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COMPLIANCE ALGORITHM FOR SOCIO-ENVIRONMENTAL SAFEGUARDS IN LEGAL AMAZON: A TRACEABILITY AND RISK ASSESSMENT MODEL FOR AGRICULTURAL COMMODITIES CHAIN UNDER REGULATION (EU) 2023/1115

ALGORITMO DE COMPLIANCE PARA SALVAGUARDAS SOCIOAMBIENTAIS NA AMAZÔNIA LEGAL: UM MODELO DE RASTREABILIDADE E AVALIAÇÃO DE RISCO PARA A CADEIA DE COMMODITIES AGRÍCOLAS SOB O REGULAMENTO (UE) 2023/1115

ALGORITMO DE CUMPLIMIENTO PARA SALVAGUARDIAS SOCIOAMBIENTALES EN LA AMAZONIA LEGAL: UN MODELO DE TRAZABILIDAD Y EVALUACIÓN DE RIESGO PARA LA CADENA DE COMMODITIES AGRÍCOLAS BAJO EL REGLAMENTO (UE) 2023/1115

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Abstract

Regulation (EU) 2023/1115 requires agricultural commodities placed on the European market to be deforestation-free from 31 December 2020, produced in line with laws in its country of origin, and covered by a due diligence statement identifying production plots by geolocation. Demonstrating compliance depends on a unit of analysis—rural property and plot—that falls between municipal-scale trade-flow models and pixel-scale remote sensing products, while relying on heterogeneous and consistently incomplete databases. This article presents COMPLY-SOY-MA, a model for assessing traceability, risk, and socio-environmental compliance across agricultural commodities supply chains

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in Legal Amazon. Its main contribution is a credibility estimator that separates two often-confused dimensions: substantive compliance, measured through a composite index of thirty-one indicators aggregated using power means with controlled compensability, and supporting-evidence quality, measured through a five-indicator index. Risk is estimated by shrinking observed deficiency toward a territorial prior, weighted by the power of the evidence index, so opaque units are not assessed using averages from units that disclose information. Under isolated changes in evidence, providing more evidence reduces risk only for genuinely compliant units. Traceability is modelled as a mass-flow-weighted multigraph, using origin entropy and a formal distinction between exposure and contamination index. Scope is stated clearly: the study delivers a formal model and reference implementation, with results based on mathematical derivation and domain characterization. It specifies but does not execute a validation protocol, and its risk score is not a calibrated probability.

Keywords: computational socio-environmental compliance; supply chain traceability; composite indicators; missing data; Legal Amazon; EUDR.

Resumo

O Regulamento (UE) 2023/1115 exige que as commodities agrícolas colocadas no mercado europeu sejam livres de desmatamento a partir de 31 de dezembro de 2020, produzidas em conformidade com a legislação do país de origem e acompanhadas de declaração de devida diligência que identifique os talhões de produção por geolocalização. Demonstrar conformidade depende de uma unidade de análise — imóvel rural e talhão — situada entre os modelos de fluxo comercial em escala municipal e os produtos de sensoriamento remoto em escala de pixel, apoiando-se em bases de dados heterogêneas e sistematicamente incompletas. Este artigo apresenta o COMPLY-SOY-MA, modelo de avaliação de rastreabilidade, risco e conformidade socioambiental em cadeias de suprimento de commodities agrícolas na Amazônia Legal. Sua principal contribuição é um estimador de credibilidade que separa duas dimensões frequentemente confundidas: a conformidade substantiva, medida por um índice composto de trinta e um indicadores agregados por médias de potência com compensabilidade controlada, e a qualidade da evidência de suporte, medida por um índice de cinco indicadores. O risco é estimado pelo encolhimento da deficiência observada em direção a uma priori territorial, ponderado pela potência do índice de evidência, de modo que unidades opacas não sejam avaliadas por médias de unidades que divulgam informação. Sob variação isolada da evidência, fornecer mais evidência reduz o risco apenas para unidades genuinamente conformes. A rastreabilidade é modelada como um multigrafo ponderado por fluxo de massa, com entropia de origem e distinção formal entre exposição e índice de contaminação. O escopo é declarado com clareza: o estudo entrega um modelo formal e uma implementação de referência, com resultados obtidos por derivação matemática e caracterização do domínio. Especifica, mas não executa, um protocolo de validação, e seu escore de risco não constitui probabilidade calibrada.

Palavras-chave: conformidade socioambiental computacional; rastreabilidade de cadeias de suprimento; indicadores compostos; dados ausentes; Amazônia Legal; EUDR.

Resumen

El Reglamento (UE) 2023/1115 exige que los commodities agrícolas colocados en el mercado europeo estén libres de deforestación a partir del 31 de diciembre de 2020, sean producidos conforme a la legislación del país de origen y estén acompañados de una declaración de diligencia debida que identifique las parcelas de producción por geolocalización. Demostrar el cumplimiento depende de una unidad de análisis — inmueble rural y parcela — situada entre los modelos de flujo comercial a escala municipal y los productos de teledetección a escala de píxel, apoyándose en bases de datos heterogéneas y sistemáticamente incompletas. Este artículo presenta COMPLY-SOY-MA, un modelo de evaluación de trazabilidad, riesgo y cumplimiento socioambiental en cadenas de suministro de commodities agrícolas en la Amazonia Legal. Su principal aporte es un estimador de credibilidad que separa dos dimensiones frecuentemente confundidas: el cumplimiento sustantivo, medido por un índice compuesto de treinta y un indicadores agregados mediante medias de potencia con compensabilidad controlada, y la calidad de la evidencia de soporte, medida por un índice de cinco

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indicadores. El riesgo se estima contrayendo la deficiencia observada hacia una previa territorial, ponderada por la potencia del índice de evidencia, de modo que las unidades opacas no sean evaluadas con promedios de unidades que sí divulgan información. Bajo variación aislada de la evidencia, aportar más evidencia reduce el riesgo solo para unidades genuinamente conformes. La trazabilidad se modela como un multigrafo ponderado por flujo de masa, con entropía de origen y distinción formal entre exposición e índice de contaminación. El alcance se declara con claridad: el estudio entrega un modelo formal y una implementación de referencia, con resultados obtenidos por derivación matemática y caracterización del dominio. Especifica, pero no ejecuta, un protocolo de validación, y su puntaje de riesgo no constituye una probabilidad calibrada.

Palabras clave: cumplimiento socioambiental computacional; trazabilidad de cadenas de suministro; indicadores compuestos; datos faltantes; Amazonia Legal; EUDR.

1 INTRODUCTION

Checking socio-environmental compliance in supply chains is no longer mainly about auditing documents; it is now a systems-engineering challenge. This shift has a clear cause: consumer markets no longer rely only on third-party certificates of conduct. They require verifiable claims tied to specific areas, supported by geographic coordinates, remote-sensing time series, and cross-checked administrative records. Such claims do not come from inspection alone. They emerge from computing across heterogeneous databases, explicitly tracking uncertainty and keeping an auditable record of every inference.

Regulation (EU) 2023/1115, commonly called EUDR, is the clearest example of this shift. It bars seven commodity groups, including agricultural commodities, from the European Union market unless operators show that each commodity is deforestation-free after 31 December 2020, complies with laws in its country of production, and comes with a due diligence statement listing geolocation for every plot. Coordinates must use at least six decimal places and plots larger than four hectares must be mapped as polygons (EUROPEAN UNION, 2023). Implementing Regulation (EU) 2025/1093 classified Brazil as standard risk, ruling out simplified procedures and requiring full due diligence. Regulation (EU) 2025/2650 set substantive obligations to apply from 30 December 2026 for medium and large operators and from 30 June 2027 for micro and small operators.

