non-compliance penetration rate;</p> <p><math>P_{target}</math>: Authentic wine retail price baseline (€15.0/L);</p> <p><math>P_{actual}</math>: Suppressed counterfeit retail price baseline (€6.5/L);</p> <p>VAT: Standard national value-added tax rate (20%).</p>	arbitrage inside the non-compliant commercial footprint.			
$V_{hc}$	<p><math>L_{lost}</math>: ~40,000 jobs lost - family-operated vineyard holdings permanently liquidated;</p> <p><math>C_{tax}</math>: Avg. Agri Contribution (€2,500);</p> <p><math>\theta</math>: 57.75%</p>	Lost payroll taxes and pension fund contributions	$L_{lost} \times \theta \times C_{tax}$	$40,000 (lost\ jobs) \times 57.75\% \times 2,500 \left(\frac{contributions}{tax}\right)$	€57.75 Million	
$V_{cap}$	<p><sup>b)</sup> <math>A_{target}</math>: 25,000 hectares (Total planned new vineyard expansion target mandated by the National Viticulture Development Strategy);</p> <p><math>A_{actual}</math>: 500 hectares (The baseline area successfully established over the observed multi-year period due to severe market depression);</p> <p><math>A_{lost}</math>: 24,500 hectares (The structural execution gap in national agrarian assets:</p> <p><math>A_{target} - A_{actual}</math>);</p> <p><math>\theta</math>: 57.75% Bayesian wine market non-compliance penetration rate acting as the investment suppression filter;</p> <p><math>I_{ha}</math>: Standard capital investment cost required for vineyard establishment and infrastructure (€24,400/ha).</p>	Loss of potential capital investment in premium vineyards, capturing the deadweight loss of unrealized strategic agrarian infrastructure suppressed by unfair non-compliant competition and retail base dilution.	$Area_{lost} \times \theta \times I_{ha}$	$24,500 \times 57.75\% \times €24,400$	€345.24 Million	
$V_{ext}$	<p><math>V_{brand}</math>: €173.16 Million (The projected annualized gross revenue baseline of premium domestic wine tourism and international origin-brand equity under full authenticity enforcement);</p> <p><math>\theta</math>: 57.75% Bayesian wine market non-compliance penetration rate functioning as the country-of-origin trust penalty filter.</p>	Quantifies the opportunity cost of lost foreign exchange reserves, structural tourism degradation, and export premium suppression driven by international compliance penalties and brand erosion.	$V_{brand} \times \theta$	$€173,160,000 \times 57.75\%$	€100 Million	
$V_{aux}$	<p><sup>a)</sup> <math>Q</math>: Apparent Domestic Consumption baseline (~37,000,000 L), systematically operationalized via national registries as: <math>Q_{production}</math> (~25.0M L) + <math>Q_{import}</math> (~23.0M L) – <math>Q_{export}</math> (~11.0M L);</p> <p><math>\theta</math>: 57.75% Bayesian wine market non-compliance penetration rate;</p> <p><math>C_{aux\_unit}</math>: Unit cost of upstream supply chain logistics, covering glass bottles, natural corks, labels, and industrial transport (€5.00/L).</p>	Quantifies collateral revenue loss and structural demand destruction within adjacent upstream sectors, including glass manufacturing, cork processing, and commercial transport logistics disrupted by non-compliant market circulation.	$Q \times \theta \times C_{aux\_unit}$	$37,000,000\ L \times 57.75\% \times €5.00/L$	€106.84 Million	
$V_{sub}$	<p><math>S_{total}</math>: €50.0 Million (Total annual state budget allocations, viticulture structural development grants, and national wine sector subsidies over the observed period);</p>	Measures the direct fiscal dissipation of public state funds and sector incentives leaked through non-	$S_{total} \times \theta$	$€50,000,000 \times 57.75\%$	€28.88 Million	

		$\theta$ : 57.75% Bayesian wine market non-compliance penetration rate functioning as the structural leakage and non-compliance filter.	compliant production chains, where state development grants fail to generate productive assets due to illicit market displacement.			
<p><sup>a)</sup> This operational parameter establishes the baseline for Apparent Domestic Consumption (<math>Q_{wine} \approx 37,000,000</math> L), systematically operationalized via national registries through the standard macroeconomic mass-balance equation: <math>Q = Q_{production} (25.0 \text{ M L}) + Q_{import} (23.0 \text{ M L}) - Q_{export} (11.0 \text{ M L})</math>. To immunize the viticulture damage vectors against single-year yield or inventory anomalies, this baseline operates as a stabilized macro-model exhibiting exceptional empirical convergence with the peer-reviewed historical indicators compiled by Vlahović et al. and the Ministry of Agriculture<sup>43</sup>. These registries document a baseline national production core of <math>\sim 24.0 \text{ M L}</math>, a mean import line of <math>22.3 \text{ M L}</math> (driven predominantly by bulk triangulation where North Macedonia commands a 69.1% share), and a mean high-tier export line of <math>11.5 \text{ M L}</math><sup>43</sup>. The minor residual variance (<math>\sim 2.2 \text{ M L}</math>) is systematically absorbed as non-marketed on-farm stock buffering and technical cellar loss (kalo), ensuring that subsequent isotopic deviation models tracking raw bulk triangulation or artificial dilution lines operate on verified, long-term commercial realities.</p>						
Dairy	$V_{md}$	<p><sup>a)</sup> <math>Q_{excl}</math>: 536,240,557 L (Volumetric baseline systematically displaced by industrial surrogates [Supp. Fig. 1], corresponding to the historical loss of 164,004 dairy cows over the last 10 years);</p> <p><math>\theta</math>: 100% attribution weight (reflecting that the entire statistical gap consists of unrecorded powder reconstitution, permeate dilution, and spot surrogates);</p> <p><math>P_{target}</math>: Sustainable domestic farm-gate target price baseline (€0.64/L);</p> <p><math>P_{actual}</math>: Suppressed actual surrogate-equivalent input price baseline driven by cheap imported powder and permeate vectors (€0.21/L);</p> <p><math>\Delta P</math>: Macroeconomic price gap (€0.43/L).</p>	Revenue gap between sustainable target farm-gate price and suppressed actual input price due to surrogate dilution (permeate, spot imports, and powder reconstitution) across fluid and fermented commercial processing lines.	$Q_{excl} \times \theta \times (P_{target} - P_{actual})$	$536,240,557 \text{ L} \times 100\% \times (\text{€}0.64 - \text{€}0.21)$	€230.58 Million
	$V_{fg}$	<p><math>Q_{iso\_dev}</math>: 84,428,872 L (Volume verified via EIM-IRMS isotope fraud lines);</p> <p><sup>b)</sup> <math>Q_{farm\_jaz}</math>: 93,912,621 L (Unrecorded farm-gate shadow processing volume);</p> <p><math>M_{analog}</math>: 35,000,000 kg (Total volume of imitation analog cheese entering commercial circulation);</p> <p><math>P_{avg}</math>: €2.857/L;</p> <p><math>P_{processing}</math>: €1.50/L;</p> <p><math>P_{cheese}</math>: €8.00/kg;</p> <p><math>P_{fake}</math>: €4.00/kg;</p> <p><math>VAT_{milk}</math>: 10% special lower rate [SORS];</p> <p><math>VAT_{analog}</math>: 20% standard national rate [SORS].</p>	Fiscal revenue erosion driving multi-vector VAT evasion: captures retail price suppression in fluid lines, unrecorded farm-gate shadow processing, and cross-sectoral tax base arbitrage from imitation analog cheese misdeclared under dairy baselines.	$\Sigma(VAT_{milk} + VAT_{farm} + \Delta VAT_{cheese}) = [(Q_{iso\_dev} \times P_{avg} \times VAT_{milk}) + (Q_{farm\_jaz} \times P_{processing} \times VAT_{milk}) + (M_{analog} \times (P_{cheese} - P_{fake}) \times (VAT_{analog} - VAT_{milk}))]$	$[(84,428,872 \text{ L} \times \text{€}2.857 \times 0.10) + (93,912,621 \text{ L} \times \text{€}1.50 \times 0.10) + (35,000,000 \text{ kg} \times (\text{€}1.60 - \text{€}0.40) \times 0.10)]$	€42.41 Million
	$V_{hc}$	<p><sup>c)</sup> <math>L_{closed}</math>: <math>\sim 127,187</math> - total smallholder dairy/livestock farm units permanently liquidated;</p> <p><math>C_{pensions}</math>: €2,400.00/year;</p> <p><math>\theta</math>: 39.31%</p>	Total loss of social security and mandatory PIO contributions for rural households forced out of business due to raw milk dumping.	$L_{closed} \times \theta \times C_{pensions}$	$127,187 \times 39.31\% \times \text{€}2,400$	€120.00 Million

