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Resilience Erosion in Global Feed Systems

Dutch Demand and Brazilian Soy Monoculture

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Introduction

The last century and especially the last few decades have seen a tendency towards long and geographically dispersed supply chains, with an increased disconnection between producers and consumers (FAO, 2022). The current system has enabled the delivery of high volumes of food and improved calorie sufficiency for societies around the world – yet food quality, nutritional outcomes, and diet compositions remain quite uneven (HLPE-FSN, 2023). Affluent societies are marked by high consumption of animal-based protein products, consistently and significantly higher than in lower- or middle-income societies (Bruinsma, 2003), and also higher than consumption levels seen a few decades earlier. Diets that center meat, dairy and other animal-based foods place upward pressure on the volumes of feed crops required to sustain livestock production (Westhoek, 2014).

Soybeans are a crucial commodity in the feed system due to their high protein content, amino acid profile, digestibility for all major livestock species, and shelf-stability (Kuepper & Rijk, 2020). While soy is directly edible with minimal processing, much of the production volume goes towards soymeal for livestock feed, leading to substantial conversion inefficiencies and a much larger land-use footprint. Over recent decades, Brazil has seen a rapid associated expansion of soybean production often with large-scale monoculture systems (Lathuillière et al. 2022) – whereby one crop and typically one commercially attractive strain or variety is grown homogenously over large swathes of land.

The Netherlands forms a crucial link in this system (Westhoek, 2014). It is representative of the system on all levels: a country with a typical animal-protein heavy diet, a major agricultural producer that generates demand for soy feed, and a gateway to Europe in the soy supply chain. The systemic Dutch demand therefore far exceeds Dutch domestic consumption, and this generates impacts on the countries where source commodities are produced.

Soy monocultures in Brazil have been predominantly analysed as local and land-use issues (Fearnside, 2001; Hospes, 2010; Bastos Lima & Persson, 2020). Here, monoculture expansion is treated as a sovereign, domestic policy choice, provided certain consequences and externalities (like deforestation) are managed. Merely managing externalities however tends to overlook the broader system dynamics: the same choices and system structures that lead to caloric sufficiency in the short term can exacerbate or create risks to food security in the long term – by concentrating production and trade along an ever-smaller set of players, regions, actors and crop varietals.

In this report, we adopt a demand-side perspective to examine the soy-based feed-food system as an emergent outcome of interacting actors, incentives, and constraints. Our analysis is informed by a critical-realist and constructivist lens: we value, quantify and analyse material processes such as land conversion, trade flows, and ecological thresholds, while also acknowledging that dietary norms, market structures, and policy frameworks shape how these processes evolve. We focus on resilience as a key system property, distinguishing it from (short-term) robustness. While caloric sufficiency has improved in the aggregate (FAO, 2024) the food system is increasingly exposed to compounding risks, including climate change, trade disruptions, and geopolitical instability, which can propagate rapidly through highly interconnected supply chains.

In this light we pose the following research question:

Through which mechanisms do Dutch imports of soy contribute to monoculture expansion in Brazil, and how does this expansion affect risks to food security?

We investigate the two parts of this question in turn. Firstly, how consumer demand in the Netherlands translates into land-use pressures in Brazil. Here, our novel contribution is a quantification of soy land use needed for a few variations on the current Dutch diet with a target protein intake – as included in the Dutch dietary guidelines (Kromhout et al., 2016; The Health Council of the Netherlands, 2025). This extends the current literature on land and water use for various meat products. Secondly, we investigate how these pressures can create and exacerbate long-term risks to food security. We apply network analysis techniques to identify key trade nodes in the soy trade market, and apply a market concentration index to trade data, confirming that the soy market is getting more concentrated along specific links. We also conduct an analysis of climate-change related risks for these critical trade nodes, and the entire soy supply chain. We then integrate both sides into a causal loop diagram that highlights key pressures and opposing feedbacks, enabling us to discuss them in the context of current geopolitical climate and global trends.

Conceptual Framework and Study Design

This study conceptualises the Dutch-Brazilian soy nexus as a coupled social-ecological-technological system (SETS) in which dietary demand, land-use change and food security risks are co-produced across distance, scales and time (McPhearson et al., 2022). Building on the positionality articulated earlier in the report, the analysis adopts a critical-realist yet constructivist stance: land conversion, climatic stress and trade concentration are treated as materially real processes with measurable consequences, while dietary norms, governance structures and market institutions are understood as socially constructed and politically contested. This dual orientation translates our normative concern with sustainability and equity into specific analytical concepts and a coherent study design.