In Legal Amazon region, state of Maranhão, a great agricultural commodities productor, for example holds a distinctive and still understudied place in this setting. Territorially, 181 of its 217 municipalities belong to Legal Amazon, west of the 44° W

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meridian, covering about 79% of state territory (IBGE, 2024). Agricultural commodities production is concentrated in southern municipalities such as Balsas, Tasso Fragoso, Alto Parnaíba, Riachão, and Sambaíba. All lie west of that meridian and therefore inside Legal Amazon, yet mostly within Cerrado biome. This overlap between an Amazonian administrative boundary and a Cerrado ecological base creates regulatory asymmetry: Law No. 12,651/2012 sets Legal Reserve percentages by phytophysiognomy rather than administrative boundary. This is one of the hardest issues when assessing compliance across this supply chain. In August 2025, suspension of Agricultural Commodities Moratorium added further complexity by removing its main private governance mechanism.

This study asks how territorial, environmental, land-tenure, production, financial, and commercial data can be combined to assess socio-environmental compliance and risk across Legal Amazon agricultural commodities chain in an objective, reproducible, and auditable way. Two technical challenges stand out. First, data sources differ in type, spatial resolution, update cycle, quality rules, and access conditions. Integrating them therefore requires reconciling incompatible meanings, not simply converting formats. Second, and more importantly, data is incomplete. Composite indices often handle missing information through imputation or exclusion, assuming observed and missing cases are interchangeable. That assumption fails in compliance assessment and systematically favours assessed units: a unit that discloses nothing is judged by averages from units that do, rewarding opacity where regulation requires proof.

This study addresses two related gaps. At unit-of-analysis level, the land plot selected by regulation sits between municipal-scale trade-flow models and pixel-scale remote-sensing products, where literature remains scarce. At methodological level, there is no formal way to handle missing evidence without quietly treating its absence as proof of compliance.

This article develops and formalizes COMPLY-SOY-MA, a model for assessing traceability, risk, and socio-environmental compliance across Legal Amazon agricultural commodities chain under EUDR and Brazilian rules incorporated by reference. Its contributions are fourfold: separating substantive compliance from

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evidence quality as two independent axes; proposing a credibility-based risk estimator with formally demonstrated properties that shrinks observed deficiency toward a territorial prior according to available evidence; converting regulatory provisions into computable declarative rules; and formalizing risk propagation through supply chains with aggregation points, while distinguishing mass exposure from contamination index.

Scope is defined from the start. This study presents a formal model and reference implementation. Reported results fall into two groups: derivation results obtained by mathematically solving elements that define the model, and characterization results drawn from public domain statistics. None comes from running the system on rural-property data. Section 6 specifies but does not execute a validation protocol, so this version reports no accuracy, calibration, or baseline-improvement measures, and its risk score is not a calibrated probability. Empirical use depends on access to restricted databases, which is itself a finding about this research domain.

2 RELATED WORK

This study uses a scoping review rather than a systematic review conducted under a PRISMA protocol. Searches covered Scopus, Web of Science, SciELO, CAPES Journal Portal, and BDTD publications from 2014 to 2026. Search terms included agricultural commodities, traceability, deforestation, supply chain, EUDR, zero deforestation, and composite indicators in both Portuguese and English. The review did not include screening by two independent reviewers or prospective protocol registration. It therefore provides a sufficient basis for positioning the study and identifying major competing approaches, but cannot, on its own, support a strong claim of absolute originality.

A quantitative landmark in this field is Rajão et al. (2020). By integrating rural environmental registry data, satellite monitoring, and trade-flow records, the authors estimated that 2% of rural properties in the Legal Amazon and Cerrado accounted for 62% of potentially illegal deforestation. They also estimated that approximately 20% of soybean exports to the European Union could be linked to illegal deforestation.

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These findings have two direct implications for verification-system design. First, risk concentration makes targeted verification far more efficient than uniform screening. Second, the level of potential contamination in exports is high enough to preclude any presumption of compliance.

In private governance, Gibbs et al. (2015) documented the effectiveness of the Amazon Soy Moratorium, while Heilmayr et al. (2020) revisited the issue using a research design intended to identify the agreement's causal effect. Two subsequent research streams qualified these results and defined the limits of supply-chain verification systems. Villoria et al. (2022) examined territorial leakage and concluded that restrictions in one biome can shift some conversion pressure to areas outside the policy's coverage without eliminating the overall effect of supply-chain policies. This finding is directly relevant to the study area because Maranhão's agricultural belt lies in Cerrado within Legal Amazon, precisely the type of frontier to which conversion pressure may migrate. Gollnow et al. (2022) showed that gaps in policy adoption and implementation constrain both current and potential effectiveness of zero-deforestation commitments for agricultural commodities. Together, these findings support this study's decision to assess compliance at property level instead of relying on declared adherence to sector-wide commitments.

Within Brazil's legal framework, Soares-Filho et al. (2014) analysed how Forest Code reform affected native vegetation deficits and amnesty for consolidated rural areas. Their findings directly inform the proposed model by supporting a distinction between land conversion before and after 22 July 2008. Combined with the EUDR cut-off date of 31 December 2020, this distinction requires two separate and simultaneous temporal benchmarks. A property may comply with Brazilian law while remaining ineligible under European regulation.

For origin verification, Maor et al. (2026) developed a probabilistic method to determine soybean provenance using isotope ratios, trace elements, and Gaussian-process regression applied to georeferenced samples from Brazil, Argentina, and Bolivia. Aparicio-Muriana et al. (2025) used inductively coupled plasma mass spectrometry and chemometric analysis to determine geographic origin. These methods complement rather than compete with the approach proposed here.

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Analytical verification confirms intrinsic properties of physical material and resists documentary fraud, but operates at regional scale and provides no information on land-conversion legality within production areas. Documentary and territorial assessments verify property-level legal compliance but cannot prove that a declared grain shipment originated from that property. Integrating these two evidentiary systems offers a promising path for cross-validation.

Among mapping frameworks, Trase initiative methodology allocates export volumes to production regions and links processing facilities to producing areas, mainly at municipal level. This scale is suitable for aggregate risk attribution but insufficient for plot-level evidence required under EUDR. From a territorial perspective, Salomon (2020) analysed competing interests and sustainability across the MATOPIBA agricultural frontier, while Ferreira (2019) developed prospective scenarios for Balsas soybean supply chain. Both studies adopt socio-territorial and prospective perspectives without proposing a computational tool for property-level assessment. At methodological level, the composite-indicator handbook by Nardo et al. (2008) provides basis for normalisation, weighting, aggregation, and sensitivity analysis used in this study.

The study's originality lies in its composition and application rather than new method invention. None of its mathematical tools is new: the analytic hierarchy process dates to Saaty (1980), entropy weighting to Shannon (1948), credibility shrinkage to the actuarial tradition established by Bühlmann (1967), record linkage to Fellegi and Sunter (1969), and sensitivity indices to Sobol' (2001) and Morris (1991). The proposed contribution is to integrate these elements into a model that treats missing evidence as independent from compliance, preserves the non-compensatory nature of absolute legal prohibitions, anchors thresholds to an explicit regulatory framework, and records provenance of each decision. The model also operates at the unit of analysis required by regulation and within specific context of agricultural commodity production in Legal Amazon.