$V_{cap}$	<p><sup>d)</sup> <math>N_{cows}</math>: 164,004 heads (The documented long-term net reduction of high-yield dairy cows within the national livestock fund [SORS]);</p> <p><math>V_{ai}</math>: €2,500/head (Standard asset valuation covering the biological replacement cost of a high-yield dairy cow and its proportional share of stranded farm infrastructure, including milking robots and automated storage tanks);</p> <p><math>T_{am}</math>: 2.417 years (The macro-amortization time horizon and remaining productive asset lifecycle of high-yield livestock herds under accelerated liquidation);</p> <p><math>N_{gen}</math>: 32,000 units (High-yield genetic core assets);</p> <p><math>P_{gen}</math>: €2,500/unit (Value of localized Simmental/Holstein strains).</p>	Aggregates the annualized amortization loss of liquidated livestock herds and stranded farm infrastructure with the permanent deadweight loss of high-yield national genetic core assets under localized selection schemes.	$\left[ \frac{N_{cows} \times V_{ai}}{T_{am}} \right] + (N_{gen} \times P_{gen})$	$\left[ \frac{164,004 \times €2,500}{2.417} \right] + (32,000 \times €2,500)$	€249.64 Million
$V_{ext}$	<p><math>V_{export}</math>: €100.0 Million (Projected annualized dairy export revenue potential under full compliance across regional networks);</p> <p><math>\theta</math>: 39.31% Bayesian milk non-compliance penetration rate functioning as the international brand discount filter.</p>	Quantifies the opportunity cost of lost foreign exchange reserves and structural export suppression driven by regional compliance penalties and brand erosion due to unrecorded surrogate utilization.	$V_{export} \times \theta$	$€100,000,000 \times 39.31\%$	€39.31 Million
$V_{aux}$	<p><math>V_{md}</math>: €230,583,439 (The validated market dislocation and dumping damage baseline driven by surrogate dilution);</p> <p><math>\theta</math>: 39.31% Bayesian milk non-compliance penetration rate, functioning as the structural upstream linkage and supply-chain contraction coefficient.</p>	Quantifies collateral revenue loss and structural demand destruction within adjacent upstream sectors, including commercial feed mills, grain suppliers, and local veterinary pharmaceutical services aggregate via integrated supply chain contraction.	$(V_{md} \times \theta)$	$(€230,583,439 \times 39.31\%)$	€90.64 Million
$V_{sub}$	<p><math>N_{fict}</math>=78,125 heads;</p> <p><math>Sub_{unit}</math>=€1,756.39/head;</p> <p><math>Q_{excl}</math>=536,240,557 L;</p> <p><math>Prem_{unit}</math>=€0.162/L</p>	Combined fiscal damage from fraudulent payments for paper-only assets, forfeited national quality premiums (19	$(N_{fict} \times Sub_{unit}) + (Q_{excl} \times Prem_{unit})$	$(78,125 \times €1,756.39) + (536,240,557L \times €0.162)$	€224.09 Million

			RSD/L) due to uncollected raw volumes			
<p><sup>a)</sup> This volumetric baseline (<math>Q_{excl} = 536,240,557</math> L) tracks the formal market-active supply-side deficit generated by the historical reduction of 164,004 dairy cows <sup>c)</sup> over the documented 10-year period, operating under a biological farm-gate productivity baseline of ~3,270 L/cow/year (~3,000 to 3,500 kg/cow/year)<sup>44</sup>. To maintain strict macroeconomic and chemical mass-balance consistency, the full integration of this volume into commercial channels is structurally mapped via Supplementary Figure 1 across three non-overlapping processing lines: (i) 350,000,000 L completely displaced by low-cost analog cheese matrices (vegetable fat/starch structures), (ii) 194,569,954 L driven by surrogate dilution (reconstituted powder, imported permeate, and spot fillers – Supplementary Figure 1) inside fluid and fermented commercial lines, and (iii) a residual 38,639,998.27 L integrated as structural fat/serum carriers (de-fatty milk serum and liquid permeates) within non-dairy processing lines, industrial confectionery bases, and industrial fat emulsions. This comprehensive tracking ensures that the calculated macroeconomic price gap vectors (<math>\Delta P</math>) reflect 100% pure industrial displacement without historical or volume overestimation.</p> <p><sup>b)</sup> This baseline volume (<math>Q_{farm\_jaz} = 93,912,621</math> L) represents a highly conservative estimate, capturing microfilm validation of roughly one-third (~32%) of the total 293.5-million-liter structural gap between total SORS biological production and formal dairy procurement (after accounting for calf nutrition). For full macro-economic transparency, the 2024 national dairy balance sheet consists of: Total Production = 1,310,679,611.65 L (SORS biological ceiling)<sup>44</sup>; Formal Dairy Procurement = 873,000,000 L; and Calf Nutrition = ~144,174,757.28 L (representing ~11% of total production). This restricted volume isolates specifically the market-active, commodified informal supply chain (artisan processing and open-air green markets), ensuring that the economic vectors calculated herein remain grounded in verifiable commercial realities rather than theoretical overestimations.</p> <p><sup>c)</sup> This parameter (<math>L_{closed} \approx 127,187</math> units) logs the net structural liquidation of smallholder dairy and livestock-rearing family farm units across the 2012–2023 census horizon<sup>44</sup>. It represents the absolute contraction of small-scale rural holdings holding fewer than 10 livestock units (LSU), calculated by subtracting the 2023 Overall Census framework from the 2012 SORS baseline matrix (Dataset 1300010204)<sup>44</sup>. This extensive destruction of decentralized production nodes serves as the primary structural explanation for the formal milk collection deficit, proving that the liquidation of these ~127,187 family farms directly mirrors the parallel disappearance of the 164,004 primary production units (cows) and the subsequent raw milk collection gap.</p> <p><sup>d)</sup> The net loss of 164,004 production units documented over the 2012–2023 timeline tracks the structural contraction of the national herd from a historical baseline of approximately 500,000 strictly dairy cows in 2012 down to the active census baseline of 335,996 heads in 2023 <sup>36,37</sup>. The 2012 historical anchor is derived from the official SORS census registry population of 537,708 cows and heifers in calf (Statistical Release PO12, No. 034)<sup>36</sup>. Econometrically, the vast majority of this population (~93%) consists of functional, active dairy cows. Accounting for standard historical structural tiers within the Serbian herd during this baseline year—where young replacement heifers represented ~6% and extensive non-milking suckler beef cows made up ~1% of the total reproductive pool – logically demonstrates that the functional dairy herd operated at a level of approximately 500,000 heads in 2012. This empirical framework cleanses the baseline of non-milking reproductive assets, confirming that the verified reduction of 164,004 units serves as the direct biometrical catalyst for the subsequent volumetric exclusion vectors (<math>Q_{excl}</math>).</p>						
Spirits	$V_{md}$	<sup>a)</sup> R-Registered: 36.2 million liters; $\theta$ : 39.50% $P_{auth}$ (Authentic Market Price): €14.65/L (Equivalent to 1,714 RSD/L; the price the market would pay for genuine fruit brandy); $P_{fraud}$ (Fraudulent Retail Price): €3.05/L (Equivalent to ~357 RSD/L; the average price at which ethanol-based "spirits" are sold); $\Delta P$ : €11.60/L (The direct revenue loss per unit suffered by the legitimate industry due to unfair price competition); G-Grey market: 20 million liters	Direct displacement of premium fruit brandy by ethanol and gray market	$(R \times \theta \times \Delta P) + (G \times \Delta P)$	$(36,200,000 \times 39.50\% \times \frac{€11.60}{L}) + (20,000,000 \times €11.60/L)$	€397.87 Million
	$V_{fg}$	<sup>a)</sup> $Q_{grey}$ : 20.0 million liters (Ministry of Agriculture estimate). Represents 100% loss of Excise ( $E_r$ ) and authentic VAT; $Q_{formal}$ : 36.2 million liters total, with a Bayesian fraud rate; $\theta$ : of 39.50% (14.30 million liters) where industrial ethanol replaces fruit brandy; $E_r$ : Excise Rate (€1.97/L adjusted Feb 2026); $V_{auth}$ : 20% VAT on authentic retail price (€2.44/L); $V_{fraud}$ : 20% VAT on suppressed fraudulent retail price (€0.50/L); VAT Gap: The discrepancy in formal VAT collection is €1.94/L due to price suppression.	Direct Loss (Grey Market): Total loss of Excise and VAT on 20M liters; Indirect Loss (VAT Gap): Loss due to suppressed taxable base on 14.3M liters of fraudulent spirits in the formal sector.	$(Q \times (E_r + V_{fraud}))$ $+ (Q_{formal} \times \theta$ $\times (V_{auth} - V_{formal}))$	$(20,000,000 L \times (€1.97 + €2.44)) + (36,200,000 L \times 39.50\% \times (€2.44 + €0.50))$	€50.86 Million

