Challenges
Journal of Planetary Health

MDPI

Article

Relational Infrastructures for Planetary Health: Network Governance and Inner Development in Brazil's Traceable Beef Export System

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Abstract

This study analyzes the relational architecture of Brazilian traceable beef exports using a tripartite network model that connects certified meatpacking plants, AgriTrace sustainability protocols, and importing countries. By leveraging export authorization data from the Brazilian Ministry of Agriculture, it is shown that certification protocols function not merely as compliance tools but as relational governance infrastructures, mediating legitimacy, market access, and coordination within global value chains. Bipartite projections allowed the deriving and analyzing of two secondary networks: one mapping connections between meatpacking plants that share certifications, and the other linking consumer nations through common supply channels. The meatpacking plant network displays high modularity, featuring two dominant clusters alongside several smaller, regionally coherent clusters. This structure reflects diverse governance capabilities and strategic certification adoptions. Conversely, the consumer nation network shows lower modularity but identifies central hubs that organize international demand and signal regulatory alignment. These patterns reveal underlying dynamics of coopetition, where actors collaborate through shared standards yet compete through innovation. By integrating the Inner Development Goals (IDG) framework, it is revealed internal capacities, such as trust, complexity awareness, and shared purpose, underpinning the efficacy of traceability systems as ethical and adaptive infrastructures. This values-based lens provides a novel perspective on how technical systems can foster resilient, inclusive, and sustainable trade, thereby contributing to planetary health and human-centered development in global livestock governance.

Keywords: agri-food governance; sustainable livestock; traceability systems; network analysis; Inner Development Goals (IDG)

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Academic Editor: Susan Prescott

Received: 29 July 2025
Revised: 5 October 2025
Accepted: 9 October 2025
Published: 16 October 2025

Citation: Bergier, I. Relational Infrastructures for Planetary Health: Network Governance and Inner Development in Brazil's Traceable Beef Export System. *Challenges* **2025**, *16*, 48. https://doi.org/10.3390/challe16040048

1. Introduction

The sustainability of global food systems is a defining challenge of our time, central to the planetary health agenda that recognizes the profound interdependence of human well-being and natural ecosystems [1]. As the world confronts climate change, biodiversity loss, and social inequality, the urgent need to transform how we produce, trade, and consume food is undeniable. This is particularly evident in Brazil's beef sector, a global powerhouse where environmental, economic, and ethical dynamics are critical to international debates on sustainable development.

Brazilian livestock farming significantly contributes to the national GDP and supports rural livelihoods, strengthening infrastructure and social services across vast regions [2]. Yet, these socioeconomic benefits are coupled with severe environmental and governance challenges [3,4]. The sector is a major source of methane emissions and a primary driver of deforestation in the Amazon and Cerrado, biomes that are vital for global climate regulation and biodiversity [5]. These tradeoffs highlight the complex tension between economic development and planetary boundaries, demanding solutions that transcend technical compliance and engage the moral and cognitive capacities of governance actors [6–10].

Addressing sustainability in beef value chains thus requires more than external policy incentives or technological fixes; it necessitates a fundamental shift in how individuals and institutions perceive, relate to, and act within complex systems. The Inner Development Goals (IDG) framework, a complement to the United Nations Sustainable Development Goals (SDGs), posits that systemic change hinges on cultivating inner capacities, including complexity awareness, empathy, trust, long-term orientation, courage, and integrity [10,11]. These capacities are essential for navigating the uncertainty, pluralism, and collaboration inherent in sustainability governance. Although initially applied to leadership and personal development, the IDG model is increasingly relevant to institutional and multi-stakeholder contexts, where ethical alignment and shared purpose are prerequisites for effective action [12].

Digital traceability systems are a key domain where these internal capabilities are being operationalized. In Brazil, platforms like SISBOV and AgriTrace [2,13] have emerged as crucial infrastructures for managing sustainable livestock trade. These systems not only ensure transparency and compliance with regulations such as the European Union's Deforestation-Free Products Regulation (EUDR) but also foster trust, accountability, and legitimacy across complex supply chains [13–18]. They function as relational governance tools, coordinating diverse actors around shared standards and providing a critical interface between production systems and global markets that are increasingly influenced by ethical and environmental concerns.

Despite growing focus on the technical and economic aspects of traceability, little is known about how internal development capacities influence the structure and function of these systems. How do values like empathy, shared purpose, and long-term vision manifest in the networked architecture of sustainable trade? How can relational network analysis inform strategies for building more ethical, resilient, and inclusive food systems?

This study addresses these questions by applying network science and the IDG framework to analyze the structure of certified beef exports from Brazil. Using publicly available data from the AgriTrace Platform and the Ministry of Agriculture, a tripartite network connecting meatpacking plants, certification protocols, and importing countries was constructed and analyzed. This approach allowed the investigation of how the network's topology reflects governance dynamics and value-based coordination [10,11], and how coopetition [12,19], shared protocol adoption, and spatial patterns relate to IDG dimensions such as trust, collaboration, and complexity awareness.

By framing traceability as both a technical and a relational, value-laden infrastructure, this article offers a novel contribution to the literature on agri-food governance. It integrates the planetary health paradigm [1] with inner development theory [10,11] and operations research [12,19], underscoring the pivotal role of human capabilities in driving sustainability transitions. The findings aim to inform policymakers, certifiers, and global trade partners who seek to advance ethical, adaptable, and inclusive livestock systems in Brazil and beyond.