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3 MATERIALS AND METHODS

This applied study follows a hypothetico-deductive approach, combining formal modelling with computational specification. It comprises five linked stages: regulatory analysis and translation of provisions into computable elements; inventory and metrological characterization of data sources; mathematical model formulation; architecture and algorithm specification; and validation protocol design.

Domain characterization draws on public, primary sources: PRODES and MapBiomas Alert for deforestation; MapBiomas Collection 10 for land use and land cover, with 93.3% average global accuracy at Level 1 under its own assessment protocol (MAPBIOMAS, 2025); CONAB surveys and an ABIOVE-Agrosatélite report for agricultural commodity production and expansion; and IBGE's geographic reference framework for Legal Amazon boundaries. Their methodological implications are direct and must remain explicit: land-cover product accuracy sets an upper limit on any dependent model's accuracy, while alert-system minimum detection areas set a lower limit on omission error.

Regulatory conversion begins with thirteen provision groups drawn from EUDR, Law No. 12,651/2012, Decree No. 6,514/2008, and Rural Credit Manual. For each group, it identifies a primitive variable, its normalizing indicator, and an operational rule. This mapping yields twenty-two declarative rules, including eight terminal prohibitions, and thirty-six indicators: thirty-one substantive indicators across seven dimensions and five evidence indicators. Rules are treated as data rather than code, allowing regulatory updates through table changes instead of programme rewrites.

Computational architecture comprises seven layers: acquisition, processing, integration, storage, computation, validation, and presentation. It explicitly separates calculation from decision-making and maintains a provenance ledger for every emitted value, recording applied formula, inputs, source versions, and a chained cryptographic digest. This design supports reconstructibility, detectable integrity, and unique identification of each decision batch through a Merkle-tree root. It does not, however, ensure legal non-repudiation. Without a digital signature tied to a certified identity, a trusted third-party timestamp, access controls, and a key-custody policy,

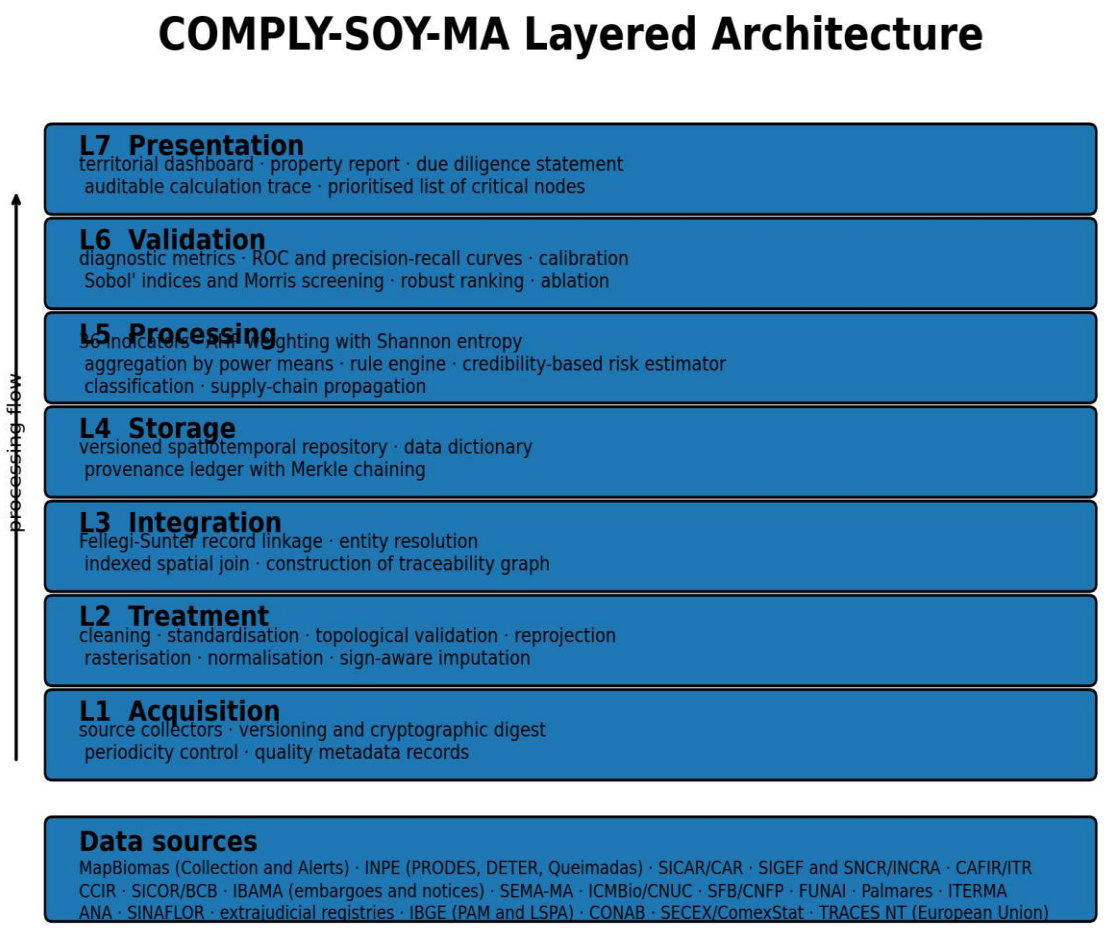
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issuers can recompute the digest chain. Section 7 revisits this distinction. Figure 1 summarizes the layered architecture and shows where each source family enters the processing flow.

Figure 1 - Seven-layer architecture of COMPLY-SOY-MA



Source: prepared by the author.

Finally, the study has a clearly defined empirical scope. Applying the model to real-world data requires access to restricted databases, including nominal Rural Environmental Registry data, rural credit records, certified georeferencing data, grain transport tax documents, and state embargo records. Limited access is not merely a research constraint but also a relevant finding. It reflects a structural weakness in

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Brazil's origin-control systems, as identified by ABRAMPA and IPAM (2026): limited transparency and poor data integration.

4 MATHEMATICAL MODEL

4.1 NOTATION AND CONCEPTUAL SCOPE

Let $\mathcal{I} = \{1, \ldots, N\}$ denote the assessed properties set and, for each $i \in \mathcal{I}$, let $r(i)$ denote the territorial unit to which it belongs. The set of compliance dimensions is $\mathcal{D} = \{D_1, \ldots, D_7\}$, supplemented by evidence dimension D_8, which is treated separately because it does not form part of the substantive index. Each indicator k of dimension d defines a mapping $I_{d,k}: \mathcal{I} \rightarrow [0,1] \cup \{\emptyset\}$, where 1 denotes full compliance, 0 denotes full non-compliance, and ∅ denotes missing evidence. The distinction between 0 and ∅ is constitutive: the former states that verification was performed and yielded a negative result; the latter states that verification could not be performed. No operation in the model converts ∅ into a numerical value.

Four concepts often treated as interchangeable must remain distinct; otherwise, the model would exceed its evidentiary limits. Legal compliance refers to a property's legal status, which exists regardless of available knowledge and can be conclusively determined only by an administrative or judicial authority. Non-compliance risk is an epistemic measure that reflects concern supported by available information. It may change as new information emerges, even when legal status remains unchanged. Evidence quality characterises the evidentiary record, not the property or resulting judgement. Eligibility for a due diligence statement is an operational decision made by an economic operator based on the previous three concepts, but cannot be reduced to any single one. Within the model, ICS estimates legal compliance from observable evidence, IEV measures evidence quality, R expresses non-compliance risk, and the DDS predicate formalises eligibility. Any transition between these levels remains explicit and never occurs automatically.