$V_{hc}$	<p><sup>b)</sup> <math>L_{sensus\_lost}</math>: 12,000 total regional fruit-orchard holdings permanently liquidated or uprooted due to market exclusion;</p> <p><math>C_{tax}</math>: €3,000 annual baseline state fiscal, health, and local corporate tax loss per formal distiller/holding.</p> <p><math>\theta</math>: 39.50%</p>	Loss of specialized vocational human capital	$L_{sensus\_lost} \times \theta \times C_{tax}$	$12,000 \times 39.50\% \times €3,000$	€14.22 Million
$V_{cap}$	<p><math>V_{proj}</math> (Projected CAPEX): €1,450 Million (Total planned investments in modern distillation technology, aging cellars, and orchard expansion);</p> <p><math>R_{real}</math> (Realization Rate): 0.60 (Reflecting that 40% of planned infrastructure remains unrealized due to market instability);</p> <p><math>V_{biomass}</math>: €1,191.6 Million (Total baseline value of the national fruit-orchard biological assets and traditional distillation infrastructure);</p> <p><math>\theta</math> (Bayesian Fraud Rate): 39.50% functioning as the structural capital erosion filter;</p> <p><math>V_{structural\_erosion}</math>: €470.68 Million (Calculated deadweight loss of existing assets driven by market displacement: <math>V_{biomass} \times \theta</math>)</p>	Unrealized infrastructure and technology investments	$V_{proj} \times (1 - R_{real}) + V_{structural\_erosion}$	$(€1,450,000,000 \times 0.40) + (€1,191,600,000 \times 39.50\%)$	€1,050.68 Million
$V_{ext}$	<p><math>V_{export}</math> (Target Export Potential): €1,400 Million (The projected annualized export revenue value of premium, geographically protected fruit brandy if market authenticity standards were fully enforced);</p> <p><math>P_{penalty}</math> (Country-of-Origin Brand Discount): 25% (The structural economic discount and trust penalty applied to developing spirit markets lacking verified traceability matrix controls).</p>	Quantifies the opportunity cost of lost foreign exchange reserves and structural export suppression. While $V_{md}$ operates strictly within the domestic retail footprint, this externality vector captures the country-of-origin trust discount applied on international markets due to unverified compliance networks, preventing premium geographic branding.	$V_{export} \times V_{penalty}$	$€1.4\ billion \times 25\%$	€350 Million
$V_{aux}$	<p><sup>a)</sup> <math>Q_{formal}</math>: 36.2 million liters (Total registered formal volume);</p> <p><math>\theta</math>: 39.50% Bayesian non-compliance penetration rate;</p> <p><math>C_{aux\_unit}</math>: €1.60/L (Estimated baseline supply-chain cost for glass, packaging, and logistics).</p>	Quantifies collateral revenue loss and structural demand destruction within adjacent upstream sectors, including glass manufacturing, packaging production, industrial logistics, and specialized veterinary services disrupted by non-compliant market circulation.	$Q_{formal} \times \theta \times C_{aux\_unit}$	$36,200,000 \times 39.50\% \times \frac{€1.60}{L}$	€22.88 Million
$V_{sub}$	$G_{incentives}$ : €40.0 Million (Total state budget marketing and export grants allocated over the observed period);	Measures the direct fiscal dissipation of public state	$G_{incentives} \times \theta$	$€40,000,000$ (marketing & export grants) $\times$ 39.50%	€15.80 Million

	$\theta$ : 39.50% Bayesian fraud rate functioning as the leakage and non-compliance filter.	funds and export incentives leaked through non-existent operational assets, compromised certification streams, or fraudulent registrations used to extract non-productive subsidies.			
<p>a) This parameter establishes the baseline for Apparent Domestic Spirits Consumption (<math>Q_{spirits} = 56,200,000</math> L), systematically operationalized through your Bayesian framework by merging official manufacturing inputs with verified shadow-market volumes. The baseline is anchored to the Ministry of Agriculture, Forestry and Water Management institutional JAP report<sup>33</sup>, which fixes the Formal Registered Production core at exactly 36.2 million liters based on annual declaration registries. To account for decentralized commercial operations, the model integrates a 20.0-million-liter informal shadow market gap, which represents the market-active commercial surplus derived from the estimated 13.8 million liters circulating outside formal industrial tracking lines (total traditional household baseline estimated at ~50 million liters minus the registered 27.1 million liters of fruit brandy). This consolidated baseline ensures that the subsequent fraud probability loops - which map a critical mass of 34.3 million liters of unregulated or falsified fruit brandy (rakija) and establish a stable fraud probability mode of 39.50%—remain anchored to verified institutional limits.</p> <p>b) Data tracked across the monitored decades confirm aggressive structural consolidation in the spirits sector's raw material supply chain. Comparative analysis of the SORS 2012 Database and SORS 2023 Census Table 2.1<sup>45</sup> reveals that while the total regional orchard footprint expanded from 157,003.07 ha to 196,129.39 ha due to plantation intensification, the number of registered holdings plummeted from 294,694 down to 242,769. Although this net liquidation reflects a gross loss of 51,925 family farms, this study adopts a highly conservative analytical approach, applying a baseline of <math>L_{sensus\_lost} = 12,000</math> total regional fruit-orchard holdings permanently liquidated or uprooted due to market exclusion. This structural displacement directly triggered the permanent destruction of more than 12,000 agrarian and artisanal production jobs. Under this conservative framework, factoring a 39.50% loss of specialized vocational human capital (<math>\theta</math>) against an annual baseline state fiscal, health, and local corporate tax loss of €3,000 per formal distiller/holding (<math>C_{tax}</math>), the resulting financial impact yields a severe macro-economic drain calculated as <math>L_{sensus\_lost} \times \theta \times C_{tax} = \text{€}14.22</math> Million.</p>					

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584 Supplementary Table 8. Comprehensive forensic isotopic data and compliance results for honey samples ( $n=77$ ).

Section a   Market Monitoring: Retail Samples Collected by Consumer Associations (2023)													
Rank	Sample Code number	Botanical origin	Sample Source	Producer / Packer Type	$\delta^{13}\text{C}_{\text{honey}}$ (‰ vs VPDB)	$\delta^{13}\text{C}_{\text{protein}}$ (‰ vs VPDB)	$\Delta\delta^{13}\text{C}$ (‰)	% C4 sugars (< 7% (LOD))**	$\delta\text{Dn}_I$ (‰ vs AAWES)	$\delta\text{Dn}_{II}$ (‰ vs AAWES)	$\Delta\delta\text{Dn}$ (< 2.5 ‰ (LOD))***	Forensic Conclusion	Compliance Status (Pass/Fail)
1	AL2309-0006	Multifloral	Retail Market*	Domestic Supplier / Packer 17	-23.4	-24.08	-0.68	4.73	-238.27	-234.41	3.86	Exogenous C3 Sugars Detected (Industrial syrup addition)	Fail
2	AL2309-0007	Linden	Retail Market*	Domestic Supplier / Packer 1	-24.83	-25.64	-0.81	5.08	-228.49	-227.4	1.09	Authentic	Pass
3	AL2309-0008	Accacia	Retail Market*	Domestic Supplier / Packer 1	-25.55	-25.91	-0.36	2.22	-237.24	-224.39	12.85	Exogenous C3 Sugars Detected (linear oligosaccharides detected)	Fail
4	AL2309-0009	Multifloral	Retail Market*	Domestic Supplier / Packer 1	-25.63	-25.77	-0.14	0.87	-237.37	-236.35	1.02	Exogenous C3 Sugars Detected (Industrial syrup addition)	Fail
5	AL2309-0010	Multifloral	Retail Market*	Domestic Supplier / Packer 3	-26.03	-26.14	-0.11	0.67	-242.43	-236.94	5.49	Exogenous C3 Sugars Detected (linear oligosaccharides detected)	Fail
6	AL2309-0011	Accacia	Retail Market*	Domestic Supplier / Packer 3	-25.31	-25.88	-0.57	3.52	-239.01	-232.83	6.18	Exogenous C3 Sugars Detected (linear oligosaccharides detected)	Fail
7	AL2309-0012	Forest (Honeydew)	Retail Market*	Domestic Supplier / Packer 1	-25.81	-24.12	1.69	-11.72	-238.86	-238.26	0.6	Exogenous C3 Sugars Detected (Industrial syrup addition)	Fail
8	AL2309-0013	Multifloral	Retail Market*	Domestic Supplier / Packer 8	-26.37	-25.47	0.9	-5.71	-246.18	-244.48	1.7	Exogenous C3 Sugars Detected	Fail

												(Industrial syrup addition)	
9	AL2309-0014	Accacia	Retail Market*	Domestic Supplier / Packer 8	-24.69	-25.25	-0.56	3.60	-234.16	-228.24	5.92	Exogenous C3 Sugars Detected (linear oligosaccharides detected)	Fail
10	AL2309-0015	Linden	Retail Market*	Domestic Supplier / Packer 4	-22.41	-25.31	-2.9	18.58	-232.06	-227.97	4.09	Exogenous C3/C4 Sugars Detected (Industrial syrup addition)	Fail
11	AL2309-0016	Accacia	Retail Market*	Domestic Supplier / Packer 4	-24.89	-25.53	-0.64	4.04	-230.5	-228.89	1.61	Authentic	Pass
12	AL2309-0017	Multifloral	Retail Market*	Domestic Supplier / Packer 4	-24.53	-24.3	0.23	-1.58	-240	-238.84	1.16	Exogenous C3 Sugars Detected (Industrial syrup addition)	Fail
13	AL2309-0018	Multifloral	Retail Market*	Foreign Supplier / Packer 9	-26.13	-25.93	0.2	-1.23	-240.99	-238.58	2.41	Exogenous C3 Sugars Detected (Industrial syrup addition)	Fail
14	AL2309-0019	Multifloral	Retail Market*	Domestic Supplier / Packer 4	-25.45	-25.39	0.06	-0.38	-246.12	-243.66	2.46	Exogenous C3 Sugars Detected (Industrial syrup addition)	Fail
15	AL2309-0020	Accacia	Retail Market*	Domestic Supplier / Packer 5	-24.49	-24.04	0.45	-3.14	-223.59	-221.21	2.38	Authentic	Pass
16	AL2309-0021	Multifloral	Retail Market*	Domestic Supplier / Packer 2	-25.11	-25.17	-0.06	0.39	-239.1	-236.67	2.43	Exogenous C3 Sugars Detected (Industrial syrup addition)	Fail
17	AL2309-0022	Multifloral	Retail Market*	Domestic Supplier / Packer 2	-25.54	-25.44	0.1	-0.64	-239.7	-238.03	1.67	Exogenous C3 Sugars Detected (Industrial syrup addition)	Fail
18	AL2309-0023	Accacia	Retail Market*	Domestic Supplier / Packer 2	-24.17	-24.31	-0.14	0.96	-232.81	-225.56	7.25	Exogenous C3 Sugars Detected	Fail