2. Materials and Methods

A network science approach was adopted to model and analyze the structural architecture of Brazil's traceable beef exports. The methodology is grounded in the principles of planetary health and the Inner Development Goals (IDG) framework, which led us to treat traceability systems not merely as logistical tools but as relational governance infrastructures. These infrastructures potentially reflect shared purpose, institutional trust, and collective problem-solving capabilities, all central to IDG domains like collaboration, complexity awareness, and long-term orientation. Network analysis is a powerful method for revealing the structures through which values, power, and accountability circulate within global agri-food chains, allowing us to identify central hubs, collaborative clusters, and peripheral innovators.

2.1. Data Source and Structuration

Data is sourced on certification protocols from the AgriTrace Animal Platform, maintained by Brazil's National Agriculture Confederation (CNA). This yielded eleven distinct traceability protocols, each defined by unique eligibility criteria encompassing breed composition, fat coverage, dentition limits (a proxy for animal age), and specific sustainability or genetic attributes (see Table 1). These protocols, developed by producer associations or certification bodies, serve as frameworks that authorize meatpacking plants to access specific export markets. Table 1 summarizes the key attributes of these protocols, highlighting how they range from those emphasizing socioenvironmental metrics (e.g., "Carne Carbono Neutro"—CCN, "Associação Brasileira de Pecuária Orgânica"—ABPO) to those focused on genetic identity and brand positioning (e.g., Angus, "Garantia de Origem Nelore", Wagyu).

Table 1. Attributes of AgriTrace protocols connected to Brazilian meatpacking plants. The information was derived from descriptive memorials of the protocols (see Data Availability Statement).

Protocol Certification	Cattle Breed	Carcass Fat Coverage (mm)	Incisors Dentition (Age)	Specific Features
ABPO (Brazilian Association of Organic Beef)	Not specified	Not specified	Not specified	100% traced; native or diversified pastures; aligned with state-level sustainability policy; human skill training
Angus	≥50% Angus blood	2 to 6	Up to 4	100% traced; no European crosses with dairy traits accepted; human skill training
Carne Carbono Neutro (*Neutral Carbon Meat*) (CCN)	Not specified	1 to 10	Up to 4 (♀) Up to 2 (♂)	100% traced; focused on carbon neutrality via tree wood for certified sawmill; human skill training
Charolês (*Charolais*)	≥50% Charolais blood	3 to 4	Up to 2	100% traced; bonus policy for efficient farmers; human skill training
Devon	≥50% Devon blood	3 to 6 or 6 to 10	Up to 4	100% traced; carcasses from certified properties; human skill training
Garantia de Origem Nelore	Max 25% non-Zebu blood	2 to 6	Not specified	100% traced; carcasses minimum weight of 195 kg or 13 @ (♀) and 225 kg or 15 @ (♂); human skill training
Hereford	≥50% Hereford blood	≥3 (boneless) ≤10 (processed)	Up to 6	100% traced; human skill training
PECBR	Not specified	Not specified	Up to 6 (♀) Up to 4 (♂)	100% traced; accepts both pasture-raised and feedlot-finished (confinement) beef systems; human skill training
Rubia Gallega	50% maternal Nelore + 50% paternal Rubia	1 to 2	0	100% traced; Crossbreed from Spain; lighter carcasses; human skill training
Senepol	≥50% Senepol blood	2 to 6	Up to 4 (♀) 0 (♂)	100% traced; clear definition for crossbreed ratios and ♀and carcass ♂weight; human skill training
Wagyu	≥50% Wagyu Kuroge/Akage blood	4 to 10	Up to 6	100% traced; premium positioning; strict breed control; human skill training

These two datasets are then cross-referenced and integrated to create a consolidated tripartite dataset containing:

- Meatpacking plants authorized for export (identified by their unique CNPJ tax ID).
- The traceability protocols under which each plant is certified.
- The destination countries to which each plant is licensed to export.

The analysis was based on a comprehensive snapshot of all active export authorizations and protocol certifications as of December 2024. To ensure precision and consistency, the municipal locations of meatpacking plants were standardized by using urban centroid coordinates assigned to consumer nations. In addition, duplicate facility entries were harmonized by relying on the unique CNPJ identifier.

2.2. Network Construction

The network was constructed and visualized using Gephi 0.10, an open-source platform for complex network analysis. A tripartite network is then built with three node types:

- Meatpacking plants (blue);
- AgriTrace certification protocols (red);
- Consumer nations (green).

Directed edges represent two types of validated linkages:

1. From a meatpacking plant to a protocol (certification relationship).
2. From a protocol to a consumer nation (authorized export relationship).

Node size was scaled by weighted degree centrality (reflecting connectivity/influence) and node label size by betweenness centrality (highlighting key intermediaries).

To examine indirect structural relationships, the tripartite graph was projected into two bipartite networks [20] using Gephi's MultiMode Network Projection plugin. This transformation creates undirected edges weighted by co-membership frequency, yielding:

- A meatpacking plant network, where nodes are connected if they share one or more protocols;
- A consumer nation network, where nodes are connected if they import from the same certified meatpacking plant(s) associated with a given protocol.

2.3. Network Analysis

The analysis focused on the bipartite networks connecting a) meatpacking plants to protocols, and b) consumer nations and protocols. Formally, it is defined a domain set D (meatpacking plants or nations) and a range set J (protocols).

The resulting bipartite graph is undirected, with edges weighted by the number of protocols a given plant or nation is attached to. The graph is given by $G = (D, J, E)$ where $D = d_1, \ldots, d_n$ and $J = j_1, \ldots, j_m$ are, respectively, the set of plants, or nations, and the set of protocols. E is the set of edges $\{(d_k, j_l) : d_k \in D, j_l \in J\}$, weighted according to the number of plants or nations d_k attached to a protocol j_l. Starting from the matrix $A(n \times m)$ of D-J network, the $(n + m) \times (n + m)$ adjacency matrix M of G is given as $M_{k,l} = E_{k,l}$ if there is an edge $\{k, l\}$ and $M_{k,l} = 0$ otherwise. The adjacency matrix M of this graph is $M = \begin{bmatrix} 0 & A \\ A^T & 0 \end{bmatrix}$.