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4.2 NORMALISATION AND AGGREGATION WITH CONTROLLED COMPENSABILITY

Four normalization families are employed, each associated with a normative nature: negative exponential, when only a zero value is fully compliant; piecewise linear with saturation, when an explicit regulatory threshold and regularization range exist; inverted logistic, when the transition is gradual and there is no legal threshold; and ordinal categorical with half-life temporal decay, $\varphi_{dec}(t; H) = 2^{-t/H}$, for sanctioning events whose relevance declines with elapsed time. The choice of family is not free: it encodes a hypothesis about how compliance deteriorates and must be justified by the applicable provision.

Within-dimension aggregation uses the family of weighted power means, special cases of quasi-arithmetic means with a power-generating function, providing a parametric continuum between full and zero compensation:

$$S_d(i) = [\ \Sigma_{k \in \mathcal{K}_d^{obs}(i)} \tilde{w}_{d,k}\ I_{d,k}(i)^{\rho_d}\ ]^{1/\rho_d},$$

where $\mathcal{K}_d^{obs}(i)$ is the subset of effectively observed indicators and $\tilde{w}$ are the weights renormalized over that subset. The exponent ρ_d encodes the compensability permitted by the normative nature of the dimension: $\rho \to 1$ corresponds to the arithmetic mean and full compensation; $\rho = 0$ to the geometric mean; and $\rho \to -\infty$ to the minimum operator and absence of compensation. Dimensions protected by absolute prohibition receive strongly negative ρ values, whereas dimensions subject to administrative regularization admit values close to zero. Cross-dimensional aggregation uses a weighted geometric mean, $\rho_0 = 0$, which prevents high performance in one dimension from compensating for a collapse in another.

At a lexicographically higher level, prohibitions set operates over substantive index. Let $\gamma_g(i)$ denote the predicate of *g-th* blocking rule; define $\Gamma(i) = \bigvee_{g \in \mathcal{G}} \gamma_g(i)$. Triggering any prohibition determines the terminal class regardless of index value: overlap with an indigenous land, a fully protected Conservation Unit, titled “quilombola” territory, or an undesignated public forest, as well as an active

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environmental embargo or conversion after the cut-off date, cannot be compensated for by regularity in any other dimension.

4.3 WEIGHTING

The weights combine two sources. The normative component results from the principal eigenvector of a positive reciprocal pairwise-comparison matrix across seven substantive dimensions, using Saaty's (1980) fundamental scale, whose consistency is assessed by CI = (λ_max − n)/(n − 1) and CR = CI / RI_n, with acceptance at CR ≤ 0.10. The informational component results from the Shannon (1948) entropy of each indicator's distribution over the assessed set, assigning zero weight to a constant indicator that does not discriminate among objects. The combination is multiplicative and normalized:

$$w_j = (w\^A_j)\^\theta \, (w\^E_j)\^\{1-\theta\} \,/\, \Sigma_l \, (w\^A_l)\^\theta \, (w\^E_l)\^\{1-\theta\}, \quad \theta \in [0,1]$$

This procedure entails two caveats. First, the consistency ratio assesses only internal coherence—specifically, transitivity and cardinal compatibility—without establishing the normative validity of the hierarchy. Internally coherent judgements may still be normatively unsound. Second, the matrix was not derived from an expert panel; the author constructed it from an explicit normative hierarchy that prioritizes constitutionally protected interests, followed by the material scope of European regulation, production-legality requirements, and the enabling condition of verifiability. Thus, the matrix represents a theoretically grounded, single-expert elicitation for which no inter-rater agreement measure applies. The resulting weights constitute a defensible and auditable, yet provisional, parameterization.

4.4 EVIDENCE INDEX AND CREDIBILITY-BASED RISK ESTIMATOR

Evidence coverage is measured by the fraction of the total index weight that is actually observed, γ(i) = Σ_d Σ_k W_d w_{d,k} 𝟙[I_{d,k}(i) ≠ ∅], and combined with the intrinsic quality of the evidence, measured by dimension D_8, completeness, timeliness, source authority, consistency across independent databases, and effective spatial resolution, through a geometric mean:

$$\mathrm{IEV(i)} = \sqrt{(\ S_\{D_8\}(i) \cdot \gamma(i)\ )}$$

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The model core is the estimator that combines substantive and evidentiary axes. Let π_r denote the irregularity prior of territorial unit r. Define the credibility factor and risk score:

$$Z(i) = IEV(i)^{\kappa}, \quad \kappa \geq 1$$

$$R(i) = Z(i) \cdot [1 - ICS(i)] + [1 - Z(i)] \cdot \pi_{r(i)}$$

The estimator forms a convex combination of observed compliance deficiency and territorial-stratum baseline risk, weighted by evidence credibility. This structure parallels Bühlmann's (1967) credibility estimators and empirical Bayes shrinkage. The exponent κ controls evidentiary stringency: κ = 1 yields credibility proportional to evidence quality, whereas κ > 1 demands stronger evidence before assigning full credibility. The model adopts κ = 1.5 as an intermediate value between linear and quadratic requirements and evaluates it through sensitivity analysis.

A semantic distinction governs the interpretation of all subsequent results. R is a risk score derived from a convex combination of normalized indices, not a calibrated probability of non-compliance. Although bounded within [0,1], the formulation does not ensure that a score of 0.30 corresponds to a 30% observed frequency of non-compliance among similarly classified units. Establishing such correspondence requires calibration against observed outcomes through Brier scores, reliability diagrams, and, when necessary, isotonic regression or Platt scaling. Section 6 specifies these procedures but does not implement them. Until calibration is performed, probabilistic interpretations of R remain structural analogies rather than statistical claims: R ranks units by regulatory concern but does not strictly estimate an individual unit's likelihood of irregularity.

The prior is estimated in production as the ratio between unauthorized deforested area and total deforested area within the territorial unit, with empirical Bayes shrinkage stabilization for units with few observed events:

$$\hat{\pi}_r = (n_r \bar{y}_r + \nu \pi_0) / (n_r + \nu)$$

where n_r is the number of observed events in the unit, $\bar{y}_r$ is the observed irregular fraction, π_0 is the reference prior, and ν is the equivalent prior size. ν = 25 is adopted, equivalent to assigning the prior the weight of twenty-five events: units with

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an inspection history exceeding this level have estimates dominated by their own evidence rather than the territorial prior. The reference value π_0 is anchored in public statistics: the 2025 Annual Deforestation Report states that 55.5% of the deforested area in Maranhão overlaps with authorizations or enforcement actions, from which, by complementarity, $\pi_0 = 0.445$ is adopted (MAPBIOMAS, 2026).

This operation relies on two non-necessary inferences that require explicit qualification. First, it treats overlap with an authorization or enforcement action as evidence of regularity, although inspection may have occurred precisely because irregularity was suspected, and an authorization may be defective or exceeded during implementation. Second, it treats absence of overlap as evidence of irregularity, although this may reflect registration delays or limited enforcement coverage over a legitimate area. Strictly, 0.445 is not an observed irregularity rate but a plausible upper bound derived from the share of deforested area lacking a known administrative record. The model adopts this parameter because it is the best publicly available approximation for the stratum, applies a conservative interpretation consistent with the regulation's allocation of evidentiary burden to operators, and remains subject to sensitivity analysis.