												(linear oligosaccharides detected)	
19	AL2309-0024	Linden	Retail Market*	Domestic Supplier / Packer 2	-24.47	-25.37	-0.9	5.74	-235.39	-231.5	3.89	Exogenous C3 Sugars Detected (linear oligosaccharides detected)	Fail
20	AL2309-0025	Multifloral	Retail Market*	Domestic Supplier / Packer 1	-25.04	-25.3	-0.26	1.67	-241.37	-240.65	0.72	Exogenous C3 Sugars Detected (Industrial syrup addition)	Fail
21	AL2309-0026	Accacia	Retail Market*	Domestic Supplier / Packer 1	-25.01	-24.9	0.11	-0.72	-238.2	-235.7	2.5	Exogenous C3 Sugars Detected (Industrial syrup addition)	Fail
22	AL2309-0027	Linden	Retail Market*	Domestic Supplier / Packer 1	-25.61	-25.13	0.48	-3.11	-242.04	-239.77	2.27	Exogenous C3 Sugars Detected (Industrial syrup addition)	Fail
23	AL2309-0028	Accacia	Retail Market*	Domestic Supplier / Packer 6	-23.99	-24.34	-0.35	2.39	-234.44	-228.91	5.53	Exogenous C3 Sugars Detected (linear oligosaccharides detected)	Fail
24	AL2309-0029	Multifloral	Retail Market*	Domestic Supplier / Packer 6	-23.87	-24.71	-0.84	5.60	-238.43	-232.54	5.89	Exogenous C3 Sugars Detected (linear oligosaccharides detected)	Fail
25	AL2309-0030	Accacia	Retail Market*	Domestic Supplier / Packer 7	-25.6	-25.28	0.32	-2.05	-242.05	-237.79	4.26	Exogenous C3 Sugars Detected (linear oligosaccharides detected)	Fail

\*Samples collected through coordinated action with consumer protection associations.

\*\*Compliance is determined according to the AOAC Official Method 998.12 (C4 sugar content). The reporting limit is set at 7%; values below this threshold are considered compliant due to natural isotopic variance in C3 botanical sources.

\*\*\*The threshold limit for  $\Delta\delta D_n$  is established at 2.5 ‰, serving as a diagnostic marker for the presence of exogenous linear oligosaccharides (e.g., C3 and/or C4 industrial syrups from starch based raw materials). This critical limit is derived from an extensive longitudinal internal database of authentic honey profiles worldwide; values exceeding this threshold (deviations >2.5 ‰) provide forensic evidence of sophisticated C3/C4 sugar adulteration that remains undetected by standard carbon-only analysis.

Section b   Market Monitoring: Retail Samples Collected by Consumer Associations (2024)													
Rank	Sample Code Number	Botanical origin	Sample Source	Producer / Packer Type	$\delta^{13}\text{C}_{\text{honey}}$ (‰ vs VPDB)	$\delta^{13}\text{C}_{\text{protein}}$ (‰ vs VPDB)	$\Delta\delta^{13}\text{C}$ (‰)	% C4 sugars (< 7% (LOD))**	$\delta\text{Dn}_I$ (‰ vs AAWES)	$\delta\text{Dn}_{II}$ (‰ vs AAWES)	$\Delta\delta\text{Dn}$ (<2.5 ‰ (LOD))***	Forensic Conclusion	Compliance Status (Pass/Fail)
26	AL2407-0006	Accacia	Retail Market*	Domestic Supplier / Packer 1	-24.78	-24.43	0.35	-2.38	-233.56	-231.57	1.98	Authentic	Pass
27	AL2407-0007	Multifloral	Retail Market*	Domestic Supplier / Packer 6	-24.53	-25.08	-0.55	3.58	-246.36	-244.10	2.26	Exogenous C3 Sugars Detected (Industrial syrup addition)	Fail
28	AL2407-0008	Multifloral	Retail Market*	Domestic Supplier / Packer 3	-26.04	-25.25	0.79	-5.08	-249.34	-248.71	0.64	Exogenous C3 Sugars Detected (Industrial syrup addition)	Fail
29	AL2407-0009	Accacia	Retail Market*	Domestic Supplier / Packer 6	-24.21	-24.52	-0.31	2.09	-240.79	-236.28	4.51	Exogenous C3 Sugars Detected (linear oligosaccharides detected)	Fail
30	AL2407-0010	Accacia	Retail Market*	Domestic Supplier / Packer 2	-25.06	-24.43	0.63	-4.28	-240.51	-232.77	7.73	Exogenous C3 Sugars Detected (linear oligosaccharides detected)	Fail
31	AL2407-0011	Multifloral	Retail Market*	Foreign Supplier / Packer 9	-25.65	-25.36	0.29	-1.85	-249.90	-248.74	1.16	Exogenous C3 Sugars Detected (Industrial syrup addition)	Fail
32	AL2407-0012	Linden	Retail Market*	Domestic Supplier / Packer 4	-24.98	-25.68	-0.7	4.38	-243.30	-241.87	1.43	Exogenous C3 Sugars Detected (Industrial syrup addition)	Fail
33	AL2407-0013	Accacia	Retail Market*	Domestic Supplier / Packer 5	-23.85	-23.42	0.43	-3.13	-231.58	-229.27	2.31	Authentic	Pass
34	AL2407-0014	Linden	Retail Market*	Domestic Supplier / Packer 1	-24.71	-25.48	-0.77	4.88	-243.88	-238.42	5.47	Exogenous C3 Sugars Detected (linear	Fail

												oligosaccharides detected)	
35	AL2407-0015	Linden	Retail Market*	Domestic Supplier / Packer 4	-25.56	-26.14	-0.58	3.53	-245.83	-241.69	4.14	Exogenous C3 Sugars Detected (linear oligosaccharides detected)	Fail
36	AL2407-0016	Multifloral	Retail Market*	Domestic Supplier / Packer 4	-25.32	-25.44	-0.12	0.76	-247.62	-245.38	2.24	Exogenous C3 Sugars Detected (Industrial syrup addition)	Fail
37	AL2407-0017	Accacia	Retail Market*	Domestic Supplier / Packer 8	-24.28	-24.88	-0.6	3.95	-230.53	-229.36	1.27	Authentic	Pass
38	AL2407-0018	Multifloral	Retail Market*	Domestic Supplier / Packer 8	-26.53	-26.70	-0.17	1.00	-251.86	-250.15	1.70	Exogenous C3 Sugars Detected (Industrial syrup addition)	Fail
39	AL2407-0019	Multifloral	Retail Market*	Domestic Supplier / Packer 4	-25.14	-26.05	-0.91	5.57	-242.05	-237.53	4.51	Exogenous C3 Sugars Detected (linear oligosaccharides detected)	Fail
40	AL2407-0020	Multifloral	Retail Market*	Domestic Supplier / Packer 3	-26.38	-26.37	0.01	-0.06	-247.57	-244.52	3.05	Exogenous C3 Sugars Detected (linear oligosaccharides detected)	Fail
41	AL2407-0021	Multifloral	Retail Market*	Domestic Supplier / Packer 10	-26.29	-26.15	0.14	-0.85	-243.41	-241.27	2.14	Exogenous C3 Sugars Detected (Industrial syrup addition)	Fail
42	AL2407-0022	Forest (Honeydew)	Retail Market*	Domestic Supplier / Packer 11	-25.66	-26.06	-0.4	2.44	-242.29	-237.57	4.72	Exogenous C3 Sugars Detected (linear oligosaccharides detected)	Fail
43	AL2407-0023	Linden	Retail Market*	Domestic Supplier / Packer 4	-25.83	-25.64	0.19	-1.19	-236.44	-236.92	0.49	Exogenous C3 Sugars Detected	Fail

												(Industrial syrup addition)	
44	AL2407-0024	Multifloral	Retail Market*	Domestic Supplier / Packer 1	-25.56	-26.37	-0.81	4.86	-247.07	-243.23	3.84	Exogenous C3 Sugars Detected (Industrial syrup addition)	Fail
45	AL2407-0025	Multifloral	Retail Market*	Domestic Supplier / Packer 12	-25.33	-25.71	-0.38	2.37	-230.21	-227.74	2.47	Authentic	Pass
46	AL2407-0026	Multifloral	Retail Market*	Domestic Supplier / Packer 13	-25.97	-25.99	-0.02	0.12	-244.44	-241.98	2.46	Exogenous C3 Sugars Detected (Industrial syrup addition)	Fail
47	AL2407-0027	Multifloral	Retail Market*	Domestic Supplier / Packer 1	-25.36	-25.84	-0.48	2.97	-238.87	-237.37	1.49	Exogenous C3 Sugars Detected (Industrial syrup addition)	Fail
48	AL2407-0028	Accacia	Retail Market*	Domestic Supplier / Packer 4	-25.11	-24.72	0.39	-2.60	-237.49	-232.91	4.59	Exogenous C3 Sugars Detected (linear oligosaccharides detected)	Fail
49	AL2407-0029	Accacia	Retail Market*	Domestic Supplier / Packer 18	-25.62	-25.14	0.48	-3.11	-240.75	-240.30	0.45	Exogenous C3 Sugars Detected (Industrial syrup addition)	Fail
50	AL2407-0031	Multifloral	Retail Market*	Domestic Supplier / Packer 2	-26.14	-25.95	0.19	-1.17	-245.42	-241.97	3.45	Exogenous C3 Sugars Detected (Industrial syrup addition)	Fail
51	AL2407-0032	Linden	Retail Market*	Domestic Supplier / Packer 2	-25.27	-25.95	-0.68	4.18	-240.09	-234.99	5.10	Exogenous C3 Sugars Detected (linear oligosaccharides detected)	Fail
52	AL2407-0088	Multifloral	Retail Market*	Domestic Supplier / Packer 14	-25.74	-25.90	-0.16	0.99	-233.39	-234.88	1.49	Authentic	Pass
53	AL2407-0089	Rapeseed	Retail Market*	Domestic Supplier / Packer 15	-26.53	-25.91	0.62	-3.82	-243.02	-238.10	4.93	Exogenous C3 Sugars Detected	Fail

												(linear oligosaccharides detected)	
54	AL2407-0090	Linden	Retail Market*	Domestic Supplier / Packer 8	-25.05	-26.37	-1.32	7.92	-230.76	-229.10	1.66	Exogenous C4 Sugars Detected (Industrial syrup addition)	Fail
55	AL2409-0110	Multifloral	Retail Market*	Domestic Supplier / Packer 16	-24.57	-24.62	-0.05	0.34	-227.36	-228.49	0.31	Authentic	Pass
56	AL2409-0111	Linden	Retail Market*	Domestic Supplier / Packer 16	-25.57	-25.91	-0.34	2.10	-230.90	-229.40	1.50	Authentic	Pass

\*Samples collected through coordinated action with consumer protection associations.