The analysis is grounded in a biophysical perspective, with the planetary boundaries framework as a central reference. We operationalise this framework as a constraint on the extent to which land-system change and biosphere integrity can be pushed before systemic resilience is undermined. From this perspective, soy-driven deforestation and ecosystem simplification contribute to global overshoot and increased systemic risk. Gerten et al. (2020) show that current food production is deeply entangled with planetary boundary transgressions, and that remaining within key terrestrial boundaries requires not only changes in production practices but, critically, shifts in diets. This is particularly relevant for the soy nexus, as it highlights that efficiency gains are insufficient when they rely on displacing ecological pressure to high-biodiversity, high-carbon, and hydrologically sensitive frontiers (cf. ibid.).

This is complemented by an ecological-economics sensibility aligned with the doughnut economy idea: food security cannot be evaluated solely on calories or short-run price efficiency, but must be assessed against ecological ceilings and the distribution of vulnerability across actors and places.

We bound the inquiry in several deliberate ways. Spatially, the demand side focuses on the Dutch diet, both because of the country's distinctive position as a major agricultural producer, economic actor, and European trade hub, and because of the policy relevance of dietary transitions within the Netherlands. On the supply side, we restrict analysis to Brazilian soy imports, as Brazil is the main supplier of soy to the Netherlands and a critical site of climate-relevant land-use dynamics, particularly given the Amazon's role in global carbon cycling and ongoing concerns about deforestation. Throughout this study, the term soy includes soybean meal used in animal feed, not just soy in its less processed form. Soy meal demand is the main driver of soy cultivation, and therefore it is crucial to include this form in our analysis, despite some authors resisting its classification as human-edible (see van Riel et al., 2023. We argue that since soy originates from a crop that is directly edible by humans, its use as feed exemplifies food–feed competition.

Food security is defined following the FAO (2015) as a condition in which all people, at all times, have physical, social and economic access to sufficient, safe and nutritious food. This broader definition allows the analysis to move beyond caloric availability and incorporate stability, affordability and long-term resilience. Reliance on broad definitions is consistent with our vulnerability framing, which emphasises systemic exposure and adaptive capacity rather than immediate scarcity alone. In this domain, the EAT-Lancet reference diet (Willett et al., 2019) has been suggested as a normative benchmark for assessing dietary sustainability, while indicators such as the Global Food Security Index (The Economist Intelligence Unit, 2022) provide complementary quantitative reference points in what remains an exploratory investigation.

Several core assumptions shape the framework. First, individual dietary patterns are treated as partially malleable but unevenly so. Some consumers and institutional actors are more likely to adjust meat consumption in response to policy incentives or normative shifts, while others are resistant in at least the short term. Accordingly, the analysis models feasible rather than universal dietary transitions. Second, concentration of power within trade networks and supply chain governance is treated as an intrinsic risk factor. The underlying assumption is that excessive concentration reduces redundancy, amplifies exposure to shocks and limits adaptive options, thereby increasing vulnerability within globally connected food systems. Third, the system cannot be exhaustively mapped; macroeconomic variables such as currency fluctuations or global geopolitical shifts remain outside the immediate analytical boundary. These constraints are acknowledged explicitly in the interpretation of results.

Dutch animal-protein consumption is understood as a primary driver shaping global feed demand (Kuepper, 2022). Through consumption-based modelling, we estimate soy-related land requirements under current and alternative dietary scenarios. This quantitative component reflects the material dimension of feed-land relations, while remaining embedded in a constructivist understanding of dietary change. Soy expansion in Brazil is conceptualised as the mediating process through which distant demand translates into ecological simplification, land concentration and heightened climate sensitivity.

Figure 1: Illustration of the Study Design adopted for this paper.

Food security risk is then analysed through a vulnerability lens structured around exposure, sensitivity and adaptive capacity. Network analysis of trade concentration and intermediary roles operationalises the proposition that power concentration can generate systemic fragility. Climate-related stressors and ecological degradation are interpreted as factors increasing system sensitivity, while diversification potential and governance flexibility are treated as elements of adaptive capacity. Acute risks, such as price volatility and supply shocks, are distinguished from cumulative risks associated with soil degradation, deforestation, and long-term climatic impacts. The integrative element of the study design is a causal loop diagram that synthesises these components into a dynamic representation of reinforcing and balancing feedbacks. The diagram makes explicit how dietary demand, infrastructural concentration, ecological degradation and vulnerability pathways interact across scales. In doing so, it provides a transparent bridge from research question to results, ensuring that the scope, scale and framing of the conceptual framework remain aligned with the systemic character of the problem.