After disambiguating meatpacking plants using their CNPJ numbers, the final dataset included 128 plants and 61 consumer nations.

Gephi was used to calculate standard topological metrics (betweenness centrality, weighted degree) and to perform cluster analysis using the "Modularity Class" algorithm [21]. The validity of the clusters was verified by running the modularity calculation multiple times with the "randomize" option enabled in the Gephi statistics panel. For multiple runs, if the number of communities is constant and the connections are stable, the clustering is assumed to be non-random.

It was employed the "MultiMode Network Projection" plugin for the bipartite analysis. The resulting clusters were color-coded and spatialized using Gephi's GeoLayout plugin to enable visual interpretation alongside Brazil's geography, though note this was for exploration and not formal spatial statistical analysis. Cluster patterns are interpreted in the context of regional certification practices and market strategies. While the model is structural, its patterns can be interpreted as reflecting relational qualities associated with IDG competencies. For instance, high co-participation in protocols may suggest shared purpose, and geospatial clustering may reflect local governance capacity.

2.4. Reproducibility and Limitations

All data and processing steps are based on publicly available sources and are fully reproducible. This network model provides a methodological foundation that can be adapted for other agri-food sectors or geographic contexts.

This approach assumes that formal protocol adoption and the resulting network structures are a meaningful proxy for relational governance and alignment. While these structural patterns offer rich insights into system-level dynamics, they cannot directly capture the internal states, motivations, or cultural norms of individual actors. Future research should integrate qualitative methods, such as interviews and surveys with meatpackers, certifiers, and regulators, to empirically validate the relationship between network position and IDG competencies.

3. Results and Discussion

3.1. Traceability as Relational Governance: Mapping the Tripartite Network

Figure 1 presents the tripartite network connecting certified Brazilian meatpacking plants (blue), AgriTrace protocols (red), and consumer nations (green). This structural configuration reveals the multi-level architecture of Brazil's sustainable beef exports and shows how traceability protocols function not only as compliance instruments but also as relational infrastructures that connect production, governance, and trade.

The network illustrates that protocols act as institutional bridges, linking national practices to foreign market demands, while also serving as value-based connectors that mediate trust, transparency, and shared purpose among heterogeneous actors. The fact that many meatpacking plants are certified for multiple protocols reflects strategic flexibility and alignment, while specialization in a single protocol (Table 1) suggests a focus on specific sustainability niches.

From an IDG perspective, this complexity signals the operationalization of capabilities such as complexity awareness, long-term vision, and integrity. Actors must navigate overlapping regulations, evolving sustainability standards, and diverse market expectations, making traceability a platform for ethical discernment and adaptive leadership. In this context, the network becomes a tangible expression of how cognitive and moral development shapes systemic resilience, a core principle of the planetary health paradigm.