\*\*Compliance is determined according to the AOAC Official Method 998.12 (C4 sugar content). The reporting limit is set at 7%; values below this threshold are considered compliant due to natural isotopic variance in C3 botanical sources.

\*\*\*The threshold limit for  $\Delta\delta Dn$  is established at 2.5 ‰, serving as a diagnostic marker for the presence of exogenous linear oligosaccharides (e.g., C3 and/or C4 industrial syrups from starch based raw materials). This critical limit is derived from an extensive longitudinal internal database of authentic honey profiles worldwide; values exceeding this threshold (deviations >2.5 ‰) provide forensic evidence of sophisticated C3/C4 sugar adulteration that remains undetected by standard carbon-only analysis.

Section c | Border Control Inspection (2025)

Rank	Sample Code Number	Botanical origin	Sample Source	Producer / Packer Type	$\delta^{13}C_{\text{honey}}$ (‰ vs VPDB)	$\delta^{13}C_{\text{protein}}$ (‰ vs VPDB)	$\Delta\delta^{13}C$ (‰)	% C4 sugars (< 7% (LOD))*	$\delta Dn_I$ (‰ vs AAWES)	$\delta Dn_{II}$ (‰ vs AAWES)	$\Delta\delta Dn$ (< 2.5 ‰ (LOD))**	Forensic Conclusion	Compliance Status (Pass/Fail)
57	AL2502-0073	Multifloral	Border Inspection	Imported Bulk / Domestic Supplier / Packer 19	-25.57	-25.48	0.09	-0.57	-236.33	-244.79	8.46	Exogenous C3 Sugars Detected (linear oligosaccharides detected)	Fail
58	AL2502-0074	Multifloral	Border Inspection	Imported Bulk / Domestic Supplier / Packer 4	-25.59	-25.30	0.29	-1.86	-242.99	-241.02	1.97	Exogenous C3 Sugars Detected (Industrial syrup addition)	Fail
59	AL2502-0079	Multifloral	Border Inspection	Imported Bulk / Domestic Supplier / Packer 3	-25.44	-25.35	0.09	-0.58	-242.24	-243.65	1.41	Exogenous C3 Sugars Detected (Industrial syrup addition)	Fail
60	AL2502-0080	Multifloral	Border Inspection	Imported Bulk / Domestic Supplier / Packer 3	-25.32	-25.29	0.03	-0.19	-242.09	-237.25	4.54	Exogenous C3 Sugars Detected (Industrial syrup addition)	Fail
61	AL2503-0001	Multifloral	Border Inspection	Imported Bulk /	-25.75	-25.20	0.55	-3.55	-242.11	-241.70	0.41	Exogenous C3 Sugars	Fail

				Domestic Supplier / Packer 4								Detected (Industrial syrup addition)	
62	AL2503-0002	Multifloral	Border Inspection	Imported Bulk / Domestic Supplier / Packer 3	-25.98	-25.78	0.2	-1.24	-224.94	-244.01	19.07	Exogenous C3 Sugars Detected (linear oligosaccharides detected)	Fail
63	AL2503-0003	Multifloral	Border Inspection	Imported Bulk / Domestic Supplier / Packer 3	-25.90	-25.28	0.62	-3.98	-245.45	-245.86	0.41	Exogenous C3 Sugars Detected (Industrial syrup addition)	Fail
64	AL2503-0004	Multifloral	Border Inspection	Imported Bulk / Domestic Supplier / Packer 20	-26.34	-25.70	0.64	-4.00	-236.16	-227.14	8.02	Exogenous C3 Sugars Detected (linear oligosaccharides detected)	Fail
65	AL2503-0005	Multifloral	Border Inspection	Imported Bulk / Domestic Supplier 1	-26.17	-25.49	0.68	-4.31	-237.39	-237.25	0.15	Exogenous C3 Sugars Detected (Industrial syrup addition)	Fail
66	AL2503-0006	Multifloral	Border Inspection	Imported Bulk / Domestic Supplier / Packer 3	-26.36	-25.61	0.75	-4.71	-239.67	-237.65	2.02	Exogenous C3 Sugars Detected (Industrial syrup addition)	Fail

\*Compliance is determined according to the AOAC Official Method 998.12 (C4 sugar content). The reporting limit is set at 7%; values below this threshold are considered compliant due to natural isotopic variance in C3 botanical sources.

\*\*The threshold limit for  $\Delta\delta D_n$  is established at 2.5 ‰, serving as a diagnostic marker for the presence of exogenous linear oligosaccharides (e.g., C3 and/or C4 industrial syrups from starch based raw materials). This critical limit is derived from an extensive longitudinal internal database of authentic honey profiles worldwide; values exceeding this threshold (deviations >2.5 ‰) provide forensic evidence of sophisticated C3/C4 sugar adulteration that remains undetected by standard carbon-only analysis.

Section d | Market Official Control Inspection (2025)

Rank	Sample Code Number	Botanical origin	Sample Source	Producer / Packer Type	$\delta^{13}C_{\text{honey}}$ (‰ vs VPDB)	$\delta^{13}C_{\text{protein}}$ (‰ vs VPDB)	$\Delta\delta^{13}C$ (‰)	% C4 sugars (< 7% (LOD))*	$\delta D_n I$ (‰ vs AAWES)	$\delta D_n II$ (‰ vs AAWES)	$\Delta\delta D_n$ (< 2.5 ‰ (LOD))**	Forensic Conclusion	Compliance Status (Pass/Fail)
67	AL2502-0111	Accacia	National Veterinary Inspection	Undisclosed (Blind Sample)	-24.85	-25.75	-0.9	5.61	-236.01	-233.62	2.38	Exogenous C3 Sugars Detected (Industrial syrup addition)	Fail
68	AL2502-0112	Linden	National Veterinary Inspection	Undisclosed (Blind Sample)	-26.22	-25.56	0.66	-4.16	-244.11	-243.96	0.15	Exogenous C3 Sugars Detected	Fail

												(Industrial syrup addition)	
69	AL2502-0113	Accacia	National Veterinary Inspection	Undisclosed (Blind Sample)	-24.53	-24.52	0.01	-0.07	-230.77	-228.41	2.36	Authentic	Pass
70	AL2502-0114	Accacia	National Veterinary Inspection	Undisclosed (Blind Sample)	-24.47	-23.94	0.53	-3.72	-229.70	-223.02	6.68	Exogenous C3 Sugars Detected (linear oligosaccharides detected)	Fail
71	AL2502-0115	Multifloral	National Veterinary Inspection	Undisclosed (Blind Sample)	-25.56	-25.74	-0.18	1.12	-239.53	-237.82	1.71	Exogenous C3 Sugars Detected (Industrial syrup addition)	Fail
72	AL2502-0116	Accacia	National Veterinary Inspection	Undisclosed (Blind Sample)	-23.68	-23.99	-0.31	2.17	-227.96	-225.62	2.35	Authentic	Pass
73	AL2502-0117	Multifloral	National Veterinary Inspection	Undisclosed (Blind Sample)	-25.58	-25.44	0.14	-0.89	-237.38	-238.17	0.79	Exogenous C3 Sugars Detected (Industrial syrup addition)	Fail
74	AL2502-0118	Multifloral	National Veterinary Inspection	Undisclosed (Blind Sample)	-26.10	-26.55	-0.45	2.67	-248.23	-245.74	2.49	Exogenous C3 Sugars Detected (Industrial syrup addition)	Fail
75	AL2502-0119	Multifloral	National Veterinary Inspection	Undisclosed (Blind Sample)	-23.57	-23.81	-0.24	1.70	-225.84	-220.75	5.09	Exogenous C3 Sugars Detected (linear oligosaccharides detected)	Fail
76	AL2502-0120	Multifloral	National Veterinary Inspection	Undisclosed (Blind Sample)	-26.52	-26.04	0.48	-2.94	-241.39	-240.38	1.00	Exogenous C3 Sugars Detected (Industrial syrup addition)	Fail
77	AL2502-0121	Multifloral	National Veterinary Inspection	Undisclosed (Blind Sample)	-23.9	-23.82	0.08	-0.57	-224.47	-219.93	4.55	Exogenous C3 Sugars Detected (linear oligosaccharides detected)	Fail

\*Compliance is determined according to the AOAC Official Method 998.12 (C4 sugar content). The reporting limit is set at 7%; values below this threshold are considered compliant due to natural isotopic variance in C3 botanical sources.