Methodology

To address the research question of how Dutch soy imports contribute to monoculture expansion in Brazil and how this expansion affects risks to food security, we apply a mixed-methods systems approach. We first quantify the role of Dutch dietary patterns by modelling soy-related land use under current consumption, as well as under alternative dietary scenarios with higher shares of plant-based protein and less meat. We then examine food security risks through a trade network analysis that identifies trade concentration and dependencies in the world market. This is complemented by a qualitative assessment of climate-related risks in soy-producing regions in Brazil. Finally, we integrate these dynamics into one holistic causal loop diagram to synthesise key feedback mechanisms, dependencies, and risk pathways within the global soy system. The code used for the quantitative analyses, along with documentation is publicly available in the project's GitHub repository.

3.1 Dietary Demand and Feed-Land Modelling

To assess how Dutch dietary patterns contribute to soy demand and associated land use we developed a quantitative, consumption-based model of meat, fish, dairy, eggs, and selected plant-based soy substitutes, and their associated protein intake in the Netherlands. The model integrates data on population size, per-capita food consumption, product-level protein content, edible meat conversion ratios (EMCRs), feed composition, and crop-specific land-use coefficients.

Consumption data for animal-based products and plant-based substitutes represent recent Dutch averages and are treated as an empirical baseline. Alternative dietary patterns were constructed as plausible transition scenarios informed by the 2025 Dutch dietary guidelines, including limits on red meat consumption (maximum 10 kg per person per year), recommended fish intake (approximately 15 g per person per day), and policy targets for shifting protein intake toward plant-based sources (50/50 animal-plant protein by 2025 and 40/60 by 2030) (The Health Council of the Netherlands, 2025). Detailed scenario definitions are provided in Appendix A.

Protein supply was calculated using product-specific protein contents from the NEVO database (RIVM, 2025) and expressed on the basis of unprocessed products (e.g., raw meat rather than processed foods). As standardized protein data for processed products are limited, protein intake from meat is likely slightly overestimated. In all transition scenarios, total dietary protein intake was held constant at 22 kg per person per year, while the empirical baseline reflects observed consumption and is not constrained to this target. This benchmark represents a conservative lower-bound estimate, as other protein-rich foods such as legumes, nuts, and cereals are excluded from the model.

Feed-related land use was calculated using edible meat conversion ratios (EMCR), defined as the amount of feed required per kilogram of edible product, rather than conventional feed conversion ratios based on live weight. Soy-related feed land was calculated separately from non-soy feed land using EMCRs, feed composition shares, and crop-specific land-use coefficients. Land-use estimates exclude pasture, grassland, housing, and other on-farm infrastructure. All data sources and parameters are documented in the Appendix A.

3.2. Food Security Risks through a Trade Network Analysis

Brokerage Function of Critical Trade Nodes

We then looked at concentration of trade flows by running quantitative and network analyses on import-export data. This analysis allows us to examine how trade relationships between countries produce structural effects, that could pose a risk to long term food security (Puma et al., 2015). We follow Wu and Güclu (2013) in building a network analysis model using trade data for soy, a method that is well suited to identifying structural dependence, intermediation and power concentration within the global soy supply chain. Analysing the network structure offers significant advantages over analysing specific bilateral trade relationships, total aggregate volumes of production for commodities, or even trade dynamics within free trade treaties.

We used Chatham House as our data source, in turn built upon the Comtrade WITS database. We chose for the Chatham House processed version of the dataset because it offers advantages over the raw data from WITS: Imports and Exports are matched symmetrically, and different HS Codes relating to soy can be retrieved together. We first queried the database for import and export values of soybeans for the years 2000 to 2022 – including meal, cakes, and other major soy-based commodities. This data was cleaned up to match a list of internationally well-recognized geographies, and discard supernational groupings, using the ISO3 code. Further preprocessing steps included the deduplication of trade flows reported multiple times, converting trade values to consistent units, and dropping columns not relevant to our analysis. We selected trade value in dollar terms rather than trade value in tonnes, due to the limited availability of data for the latter.