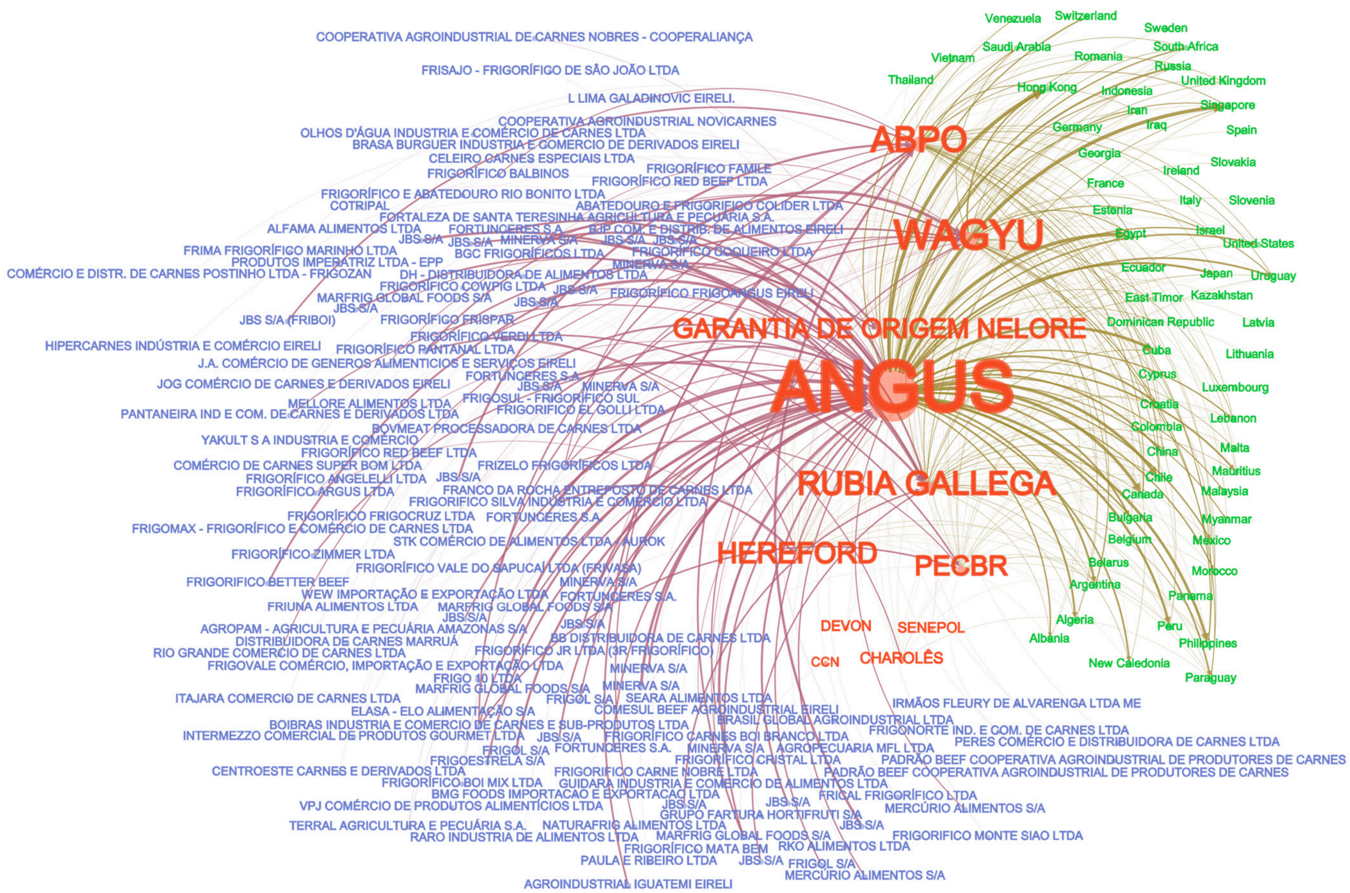

Figure 1. Tripartite directed network of certified Brazilian beef exports showing relational dependencies among meatpacking plants, certification protocols, and consumer nations. The relative size of labels and nodes is associated with their centrality in the network.

3.2. Coopetition and Ethical Infrastructure: The Projected Meatpacking Plant Network

Figure 2 shows the projected undirected network of 128 meatpacking plants, connected based on shared participation in AgriTrace protocols. This bipartite projection reveals six structural clusters, with two dominant clusters comprising 84% of all nodes and four smaller clusters reflecting peripheral or specialized activities.

This modular structure reflects an emerging logic of coopetition [12], where dominant plants coordinate around widely adopted protocols to maintain scale and legitimacy, while smaller clusters pursue innovation through niche certifications (e.g., organic, low-carbon, breed-specific). This dual structure supports the industry's ability to balance efficiency with experimentation, addressing both current demands and future market shifts.

Critically, this pattern is not merely technical but is underpinned by internal values and capabilities. IDG dimensions such as collaboration, courage, and integrity are reflected in how actors manage interdependence: they cooperate on shared infrastructure (protocols) while competing through ethical innovation. This coopetitive dynamic transforms the traceability system into an ethical infrastructure that supports diversified value propositions while fostering systemic alignment.

Rather than treating sustainability as a compliance burden, participants in this network may take advantages to use certification as a space for shared learning and purpose-building. This aligns with IDG principles [10,11] by framing governance as a relational practice in which trust, humility, and long-term orientation guide institutional behavior and supply chain evolution. From a planetary health perspective [1], this approach enhances sector resilience, enabling coordinated responses to global challenges like deforestation, climate change, labor ethics, and animal welfare [13–18,22].