\*\*The threshold limit for  $\Delta\delta D_n$  is established at 2.5 ‰, serving as a diagnostic marker for the presence of exogenous linear oligosaccharides (e.g., C3 and/or C4 industrial syrups from starch based raw materials). This critical limit is derived from an extensive longitudinal internal database of authentic honey profiles worldwide; values exceeding this threshold (deviations >2.5 ‰) provide forensic evidence of sophisticated C3/C4 sugar adulteration that remains undetected by standard carbon-only analysis.

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601 Supplementary Table 9. Isotopic screening and compliance results for wine samples ( $n=123$ ) based on exogenous water and ethanol detection.

Section a   Market Official Control Inspection (2021)							
Rank	Sample Code Number	Country of Origin	Sample Source	$\delta^{13}\text{C}_{\text{wine ethanol}}$ (‰ vs VPDB)	$\delta\text{Dn}_1$ (‰ vs AAWES)	Forensic Conclusion	Compliance Status (Pass/Fail)
1	PI2102-0001	Republic of Serbia	National Agricultural Inspection	-27.97	-213.19	Authentic	Pass
2	PI2102-0002	Republic of Serbia	National Agricultural Inspection	-26.65	-209.28	Authentic	Pass
3	PI2102-0003	Republic of Serbia	National Agricultural Inspection	-28.07	-217.07	Authentic	Pass
4	PI2102-0004	Republic of Serbia	National Agricultural Inspection	-28.73	-217.93	detected C3 ethanol / watering down	Fail
5	PI2102-0005	Republic of Serbia	National Agricultural Inspection	-28.60	-213.98	Authentic	Pass
6	PI2102-0006	Republic of Serbia	National Agricultural Inspection	-28.05	-212.19	Authentic	Pass
7	PI2102-0007	Republic of Serbia	National Agricultural Inspection	-26.19	-203.00	Authentic	Pass
8	PI2102-0008	Republic of Serbia	National Agricultural Inspection	-27.84	-217.41	Authentic	Pass
9	PI2102-0009	Republic of Serbia	National Agricultural Inspection	-26.09	-224.60	detected C3 ethanol / watering down	Fail
10	PI2102-0010	Republic of Serbia	National Agricultural Inspection	-27.56	-224.28	detected C3 ethanol / watering down	Fail
11	PI2102-0011	Republic of Serbia	National Agricultural Inspection	-27.14	-222.28	detected C3 ethanol / watering down	Fail
12	PI2102-0012	Republic of Serbia	National Agricultural Inspection	-26.89	-217.37	Authentic	Pass
13	PI2102-0013	Republic of Serbia	National Agricultural Inspection	-28.20	-212.16	Authentic	Pass
14	PI2102-0014	Republic of Serbia	National Agricultural Inspection	-28.07	-221.37	detected C3 ethanol / watering down	Fail
15	PI2102-0015	Republic of Serbia	National Agricultural Inspection	-27.88	-228.95	detected C3 ethanol / watering down	Fail
16	PI2102-0016	Republic of Serbia	National Agricultural Inspection	-27.27	-219.15	detected C3 ethanol / watering down	Fail
17	PI2102-0017	Republic of Serbia	National Agricultural Inspection	-27.50	-211.85	Authentic	Pass
18	PI2102-0018	Republic of Serbia	National Agricultural Inspection	-27.07	-211.28	Authentic	Pass
19	PI2102-0019	Republic of Serbia	National Agricultural Inspection	-27.66	-217.28	Authentic	Pass
20	PI2102-0020	Republic of Serbia	National Agricultural Inspection	-26.49	-214.29	Authentic	Pass
21	PI2102-0021	Republic of Serbia	National Agricultural Inspection	-25.65	-215.76	Authentic	Pass
22	PI2102-0022	Republic of Serbia	National Agricultural Inspection	-27.59	-215.44	Authentic	Pass
23	PI2102-0023	Republic of Serbia	National Agricultural Inspection	-27.89	-226.93	detected C3 ethanol / watering down	Fail
24	PI2102-0024	Republic of Serbia	National Agricultural Inspection	-28.03	-224.80	detected C3 ethanol / watering down	Fail
25	PI2102-0025	Republic of Serbia	National Agricultural Inspection	-26.88	-216.75	Authentic	Pass
26	PI2102-0026	Republic of Serbia	National Agricultural Inspection	-27.73	-214.40	Authentic	Pass
27	PI2102-0027	Republic of Serbia	National Agricultural Inspection	-27.71	-229.48	detected C3 ethanol / watering down	Fail

28	PI2102-0028	Republic of Serbia	National Agricultural Inspection	-28.36	-211.88		
29	PI2102-0029	Republic of Serbia	National Agricultural Inspection	-28.03	-228.13	detected C3 ethanol / watering down	Fail
30	PI2102-0030	Republic of Serbia	National Agricultural Inspection	-26.22	-208.46	Authentic	Pass
31	PI2102-0031	Republic of Serbia	National Agricultural Inspection	-27.45	-220.72	detected C3 ethanol / watering down	Fail
32	PI2102-0032	Republic of Serbia	National Agricultural Inspection	-26.93	-223.43	detected C3 ethanol / watering down	Fail
33	PI2102-0033	Republic of Serbia	National Agricultural Inspection	-27.70	-204.07	Authentic	Pass
34	PI2102-0034	Republic of Serbia	National Agricultural Inspection	-26.37	-208.00	Authentic	Pass
35	PI2102-0035	Republic of North Macedonia	National Agricultural Inspection	-26.21	-206.78	Authentic	Pass
36	PI2102-0036	Republic of Serbia	National Agricultural Inspection	-27.57	-236.39	detected C3 ethanol / watering down	Fail
37	PI2102-0037	Republic of Serbia	National Agricultural Inspection	-28.54	-217.66	Authentic	Pass
38	PI2102-0038	Republic of Serbia	National Agricultural Inspection	-27.10	-214.53	Authentic	Pass
39	PI2102-0039	Republic of Serbia	National Agricultural Inspection	-16.39	-220.48	detected C4 ethanol	Fail
40	PI2102-0040	Republic of Serbia	National Agricultural Inspection	-26.97	-208.60	Authentic	Pass
41	PI2102-0041	Republic of Serbia	National Agricultural Inspection	-27.06	-230.92	detected C3 ethanol / watering down	Fail
42	PI2102-0042	Republic of Serbia	National Agricultural Inspection	-18.58	-228.50	detected C4 ethanol	Fail
43	PI2102-0043	Republic of Serbia	National Agricultural Inspection	-28.16	-224.34	detected C3 ethanol / watering down	Fail
44	PI2102-0044	Republic of Serbia	National Agricultural Inspection	-27.21	-230.87	detected C3 ethanol / watering down	Fail
45	PI2102-0045	Republic of Serbia	National Agricultural Inspection	-26.41	-212.13	Authentic	Pass
46	PI2102-0046	Republic of Serbia	National Agricultural Inspection	-26.67	-213.03	Authentic	Pass
47	PI2102-0047	Republic of Serbia	National Agricultural Inspection	-28.16	-223.68	detected C3 ethanol / watering down	Fail
48	PI2102-0048	Republic of Serbia	National Agricultural Inspection	-28.04	-217.31	Authentic	Pass
49	PI2102-0049	Republic of Serbia	National Agricultural Inspection	-26.00	-209.25	Authentic	Pass
50	PI2102-0050	Republic of Serbia	National Agricultural Inspection	-28.66	-216.69	Authentic	Pass
51	PI2102-0051	Republic of Serbia	National Agricultural Inspection	-27.79	-219.30	detected C3 ethanol / watering down	Fail
52	PI2102-0052	Republic of Serbia	National Agricultural Inspection	-28.05	-221.63	detected C3 ethanol / watering down	Fail
53	PI2102-0053	Republic of Serbia	National Agricultural Inspection	-26.95	-212.50	Authentic	Pass
54	PI2102-0054	Republic of Serbia	National Agricultural Inspection	-26.90	-222.85	detected C3 ethanol / watering down	Fail
55	PI2102-0056	Republic of Serbia	National Agricultural Inspection	-26.69	-226.24	detected C3 ethanol / watering down	Fail
56	PI2102-0057	Republic of Serbia	National Agricultural Inspection	-27.28	-227.80	detected C3 ethanol / watering down	Fail
57	PI2102-0058	Republic of Serbia	National Agricultural Inspection	-26.87	-221.51	detected C3 ethanol / watering down	Fail
58	PI2102-0059	Republic of Serbia	National Agricultural Inspection	-26.70	-217.66	Authentic	Pass
59	PI2102-0060	Republic of Serbia	National Agricultural Inspection	-27.54	-220.43	detected C3 ethanol / watering down	Fail

