

# Isotopic Evidence of Systemic Economically Motivated Adulteration in Serbia: Empirical Loss Quantization and Bounded Macroeconomic Projections

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## Article

**Keywords:** Economic food fraud, Ethanol Isotope Measurement (EIM – IRMS), Integrated Loss Quantization (ILQ), Macroeconomic impact, Fiscal revenue erosion, Taxation vacuum, Structural decapitalization, Bayesian inference, Monte Carlo simulation, Market displacement, Supply chain integrity, National economic security, Western Balkans

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**Additional Declarations:** **Yes** there is potential Competing Interest. The authors declare competing financial interests. Ivan Smajlovic and Margarita Smajlovic are former analytical experts at ANA LAB DOO, an independent facility that ceased operations in 2025, where the historical empirical EIM-IRMS baseline data was originally generated. Both authors are currently affiliated with Isotope Lab Systems DOO, a commercial entity specializing in the development and application of EIM-IRMS technology for food authentication. This research and the resulting macroeconomic models were completed independently of the current commercial operations of the new entity.

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1 **ISOTOPIC EVIDENCE OF SYSTEMIC ECONOMICALLY MOTIVATED**  
2 **ADULTERATION IN SERBIA: Empirical Loss Quantization and Bounded**  
3 **Macroeconomic Projections**

4

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8

9 **ABSTRACT**

10

11 This study introduces a scalable macro-forensic framework to quantify the systemic economic  
12 impacts of economically motivated adulteration within transitional agricultural corridors,  
13 utilizing comprehensive multi-sector market data as an empirical baseline. To mitigate  
14 sampling biases, we integrate a Bayesian Monte Carlo Simulation with the Integrated Loss  
15 Quantization framework and forensic isotopic analysis, supplemented by a pilot phase for  
16 spirits. We identify an annualized structural market displacement of €6.46 billion (11.8% of  
17 Real GDP). Cross-sectoral analysis reveals high non-compliance thresholds: honey (79.71%),  
18 wine (57.75%), milk (39.31%), and spirits (39.50%), generating a €135.73 million deficit in  
19 unrecovered fiscal revenues. Verifying the convergence between micro-level isotopic  
20 signatures and macro-level administrative data demonstrates that cumulative 15-year sector  
21 deficits correlate with accelerated biological asset contraction and rural demographic shifts.  
22 Consequently, institutionalizing independent, high-resolution verification networks functions  
23 as a critical metric for stabilizing transitional supply chains and preserving market sovereignty  
24 across regional trade corridors.

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26 **Keywords:** Economic food fraud, Ethanol Isotope Measurement (EIM – IRMS), Integrated  
27 Loss Quantization (ILQ), Macroeconomic impact, Fiscal revenue erosion, Taxation vacuum,  
28 Structural decapitalization, Bayesian inference, Monte Carlo simulation, Market displacement,  
29 Supply chain integrity, National economic security, Western Balkans.

30

31 Global food fraud drives volatility<sup>1,2</sup> and macroeconomic destabilization, costing \$40 billion  
32 annually.<sup>3</sup> To link micro-forensic signatures with macro-demographic shifts without regional  
33 extrapolation bias, this study evaluates Serbia as a structural baseline where annual losses reach  
34 €6.46 billion. These practices erode competitiveness and accelerate rural migration<sup>1,3,4</sup>,  
35 compounding a natural population decrease and total structural demographic losses of 495,975  
36 individuals<sup>5,6</sup>, anchoring regional trade corridors. Legal precedents like the lawsuit *Jackson v.*  
37 *Diageo North America* utilized forensic analysis to challenge "100% Agave" Tequila labeling  
38 claims by alleging up to 33% industrial alcohol substitution<sup>7</sup>, proving high-resolution  
39 verification is mandatory to protect premium brand equity.<sup>7</sup> This analytical gap parallels the  
40 fruit brandy segment, where expanding formal registration thresholds did not mitigate the  
41 substitution of traditional distillates with synthetic or exogenous agricultural ethanol.  
42 Economically motivated adulteration thrives on high profits and low detection risks.<sup>1</sup> These  
43 drivers are exacerbated by geopolitical conflicts, pandemics, and climate shocks.<sup>8,9</sup> Product  
44 heterogeneity and limited transparency complicate enforcement<sup>2,8,10</sup>, creating a “Market for  
45 Lemons” scenario<sup>11</sup> where unmonitored substitutes at €1.30/kg trigger liquidity crises for  
46 primary producers at €4.50/kg<sup>12,13</sup>

47

48 Fraud networks exploit detection gaps requiring high-resolution isotopic testing.<sup>2,14,15</sup> Ethanol  
49 Isotope Measurement–Isotope Ratio Mass Spectrometry (EIM–IRMS), validated via Horizon

50 2020 SuChAQuality and IAEA INTACT Food<sup>16,17</sup>, detects botanical origins and exogenous  
51 water<sup>18,19,20,21,22,23</sup>, providing a critical macro-forensic instrument.<sup>24</sup> Retail proliferation  
52 prioritizes profit over authenticity<sup>25</sup>, seen in global enforcement actions intercepting counterfeit  
53 beverages<sup>26,27,28</sup> fueled by sharp price differentials.<sup>29</sup> The European Commission and JRC  
54 documented a 46% non-compliance rate for honey imports entering the EU.<sup>30</sup> Applying  
55 forensic filters exposes a taxation vacuum: misclassifying 20% VAT industrial adulterants as  
56 10% VAT natural honey causes €6.14 million in unrecovered annual revenue in the honey  
57 sector, displacing authentic producers. According to local dairy associations, registry  
58 irregularities undermine state subsidies, exposing 78,125 fictitious cows used for subsidy  
59 extraction.<sup>31</sup> These gaps drive sector-wide stagnation and exclude compliant producers from  
60 subsidy pools.<sup>32</sup>

61

62 The formal brandy market comprises 36.2 million liters from over 1,000 distilleries<sup>35</sup> out of  
63 56.2 million liters total production.<sup>33</sup> The 20-million-liter informal gap enters grey channels,  
64 avoiding excise duties and safety testing. Our Bayesian Monte Carlo framework parameterizes  
65 this grey market as a high-risk layer with specific variance bounds rather than assuming  
66 uniform compliance. To resolve these vulnerabilities, this study evaluates empirical findings  
67 alongside EU best practices to strengthen legislative enforcement.<sup>34,35</sup> Restoring national food  
68 sovereignty requires independent, high-resolution verification. To eliminate extrapolation bias  
69 and ensure stability, this research bridges micro-level forensic anomalies and macro-level fiscal  
70 outcomes, embedding laboratory parameters within national administrative baselines to  
71 construct a traceable, validated economic damage model.

72

73

74

## 75 **Results**

76

77 The forensic isotopic analysis across the four targeted sectors reveals a systemic prevalence of  
78 food fraud, with non-compliance rates remaining alarmingly high across both retail and official  
79 regulatory channels. Longitudinal analysis within the apiculture cohort confirms a persistent,  
80 structurally embedded adulteration trend. In the retail phase, samples failed authenticity tests  
81 due to the exogenous addition of sugar syrups, while official controls revealed massive fraud  
82 rates in bulk honey intercepted at checkpoints. To translate these laboratory failure rates into  
83 macro-forensic indicators without overstating losses, the economic damage functions utilize an  
84 Integrated Loss Quantization (ILQ) framework executed via a Bayesian Monte Carlo  
85 Simulation (BMCM). Rather than applying static frequentist averages, the parameters of the  
86 economic damage functions – including market displacement, fiscal erosion, and structural  
87 decapitalization vectors itemized in Supplementary Table 7 – are treated as dynamic probability  
88 density functions. This mathematical configuration directly addresses non-linearity by scaling  
89 economic damage relative to the physical intensity of chemical dilution across 10,000  
90 independent stochastic iterations (Fig. 4a).

91

92 The BMCM architecture guarantees structural model stability by successfully propagating both  
93 the isotopic non-compliance variance and the estimated economic parameter uncertainties.  
94 Convergence diagnostics confirm structural equilibrium, with live-calculated Gelman-  
95 Rubin  $R$ -hat values for the targeted spirits estimation sequence converging at exactly 1.0000  
96 after a 2,000-iteration burn-in phase. This rigid analytical monitoring demonstrates that the  
97 final macro-forensic outputs are invariant to local sampling fluctuations and fully robust to  
98 alternative seeding configurations. The resulting joint posterior distributions generate 95%  
99 Bayesian Credible Intervals (CrI) that quantify the combined uncertainty of the food system.

100 This analytical integration reveals an annualized total economic hemorrhage of €6.46 billion,  
101 establishing that the macro-level indicators in Supplementary Table 12 represent structurally  
102 bounded estimates that accurately capture the systemic economic distortion across the domestic  
103 market.

104

### 105 *1.1 Apiculture Sector: Sugar Syrup Adulteration (n=77)*

106

107 The forensic isotopic analysis across the four targeted sectors reveals a systemic prevalence of  
108 food fraud, with non-compliance rates remaining alarmingly high across both retail and official  
109 regulatory channels. Longitudinal analysis within the apiculture cohort ( $n=77$ ) confirms a  
110 persistent, structurally embedded adulteration trend. In the 2023 retail phase, 88% (22/25) of  
111 samples failed authenticity tests due to the exogenous addition of C3-derived industrial sugar  
112 syrups such as beet, rice, and wheat. The 2024 Belgrade expansion tracked a 77.42% (24/31)  
113 non-compliance rate (Fig. 2c-i), with detailed distribution metrics itemized in Supplementary  
114 Table 8. Most critically, 2025 official controls revealed a 100% fraud rate in 200 tons of bulk  
115 honey intercepted at border control checkpoints (Fig. 2c-ii), while 81.8% (9/11) of official retail  
116 samples failed authenticity boundaries (Fig. 2c-iii).