4.5 FORMAL PROPERTIES

Proposition 1 (consistency at the extremes). With full evidence, IEV = 1, so Z = 1 and R = 1 − ICS: risk is exactly the observed deficiency. With no evidence, IEV = 0, so Z = 0 and R = π_r: risk is that of the territorial stratum, not zero. The result follows immediately by substitution into Equation 5, noting that Z = IEV^κ is continuous on [0,1], with Z(0) = 0 and Z(1) = 1 for every κ ≥ 1.

Proposition 1 is the rationale for the model. Under usual imputation schemes, a unit with no information receives the mean value of others and tends to be classified as compliant; under the proposed estimator, it receives the risk of the territory in which it is located. In a stratum with π_r = 0.445, the opaque unit is classified as non-compliant, which is precisely the outcome intended by regulation when it requires the operator to demonstrate the absence of risk.

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Proposition 2 (monotonicity in compliance). For every IEV > 0, ∂R/∂ICS = −Z < 0: increasing observed compliance strictly reduces estimated risk. The result follows by differentiating Equation 5 with respect to ICS, with Z independent of ICS.

Proposition 3 (directional resistance to selective documentation). The derivative of the score with respect to evidence is

$$\partial \mathrm{R}/\partial \mathrm{IEV} = \kappa \cdot \mathrm{IEV}^{\{\kappa-1\}} \cdot [\ (1 - \mathrm{ICS}) - \pi_\mathrm{r}\ ]$$

whose sign is that of (1 − ICS) − π_r. Consequently, producing evidence reduces estimated risk if and only if the unit's compliance deficiency is lower than the prior of its stratum. The result follows by writing R = π_r + Z[(1 − ICS) − π_r] and differentiating with respect to IEV, with dZ/dIEV = κ IEV^{κ−1} ≥ 0.

The proposition establishes the model's incentive property: a compliant unit benefits from documenting its status, whereas one whose deficiency exceeds the regional prior does not. This reverses the logic of additive evidence-based scoring, under which omission is always weakly advantageous. Its scope, however, requires qualification. The derivative holds ICS constant while varying only IEV—an unrealistic general assumption because new documentation typically alters IEV, γ, and at least one ICS indicator simultaneously and correlatively. Thus, the result demonstrates directional resistance under isolated evidentiary variation, not immunity to selective disclosure. A stronger guarantee would require framing the problem as a disclosure game and modelling missing data under a missing-not-at-random mechanism.

Proposition 4 (boundedness and continuity). R(i) ∈ [0,1] for every i and R is continuous on (ICS, IEV) ∈ [0,1]², because it is a convex combination of two values in [0,1] with coefficients that sum to one.

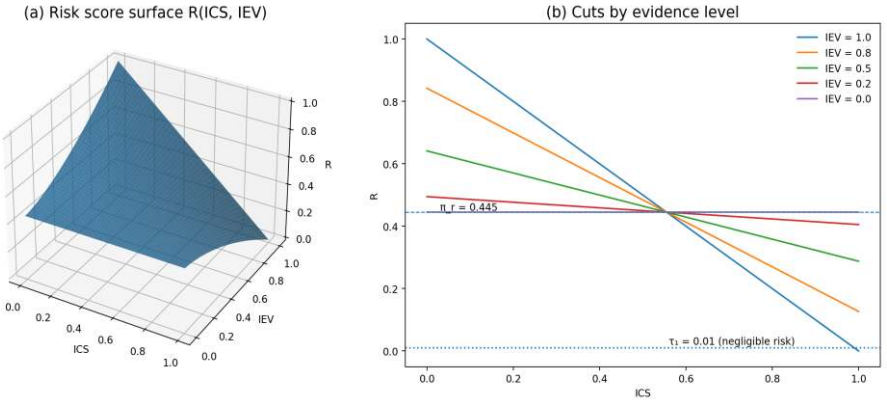
Figure 2 represents the score surface over the (ICS, IEV) square and makes the four propositions visible: the value at the full-evidence vertex coincides with the observed deficiency, the zero-evidence edge is constant and equal to the prior, the surface decreases monotonically in ICS, and the slope with respect to IEV changes sign exactly where deficiency equals the stratum prior.

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Figure 2 - Risk score surface and cuts by evidence level



Source: prepared by the author, with π_r = 0.445 and κ = 1.5.

4.6 CLASSIFICATION AND THRESHOLD ANCHORING

Classification operates under a two-level lexicographic structure: triggering any prohibition determines the terminal class; in prohibition absence, thresholds are applied to R, defining five classes, high compliance, moderate compliance, attention, high risk, and non-compliance. Eligibility for issuing the due diligence statement requires no blocking conditions and a score no greater than the negligible-risk threshold:

$$\mathrm{DDS(i)} = 1 \Leftrightarrow \Gamma(\mathrm{i}) = 0 \wedge \mathrm{R(i)} \leq \tau_1$$

Threshold definition is the point at which composite indices typically lose defensibility because they rely on quantiles or convenience choices. Here, as an operational normative hypothesis, anchoring inspired by Article 16 of the EUDR is adopted, which establishes differentiated minimum annual verification rates by country-risk category, 9% for high risk, 3% for standard risk, and 1% for low risk, yielding $\tau_1 = 0.01$, $\tau_2 = 0.03$, and $\tau_3 = 0.09$.

Anchoring requires an epistemic qualification that cannot be omitted, otherwise the regulation would be attributed to a claim it does not make. The rates in Article 16 are parameters of minimum administrative-control intensity over the operators set in a country; they are not statements about a tolerable probability for an individual property non-compliance. An inspection sampling rate answers how much verification effort should be allocated to a population; a classification threshold answers from

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what point a specific unit should be treated as suspicious. Converting the former quantity into the latter is a plausible transposition because both order strata of concern in the same direction, but it is not a deduction: it is a working hypothesis that requires empirical validation. The fourth cut-off requires an even stronger caveat: $\tau_4 = 3 \times 0.09 = 0.27$ results from extending the geometric progression with ratio 3 observed in the regulatory sequence and is therefore a purely mathematical extrapolation, with no provision establishing a fourth risk category. It is the model parameter with the weakest normative basis.

4.7 PROPAGATION ALONG THE SUPPLY CHAIN

The supply chain is represented as a weighted directed acyclic multigraph *G = (V, E, f)*, where *V* includes production units, aggregation nodes, exporting operators, and lots, while *f(u,v)* denotes mass flow along each edge. Let *p(u|n)* denote origin *u's* mass share at node *n*. Normalized origin entropy measures traceability loss from mixing:

$$H(n) = -\Sigma_{u \in pred(n)}\, p(u|n) \ln p(u|n), \quad H^*(n) = H(n) / \ln k(n)$$

Two propagation operators are defined, whose confusion is an error recurring source in the applied literature. Exposure is the expected mass fraction of non-compliant material, $\mathcal{E}(n) = \Sigma_u\, p(u|n)\, R(u)$. The contamination index expresses the possibility that at least some fraction of the lot originates from a non-compliant source:

$$\mathcal{P}(n) = 1 - \prod_{u \in pred(n)} [1 - R(u)]$$

For purposes of Article 3 of the EUDR, which prohibits placing any non-compliant product on the market, the relevant quantity is $\mathcal{P}$; for enforcement prioritization and mitigation under Article 11, it is $\mathcal{E}$. Divergence between two grows rapidly with the number of mixed origins: with k origins having homogeneous risk $\bar{r}$, $\mathcal{E} = \bar{r}$ and $\mathcal{P} = 1 - (1 - \bar{r})^k$, so that, for $\bar{r} = 0.03$, exactly the threshold corresponding to standard-risk category assigned to Brazil, the index reaches 0.26 with ten origins and exceeds 0.78 with fifty. This demonstrates why physical segregation of lots is, under European regime, structurally distinct from mass balance.