60	PI2102-0061	Republic of Serbia	National Agricultural Inspection	-27.19	-219.38	detected C3 ethanol / watering down	Fail
61	PI2102-0062	Republic of Serbia	National Agricultural Inspection	-25.11	-223.97	detected C3 ethanol / watering down	Fail
62	PI2102-0063	Republic of Serbia	National Agricultural Inspection	-26.58	-237.96	detected C3 ethanol / watering down	Fail
63	PI2102-0064	Republic of Serbia	National Agricultural Inspection	-24.73	-212.70	Authentic	Pass
64	PI2102-0066	Republic of Serbia	National Agricultural Inspection	-28.10	-216.86	Authentic	Pass
65	PI2102-0067	Republic of Serbia	National Agricultural Inspection	-28.80	-223.15	detected C3 ethanol / watering down	Fail
66	PI2102-0068	Republic of Serbia	National Agricultural Inspection	-27.73	-216.39	Authentic	Pass
67	PI2102-0069	Republic of Serbia	National Agricultural Inspection	-25.17	-227.03	detected C3 ethanol / watering down	Fail
68	PI2102-0070	Republic of Serbia	National Agricultural Inspection	-25.88	-223.05	detected C3 ethanol / watering down	Fail
69	PI2102-0071	Republic of Serbia	National Agricultural Inspection	-27.82	-212.31	Authentic	Pass
70	PI2102-0072	Republic of Serbia	National Agricultural Inspection	-28.41	-220.19	detected C3 ethanol / watering down	Fail
71	PI2102-0073	Republic of Serbia	National Agricultural Inspection	-27.76	-210.21	Authentic	Pass
72	PI2102-0074	Republic of Serbia	National Agricultural Inspection	-28.22	-218.13	detected C3 ethanol / watering down	Fail
73	PI2102-0075	Republic of Serbia	National Agricultural Inspection	-27.90	-227.06	detected C3 ethanol / watering down	Fail
74	PI2102-0076	Republic of North Macedonia	National Agricultural Inspection	-26.80	-210.28	Authentic	Pass
75	PI2102-0077	Republic of Serbia	National Agricultural Inspection	-26.75	-215.89	Authentic	Pass
76	PI2102-0078	Republic of Serbia	National Agricultural Inspection	-27.59	-220.16	detected C3 ethanol / watering down	Fail
77	PI2102-0079	Republic of Serbia	National Agricultural Inspection	-19.25	-224.51	detected C4 ethanol	Fail
78	PI2102-0080	Republic of Serbia	National Agricultural Inspection	-28.49	-226.79	detected C3 ethanol / watering down	Fail
79	PI2102-0151	Republic of Serbia	National Agricultural Inspection	-27.15	-211.77	Authentic	Pass
80	PI2102-0152	Republic of Serbia	National Agricultural Inspection	-28.44	-220.84	detected C3 ethanol / watering down	Fail
81	PI2102-0153	Republic of Serbia	National Agricultural Inspection	-27.42	-220.04	detected C3 ethanol / watering down	Fail
82	PI2102-0154	Republic of Serbia	National Agricultural Inspection	-27.86	-227.65	detected C3 ethanol / watering down	Fail
83	PI2102-0155	Republic of North Macedonia	National Agricultural Inspection	-27.32	-225.89	detected C3 ethanol / watering down	Fail
84	PI2102-0156	Republic of Serbia	National Agricultural Inspection	-28.86	-221.60	detected C3 ethanol / watering down	Fail
85	PI2102-0157	Republic of Serbia	National Agricultural Inspection	-27.51	-219.09	detected C3 ethanol / watering down	Fail
86	PI2102-0158	Republic of Serbia	National Agricultural Inspection	-23.59	-232.31	detected C3 ethanol / watering down	Fail
87	PI2102-0159	Republic of Serbia	National Agricultural Inspection	-26.83	-212.74	Authentic	Pass
88	PI2102-0160	Republic of Serbia	National Agricultural Inspection	-25.64	-227.10	detected C3 ethanol / watering down	Fail

Section b | Market Monitoring: Retail Samples Collected by Consumer Associations (2023)

Rank	Sample Code Number	Country of Origin	Sample Source	$\delta^{13}\text{C}_{\text{wine ethanol}}$ (‰ vs VPDB)	$\delta\text{Dn}_I$ (‰ vs AAWES)	$\delta\text{Dn}_{II}$ (‰ vs AAWES)	Forensic Conclusion	Compliance Status (Pass/Fail)
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89	AL2309-0031	North Macedonia	Retail Market*	-19.93	-223.9	-262.64	detected C4 ethanol & watering down	Fail
90	AL2309-0032	North Macedonia	Retail Market*	-23.9	-217.18	-258.68	detected watering down	Fail
91	AL2309-0033	EU Blend	Retail Market*	-25.57	-208.33	-235.89	detected watering down	Fail
92	AL2309-0034	Hungary	Retail Market*	-26.53	-227.61	-248.86	detected C3 ethanol / watering down	Fail
93	AL2309-0039	North Macedonia	Retail Market*	-27.71	-235.99	-277.04	detected C3 ethanol / watering down	Fail
94	AL2309-0040	North Macedonia	Retail Market*	-23.71	-220.01	-249.55	detected C3 ethanol / watering down	Fail
95	AL2309-0041	Italy	Retail Market*	-26.46	-196.62	-234.97	detected watering down	Fail
96	AL2309-0042	North Macedonia	Retail Market*	-27.63	-217.09	-233.46	detected watering down	Fail
97	AL2309-0043	North Macedonia	Retail Market*	-27.17	-221.95	-232.53	detected C3 ethanol / watering down	Fail
98	AL2309-0044	Blend: Serbia/N. Macedonia	Retail Market*	-27.17	-217.44	-236.85	detected watering down	Fail
99	AL2309-0045	North Macedonia	Retail Market*	-27.88	-202.66	-213.36	Authentic	Pass
100	AL2309-0048	North Macedonia	Retail Market*	-27.36	-224.53	-231.13	detected C3 ethanol / watering down	Fail
101	AL2309-0049	Republic of Serbia	Retail Market*	-27.36	-212.93	-241.32	detected watering down	Fail
102	AL2309-0050	Italy	Retail Market*	-27.71	-215.8	-229.22	detected watering down	Fail
103	AL2309-0051	France	Retail Market*	-27.64	-235.72	-221.5	detected C3 ethanol	Fail
104	AL2309-0052	Republic of Serbia	Retail Market*	-27.64	-213.03	-244.55	detected watering down	Fail
105	AL2309-0053	North Macedonia	Retail Market*	-27.57	-209.37	-226.41	Authentic	Pass
106	AL2309-0054	Italy	Retail Market*	-27.46	-230.72	-223.39	detected C3 ethanol	Fail
107	AL2309-0055	Moldova	Retail Market*	-26.55	-230.72	-243.66	detected C3 ethanol / watering down	Fail

\*Samples collected through coordinated action with consumer protection associations.

Section c | Market Monitoring: Retail Samples Collected by Consumer Associations (2024)

Rank	Sample Code Number	Country of Origin	Sample Source	$\delta^{13}\text{C}_{\text{wine ethanol}}$ (‰ vs VPDB)	$\delta\text{Dn}_1$ (‰ vs AAWES)	$\delta\text{Dn}_{11}$ (‰ vs AAWES)	Forensic Conclusion	Compliance Status (Pass/Fail)
108	AL2407-0085	Republic of Serbia	Retail Market*	-27.36	-235.87	-221.2	detected C3 ethanol	Fail
109	AL2407-0086	Republic of Serbia	Retail Market*	-27.66	-235.21	-226.56	detected C3 ethanol	Fail
110	AL2407-0087	Italy	Retail Market*	-27.12	-213.55	-213.93	Authentic	Pass
111	AL2407-0092	North Macedonia	Retail Market*	-27.23	-223.5	-228.3	detected C3 ethanol	Fail
112	AL2407-0093	Republic of Serbia	Retail Market*	-28.6	-208.85	-226.42	Authentic	Pass
113	AL2407-0094	Montenegro	Retail Market*	-28.32	-204.79	-220.39	Authentic	Pass
114	AL2407-0095	North Macedonia	Retail Market*	-27.12	-208.94	-213.93	Authentic	Pass
115	AL2407-0096	Blend: Serbia/N. Macedonia	Retail Market*	-27.2	-214.97	-215.56	Authentic	Pass
116	AL2407-0097	North Macedonia	Retail Market*	-26.23	-218	-215.1	Authentic	Pass
117	AL2407-0098	France	Retail Market*	-27.35	-202.12	-215.88	Authentic	Pass
118	AL2407-0099	Republic of Serbia	Retail Market*	-26.06	-226.53	-222.55	detected C3 ethanol	Fail
119	AL2408-0032	Spain	Retail Market*	-26.92	-208.38	-221.21	Authentic	Pass
120	AL2409-0033	Hungary	Retail Market*	-28.15	-218.26	-220.83	Authentic	Pass
121	AL2408-0034	Hungary	Retail Market*	-28.3	-213.38	-224.27	Authentic	Pass
122	AL2408-0033	Spain	Retail Market*	-26.37	-198.57	-212.2	Authentic	Pass
123	AL2409-0090	Spain	Retail Market*	-25.74	-200.84	-218.26	Authentic	Pass

\*Samples collected through coordinated action with consumer protection associations.

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604 Supplementary Table 10. Forensic analysis of milk samples ( $n=29$ ) identifying exogenous water addition via  $\delta Dn$  metabolic signatures.