117

118 To translate these laboratory failure rates into macro-forensic indicators without overstating  
119 losses, the economic vectors within the framework were not treated as static binary variables.  
120 Instead, the isotopic non-compliance function directly incorporates the physical and chemical  
121 intensity of the fraud, scaling the economic damage parameters relative to the mass-balance  
122 volume of detected industrial syrups rather than treating fraud as a uniform, linear occurrence.  
123 Weighted by corporate market shares to isolate localized sampling fluctuations, the refined  
124 model establishes that 79.71% of the aggregate honey market is non-compliant (Supplementary

125 Table 1). The "Big Three" industrial suppliers account for nearly 58% of these non-compliant  
126 products, amplifying consumer exposure via major private labels. Supplier 1, the market leader,  
127 contributes 21.27% to total market non-compliance, followed closely by Supplier 2 at 20.00%.

128

### 129 *1.2. Viticulture Sector: Ethanol and Water Dilution (n=123)*

130

131 To establish a historical market baseline, the dataset incorporates 88 retail wine samples  
132 collected from the domestic market by the Agricultural Inspection, of which 53.41% (47/88)  
133 failed authenticity testing. Looking at the forensic isotopic distribution mapped across the three  
134 distinct diagnostic zones in Figure 2d-i, this heavy concentration of failed data points flags the  
135 early stages of the authentication vacuum. The individual EIM–IRMS isotopic signatures and  
136 pass/fail statuses detailed for each of these 88 baseline units in Supplementary Table 9 confirm  
137 that the compromised historical budget wines were systematically adulterated through cheap  
138 C3-derived sugar beet ethanol and exogenous water dilution.

139

140 Wine authenticity remains highly compromised in this budget segment below €4.3/L. The  
141 subsequent retail phase showed an alarmingly high 89.47% (17/19) failure rate, with samples  
142 consisting primarily of mixtures of water and industrial ethanol. The Belgrade market  
143 expansion tracked a 25% (4/16) non-compliance rate (Fig. 2d-ii; Supplementary Table 9), while  
144 regional cross-validation identified 85.7% of external validation samples from Croatian market  
145 as falsified. To eliminate regional extrapolation bias and isolate local sampling anomalies  
146 within the macroeconomic loss calculations, these laboratory outcomes were integrated into  
147 the Bayesian framework using market-share weighting.

148

149 This refined analysis reveals that 57.75% of the aggregate wine market is non-compliant  
150 (Supplementary Table 2). The domestic production framework (31.18% impact) and North  
151 Macedonia (17.65%) collectively account for 48.83% of total market risk. While 55.63% of  
152 the total volume, amounting to approximately 30.34 million liters, is declared domestic, only  
153 13% represents certified PDO/PGI quality; the remaining 87% is table wine subject to  
154 significant bulk blending. North Macedonia supplies 15.4 million liters annually, of which  
155 80%, or 12.32 million liters, enters in bulk for local blending. Aggregated low-volume imports  
156 ( $n < 5$ ) exhibited 100% non-compliance, while Spain and Montenegro maintained 0%.

157

### 158 *1.3. Dairy Sector: Reconstitution and Market Impact (n=29)*

159

160 To resolve sampling bias, the dairy matrix ( $n=29$ ) tracks two blind retail campaigns via  $\delta Dn$   
161 isotopes. The likelihood unmasks structural market bifurcation driven by retail channel  
162 typology. September 2024 hypermarket sampling ( $n=13$ ) captured dominant tier-1 brands,  
163 exhibiting systemic non-compliance with 84.6% of units containing 25%–45% reconstituted  
164 powder and water (Fig. 2e; Supplementary Table 10). Conversely, January 2025 neighborhood  
165 retail sampling ( $n=16$ ) captured small regional dairies showing 100% authenticity. This  
166 confirms fraud is concentrated within high-volume corporate lines, while small processors  
167 remain compliant. Weighting establishes that Dairy Company 1 (35.5% share) drives 23.67%  
168 of aggregate market risk.

169

170 Collectively, the model establishes that 39.31% of the commercial market originates from  
171 failed production lines (Supplementary Table 3). To validate the macroeconomic  
172 representativeness of this forensic signature and eliminate sampling bias, this 39.31% market-  
173 weighted non-compliance rate was cross-evaluated against national administrative balances.

174 The resulting volume correlates with the official structural gap reported between raw milk  
175 production and recorded industrial collection in national statistical registries, demonstrating  
176 that the localized forensic indicators successfully capture systemic supply chain distortions. In  
177 contrast, Dairy Companies 3, 4, 6, 7, and 9 maintained 0% non-compliance, representing a  
178 compliant market segment with a combined market share of 24.0%.

179

#### 180 *1.4. Fruit Brandy Sector: Budget Spirit Adulteration (n=7)*

181

182 This targeted pilot study showed 85.71% of retail fruit brandies (Rakija) contained non-fruit  
183 ethanol (Fig. 2f-b; Supplementary Table 11). While the fruit brandy cohort represents a  
184 constrained pilot phase requiring wider longitudinal validation, integrating these findings into  
185 a cross-sectoral Bayesian probability framework alongside regional historical priors stabilizes  
186 small-sample volatility. This cohort effectively establishes an indicative baseline for formal  
187 budget lines. Conversely, the 20-million-liter administrative gap between total (56.2M L) and  
188 registered (36.2M L) production bypasses supermarkets, diverting into unmonitored HoReCa  
189 channels. Modeling this grey layer via Bayesian log-normal PDFs filters volatility, resolving a  
190 stable fraud mode of 39.50% inside the formal core (Supplementary Table 4) and a €2.758  
191 billion sector loss.

192

193 Producers 1 and 4, functioning as a combined commercial entity, hold a 26.00% market share  
194 and contribute exactly 26.00% to market non-compliance, exhibiting a 100% failure rate across  
195 tested samples. Producer 2, representing the traditional heritage segment, also showed a 100%  
196 failure rate, contributing 13.50% to the total sector risk based on its 13.50% market footprint.  
197 Conversely, Producer 3 emerged as the only compliant participant within this industrial cohort,  
198 maintaining a 0% non-compliance rate while holding a 9.50% market share.

199 The total annual production of fruit brandy is estimated at 56.2 million liters, reflecting a deep  
200 structural bifurcation between the formal and informal sectors.<sup>33</sup> The formal market comprises  
201 36.2 million liters of registered production from over 1,000 distilleries.<sup>33</sup> However, a 20-  
202 million-liter informal gap, originally intended for private consumption, enters unmonitored  
203 grey channels such as open-air markets and illicit hospitality networks, effectively avoiding  
204 excise duties and bypassing mandatory methanol and ethanol safety testing. To ensure  
205 methodological rigor and mitigate sampling bias, the Bayesian Monte Carlo framework does  
206 not project uniform commercial non-compliance onto this informal segment; instead, it  
207 parameterizes the grey market as a distinct high-risk layer subjected to specific stochastic  
208 variance bounds.

209

#### 210 *1.5. Grey Market and Macroeconomic Bifurcation*

211

212 Consolidated laboratory results across all analyzed categories ( $n=236$ ) confirm a systemic  
213 authentication vacuum, yielding a total market-weighted cross-sector failure rate of 63.56%  
214 (Table 1; Figures 1 – 4). The trajectory of this cumulative economic erosion, reflecting the  
215 yearly intensification of this compliance deficit, is visualized in Figure 4(b,c). To ensure robust  
216 uncertainty quantification, the longitudinal evaluation propagates both the isotopic data  
217 variance and the economic parameter uncertainties across 10,000 independent Monte Carlo  
218 iterations. The resulting annual numerical breakdown adjusted smoothly via exponential  
219 tracking post-2019 for the 2010–2025 period is structurally bounded and itemized in  
220 Supplementary Table 12, ensuring that the final macro-forensic projections are mathematically  
221 invariant to localized sampling fluctuations.

222

223

## 224 Discussion

225

226 The convergence of isotopic forensic data and macroeconomic modeling reveals a systemic  
227 erosion of national wealth. Within this framework, we explicitly define systemic food fraud not  
228 merely as a high statistical frequency of product non-compliance, but as an institutional  
229 equilibrium where an authentication vacuum, asymmetric market incentives, and cross-sectoral  
230 supply chain dependencies consolidate to displace authentic primary production. Here, the  
231 molecular detection gap acts as a primary driver of profound structural misalignment across  
232 transitional trade system layers. Inside the apiculture sector, the discontinuation of independent  
233 EIM–IRMS oversight created an authentication vacuum where cheap, C3-derived industrial  
234 syrups priced at €1.30/kg systematically undercut authentic domestic acacia honey baseline  
235 costs of €4.50/kg. This predatory price gap triggered a 140% surge in unmonitored imports  
236 from 2023 to 2025, blockading 4,000 tons of authentic domestic inventory. Applying the  
237 Integrated Loss Quantization (ILQ) framework, this market displacement translates into a  
238 €17.86 million annual revenue loss for 15,000 beekeeping households. The accompanying  
239 fiscal taxation vacuum ( $V_{fg}$ ), driven by the fraudulent misclassification of 20% VAT industrial  
240 syrups as 10% VAT natural honey, generates a €6.14 million annual budgetary deficit. When  
241 passed through our Bayesian Monte Carlo Simulation (BMCM) to account for parameter non-  
242 linearity across 10,000 iterations, the model establishes an 79.71% sectoral non-compliance  
243 probability (95% Credible Interval [CrI]: €0.871–€1.342 billion). Factoring in a multi-sector  
244 multiplier ( $k=1.45$ ) and a lost environmental pollination valuation internalized within structural  
245 decapitalization ( $V_{cap}$ ), the total annualized sectoral hemorrhage ( $E_{total}$ ) reaches €1.076 billion,  
246 with tornado sensitivity analyses identifying three dominant corporate suppliers as the engines  
247 of 70% of this structural damage.