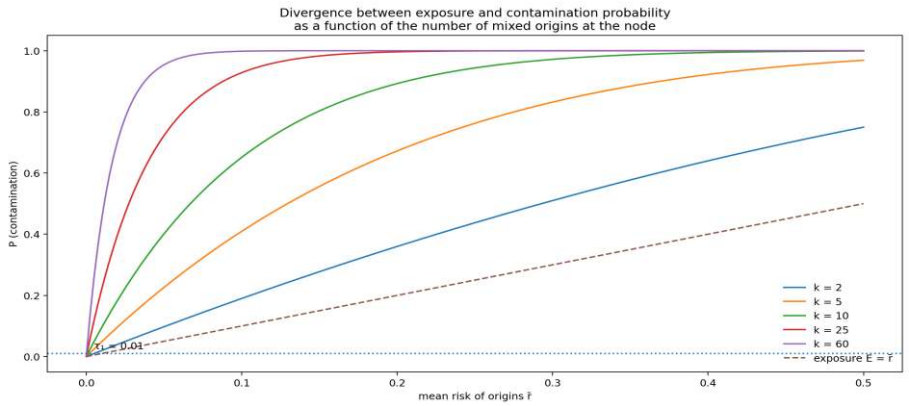
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The expression for $\mathcal{P}$ rests on two conditions that delimit its validity. The first is that R has a calibrated probabilistic interpretation, a condition not yet satisfied. The second is conditional independence among origins, a fragile assumption in this domain: neighboring units share territorial strata, priors, credit instruments, and sometimes the same controller, so their irregularities tend to be positively correlated, under which the product expression overestimates $\mathcal{P}$. Until both conditions are verified, $\mathcal{P}$ should be read as an ordinal quantity, useful for comparing aggregation nodes and showing the effect of mixing, rather than as a probability in the strict sense. Figure 3 shows the divergence between the two quantities as a function of the number of origins, for three levels of homogeneous individual risk.

Figure 3, Divergence between exposure and contamination index as a function of number of mixed origins



Source: prepared by the author.

5 RESULTS

The results fall into two rigorously distinct categories. Derivation results are obtained by mathematically solving the model's defining elements, whereas characterization results are based on publicly available domain statistics. Neither category results from applying the system to actual property data.

5.1 DERIVED WEIGHTS

Solving the eigenvalue problem for the pairwise comparison matrix across the seven dimensions yielded $\lambda_{\max} = 7.080313$, corresponding to $CI = 0.013386$. Using

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$RI_7 = 1.32$, the resulting consistency ratio was $CR = 0.010141$, approximately one order of magnitude below the conventional threshold of 0.10. This result supports using the eigenvector as the weight vector; however, as previously noted, it does not validate the hierarchy's normative assumptions. Table 1 presents the resulting weight vector.

Table 1, Normative weights of substantive dimensions

Dimension	Designation	W_d	Cumulative
D_4	Protected areas and territories	0.3528	35.28%
D_1	Deforestation and conversion	0.2160	56.88%
D_5	Sanction regularity	0.1270	69.58%
D_7	Supply chain traceability	0.1270	82.28%
D_2	Cadastral environmental regularity	0.0723	89.51%
D_3	Land-tenure regularity	0.0723	96.74%
D_6	Rural credit and tax regularity	0.0326	100.00%

Source: prepared by the author. λ_max = 7.080313; CI = 0.013386; RI_7 = 1.32; CR = 0.010141.

The five indicators with the highest global weights are non-overlap with Indigenous Lands (0.10584), Conservation Units (0.09878), and quilombola territories (0.08467); absence of land conversion after the established cut-off date (0.07344); and non-overlap with Undesignated Public Forests (0.06350). Together, these indicators account for 42.62% of the total weight. The resulting hierarchy is substantively aligned with the underlying normative framework, as restrictions associated with constitutionally protected areas receive the greatest weight in the index.

5.2 THRESHOLDS AND ESTIMATOR BEHAVIOUR

Table 2 consolidates the five compliance classes, score intervals delimit them under provisional thresholds of Section 4.6, and the operational effect that each class determines for economic operator.

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Table 2, Compliance classes, thresholds, and operational effect

Class	Designation	Interval	Operational effect
1	High compliance	$R \leq 0.01$	Eligible for due diligence statement
2	Moderate compliance	$0.01 < R \leq 0.03$	Requires prior documentary mitigation
3	Attention	$0.03 < R \leq 0.09$	Requires independent verification or segregation
4	High risk	$0.09 < R \leq 0.27$	Suspension of acquisition until regularisation
5	Non-compliance	$R > 0.27$ or $\Gamma = 1$	Acquisition prohibited; authority notification

Source: prepared by the author. The thresholds derive from the heuristic anchoring discussed in Section 4.6 and are provisional.

Estimator behavior is illustrated through direct evaluation of Equation 5 in characteristic configurations, with $\pi_r = 0.445$ and $\kappa = 1.5$. Values in Table 3 are obtained by algebraic substitution rather than by application to real properties.

Table 3, Risk score in characteristic configurations

Configuration	ICS	IEV	Z	R	Class	Interpretation
Compliant and documented	1.000	1.000	1.000	0.000	1	Eligible for declaration
Compliant, partial evidence	1.000	0.600	0.465	0.238	4	Insufficient documentation
Compliant, no evidence	1.000	0.000	0.000	0.445	5	Territorial-stratum risk
Deficient and documented	0.400	1.000	1.000	0.600	5	Demonstrated deficiency
Deficient, no evidence	0.400	0.000	0.000	0.445	5	Converges to prior
Slightly deficient, documented	0.980	1.000	1.000	0.020	2	Mitigation required

Source: prepared by the author. Values obtained by direct evaluation of Equation 5 with $\pi_r = 0.445$ and $\kappa = 1.5$.

The second row highlights the model's key departure from conventional approaches: a unit showing full compliance across verified indicators but only 60% evidence coverage receives a score of 0.238 and is classified as high risk. Mean imputation, by contrast, would likely place the same unit in the compliance category. The third and fifth rows show convergence toward the prior when evidence is entirely absent. An opaque unit therefore receives the same assessment regardless of its declared status—an intended outcome, since no claim has been substantiated.

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5.3 DOMAIN CHARACTERISATION

Table 4 compiles public statistics that quantitatively characterize the application domain. They are not outputs of the model; they delimit the problem magnitude to which it responds.