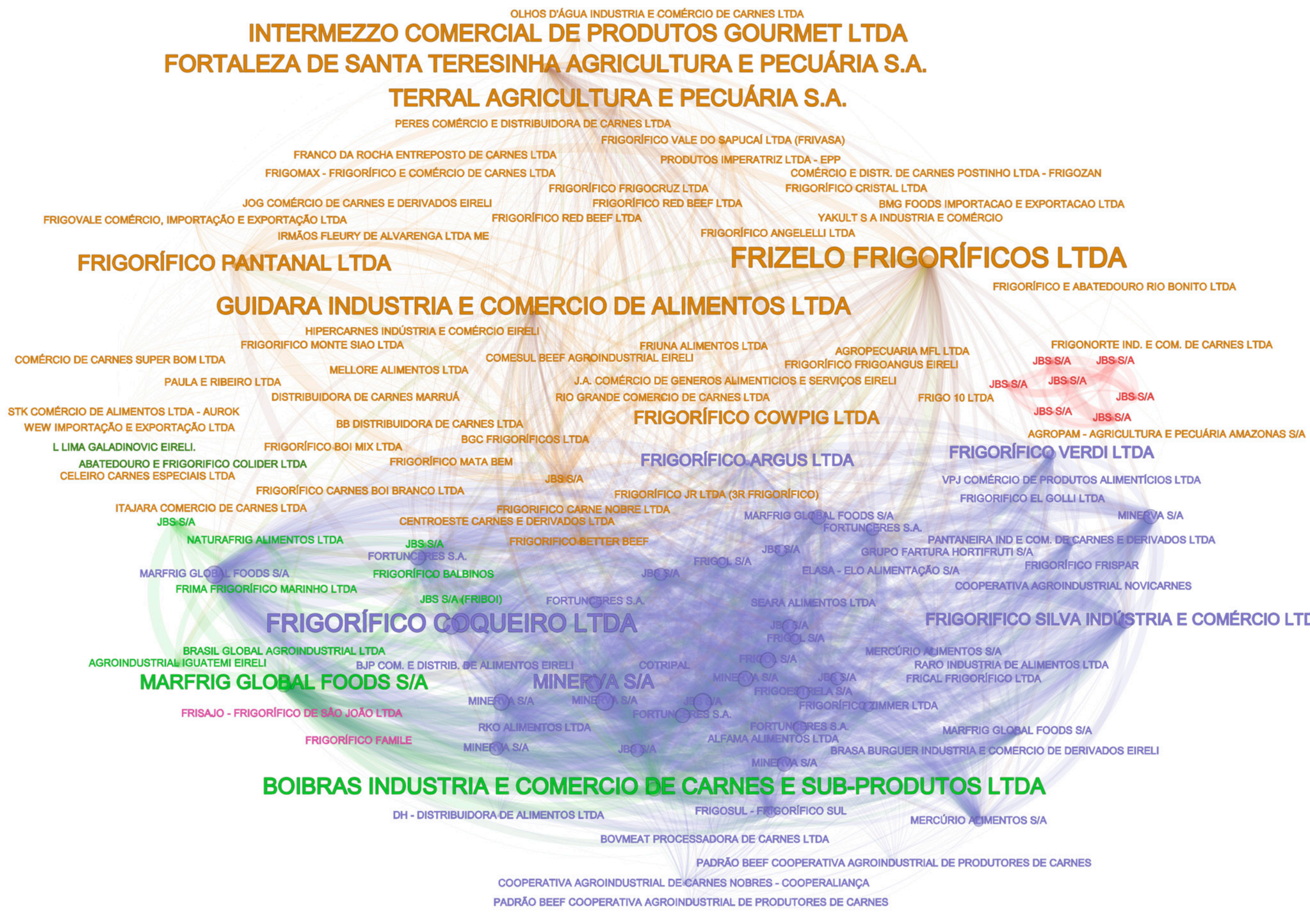

Figure 2. Projected undirected network of 128 meatpacking plants distributed in 6 clusters.

3.3. Territory, Trust, and Purpose: Geospatial Patterns of Governance

Figure 3 shows the spatial distribution of meatpacking network clusters, illustrating how traceability governance is shaped by Brazil's territorial diversity.

The largest cluster (blue, 42.2%) is widely dispersed across the South, Southeast, and Central-West regions, indicating institutional consolidation and logistical infrastructure aligned with major protocols. The second-largest cluster (orange, 41.4%) is more concentrated in São Paulo, suggesting a strategic alignment with localized regulatory and commercial ecosystems. Smaller clusters exhibit distinct regional identities: one in Mato Grosso do Sul (7.8%) focused on organic or pasture-fed production; another in Mato Grosso (5.5%); and a cluster in the South (1.6%) linked to breed-specific differentiation.

These spatial patterns demonstrate that traceability governance is not geographically neutral. Instead, it reflects localized networks of trust, learning, and coordination, or territorial expressions of shared purpose and relational agency. IDG capacities such as connection with nature, humility, and responsibility are embedded in these regional systems, where stakeholders co-create ethical practices aligned with local ecologies, social realities, and value commitments.

These findings suggest that scaling sustainability requires attention to internal development at a collective level. Regions that excel in traceability innovation are not only better resourced but also exhibit greater relational maturity, with stronger traditions of collaboration, foresight, and institutional coherence. Recognizing and investing in these internal capacities is essential for achieving planetary health outcomes such as ecosystem conservation, social equity, and inclusive economic development.