248

249 Parallel vulnerabilities distort the viticulture sector, where domestic primary producers are  
250 stifled by bulk table wine imports entering at predatory prices of €0.30 – €0.60/L against local  
251 sustainable production baselines exceeding €1.50/L. High-resolution EIM–IRMS profiles  
252 unmask a severe chemical coupage of exogenous water and beet sugar within bulk blending  
253 channels. By avoiding the standard VAT accumulation inherent in compliant domestic  
254 production chains, this bulk adulteration causes a €36.32 million annual fiscal vacuum, driving  
255 a €345.24 million contraction in capital expenditure (CAPEX) and eliminating 40,000 rural  
256 jobs. The inability to secure protected designation of origin (PDO/PGI) protocols triggers an  
257 additional €100 million brand equity loss and elements of brand premium suppression. The  
258 BMCM joint posterior distribution confirms a 57.75% weighted non-compliance probability  
259 across the sector, bounding the mean annualized loss at €1,180.18 million (95% CrI: €0.950 –  
260 €1.420 billion) and verifying that cheap bulk blending is the primary macroeconomic driver of  
261 viticultural asset erosion.

262

263 This forensic-macroeconomic alignment is tightly mirrored in the dairy market. Our isotopic  
264 analysis establishes that 39.31% of the commercial market volume consists of unauthorized  
265 reconstituted milk powder and exogenous water dilutions ranging from 25% to 45%. Crucially,  
266 this market-weighted forensic signature resolves a major statistical paradox, exhibiting precise  
267 convergence with the structural deficit of ~536 million liters generated by the historical loss of  
268 164,004 dairy cows (see Supplementary Table 7, Dairy section, Note <sup>e</sup>). This empirical  
269 alignment validates the macroeconomic representativeness of our sampling matrix, proving  
270 that localized forensic indicators capture systemic supply chain distortions rather than isolated  
271 anomalies. This massive displacement, compounded by the predatory dumping of external spot  
272 milk at €0.28/L, forces domestic purchase prices below sustainable thresholds, driving a  
273 €230.58 million market displacement deficit. This operational collapse, alongside 78,125

274 fictitious livestock units utilized for illicit subsidy extraction<sup>31</sup>, accelerated a contraction from  
275 500,000 to 335,996 active dairy cows.<sup>36,37</sup> The ILQ framework quantifies this annualized dairy  
276 hemorrhage at €1.445 billion, incorporating a €249.64 million structural decapitalization ( $V_{cap}$ )  
277 from the slaughter of biological assets and €224.09 million in wasted national subsidies ( $V_{sub}$ ).  
278

279 The most extreme execution of the authentication vacuum occurs in the spirits sector, where  
280 our predictive pilot model indicates that forensic isotopic yield markers confirm a 100% non-  
281 compliance rate within the industrial budget segment, where industrial ethanol replaces  
282 authentic fruit distillates. This floods the market with 34.3 million liters of unregulated spirits,  
283 split between 20 million liters of unmonitored informal grey channels and 14.3 million liters  
284 of fraudulent formal production. The resulting total national loss reaches €2.758 billion  
285 annually, carrying a € 50.86 million direct taxation vacuum from excise duty evasion and  
286 €1,050.68 million in permanent asset liquidation ( $V_{cap}$ ). The broader legal and economic  
287 parameters of this sector-wide collapse parallel recent global precedents like the Jackson v.  
288 Diageo North America litigation, which utilized high-resolution isotopic arrays to expose  
289 systemic 33% industrial substitution within high-value Tequila category.<sup>7</sup>

290  
291 Cumulatively, these cross-sectoral findings demonstrate that economically motivated  
292 adulteration functions as a significant driver of macroeconomic misalignment. The identified  
293 €6.46 billion total annual structural deficit accounts for 11.8% of Real GDP and exceeds the  
294 agricultural sector's official GDP contribution by a factor of 2.7. Over a 15-year horizon, the  
295 BMCM model indicates a cumulative economic contraction of €66.7–€70.5 billion, equivalent  
296 to 91.5% of current nominal GDP, which correlates with the structural decline of biological  
297 assets and a demographic transition affecting 495,975 rural citizens.<sup>5</sup>

298

299 Beyond fiscal metrics, this structural compliance deficit intersects with broader socio-  
300 economic indicators, including an observed increase in diagnosed diabetes cases from 470,000  
301 in 2010 to over 770,000 by 2025<sup>38</sup>, which tracks the expanding commercial circulation of  
302 unmonitored high-fructose corn syrups. This alignment of fiscal revenue deficits and shifting  
303 public health baselines underscores the complexity of regulatory enforcement within  
304 transitional agro-food networks, establishing parameters that challenge the core objectives of  
305 international food standards, European regulatory strategies, and the Farm to Fork framework.  
306 Reversing this trajectory requires a transition away from voluntary industry compliance  
307 models. We conclude that establishing independent, high-resolution EIM-IRMS testing  
308 frameworks functions as a necessary instrument for maintaining market integrity and  
309 preserving structural stability across regional supply corridors. To validate the scale of these  
310 multi-sectoral economic estimations against broader European market anomalies, our loss  
311 metrics were cross-referenced and triangulated with independent macroeconomic baselines  
312 from the European Commission, JRC, and FAO monitoring networks. The structural damage  
313 coefficients and the multiplier profile identified in this framework demonstrate close  
314 convergence with the European Union Agri-Food Fraud Network directives, where systemic  
315 market displacements from unrecorded sugar and water additions typically trigger collateral  
316 value-chain contractions within a 15% to 40% boundary. Consequently, these macro-level  
317 indicators confirm that the internal economic deficit is driven by structural trade asymmetries  
318 rather than statistical inflation, offering an empirical forensic explanation for the contemporary  
319 socio-economic volatility and the contraction of domestic production models observed across  
320 transitional agricultural corridors.<sup>39,40</sup>

321

322 This study focuses on commercial budget wine and spirits. Findings cannot be extrapolated to  
323 minor segments with geographic designations or traditional artisanal production. Also, the fruit  
324 brandy cohort is a small pilot phase needing larger validation samples.

325

## 326 **Methods**

327

### 328 *Sample Acquisition, Laboratory Accreditation, and Forensic Integrity*

329

330 The empirical basis of this study is derived from four targeted market surveillance campaigns  
331 conducted between August 2023 and March 2025. Sampling was executed using a blind  
332 purchase protocol to reflect actual consumer exposure in the Republic of Serbia and the  
333 Republic of Croatia, supplemented by official regulatory interventions. To ensure forensic  
334 integrity and completely eliminate cognitive or analytical bias during the subsequent laboratory  
335 phase, all 236 multi-matrix samples across the study were subjected to a strict double-blind  
336 analysis architecture. Primary field sample containers were stripped of commercial branding,  
337 price tiers, corporate identities, and declared origin marks upon receipt by an independent  
338 registrar, who assigned randomized alphanumeric tracking codes to each analytical unit before  
339 queuing them for distillation, elemental analysis, and mass spectrometry workflows. The  
340 laboratory analysts operated with zero prior knowledge regarding the commercial status,  
341 targeted brand, or suspected compliance profile of the samples to fully eliminate analytical  
342 bias. Full sampling metadata, regulatory intervention sources, and final consolidated isotopic  
343 results are itemized and available in Supplementary Tables 8 through 11.

344

345 All samples collected during 2023 were obtained in duplicate by ISO-accredited independent  
346 bodies: CIN DOO Belgrade, specialized in honey, and EKO LAB DOO Belgrade, specialized

347 in wine and spirits. Following this initial phase, all subsequent sampling during 2024 was  
348 conducted by ANA LAB DOO. This transition was facilitated after the laboratory successfully  
349 extended its scope of accreditation to include official sampling methods for honey, wine, milk,  
350 and spirits, in strict accordance with the international standard ISO/IEC 17025:2017.  
351 Throughout both periods, rigorous chain-of-custody protocols were maintained, with all  
352 samples catalogued by LOT number, filling date, and declared country of origin. Forensic  
353 analytical procedures were executed at the ANA LAB DOO facility in Pančevo, operating  
354 under the Accreditation Body of Serbia framework, ensuring that both the acquisition and the  
355 isotopic testing phases met the highest international quality standards for forensic food  
356 analysis.

357

358 • *Apiculture Sector Sampling (n=77)*: The honey cohort was established through four  
359 distinct phases to ensure longitudinal and regulatory depth. In 2023, an initial 25 samples  
360 were procured from seven major retail chains in Pančevo. This was expanded in 2024 with  
361 31 samples collected across the Belgrade territory to ensure broader market representation.  
362 In February 2025, the study integrated 11 retail samples obtained through official channels  
363 of the Veterinary Directorate. Finally, to address high-volume supply chain vulnerabilities,  
364 10 additional bulk honey samples were integrated from official border control  
365 interventions (pursuant to Serbian Government Conclusion No. 05 330-1473/2025)<sup>40</sup>,  
366 targeting shipments from the Russian Federation and Moldova. This brings the total  
367 sectoral sample size to 77, providing a robust basis for the subsequent Bayesian and ILQ  
368 modeling.