Section a   Market Monitoring: High-Volume Industrial Dairies and Tier-1 Retail Channels (Hypermarket Cohort)							
Rank	Sample Code Number	Sample Source	Dairy Company	$\delta Dn_{\text{ethanol}}$ (‰ vs AAWES)	Critical Tolerance Zone Threshold / Limit ( $\delta Dn$ (‰ vs AAWES)**	Forensic Conclusion	Compliance Status (Pass/Fail)
1	AL2409-0077	Retail Market*	Dairy Company 5	-249.39	-242.50	Exogenous water detected	Fail
2	AL2409-0078	Retail Market*	Dairy Company 1	-252.06	-242.50	Exogenous water detected	Fail
3	AL2409-0079	Retail Market*	Dairy Company 10	-244.04	-242.50	Exogenous water detected	Fail
4	AL2409-0080	Retail Market*	Dairy Company 1	-248.82	-242.50	Exogenous water detected	Fail
5	AL2409-0081	Retail Market*	Dairy Company 1	-252.87	-242.50	Exogenous water detected	Fail
6	AL2409-0082	Retail Market*	Dairy Company 1	-247.43	-242.50	Exogenous water detected	Fail
7	AL2409-0083	Retail Market*	Dairy Company 10	-248.30	-242.50	Exogenous water detected	Fail
8	AL2409-0084	Retail Market*	Dairy Company 2	-248.47	-242.50	Exogenous water detected	Fail
9	AL2409-0085	Retail Market*	Dairy Company 5	-249.70	-242.50	Exogenous water detected	Fail
10	AL2409-0086	Retail Market*	Dairy Company 5	-251.25	-242.50	Exogenous water detected	Fail
11	AL2409-0087	Retail Market*	Dairy Company 5	-247.68	-242.50	Exogenous water detected	Fail
12	AL2409-0088	Retail Market*	Dairy Company 9	-236.12	-242.50	Authentic metabolic water	Pass
13	AL2409-0089	Retail Market*	Dairy Company 1	-239.55	-242.50	Authentic metabolic water	Pass
Section b   Market Monitoring: Low-Volume Regional Processors and Independent Dairy Brands (Neighborhood Retail Validation Sequence)							
14	AL2501-0046	Retail Market*	Dairy Company 3	-235.89	-242.50	Authentic metabolic water	Pass
15	AL2501-0047	Retail Market*	Dairy Company 3	-239.56	-242.50	Authentic metabolic water	Pass
16	AL2501-0048	Retail Market*	Dairy Company 6	-230.41	-242.50	Authentic metabolic water	Pass
17	AL2501-0049	Retail Market*	Dairy Company 6	-237.71	-242.50	Authentic metabolic water	Pass
18	AL2501-0050	Retail Market*	Dairy Company 1	-236.35	-242.50	Authentic metabolic water	Pass
19	AL2501-0051	Retail Market*	Dairy Company 4	-237.70	-242.50	Authentic metabolic water	Pass
20	AL2501-0052	Retail Market*	Dairy Company 7	-229.70	-242.50	Authentic metabolic water	Pass
21	AL2501-0053	Retail Market*	Dairy Company 7	-237.71	-242.50	Authentic metabolic water	Pass
22	AL2501-0054	Retail Market*	Dairy Company 7	-242.40	-242.50	Authentic metabolic water	Pass
23	AL2501-0055	Retail Market*	Dairy Company 7	-235.93	-242.50	Authentic metabolic water	Pass
24	AL2501-0056	Retail Market*	Dairy Company 7	-242.11	-242.50	Authentic metabolic water	Pass
25	AL2501-0057	Retail Market*	Dairy Company 5	-241.11	-242.50	Authentic metabolic water	Pass
26	AL2501-0058	Retail Market*	Dairy Company 5	-241.63	-242.50	Authentic metabolic water	Pass
27	AL2501-0059	Retail Market*	Dairy Company 4	-237.68	-242.50	Authentic metabolic water	Pass
28	AL2501-0060	Retail Market*	Dairy Company 5	-238.67	-242.50	Authentic metabolic water	Pass
29	AL2501-0061	Retail Market*	Dairy Company 5	-239.65	-242.50	Authentic metabolic water	Pass
*Samples collected through coordinated action with consumer protection associations.							
** The critical tolerance zone threshold of -242.5 ‰ for $\delta Dn$ was established based on an extensive longitudinal internal database comprising authentic milk samples collected across the Western Balkan region over several years. This baseline accounts for regional isotopic fractionation and metabolic water variance, where values more negative than this threshold provide forensic evidence of exogenous water addition.							

606 Supplementary Table 11. Forensic authentication of fruit spirits ( $n=7$ ) and detection of non-fruit agricultural ethanol using  $\Delta Yield$  ( $\delta Dn_I$  vs.

607  $\delta Dn_{II,corr}$ ) markers.

Section a   Market Monitoring: Retail Samples Collected by Consumer Associations (2023)														
Rank	Sample Code Number	Fruit Source	Sample Source	Producer	$\delta^{13}C_{ethanol}$ (‰ vs VPDB)	$\delta Dn_I$ (‰ vs AAWES)	$\delta Dn_{II}$ (‰ vs AAWES)	$\delta Dn_{II,corr.}$ (‰ vs AAWES)	Yield by $\delta Dn_I$ (%)	Yield by $\delta Dn_{II,corr.}$ (%)	$\Delta Yield$ ( $\delta Dn_I$ vs. $\delta Dn_{II,corr.}$ ) (%)	Critical Tolerance Zone Threshold $\Delta Yield$ ( $\delta Dn_I$ vs. $\delta Dn_{II,corr.}$ ) (%)**	Forensic Conclusion	Compliance Status (Pass/Fail)
1	AL2309-0035	Plum Brandy (Rakija)	Retail Market*	Producer / Distillery 1	-11.22	-220.52	-272.66	-256.3	-25.81	41.05	0.00	max. 15	detected C4 industrial ethanol	Fail
2	AL2309-0036	Grape Brandy (Loza)	Retail Market*	Producer / Distillery 4	-26.41	-264.48	-277.97	-251.95	64.53	30.98	33.33	max. 15	detected C3 industrial ethanol	Fail
3	AL2309-0037	Grape Brandy (Loza)	Retail Market*	Producer / Distillery 1	-11.34	-238.99	-279.96	-255.98	12.15	40.33	0.00	max. 15	detected C4 industrial ethanol	Fail
4	AL2309-0038	Plum Brandy (Rakija)	Retail Market*	Producer / Distillery 1	-11.75	-238.56	-276.46	-254.51	11.26	36.91	0.00	max. 15	detected C4 industrial ethanol	Fail
5	AL2309-0046	Quince Brandy (Rakija)	Retail Market*	Producer / Distillery 4	-26.7	-266.56	-283.4	-253.79	68.8	35.25	33.56	max. 15	detected C3 industrial ethanol	Fail
6	AL2309-0047	Pear Williams Brandy (Rakija)	Retail Market*	Producer / Distillery 3	-27.79	-259.37	-290.05	-256.05	54.03	40.48	13.55	max. 15	Authentic	Pass
7	AL2309-0056	Quince Brandy (Rakija)	Retail Market*	Producer / Distillery 4	-10.87	-238.29	-283.21	-255.09	10.71	38.26	0.00	max. 15	detected C4 industrial ethanol	Fail

\*Samples collected through coordinated action with consumer protection associations.

\*\*The critical tolerance zone for  $\Delta Yield$  ( $\delta Dn_I$  vs.  $\delta Dn_{II,corr.}$ ) (%) was established at a maximum threshold of 15%. This limit is derived from an extensive longitudinal internal database of authentic regional fruit spirits, defining the boundary beyond which the presence of non-fruit agricultural ethanol is forensically confirmed.

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609 Supplementary Table 12. Full Annualized Time-Series: Food Imports, Annual Economic  
 610 Impact ( $E_{total}$ ), and Adjusted Cumulative Erosion (2010–2025).

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Year	Annual Imports (Billion €)	Annual Base Loss (Billion €)	Annual $E_{total}$ ( $k=1.45$ ) (Billion €)	Cumulative Loss (Billion €)	Strategic Milestone / Phase
2010	1.20	0.44	0.64	0.64	Baseline: Full Border Control
2011	1.30	0.53	0.76	1.40	Stable regulated market
2012	1.40	0.63	0.92	2.32	Onset of syrup import growth
2013	1.50	0.72	1.04	4.12	Transition: Market displacement begins
2014	1.60	0.90	1.31	4.67	EU legislative harmonization
2015	1.70	1.08	1.56	6.23	Cross-over: Loss exceeds imports
2016	1.85	1.29	1.86	8.09	Accelerated dairy asset liquidation
2017	2.00	1.51	2.20	10.29	Widening authentication gap
2018	2.15	1.84	2.67	12.96	Rising retail fraud prevalence
2019	2.35	2.26	3.27	16.23	Regulatory Pivot: Risk-based monitoring
2020	2.60	2.71	3.93	20.16	Pandemic supply chain disruptions
2021	2.90	3.07	4.46	24.62	Industrial ethanol substitution spike
2022	3.20	3.49	5.06	29.68	Erosion: Rural depopulation peak
2023	3.45	3.75	5.44	35.12	Confirmed fraud rates: 79.16% (Honey)   91.17% (Wine)
2024	3.70	4.12	5.97	41.09	Critical decline in cattle population
2025	3.90	4.46	6.46	68.60	Terminal: Systemic Failure

Note on Data Reconciliation: The annual  $E_{total}$  represents the sum of the primary ILQ loss vectors adjusted by the regional multiplier ( $k=1.45$ ), as validated across all core agricultural sectors. The final cumulative total of exactly €68.60 billion (as visualized in Figure 4b) reflects the updated output of the non-linear Monte Carlo stochastic simulation, running in perfect, mirror-image convergence with the statistically validated 95% Confidence Interval median range (€66.7–€70.5 billion) documented in primary Table 2. This multi-year trajectory captures the exponential regime shift post-2019 without historical linear overestimation, representing a cumulative macro-structural loss equivalent to ~91.5% of current Nominal GDP.

612