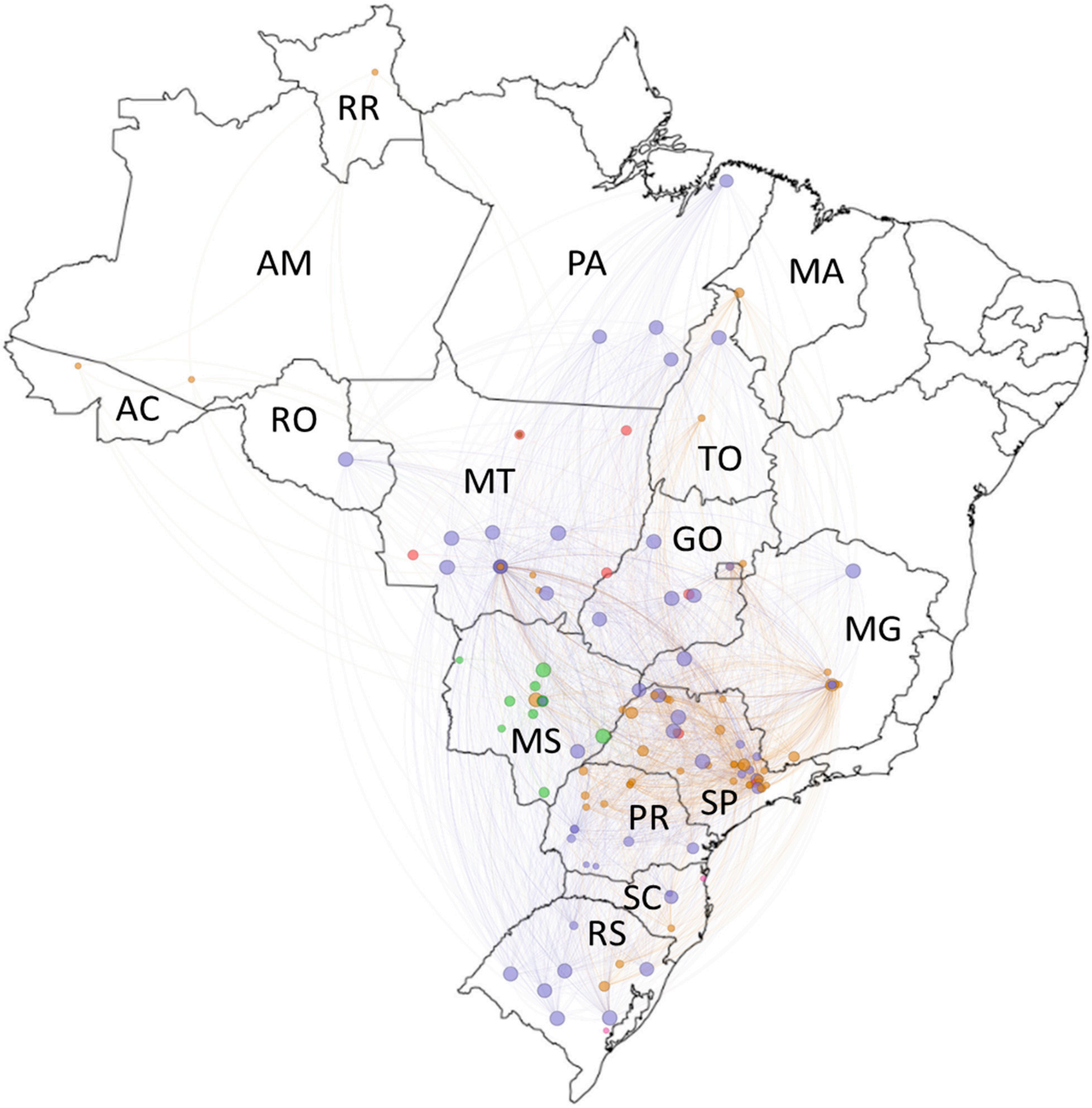

Figure 3. Projected undirected network of meatpacking plants as a function of AgriTrace protocols and geographic coordinates. Colors and nodes are the same as in Figure 2.

3.4. Projected Network of Consumer Nations

Figure 4 shows the projected network of 61 consumer countries, interconnected through shared supply chains of certified Brazilian beef. Although less modular than the meatpacking network, it reveals distinct market hubs, such as Hong Kong, Singapore, Canada, and Egypt, that serve as critical connectors between multiple meatpacking plants and protocols. In contrast, peripheral nodes include stringent markets like those in the European Union and Oceania, suggesting regulatory misalignment or pending convergence.

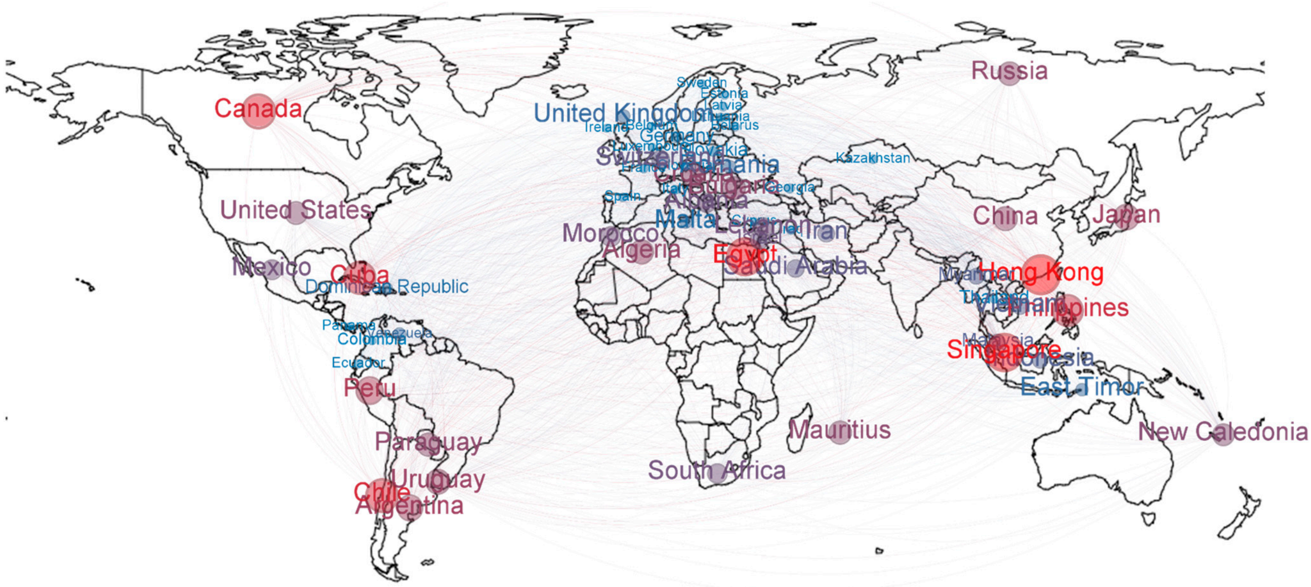

Figure 4. Projected undirected network of nations (consumers) as a function of the AgriTrace protocols and geographic coordinates. Reddish (bluish) colors indicate greater (lesser) connectivity driven by AgriTrace protocols.

This structure highlights that traceability systems operate not only within national supply chains but also as interfaces for international trust. These systems function as instruments of regulatory diplomacy. For instance, nationally developed protocols like Carne Carbono Neutro (CCN) can be interpreted as strategic efforts to create compliance bridges to stringent markets like the EU. The peripheral position of EU nations in the current network likely reflects the barrier effect of the EUDR, which restricts supply to a smaller subset of fully compliant plants. In contrast, the central hub status of other nations reflects less restrictive regulatory environments that allow for a broader and more interconnected supplier base. This demonstrates that the network is shaped as much by policy barriers as by market demand.

However, this legitimacy relies not only on documentation but also on the relational competence of the actors who develop, implement, and negotiate certification standards. IDG capabilities such as perspective-taking, intercultural competence and trust-building are therefore crucial for how Brazil navigates the geopolitics of ethical trade. These human-centered competencies shape how protocols are interpreted, adapted, and adopted across borders, determining whether sustainability becomes a space for mutual recognition and shared purpose or one of distrust and exclusion.

Moreover, the ability of nations to form structural bridges within the network depends not only on trade volume but also on the ethical alignment of their governance systems. In this sense, IDG-informed diplomacy becomes a prerequisite for integrating sustainability into international markets, reinforcing the central planetary health principle that global well-being depends on the integrity of both institutions and relationships.