Table 4, Quantitative characterization of the application domain

Indicator	Value	Period	Source
Municipalities of Maranhão in the Legal Amazon	181 of 217	2024	IBGE
Clear-cut deforestation in Maranhão (Legal Amazon)	227 km² (−26.06%)	2025	INPE/PRODES
Deforested area in Maranhão, 1st nationally	152,294 ha (−29.3%)	2025	MapBiomas/RAD
Overlap with authorizations or enforcement in Maranhão	55.5%	2025	MapBiomas/RAD
Deforested area with indication of irregularity (national context)	89%	2025	MapBiomas/RAD
MATOPIBA share of national deforestation	40%	2025	MapBiomas/RAD
Agricultural commodities area in Maranhão	1,130,406 ha (+65.6%)	2013/14–2022/23	ABIOVE and Agrosatélite
Agricultural commodities associated with deforestation in MATOPIBA	238,332 ha	2019/20–2022/23	ABIOVE and Agrosatélite
Agricultural commodities from the Balsas region shipped through Itaqui	3.98 million t	2025	Port administration
Brazil's share of EU agricultural commodities imports	64.6%	2025/26 crop year (through 07/09/2025)	EU import statistics

Source: prepared by the author from the indicated sources.

Three findings are particularly relevant to the model's design. First, despite a substantial decline in deforestation across Maranhão in 2025, the state recorded the largest deforested area nationwide, thereby sustaining a high territorial prior. Second, agricultural commodity production expanded by 65.6% over nine crop seasons, primarily across previously converted land. However, part of this growth involved native vegetation conversion, making it directly relevant under European regulations. Third, export flows remain concentrated along a single logistics corridor, limiting the number of aggregation nodes requiring oversight. This configuration facilitates plot-level verification rather than constraining its implementation.

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6 VALIDATION PROTOCOL

The protocol is specified but not implemented here because of the data-access constraints described in Section 3. Nevertheless, its full specification constitutes an integral part of the results, as it establishes the conditions under which the hypothesis of the model's superior diagnostic performance may be empirically tested and potentially refuted.

Diagnostic performance would be evaluated using accuracy, precision, sensitivity, specificity, the F_1 score, the Matthews correlation coefficient, and the area under the receiver operating characteristic curve. Agreement with expert judgement would be measured using weighted kappa. Thresholds would be triangulated according to three independent criteria: the normative anchoring established in Section 4.6; natural breaks identified by minimizing within-class variance in the empirical distribution of R; and the cut-off value that maximizes the Youden index in a reference dataset. Convergence among these criteria would strengthen the defensibility of the selected thresholds, whereas divergence would itself constitute relevant diagnostic evidence and would therefore be reported.

Global sensitivity analysis would decompose output variance across fourteen factors: the weight-mixing factor, the credibility exponent, the seven compensability exponents, the four classification thresholds, and the prior. First-order and total-order sensitivity indices would be estimated using the Saltelli sampling design, preceded by preliminary screening based on Morris's elementary-effects method (1991). This procedure would be complemented by an assessment of three alternative weighting scenarios—equal weighting, environmental primacy, and documentary primacy—designed to reveal the sensitivity of classification outcomes to competing normative hierarchies, an issue not fully captured by the weight-mixing factor alone.

Probabilistic calibration constitutes a mandatory stage rather than an ancillary validation step, as it transforms R into a measure with valid probabilistic meaning. Calibration would be assessed using the Brier score, decomposed into reliability, resolution, and uncertainty through Murphy's framework, alongside a reliability diagram. Systematic deviations would prompt recalibration through isotonic regression or Platt scaling, followed by threshold adjustment on the calibrated scale.

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Benefits attributable to the proposed architecture would be isolated through comparison with three deliberately simple baselines: a binary rule based on environmental registry status, replicating the criterion currently applied to Brazilian rural credit; independent detection of post-cut-off conversion without cadastral or land-tenure integration; and an unweighted arithmetic mean across indicators, which isolates effects associated with the weighting structure. An ablation study would then remove each dimension successively, quantifying performance losses caused by unavailable database families. Results would thus provide an objective basis for prioritizing data disclosure.

An adversarial scenario analysis would assess resistance to selective documentation beyond Proposition 3's scope. Simulations would assume an operator with access to the complete dataset who strategically selects which subset to disclose to minimize the assigned risk class. Four omission mechanisms would be examined: random omission, omission correlated with substantive deficiencies, missing-not-at-random patterns, and omission optimized through subset searches. Acceptance would require that strategic omission yield an average advantage no greater than half a risk class and that no high-risk property become eligible for declaration solely through omitted evidence.

7 DISCUSSION AND LIMITATIONS

At the formal level, the model resolves three problems that applied literature treats inadequately. The first is the treatment of missing evidence: rather than inputting or excluding, the model shifts the opaque unit to the risk of its stratum, with a demonstrated incentive property. The second is compensability: rather than implicit arithmetic averaging, a parametric continuum governed by the normative nature of each dimension is adopted, with a lexicographic structure reserved for absolute prohibitions. The third is justifiability: every decision can be reconstructed from the provenance ledger, a condition for technically contesting a classification with commercial effects.

The limitations fall into four categories and should accompany any use of the model. Data limitations arise from dependence on restricted-circulation databases

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and the accuracy ceiling imposed by remote-sensing products; moreover, the territorial prior is adopted at the state level because no public disaggregation exists for the Maranhão Legal Amazon.

Modelling limitations are the most consequential. The risk score has no calibrated probabilistic interpretation, restricting the reading of R and the contamination index to the ordinal level. The assumption of conditional independence among origins is fragile under spatial correlation of irregularities. The threshold τ_4 = 0.27 lacks direct normative support, being an arithmetic continuation of a progression to which no provision gives existence. Proposition 3 operates under isolated variation of evidence and does not amount to immunity to selective disclosure. The territorial prior is treated as a known parameter although it is estimated with uncertainty, and the pairwise-comparison matrix results from single-expert elicitation, without established intersubjective normative validity.

Scope limitations include treating agricultural commodities in isolation, without interactions with cattle production, whose conversion dynamics precede and enable agricultural expansion, and without the indirect displacement examined by Villoria et al. (2022). They also include cryptographic governance: institutional deployment would require a digital signature over the root of each execution, with a key linked to a certified identity, a trusted timestamp, access control, and a key-custody policy, without which the digest chain remains recomputable by the issuer.

The validation limitations are decisive for interpreting this article: without application to real properties and lots, there is no evidence of accuracy, calibration, error rates, or gains over baselines. The hypothesis of diagnostic superiority therefore remains open and must be treated as such.

From a public-policy perspective, the most far-reaching result is not the model itself, but what its specification makes measurable. The planned ablation study converts the unavailability of each database into a quantified loss of diagnostic performance, transforming data opening from a generic claim into an orderable priority. A system that issues classifications with commercial effects must expose its mathematical structure, parameters, and uncertainties to technical scrutiny, and this exposure, more than any numerical result, is what this study seeks to provide.

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8 CONCLUSIONS

This article proposed COMPLY-SOY-MA, a formal model for assessing traceability, risk, and socio-environmental compliance in agricultural commodities chain produced in Legal Amazon under Regulation (EU) 2023/1115. Its central contribution is the separation of substantive compliance and evidence quality into two orthogonal axes, articulated through a credibility estimator whose fundamental demonstrated property is that a unit without information converges to the risk of its territorial stratum rather than the units meaning that provide information. This inversion of usual treatment of incompleteness is transferable to other compliance domains in which opacity is endogenous to the assessed object.