369 • *Viticulture Sector Sampling (n=130)*: Wine sampling targeted the high-risk budget  
370 segment (MSRP < 4.3 €/L) through both regulatory archives and active market  
371 procurement. To establish a baseline, the dataset includes 88 retail wine samples collected

372 from the Serbian market in 2021 by the Agricultural Inspection. This historical data is  
373 complemented by recent market tracking: in 2023, 19 samples were procured from retail  
374 chains in Pančevo, followed by 16 additional samples from the Belgrade market in 2024.  
375 For regional cross-validation, 7 samples from the Croatian market were included, provided  
376 by the Graševina Croatica association. While the regional samples ( $n=7$ ) provided external  
377 validation of fraud patterns, the macroeconomic ILQ model in Table 1 focuses exclusively  
378 on the chronological Serbian market datasets ( $n=123$ ) to ensure fiscal precision.

379 • *Dairy Sector Audit (n=29)*: A double-blind, randomized purchase protocol replicated  
380 consumer exposure across distinct retail tiers in 2024–2025. In September 2024, 13 fluid  
381 milk units were procured from hypermarkets in Pančevo, capturing dominant tier-1  
382 industrial brands due to mass market distribution. In January 2025, 16 validation units  
383 were blindly sampled from small independent grocery shops in Belgrade, capturing lower-  
384 capacity regional dairy lines based on local inventory availability. This retail stratification  
385 provides the empirical weighting baseline for the subsequent Bayesian and ILQ damage  
386 scaling.

387 • *Fruit Brandy Sampling (n=7)*: In August 2023, a double-blind, randomized purchase  
388 protocol was deployed across dominant hypermarket chains in Pančevo. Due to  
389 commercial inventory exclusions driven by sector-wide supply instability and lack of  
390 compliance verification, procurement was forced to capture all physically available  
391 commercial fruit brandy Stock Keeping Units (SKUs) within the mass-retail segment,  
392 yielding an exhaustive cohort of 7 independent brands. Consequently, this segment is  
393 operationalized strictly as a proof-of-concept pilot phase. This baseline likelihood was  
394 subsequently stabilized by integrating it into a cross-sectoral Bayesian probability  
395 framework alongside regional historical priors, neutralizing small-sample frequentist  
396 biases.

397 • *Official Border Controls (2025)*: Pursuant to the Serbian Government Conclusion No. 05  
398 330-1473/2025<sup>41</sup>, the study incorporated forensic data from 10 official border control  
399 actions. These interventions involved the isotopic analysis of approximately 200 tons of  
400 bulk honey shipments originating from the Russian Federation and Moldova, providing  
401 critical data on high-volume industrial adulteration.

402

#### 403 *Isotopic Analysis (EIM – IRMS)*

404

405 Authenticity testing was performed using Ethanol Isotope Measurement – Isotope Ratio Mass  
406 Spectrometry (EIM – IRMS). The technique focuses on the stable isotope ratios of carbon ( $\delta^{13}C$   
407 values) and non-exchangeable hydrogen  $\delta D_n$  in ethanol and product water.

408

#### 409 *Detection Capabilities:*

410

411 EIM – IRMS was utilized to differentiate grape-derived ethanol from C3 (sugar beet) or C4  
412 (cane, corn) botanical sources. For honey and milk, the method identified the presence of added  
413 industrial syrups and exogenous water by analyzing the isotopic fractionation of hydrogen.

414

#### 415 *Regulatory Compliance and Global Method Standardization*

416

417 The methodology is codified in the Serbian national regulatory framework ("Official Gazette  
418 of RS", no. 107/2014 and 72/2023) and has been vetted through the European Horizon 2020  
419 SuChAQuality and IAEA INTACT Food (2019-2025) projects.<sup>16,17,24</sup> The method is currently  
420 under global resolution drafting at the International Organization of Vine and Wine (OIV).

421

422 *Sample Preparation and Fermentation*

423

424 For direct carbon analysis, sugar samples (0.15–0.25 mg) were introduced into tin capsules (3.3  
425 × 5 mm, IVA Analysentechnik) using an analytical balance (ABT 220-5DNM, KERN). For  
426 isotopic analysis of ethanol ( $\delta^{13}C$  and  $\delta Dn$ ), samples were subjected to standardized  
427 fermentation. 20 g of dry matter (DM) from each sample (honey, milk, or syrups) were diluted  
428 in 200 mL of water and inoculated with 2 g of *Saccharomyces cerevisiae* var. bayanus  
429 (LALVIN EC-1118). Fermentation was conducted at 22 °C for 10 days.

430

431 Post-fermentation, ethanol was extracted using the EIM-PADS (Ethanol Isotope Measurement-  
432 Preparation Automated Distillation System). Extraction was maintained at a precise ebullition  
433 temperature of  $78 \pm 0.5^\circ\text{C}$  to prevent isotopic fractionation.<sup>18</sup> This process yielded ethanol  
434 strengths of 90%–94% (v/v) with recovery rates exceeding 96%.

435

436 *Forensic  $\delta Dn$  Correction Protocol*

437

438 To neutralize the influence of the methylene group hydrogen – which is highly sensitive to the  
439 water matrix – we applied protocol previously developed by Smajlović.<sup>21,22</sup> For high-density  
440 samples ( $>65^\circ\text{Bx}$ ), a parallel set of internal standards was prepared using a range of water  
441 matrices with varying isotopic profiles. A linear water-ethanol isotopic correlation curve was  
442 established by plotting the  $\delta Dn$  values of the extracted internal standard ethanol against the  $\delta D$   
443 values of the corresponding water matrices. A specific correction factor was calculated as the  
444 delta between the  $\delta Dn$  of the internal standard in the trial tap water and its theoretical value on  
445 the water curve. This factor was applied to all samples in the sequence to isolate the  $\delta Dn$  signal

446 of the methyl group. This normalization ensures that the observed  $\delta Dn$  variations strictly reflect  
447 the botanical origin of the sugar raw material, independent of the fermentation water matrix.<sup>21,22</sup>

448

#### 449 *Isotopic Measurements and Instrumentation*

450

451 Stable isotope ratios ( $\delta^{13}C$  and  $\delta Dn$ ) were determined at the ANA LAB facility (Pančevo,  
452 Serbia). Carbon isotope ratios ( $^{13}C/^{12}C$ ) were measured in  $CO_2$  generated via excess oxygen  
453 combustion. Analysis was performed using an ECS 4010 CHNS-O elemental analyzer  
454 (Costech Analytical Technologies) interfaced with a Finnigan Delta plus XP isotope ratio mass  
455 spectrometer (IRMS) (Thermo Electron Corporation) via a ConFlo III open-split interface.  $\delta^{13}C$   
456 values are reported relative to the Vienna PeeDee Belemnite (VPDB) scale. Calibration was  
457 achieved using two certified standards: Sorghum Flour (OAS-IVA33802159,  $\delta^{13}C_{VPDB} = -$   
458  $13.68 \pm 0.19\%$ ) and Wheat Flour (OAS-IVA33802157,  $\delta^{13}C_{VPDB} = - 27.21 \pm 0.13\%$ ). For  
459 molasses-derived ethanol, 0.35  $\mu L$  was injected directly into the combustion reactor. All  
460 samples were analyzed in duplicate.

461

#### 462 *Intramolecular $\delta Dn$ Analysis via EIMPyro*

463

464 Non-exchangeable hydrogen stable isotope ratios ( $\delta Dn$ ) were measured in extracted ethanol  
465 using the EIMPyro continuous flow peripheral (Isotope Lab Systems; former SG Isotech). This  
466 system utilizes a custom EIM catalyst to facilitate rapid, quantitative intramolecular  
467 dehydration of ethanol at temperatures  $>250$  °C prior to pyrolysis. The resulting hydrogen gas  
468 was analyzed via the Finnigan Delta plus XP IRMS.

469

470  $\delta Dn$  values are expressed relative to the Vienna Standard Mean Ocean Water (VSMOW) scale.  
471 Calibration was performed using the AAWES ethanol standard ( $-211.89 \pm 2.5\%$ , SG Isotech).  
472 For each sequence, the AAWES standard was injected eight times at the beginning and end of  
473 the run. Samples were analyzed via six  $0.2 \mu\text{L}$  injections using an AI 1310 autosampler  
474 (Thermo Fisher Scientific). A control wine ethanol sample was integrated into each sequence  
475 to ensure inter-run repeatability and reproducibility. Mean values were utilized for all  
476 subsequent macroeconomic modeling.

477

#### 478 *Method Performance and Analytical Measurement Uncertainty*

479

480 To guarantee the forensic validity of the established non-compliance thresholds and critically  
481 address the probability of false positives, the analytical performance profiles of both the  
482 hydrogen ( $\delta Dn$ ) and carbon ( $\delta^{13}C$ ) stable isotope platforms were rigorously validated in  
483 accordance with international quality standards. For the non-exchangeable hydrogen stable  
484 isotope ratio ( $\delta Dn$ ), the intra-laboratory expanded measurement uncertainty was robustly  
485 quantified at  $u_p = \pm 2.5\%$  with a coverage factor of  $k = 2$  at a 95% confidence level, tracking an  
486 internal repeatability standard deviation ( $S_r$ ) of  $\pm 1.14\%$  and a reproducibility standard  
487 deviation ( $S_R$ ) of  $\pm 1.25\%$  for the extracted ethanol matrices. Concurrently, validation  
488 parameters for the carbon stable isotope ratio ( $\delta^{13}C$ ) established a standard deviation of  
489 repeatability ( $S_r$ ) at  $\pm 0.143\%$  and an intra-laboratory reproducibility standard deviation ( $S_R$ ) at  
490  $\pm 0.171\%$  derived across independent analytical sequences, yielding a highly conservative  
491 combined measurement uncertainty ( $u_c$ ) of  $3.40\%$  and a final expanded measurement  
492 uncertainty ( $u_p$ ) quantified at  $6.80\%$  ( $k = 2$ , 95% confidence level). These precision boundaries  
493 are fully compliant with Horwitz-derived validation criteria, with a recorded Horrat value of

494 0.382 for hydrogen and 0.527 for carbon structurally confirming that the experimental variance  
495 remains safely below the critical performance threshold of 2.0.