3.5. Synthesis: From Technical Topology to Ethical Systems

Collectively, the network patterns revealed in this study demonstrate that traceability is not merely a technical or administrative system but a moral and cognitive infrastructure. It depends as much on shared meaning, mutual learning, and ethical commitment as on data verification and compliance.

The tripartite topology maps a system in which meatpacking processors, protocols, and consumer nations are interconnected not only by market logics but also by value-based coordination mechanisms. The modular clusters of processors reflect internal ecosystems of cooperation and innovation; the territorial distribution reveals place-based trust systems and learning communities; and the consumer network shows how legitimacy flows through channels shaped by shared vision and intercultural dialogue.

Through the lens of the IDG framework, these structural dynamics can be interpreted as expressions of internal development at scale. Trust, complexity awareness, empathy, and shared purpose are not abstract values but operative forces that shape how networks are built, sustained, and adapted. Integrating these capabilities into governance systems is essential for building ethical food systems capable of addressing the teleconnected crises of our time.

By aligning these findings with the planetary health agenda, one realizes that relational integrity, ethical coordination, and internal development are fundamental to protecting ecosystems and securing a viable human future. As climate regulations tighten, consumer expectations evolve, and geopolitical tensions intensify, sustainability will increasingly depend on the quality of relationships within networks, across borders, and among people.

4. Scaling Sustainability Through Network-Based Governance

The findings of this study open a new frontier for sustainability research at the intersection of network science, operations research, and values-based governance. By mapping the structural interdependencies among meatpacking plants, certification protocols, and international markets, the tripartite traceability model provides more than a descriptive map; it offers a dynamic analytical framework for developing decision-support systems, ethical supply chain planning, and innovation strategies aligned with planetary boundaries and human development goals.

This network architecture can be leveraged to explore multi-objective optimization in traceable beef systems, balancing economic performance (e.g., market expansion, profitability) against environmental and social objectives (e.g., deforestation reduction, carbon mitigation, labor inclusion). For instance, facility location models [23] could be adapted to optimize the siting of certification centers or meatpacking plants by incorporating not only logistical efficiency but also regional disparities in governance, digital infrastructure, and smallholder (breeders) access to certification, historically marginalized in formal markets.

The network analysis reveals a governance structure that currently revolves around meatpacking plants and protocols. Integrating breeders requires deliberate, multi-faceted mechanisms that address economic, technological, and relational barriers. Drawing on findings herein described and the IDG framework, this work proposes the following concrete mechanisms:

a. *Protocol-Based Inclusion through "Nested Certification"*: develop and incentivize protocols that include group certification models. A meatpacking plant or cooperative could achieve certification as an entity, which then allows the breeders in its supply network to be grandfathered into the traceability system under a shared umbrella. This reduces the individual audit burden and cost for each small farmer. This requires trust-building between the plant and its suppliers and fosters a collaborative mindset and shared purpose across the chain.

b. *Technological Leapfrogging with Lightweight Digital Tools*: instead of complex, expensive systems, leverage ubiquitous mobile phones for low-cost traceability. Implement systems based on SMS (Short Message Service), USSD (Unstructured Supplementary Service Data), or lightweight apps that allow breeders to record key data (e.g., animal births, transfers, and health records) and receive payments directly. These data can be integrated with platforms like AgriTrace via APIs. This builds digital competence and empowers farmers through transparency, making them active participants rather than passive subjects of the traceability system.

c. *Financial Mechanisms and Differentiated Premiums*: create transparent payment models where sustainability premiums are visibly shared with the farmers who produce the certified calves. This provides a direct economic incentive for participation. Development banks or impact investors could provide upfront financing for the transition costs (e.g., ear tags, initial audits), which is repaid through the future premium streams. This aligns with long-term orientation by showing a clear path to economic benefit and requires integrity from meatpackers to ensure fair revenue sharing.

d. *Formation of Producer Cooperatives and Associations*: encourage and support the formation of breeders' cooperatives. A cooperative can aggregate production to achieve the scale needed to engage directly with certification protocols and meatpackers, negotiate better terms, and manage the administrative burden collectively. Such a mechanism is fundamentally built on IDG capacities as collaboration, collective action, trust, and communication skills.

e. *Government and NGO-Facilitated "On-Ramps"*: MAPA, CNA and development agencies could create simplified, subsidized "starter" versions of major protocols with graduated requirements. This would provide a clear pathway for breeders to enter the system and gradually upgrade their practices over time, rather than facing a single, insurmountable barrier to entry. This demonstrates empathy and perspective-taking from regulators and certifiers, acknowledging the different starting points of producers.

Such approach aligns with the Inner Development Goals (IDG) focus on equity, empathy, and systemic awareness, positioning inclusive design as both a technical and ethical imperative. Embedding IDG principles into optimization routines would help ensure that scaling sustainability remains sensitive to local realities and human dignity, especially across Brazil's socio-ecologically diverse regions. Similarly, integrating flow optimization and capacity allocation models with operational data (e.g., daily shipments, export destinations) could improve real-time responsiveness to shifting trade patterns or emerging regulations [24], such as the EUDR or new tariffs in an era of declining multilateralism. Implementing such dynamic models demands not only computational agility but also governance agility, a capacity grounded in IDG domains like "Doing" (e.g., courage, perseverance) and "Thinking" (e.g., complexity awareness, long-term vision).