The assessment of socio-environmental compliance under the European regime is technically a decision problem under incomplete evidence, not a classification problem. This distinction determines that the object of estimation should be risk jointly conditioned on the observed state and the quality of observation, rather than compliance itself. Anchoring thresholds in parameters internal to the regulation is preferable to statistically convenient choices because it gives cut-off points an explicit, auditable, and contestable normative reference, a methodological preference that does not, however, imply that the regulator has established tolerable risk at individual-property level.

The results reported here are those of mathematical derivation and domain characterization. The validation protocol was specified but not executed; diagnostic superiority over baselines remains an open hypothesis, and the risk score does not constitute a calibrated probability until the calibration in Section 6 is performed. The priority for future work is therefore to execute the protocol on real data through an institutional agreement enabling access to restricted databases, together with probabilistic calibration, structured elicitation of weights from an expert panel, and independent cross-validation of origin through analytical methods.

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DOI: 10.66104/5gcafj90
Pages: 1-28

REFERENCES

ABIOVE, BRAZILIAN ASSOCIATION OF VEGETABLE OIL INDUSTRIES; AGROSATÉLITE APPLIED GEOTECHNOLOGY. Cerrado Report 2024: dynamics of agricultural soybean expansion from 2014 to 2023. São Paulo: ABIOVE, 2024.

ABRAMPA, BRAZILIAN ASSOCIATION OF MEMBERS OF THE ENVIRONMENTAL PUBLIC PROSECUTION SERVICE; IPAM, AMAZON ENVIRONMENTAL RESEARCH INSTITUTE. Technical note on the need to improve control and transparency systems for traceability of cattle, timber, and gold supply chains in the Legal Amazon. Belo Horizonte; Belém: ABRAMPA; IPAM, 2026.

APARICIO-MURIANA, María M. et al. Mapping the global origins of agricultural soybean: a study using ICP-MS and chemometrics. npj Science of Food, v. 9, n. 1, art. 263, 2025. DOI: 10.1038/s41538-025-00630-5.

BRAZIL. Law No. 12,651, of 25 May 2012. Provides for the protection of native vegetation. Brasília, DF: Presidency of the Republic, 2012.

BÜHLMANN, Hans. Experience rating and credibility. ASTIN Bulletin, v. 4, n. 3, p. 199-207, 1967.

CONAB, NATIONAL SUPPLY COMPANY. Brazilian grain crop monitoring: 2025/26 crop, fifth survey. Brasília, DF: CONAB, v. 13, n. 5, Feb. 2026.

EUROPEAN UNION. Commission Implementing Regulation (EU) 2025/1093 of 22 May 2025 establishing the list of countries by risk level. Official Journal of the European Union, 2025.

EUROPEAN UNION. Regulation (EU) 2023/1115 of the European Parliament and of the Council of 31 May 2023 on the making available on the Union market and the export from the Union of certain commodities and products associated with deforestation and forest degradation. Official Journal of the European Union, L 150, 9 June 2023.

EUROPEAN UNION. Regulation (EU) 2025/2650 of the European Parliament and of the Council amending Regulation (EU) 2023/1115. Official Journal of the European Union, 2025.

FELLEGI, Ivan P.; SUNTER, Alan B. A theory for record linkage. Journal of the American Statistical Association, v. 64, n. 328, p. 1183-1210, 1969.

FERREIRA, Johnny Herberthy Martins. Prospective scenarios for the agricultural soybean chain in Balsas, Maranhão: economic, social, and environmental aspects for 2027. 2019. Doctoral thesis (Development and Environment), Federal University of Piauí, Teresina, 2019.

CC BY

REMUNOM
ISSN 2178-6925

Received: 13/01/2026 - **Accepted:** 13/02/2026
Vol: 13.20
DOI: 10.66104/5gcafj90
Pages: 1-28

GIBBS, Holly K. et al. Brazil's Agricultural Soybean Moratorium: supply-chain governance is needed to avoid deforestation. Science, v. 347, n. 6220, p. 377-378, 2015. DOI: 10.1126/science.aaa0181.

GOLLNOW, Florian et al. Gaps in adoption and implementation limit the current and potential effectiveness of zero-deforestation supply chain policies for agricultural commodities. Environmental Research Letters, v. 17, n. 11, art. 114003, 2022. DOI: 10.1088/1748-9326/ac97f6.

HEILMAYR, Robert et al. Brazil's Amazon Soybean Moratorium reduced deforestation. Nature Food, v. 1, n. 12, p. 801-810, 2020. DOI: 10.1038/s43016-020-00194-5.

IBGE, BRAZILIAN INSTITUTE OF GEOGRAPHY AND STATISTICS. Legal Amazon: geographic reference framework for the production, analysis, and dissemination of statistics. Rio de Janeiro: IBGE, 2024.

INPE, NATIONAL INSTITUTE FOR SPACE RESEARCH. Estimate of clear-cut deforestation in the Legal Amazon for 2025. São José dos Campos: INPE, 2025. PRODES Programme technical note.

MAOR, Rotem et al. High-resolution soybeanbean tracing for deforestation-free supply chains. Communications Earth & Environment, v. 7, art. 310, 2026. DOI: 10.1038/s43247-026-03380-8.

MAPBIOMAS. Algorithm Theoretical Basis Document (ATBD), Collection 10, v. 2. São Paulo: MapBiomas Project, 2025.

MAPBIOMAS. RAD 2025: Annual Deforestation Report in Brazil. São Paulo: MapBiomas Alert, 2026.

MORRIS, Max D. Factorial sampling plans for preliminary computational experiments. Technometrics, v. 33, n. 2, p. 161-174, 1991.

NARDO, Michela et al. Handbook on constructing composite indicators: methodology and user guide. Paris: OECD Publishing; Joint Research Centre, 2008.

RAJÃO, Raoni et al. The rotten apples of Brazil's agribusiness. Science, v. 369, n. 6501, p. 246-248, 2020. DOI: 10.1126/science.aba6646.

SAATY, Thomas L. The analytic hierarchy process: planning, priority setting, resource allocation. New York: McGraw-Hill, 1980.

SALOMON, Marta Maria Röhe. Who competes for MATOPIBA?: interests and sustainability on the agricultural frontier. 2020. Doctoral thesis (Sustainable Development), University of Brasília, Brasília, DF, 2020.

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REMUNOM
ISSN 2178-6925

Received: 13/01/2026 - **Accepted:** 13/02/2026
Vol: 13.20
DOI: 10.66104/5gcafj90
Pages: 1-28

SALTELLI, Andrea et al. Global sensitivity analysis: the primer. Chichester: John Wiley & Sons, 2008.

SHANNON, Claude E. A mathematical theory of communication. Bell System Technical Journal, v. 27, n. 3, p. 379-423, 1948.

SOARES-FILHO, Britaldo et al. Cracking Brazil's Forest Code. Science, v. 344, n. 6182, p. 363-364, 2014. DOI: 10.1126/science.1246663.

SOBOL', Ilya M. Global sensitivity indices for nonlinear mathematical models and their Monte Carlo estimates. Mathematics and Computers in Simulation, v. 55, n. 1-3, p. 271-280, 2001.

TRASE. Supply chains methodology. Stockholm: Stockholm Environment Institute; Global Canopy, [n.d.]. Available at: https://trase.earth/methodology/supply-chains-methodology. Accessed: 31 Aug. 2026.

VILLORIA, Nelson et al. Leakage does not fully offset soybean supply-chain efforts to reduce deforestation in Brazil. Nature Communications, v. 13, n. 1, art. 5476, 2022. DOI: 10.1038/s41467-022-33213-z.

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