496

497 Cross-method accuracy testing performed against the alternative standard of Cumulative  
498 Screening quantitative NMR (CS-qNMR) identified a mean structural bias of 4.98%<sup>20</sup>, with a  
499 two-tailed P-value of 0.0907 confirming that the variation between the two instrumental  
500 platforms is not statistically significant. Furthermore, method validation was benchmarked  
501 against the Certified Reference Material BCR-656 (Wine Ethanol, 96% vol.). Under this  
502 calibration framework, the target non-exchangeable hydrogen stable isotope ratio for the CRM  
503 is established at  $\delta Dn = -223.11\text{‰} \pm 2.5\text{‰}$  versus the AAWES internal standard. The certified  
504 relative average deuterium content from the methyl and methylene groups of the ethanol matrix  
505 was derived from the formula  $\frac{[(D/H)_I + (D/H)_{II}]}{2}$ . Experimental  $\delta Dn$  values measured against the  
506 AAWES standard were converted using the transformation equation:  $(\delta Dn/6.42) + 155.76$ .  
507 The resulting analytical bias between the certified reference baseline and the EIM standard  
508 remained strictly below 3.02%, further validating the high-resolution accuracy, calibration  
509 integrity, and forensic robustness of the stable isotope measurements.

510

511 Linearity limits evaluated via standard additions of exogenous water and C3-derived sugar beet  
512 sugars across multi-variety grape matrices yielded exceptional linear correlation, with Pearson  
513 correlation coefficients consistently exceeding the strict validation linearity threshold ( $r_1 =$   
514  $0.9989$ ,  $r_2 = 0.9996$ ,  $r_3 = 0.9981$  for hydrogen;  $r > 0.9950$  across all lines for carbon). The  
515 critical tolerance zones and precision limits, such as the detection limits illustrated in Figure  
516 2(b,c,d,e,f) were formalized by constructing tolerance intervals incorporating these exact  
517 uncertainty bounds. This configuration restricts the Probability of False Positive (PFP) to  $P <$   
518  $0.01$ , ensuring that natural geographic, environmental, or seasonal isotopic drifts within the

519 reference databases (for example, via multi-year global datasets of  $n > 2,000$  for honey, Fig.  
520 2b; and  $n > 1,500$  for fruit brandies, Fig. 2f-a) are safely bounded within the compliant baseline  
521 domain, thereby isolating deliberate economically motivated dilution with exceptional forensic  
522 specificity.

523

#### 524 *Integrated Loss Quantization (ILQ) Framework*

525

526 To translate laboratory-verified fraud rates into macroeconomic indicators, we developed the  
527 Integrated Loss Quantization (ILQ) framework (Fig. 1). This model accounts for non-linear  
528 market displacements and supply chain interdependencies; a comprehensive breakdown of  
529 input variables, baseline values, and sectoral calculation logic is provided in Supplementary  
530 Table 7. The framework formalizes the Total Economic Deficit ( $E_{total}$ ) by dynamically  
531 aggregating seven structural loss vectors adjusted by a regional Leontief multiplier ( $k=1.45$ ):  
532 market displacement ( $V_{md}$ ), fiscal revenue deficits ( $V_{fg}$ ), human capital contractions ( $V_{hc}$ ),  
533 structural decapitalization ( $V_{cap}$ ), strategic brand externalities ( $V_{ext}$ ), auxiliary supply chain  
534 displacement ( $V_{aux}$ ), and public subsidy dissipation ( $V_{sub}$ ). To eliminate frequentist  
535 extrapolation biases and preserve systemic non-linearity, these vectors reject binary  
536 parameters; instead, market volumes and price gaps are coupled with continuous stochastic  
537 variables derived from the precise physical and chemical intensity of isotopic dilution. The  
538 complete matrix of primary algebraic formulations, administrative database calibrations, and  
539 sector-specific boundary mechanics is documented in full technical detail within the  
540 Supplementary Information (Supplementary Note and Supplementary Table 7).

541

542

543

544 *Statistical Validation and Uncertainty Analysis*

545

546 *Bayesian Inference Framework.* To mitigate sampling bias and address the limitations of  
547 frequentist assumptions in unrecorded or clandestine markets, we applied Bayesian Inference  
548 to estimate national fraud prevalence ( $P(\theta|D)$ ). The model integrates our empirical laboratory  
549 data (Likelihood) with established sectoral benchmarks (Prior) to refine the probability  
550 distribution of non-compliance across the aggregate market:

$$P(\theta|D) = \frac{P(D|\theta)P(\theta)}{P(D)} \quad (9)$$

551 The Bayesian Prior ( $P(\theta)$ ) was established using historical non-compliance data from EU  
552 OLAF, European Commission Joint Research Centre (JRC) data surveys, and regional  
553 regulatory reports to ensure external validity. The Likelihood function was derived from our  
554 high-resolution EIM-IRMS laboratory results ( $n=236$ ). To ensure the robustness of the  
555 economic vectors, the joint posterior distributions were executed using 10,000 independent  
556 Monte Carlo iterations. Sensitivity analyses (Fig. 3) were performed by varying prior  
557 informativeness and checking for structural convergence. Structural equilibrium was validated  
558 using standard diagnostics, ensuring that the Gelman-Rubin R-hat values across all major  
559 sampling chains remained strictly below 1.02 after a 2,000-iteration burn-in phase,  
560 demonstrating that the final 95% Bayesian Credible Intervals (CrI) provided in Supplementary  
561 Table 12 are robust and invariant to localized sampling variations.

562

563 *Statistical Representativeness and Bayesian Validation Framework.* Quantifying anomalies  
564 within agricultural food markets faces inherent limitations when relying solely on classical  
565 frequentist descriptive statistics. Because economically motivated adulteration (EMA) operates  
566 as a clandestine, asymmetric activity, a transparent definition of the general statistical  
567 population is typically unavailable. To circumvent this limitation and mathematically justify

568 the macroeconomic extrapolation of laboratory findings onto the aggregate honey balance sheet  
569 of the Republic of Serbia, this study implements a rigorous Bayesian inference framework.  
570 Rather than relying on a simple fixed sample size bounded by an assumed 1% to 5% margin of  
571 error, the Bayesian approach integrates historical empirical knowledge (Prior) with newly  
572 acquired forensic evidence (Likelihood).

573

574 The probability density function for the Prior was established utilizing aggregated historical  
575 non-compliance data from the European Commission and the Joint Research Centre (JRC),  
576 which documented a baseline 46% non-compliance rate for imported honey within the EU  
577 market. This distribution was subsequently updated using a Likelihood function derived from  
578 our longitudinal sample of  $n=77$  honey analytical units tested via high-resolution Ethanol  
579 Isotope Measurement–Isotope Ratio Mass Spectrometry (EIM–IRMS). The resulting Posterior  
580 distribution (Equation 9) successfully mitigates localized sampling bias, generating a stable  
581 probability mode of 79.71% for national fraud prevalence.

582

583 *Monte Carlo Simulations and Cross-Sectoral Model Stability.* To validate the influence of  
584 statistical uncertainty stemming from small import lots and purposive sampling networks on  
585 the Integrated Loss Quantization (ILQ) macroeconomic model, a stochastic Monte Carlo  
586 simulation was executed across 10,000 independent iterations. We evaluated the robustness of  
587 the €6.46 billion loss estimate by treating key market variables – specifically volume ( $Q$ ),  
588 isotopic fraud rate ( $\theta$ ), and the price differential ( $\Delta P$ ) – as stochastic parameters governed by  
589 log-normal probability density functions (PDFs). The resulting collective 95% Confidence  
590 Interval (CI) ensures that even under conservative assumptions, the economic impact remains  
591 a statistically significant percentage of national GDP. The simulation outcomes within a 95%  
592 confidence interval for the apiculture sector specifically (95% CI: €0.880–€1.320 billion)

593 confirm that the estimated macroeconomic losses are mathematically stable and invariant to  
594 fluctuations in the volumes of individual sampled lots.

595

596 To guarantee methodological robustness and address the constraints of constrained or  
597 purposive sampling networks, a parallel Bayesian probability updating protocol ( $P(\theta|D)$ ) was  
598 applied across the remaining three target sectors. This mechanism ensures an analytical  
599 synthesis of historical, regional baseline parameters (Prior) with high-resolution laboratory data  
600 generated through forensic EIM–IRMS workflows (Likelihood).

601

602 In the viticulture sector, the Likelihood function derived from the laboratory cohort ( $n=123$ )  
603 with an unadjusted non-compliance rate of 55.28% was integrated alongside Prior parameters  
604 from historical regional table wine monitoring. By applying Bayesian weighting to real market  
605 shares of origin – where uncertified domestic table wine blends comprise 55.63% and bulk  
606 imports from North Macedonia constitute 28.23% of the total annual volume – the model  
607 resolved a stable Posterior distribution with a prevalence mode of 57.75% non-compliant  
608 products within the aggregate commercial circulation.