The tripartite structure of the traceability network also supports three-tiered optimization approaches [25], where protocols are treated not only as technical constraints but also as relational gatekeepers that govern legitimacy, shape identity, and differentiate market access. This creates opportunities to model strategic coopetition, wherein supply chain actors collaborate through shared certification infrastructure while competing via innovation (e.g., carbon-neutral beef, breed-specific brands, organic sourcing). Such dynamics reflect IDG competencies like trust-building, ethical commitment, and collaborative mindset.

To better capture actor heterogeneity and the moral complexity of sustainability transitions, future work could employ agent-based models (ABMs) or behavioral simulations [12,19,26]. These models might represent varied decision-making profiles among producers, certifiers, consumers, and regulators, incorporating IDG-informed assumptions about empathy, trust, and learning orientation. This would enhance predictive realism and ethical robustness under uncertainties arising from climate events, trade disruptions, or political change. Behavioral modeling could also guide the design of adaptive decision support systems (DSS) that merge technical, spatial, and relational intelligence [27], enabling stakeholders to assess policies and certifications not only by cost or emissions, but also by inclusive governance, ethical alignment, and long-term resilience [28]. This is especially critical in Brazil's beef sector, where environmental issues intersect with challenges like modern slavery, gender exclusion, rural inequality, and animal welfare [13–18,22].

Ultimately, this study establishes a foundation for integrating systems modeling with human development theory. Framing meat traceability as a moral-technical system [29] rather than just a logistical artifact can stimulate the development of food governance models that are operationally efficient, socially just, and environmentally sound [30]. This hybrid approach—combining data analysis with attention to inner development—can support the necessary transformation of livestock systems toward regenerative, inclusive, and planetary health-aligned futures [31].

5. Conclusions

This study provides a novel, data-driven analysis of Brazil's traceable beef exports, modeling a tripartite network that interconnects meatpacking plants, AgriTrace certification protocols, and consumer nations. Applying network science reveals that sustainability protocols function not merely as verification tools, but as relational governance infrastructures that mediate global market access, organize production, and shape reputational legitimacy.

The projected network of meatpacking plants revealed a modular structure, underscoring significant heterogeneity in territorial governance capabilities and strategic protocol adoption. Conversely, the consumer nation network identified central hubs that anchor sustainability-oriented trade flows. Together, these findings illustrate that traceability is a spatial, institutional, and geopolitical construct embedded within a web of relationships defined by trust, strategic alignment, and shared values.

The findings underscore the dual role of traceability systems: as facilitators of international trade and as instruments for environmental, social, and ethical governance. Certification protocols do more than ensure compliance; they coordinate collective action, embody ethical commitments, and enable differentiated market positioning in an era of heightened climate regulation and consumer scrutiny. Enhancing the interoperability, inclusiveness, and transparency of these systems can empower institutions like CNA, MAPA, and export consortia to align certification strategies with both local production realities and global sustainability expectations. As regulations like the EUDR and ethical sourcing standards gain prominence, network-based traceability becomes a strategic necessity by securing market access while fostering collaboration in a fragmented sector.

This study contributes a robust analytical framework to guide future research in dynamic simulation, multi-objective optimization, and the integration of metrics for greenhouse gas emissions, animal welfare, labor equity, and sociocultural inclusion. Beyond methodology, it advances a values-based interpretation of governance by showing how human capabilities, as framed by the Inner Development Goals (IDG), shape the evolution of sustainability networks. The coexistence of dominant and niche protocol clusters illustrates the system's capacity for coopetition, where actors balance competition and collaboration toward shared socio-environmental goals. Capabilities like complexity awareness, trust-building, empathy, and courage are not abstract ideals but are embedded in the relationships and decisions that underpin viable certification systems.

Consequently, traceability systems should be recognized not only as data infrastructures but also as ethical infrastructures or platforms for cultivating shared responsibility among producers, institutions, and consumers. They translate abstract sustainability ideals into verifiable, place-based, and values-aligned practices, advancing a planetary health vision where human and ecological well-being are mutually sustained.

Integrating these insights into policy, certification governance, and technical development is essential for scaling systemic sustainability. Such integration can support the transition of livestock production toward inclusive, adaptable, and ethically grounded systems capable of addressing the interconnected challenges of climate change, biodiversity loss, food security, and human dignity in the decades ahead.

Finally, while the network topology provides a powerful proxy for inferring relational capabilities, future work should seek direct empirical confirmation through interviews and surveys to understand how IDG capacities are expressed and cultivated among individual actors within these systems.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/challe16040048/s1. Table S1. List of anonymized secondary data (labeled and weighted links between sources and targets) used in the tripartite network in Figure 2, which was used for the further analyses of the projected bipartite networks presented in the remaining figures of this work.

Funding: This research was partially funded by Fapesp, grant number 2022/09319-9.

Data Availability Statement: The secondary data presented in this study are made anonymously available in Supplementary Materials (Supplementary Table S1) and primary data is available in the public domain at https://extranet.agricultura.gov.br/sigsif_cons/!ap_estabelec_nacional_cons and https://www.cnabrasil.org.br/agritrace, both accessed on 29 July 2025.

Acknowledgments: The author thanks the Brazilian Ministry of Agriculture (MAPA), the National Agriculture Confederation (CNA/AgriTrace), and the Brazilian Beef Exporters Association (ABIEC) for making crucial data available. The author has reviewed and edited the output and takes full responsibility for the content of this publication.

Conflicts of Interest: The author declares no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

ABIEC	Brazilian Beef Exporters Association
ABPO	Brazilian Association of Organic Beef Production
CNA	National Agriculture Confederation of Brazil
CCN	Neutral Carbon Meat
EUDR	European Union Deforestation Regulation
IDG	Inner Development Goals
MAPA	Brazilian Ministry of Agriculture and Livestock

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