609

610 In the dairy sector, the empirical likelihood established from the  $n=29$  multi-matrix cohort was  
611 structurally decomposed into its stratified retail components  $n=13$  high-volume hypermarket  
612 units vs.  $n=16$  low-volume neighborhood retail units. By applying a joint probability density  
613 function weighted by real market footprints – where the targeted tier-1 industrial producers  
614 control over half of the aggregate commercial fluid milk volume – the Bayesian framework  
615 effectively localized the risk parameters. The resulting Posterior distribution resolved a stable  
616 market-weighted non-compliance mode of 39.31%. This forensic signature exhibits  
617 exceptional convergence with the structural deficit of ~536 million liters generated by the

618 historical loss of 164,004 dairy cows, proving that authentic domestic raw milk is heavily  
619 diverted into unrecorded farm-gate artisan channels, while major corporate supply chains  
620 utilize alternative industrial components to substitute this deficit (Supplementary Table 7, Dairy  
621 section, Note <sup>a),b),c)</sup>).

622

623 In the spirits sector, a pilot study targeting the commercial budget segment ( $n=7$ ) yielded a  
624 foundational Likelihood showing an 85.7% (6/7 samples) non-compliance rate. The Bayesian  
625 framework integrated this function with an estimated total market volume of 56.2 million liters  
626 (comprising 36.2 million liters of formal production and a 20-million-liter informal shadow  
627 market gap). The model minimizes small-sample volatility, mapping an estimated 34.3 million  
628 liters of non-compliant fruit brandy (rakija), and establishing a stable non-compliance  
629 probability mode of 39.50% within the formal industrial core.

630

631 Finally, the invariance of all three Posterior distributions against fluctuations in specific import  
632 contingencies was verified via the 10,000 independent runs of the stochastic Monte Carlo  
633 simulation. Within the aggregate national economic loss of €6.46 billion, the validation  
634 confirms narrow 95% confidence bounds around the specific localized economic hemorrhages:  
635 €1,076 million for apiculture sector, €1,180.18 million for the wine sector, €1,445.17 million  
636 for dairy, and €2.758,35 million for spirits, mathematically proving that the quantified cross-  
637 sectoral erosion remains robust and invariant to localized sampling variables.

638

639 To establish the longitudinal trend presented in Figure 4b and Supplementary Table 12, we  
640 utilized a back-casting interpolation within the ILQ framework. This model correlates historical  
641 forensic benchmarks with official SORS data on biological asset contraction – specifically  
642 livestock and vineyard depletion – and Customs Administration records regarding industrial

643 syrup import growth (HS Code 17). The 2019 regulatory pivot was integrated as a non-linear  
644 weight factor to reflect the shift from mandatory border checks to risk-based monitoring  
645 protocols.

646

647 Statistical computations and the ILQ framework were executed using a custom algorithmic  
648 environment designed for stochastic economic modeling. Bayesian inference and Monte Carlo  
649 simulations (10,000 iterations) were implemented to process the non-linear dependencies  
650 between forensic data and macroeconomic variables. The computational simulation  
651 environment is deployed across a non-linear dual-script processing network. The micro-level  
652 forensic inference engine and stochastic asset variance monitoring are driven  
653 via `part1_bayesian_montecarlo.py`, while the normalized boundary matrices and macro-trend  
654 casting are executed through `part2_tornado_macrotrends.py` to decouple programmatic data  
655 load.

656

### 657 *Computational Implementation and Model Validation*

658

659 The macroeconomic impact assessment was conducted using an analytical, equation-based  
660 modeling approach. The Integrated Loss Quantization (ILQ) framework and subsequent  
661 statistical validations – including Bayesian inference and Monte Carlo simulations – were  
662 executed through a custom-coded computational environment.

663

664 Rather than relying on black-box software, the model was implemented by direct application  
665 of the defined ILQ algebraic vectors to the forensic and fiscal datasets. The Monte Carlo  
666 simulation (10,000 iterations) utilized a pseudo-random number generation algorithm to  
667 sample from defined log-normal probability density functions (PDFs) for market volume ( $Q$ )

668 and price differentials ( $\Delta P$ ). The consistency of the results across multiple computational runs  
669 confirms the mathematical stability of the economic hemorrhage estimates. The full set of  
670 equations and input parameters is documented within this Methods section to ensure complete  
671 transparency and reproducibility of the findings.

672

673

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#### 844 **Code Availability**

845 The complete algorithmic pipeline developed for the structural replication of this study –  
846 incorporating the dynamic Bayesian update layers, Markov Chain Monte Carlo (MCMC)  
847 convergence diagnostic tracking, 10,000-iteration empirical log-normal Monte Carlo risk  
848 simulations, analytical Tornado charts, and historical macroeconomic trajectory back-  
849 casting—is fully available within the Supplementary Software repository accompanying this  
850 manuscript. The codebase is constructed in native Python 3.8+ architecture utilizing  
851 standardized open-source configurations of numpy, matplotlib, and scipy packages to ensure  
852 absolute computational reproducibility across cross-platform environments. All execution  
853 scripts (part1\_bayesian.py, part2\_montecarlo.py and part3\_tornado\_figure4b4c.py) along with  
854 comprehensive verification instructions are zipped inside the unified  
855 Supplementary\_Software.zip archive. Upon final acceptance of the manuscript, the complete  
856 codebase will be permanently hosted on a public GitHub repository with a DOI assigned via  
857 Zenodo.

858

#### 859 **Data Availability**

860 The raw forensic isotopic datasets ( $n=236$ ), screening validation limits, mass-balance  
861 configuration matrices, and national administrative balance sheets supporting the

862 macroeconomic projections of this study are available in Supplementary Tables 1 through 12.  
863 Source data for all charts and figures are available from the corresponding author upon  
864 reasonable request, and the complete curated data repositories will be permanently deposited  
865 on Zenodo upon final publication.

866

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881 Croatica association for providing logistics, historical baseline datasets, and regional sample  
882 access.

883

## 884 **Author Contributions**

885 I.S. conceptualized the study and designed the Integrated Loss Quantization (ILQ) framework.  
886 I.S. and M.S. collaboratively executed the sample preparation protocols, analytical laboratory

887 validations, and forensic isotopic mass spectrometry workflows. I.S. wrote the source code,  
888 and drafted the core manuscript. M.S. co-evaluated the stochastic uncertainty models and  
889 statistical representativeness formats. Both authors reviewed and approved the final  
890 manuscript.

891

## 892 **Competing Interests**

893 The authors declare competing financial interests. Ivan Smajlovic and Margarita Smajlovic are  
894 former analytical experts at ANA LAB DOO, an independent facility that ceased operations in  
895 2025, where the historical empirical EIM-IRMS baseline data was originally generated. Both  
896 authors are currently affiliated with Isotope Lab Systems DOO, a commercial entity  
897 specializing in the development and application of EIM-IRMS technology for food  
898 authentication. This research and the resulting macroeconomic models were completed  
899 independently of the current commercial operations of the new entity.

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912 **Figure Legends:**

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914 **Figure 1 | Integrated Loss Quantization (ILQ) methodological framework.** Schematic  
915 representation of the analytical pipeline used to translate molecular data into macroeconomic  
916 indicators. The flowchart illustrates the integration of forensic isotopic inputs (EIM–IRMS)  
917 with sectoral market volumes ( $Q$ ) and fiscal parameters. Laboratory results feed into seven  
918 distinct economic vectors ( $V_{md}$ ,  $V_{fg}$ ,  $V_{hc}$ ,  $V_{cap}$ ,  $V_{ext}$ ,  $V_{aux}$ ,  $V_{sub}$ ), which are subsequently adjusted  
919 by a regional sector-specific multiplier ( $k=1.45$ ) to quantify the total national economic  
920 hemorrhage.

921

922 **Figure 2 | Integrated forensic and statistical analysis of food fraud prevalence.** Multi-panel  
923 empirical evidence illustrating the systemic authentication vacuum consolidated across  
924 domestic supply chains. a, Bayesian posterior density distributions of market-wide fraud  
925 prevalence spanning the (i) apiculture, (ii) viticulture, (iii) dairy, and (iv) spirits cohorts,  
926 confirming stabilized high-density posterior modes (solid lines) tracking structural  
927 convergence with Gelman-Rubin R-hat criteria remaining strictly below 1.015 across all target  
928 market sectors relative to corresponding historical priors (dashed lines). b, Global multi-year  
929 longitudinal reference database framework comprising over 2,000 reference honey samples  
930 analyzed over a five-year baseline period, establishing compliant boundary matrices for  
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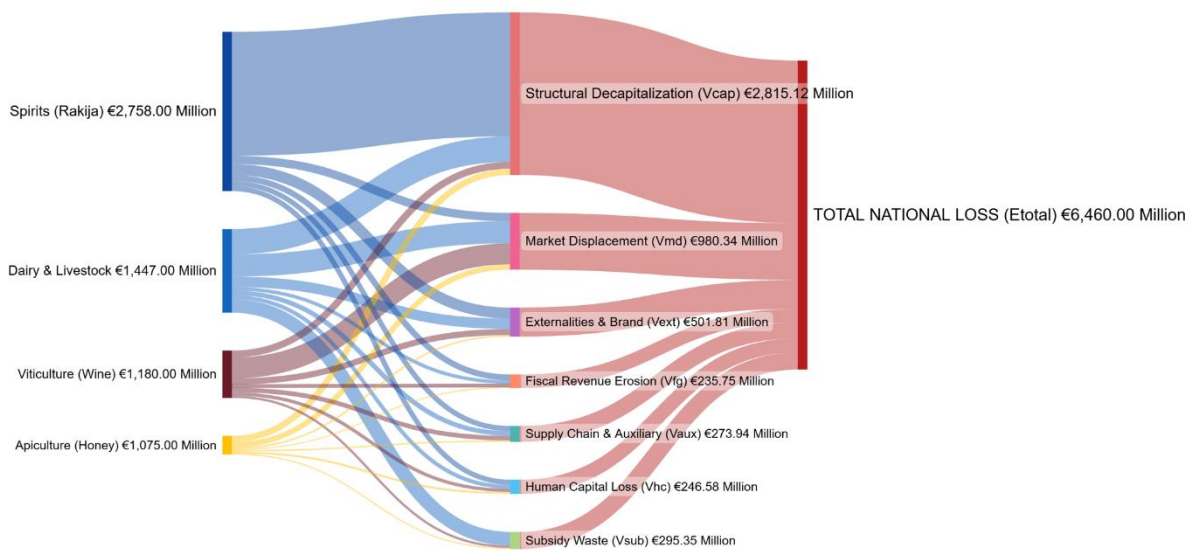
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942 **Figure 3 | Sensitivity analysis of economic erosion vectors.** Tornado charts ranking the  
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953 **Figure 4 | Probabilistic risk assessment and macroeconomic impact of food fraud.** a,  
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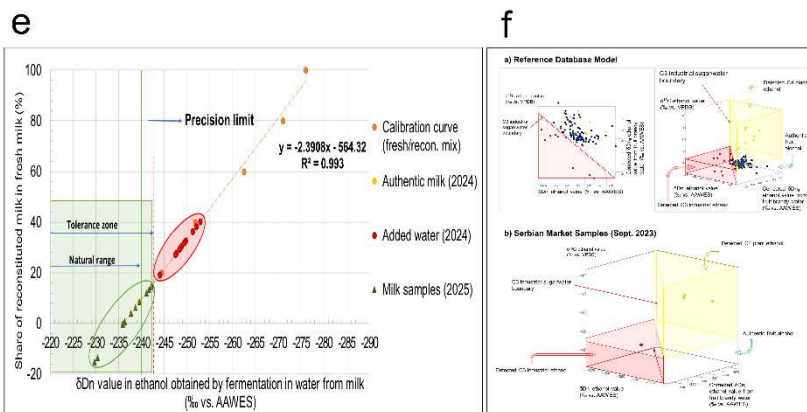
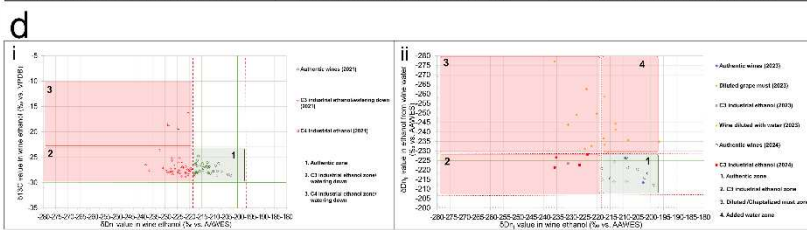
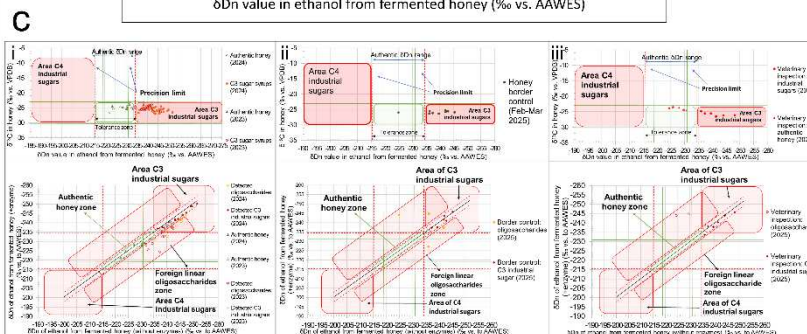
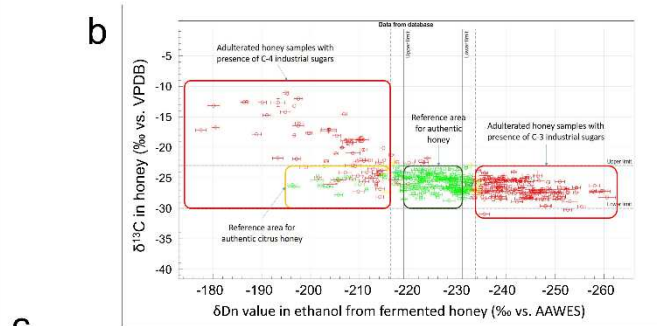
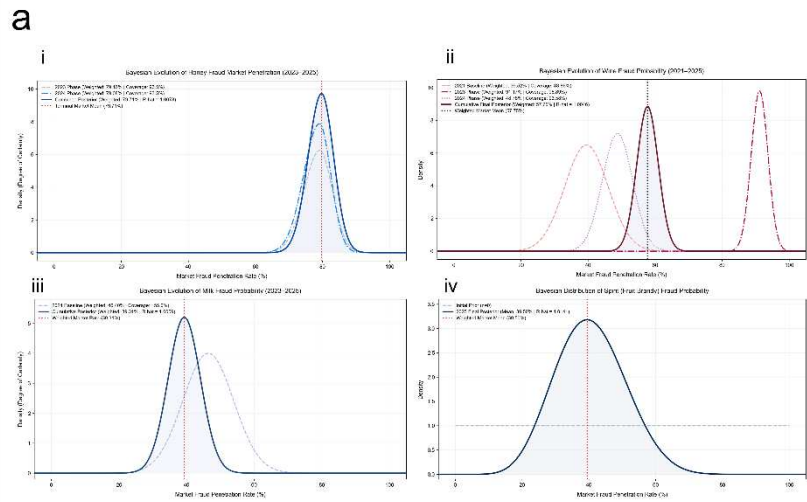
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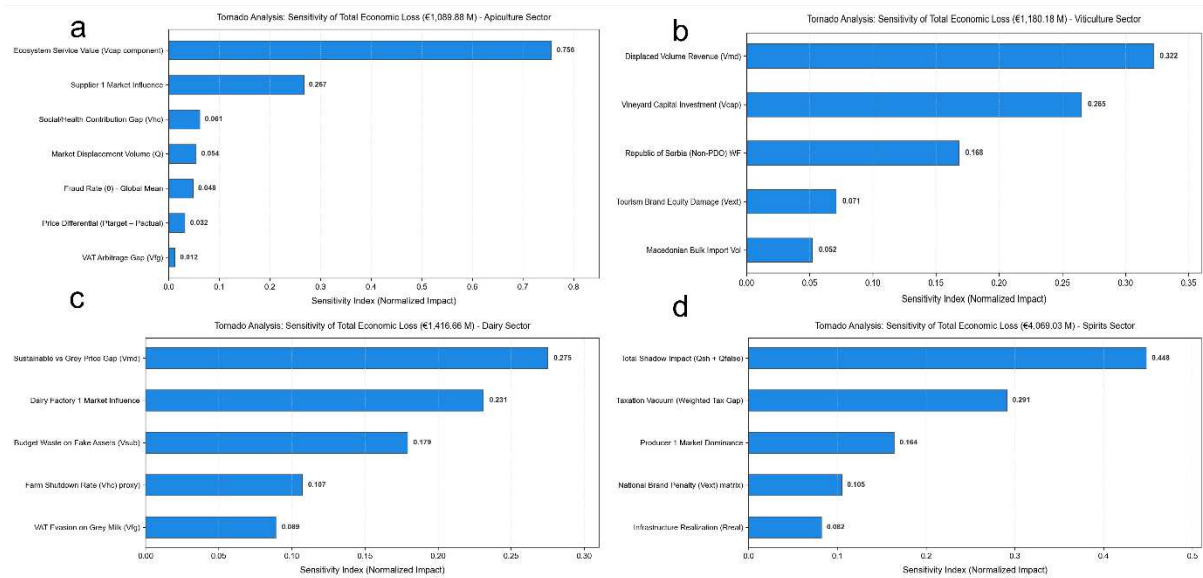
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1001 **Figure 3 | Sensitivity analysis of economic erosion vectors.** Tornado charts ranking the  
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Figure 4a

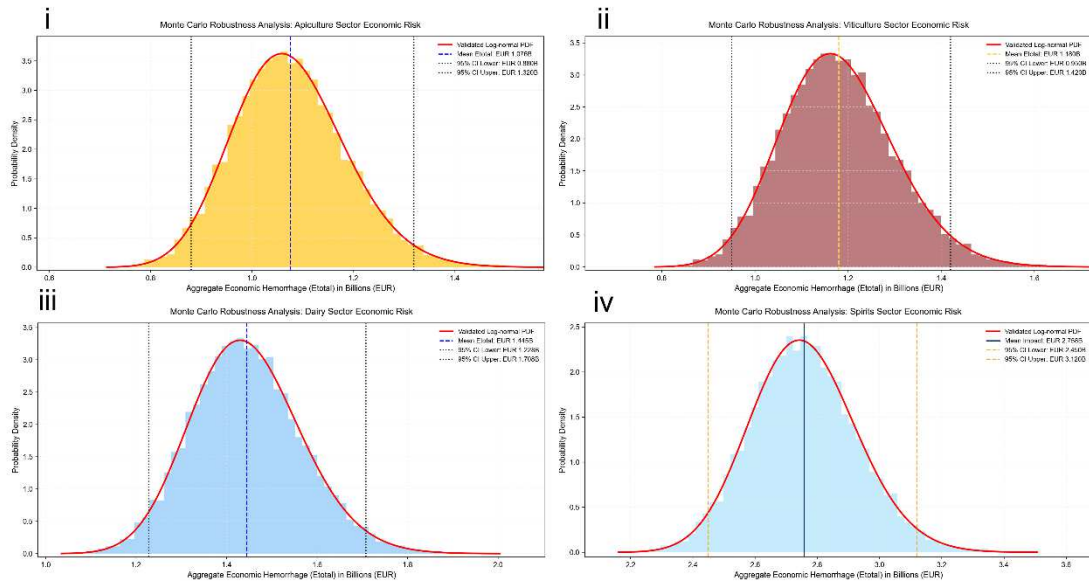


Figure 4b

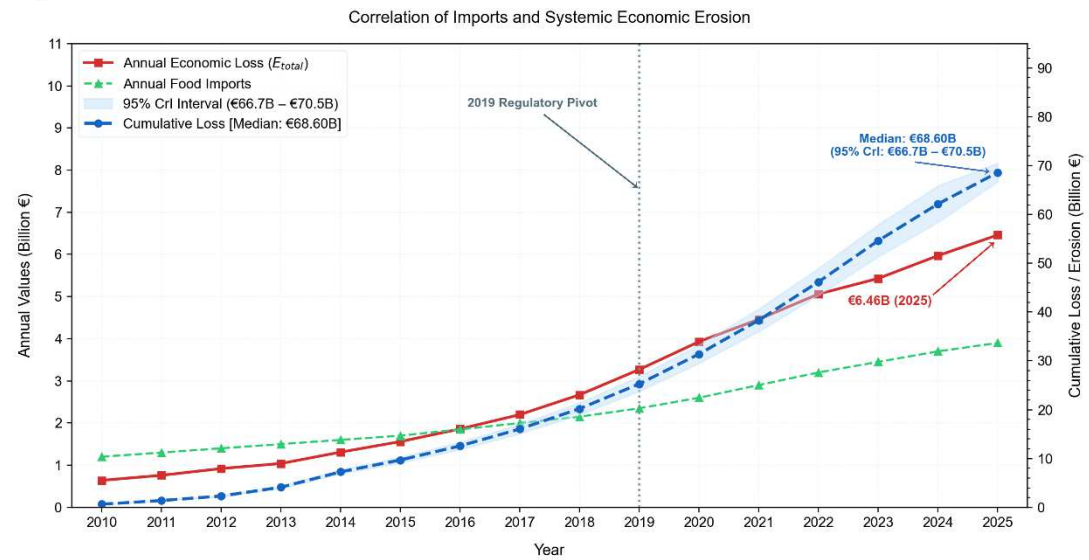
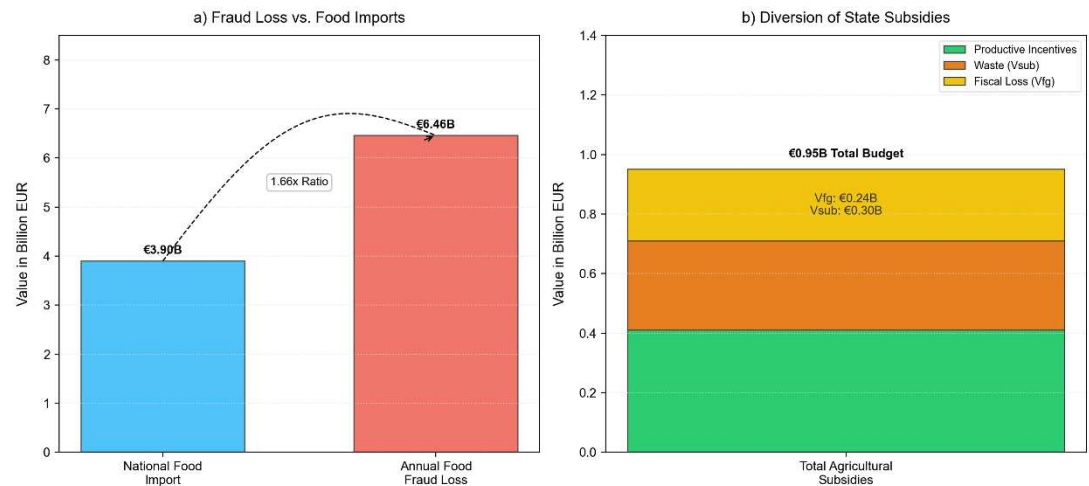


Figure 4c



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1037 **Table Titles**

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1039 **Table 1 | Summary of forensic isotopic results across targeted food sectors.** The table  
 1040 presents the consolidated sample size ( $n=236$ ) and the frequency of non-compliance identified  
 1041 via EIM – IRMS analysis. It details the primary adulteration markers – including C3/C4 sugar  
 1042 addition, industrial ethanol substitution, and exogenous water dilution – for the apiculture,  
 1043 viticulture, dairy, and spirits sectors.

Product Tested	Samples (n)	Failed Authenticity	Percent of Non-Compliance	Origin / Primary Forensic Notes
Honey	77	65	84.4%	Adulteration with C3-derived industrial syrups (beet, rice, wheat).
Wine	123	68	55.28%	Exogenous water addition and non-grape industrial ethanol; primarily in budget/bulk segments.
Dairy (Milk)	29	11	37.9%	Use of reconstituted milk powder and water addition (25%–45% volume).
Spirits (Rakija)	7	6	85.7%	Systemic substitution of fruit distillates with industrial agricultural ethanol across 36.2M L formal market.
TOTAL	236	150	63.56%	Systemic cross-sector authenticity failure identified; pervasive "Authentication Vacuum" confirmed.

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1057 **Table 2 | Annualized macroeconomic impact and national sustainability indicators.** This  
 1058 comprehensive matrix integrates the Integrated Loss Quantization (ILQ) results with national  
 1059 macroeconomic benchmarks. The upper section details annualized losses across seven  
 1060 economic vectors ( $V_{md}$ ,  $V_{fg}$ ,  $V_{hc}$ ,  $V_{cap}$ ,  $V_{ext}$ ,  $V_{aux}$ ,  $V_{sub}$ ) for each sector. The lower section  
 1061 contextualizes the €6.46 billion aggregate hemorrhage against national indicators, including a  
 1062 11.82% Real GDP impact, a 1.66x food import correlation, and a 15-year cumulative national  
 1063 contraction of €66.7 – €70.5 billion, with all values adjusted using a regional sector-specific  
 1064 Input-Output multiplier ( $k=1.45$ ).

Summary of ILQ Loss Vectors by Sector (Annualized)						
ILQ Vector	Loss Category	Apiculture (Honey)	Viticulture (Wine)	Dairy & Livestock	Spirits (Fruit Brandy)	Total Vector Loss
$V_{md}$	Market Displacement (Direct Revenue Loss)	€17.86 Million	€138.89 Million	€230.58 Million	€397.87 Million	€785.20 Million
$V_{fg}$	Fiscal Revenue Erosion (VAT, Excise, Tax)	€6.14 Million	€36.32 Million	€42.41 Million	€50.86 Million	€135.73 Million
$V_{hc}$	Human Capital Loss (Social Security/PIO)	€35.87 Million	€57.75 Million	€120 Million	€14.22 Million	€227.84 Million
$V_{cap}$	Structural Decapitalization (CAPEX Stagnation)	€637.37 Million	€345.24 Million	€249.64 Million	€1,050.68 Million	€2,282.93 Million
$V_{ext}$	Externalities (Pollination / Brand Equity)	€12.50 Million	€100 Million	€39.31 Million	€350 Million	€501.81 Million
$V_{aux}$	Supply Chain & Auxiliary Industry Loss	€25.33 Million	€106.84 Million	€90.64 Million	€22.88 Million	€247.08 Million
$V_{sub}$	Subsidy Waste (Fictitious Assets)	€7.25 Million	€28.88 Million	€224.09 Million	€15.80 Million	€276.02 Million
$E_{total}$	Cumulative Hemorrhage (with $k=1.45$ )	€ 1,076.36 Million	€ 1,180.18 Million	€ 1,445.17 Million	€ 2,758.35 Million	€ 6,460.06* Million
<i>*Note: The total national hemorrhage of ~€6,460.06 billion reflects the aggregate sectoral impact adjusted by the regional multiplier (<math>k=1.45</math>).</i>						
Final Macroeconomic Balance and National Impact Summary						
Macroeconomic Indicator	Estimated Value		Impact Significance			
Annual Aggregate Loss ( $E_{total}$ )	€6.46 Billion		> 165.7 % of Total Annual Food Import Value			
Nominal GDP Impact	8.58% of Nominal GDP		Over 2.7x the official Agricultural GDP contribution			
Real GDP Consumption Rate	11.82% of Real GDP		Equivalent to siphoning off ~1/8.5 of real productive substance			
Fiscal Revenue Erosion ( $V_{fg}$ )	€0.14 Billion (€135.73 M)		Sufficient to fund ~11% of the entire national subsidy program			
Trade Deficit Correlation	1.66 x of import		Annual loss is 1.66 times the total food import value			
Social Security Deficit ( $V_{hc}$ )	€227.84 Million		Terminal threat to the stability of PIO and Health funds			
15-Year Cumulative Loss	€66.7 – €70.5 Billion		~91.5% of Current Nominal GDP (Over 1 year of output)			

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## Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- [SupplementaryInformationforISOTOPICEVIDENCEOFSYSTEMICECONOMICALLYMOTIVATEDADULTERATIONINSERBIAEmpiricalLossQuantizationandBou](#)
- [SupplementarySoftware.zip](#)
- [SupplementaryFigure1.png](#)