For each year, a directed, weighted trade network was constructed – with nodes representing countries, and edge weights representing trade value. We then calculated *betweenness centrality* for different nodes/countries within this network – as a measure of the brokerage function of the countries. From these centrality metrics, which were calculated per year, we were not only able to find the countries that have a crucial intermediary role now, but also countries that have seen their intermediary role grow in the last few years. For this latter trend analysis, we used the data and fitted a linear regression line to the data available, providing an overall slope.

Soy Market Concentration

Another metric we calculated was the Herfindal-Hirschmann index, which has been used extensively in literature on market dominance of specific firms, and in competition literature (Rhoades 1993). This measure provides a total index of dominance of certain elements over others – in this case specific trade links compared to others. This index was plotted for each of the years we have data for the soy market, to investigate our hypothesis that trade is indeed becoming more concentrated along specific trade routes.

3.3. Climate-related Risks Assessment in Soy-producing Regions in Brazil

To complement the demand-side modelling and trade network analysis, we conducted a qualitative climate-related risk assessment focused on soy-producing regions in Brazil. This component examines how monoculture expansion interacts with climate dynamics and land-use change to shape vulnerabilities, and how these interactions may translate into food security risks. The assessment focuses on identifying systemic mechanisms and consequences of climate vulnerability, rather than quantifying impacts directly.

We began by examining established work on soy production, land-use change, and climate impacts in Brazil, and expanded the document set as additional risk pathways emerged. Both peer-reviewed studies and selected grey literature, such as policy reports and institutional assessments, were included where they provided relevant empirical, regional, or process-level insights. The material was screened for evidence on climate drivers and sensitivities relevant to soy monocultures, including temperature and rainfall variability, droughts, and land-atmosphere feedbacks. Where possible, we placed spatial emphasis on major production regions such as the Cerrado and the Amazon.

Extracted findings were then classified in a structured table along five dimensions: (i) climate stressors, (ii) drivers and (iii) associated biophysical mechanisms, (iv) impacts on production, and (v) systemic implications, including potential consequences for food security at local and global scales.

To complement the qualitative literature review, we constructed a simple spatial indicator capturing the intensity of Dutch soy sourcing across Brazilian states. State-level import volumes derived from the soy trade panel (from Trase – Lathuillière et al 2022) were aggregated and linked to Brazilian administrative units (from IBGE, n.d), then normalised by territorial area to allow comparison across regions of different sizes. This indicator is used descriptively to visualise where Dutch-linked soy sourcing is most geographically concentrated and to situate qualitative evidence on climate hazards and yield sensitivity in major producing regions. It does not constitute an independent risk metric, but supports the climate-related assessment by providing spatial context for exposure pathways discussed in the literature.

3.4. Global Soy Systems Mapping using a Causal Loop Diagram

To synthesise the mechanisms identified across our empirical analyses and literature review and to directly address the overarching research question, we developed a causal loop diagram (CLD) representing the structural dynamics linking Dutch soy demand to monoculture expansion in Brazil and associated food security risks. Whereas Sections 3.1-3.3 analyse specific components of this relationship, the CLD integrates them into a coherent systems representation, making explicit the feedback processes that stabilise or amplify observed trends. The CLD reflects deliberate boundary choices that foreground demand, trade concentration and ecological degradation, while abstracting from financial and geopolitical.

The diagram was constructed iteratively, drawing on three empirical inputs: quantified soy-driven land requirements from the dietary demand model, trade concentration metrics from the network analysis, and the climate and governance risk assessment for Brazilian soy-producing regions. These informed the identification of core system variables, including global soy demand, production volume, land conversion, market dominance of major traders, farmer bargaining power, ecological resilience, and food security risk. Causal relationships were defined directionally and assigned polarity based on empirical findings and established literature on agricultural expansion and commodity trade dependency.

Results

4.1 Meat-Demand and Food-Feed Competition

The dietary model shows that current Dutch consumption patterns generate substantial demand for soy as livestock feed, thereby exerting pressure on soy-producing regions such as Brazil. In the baseline scenario (Table 1), per capita soy feed land use amounts to 312 m² per person per year, embedded within a total feed-related land demand of 982 m²/person/year. This high land footprint is driven primarily by beef, pork, poultry, and dairy consumption (Figure 3, Table A3 & A4).

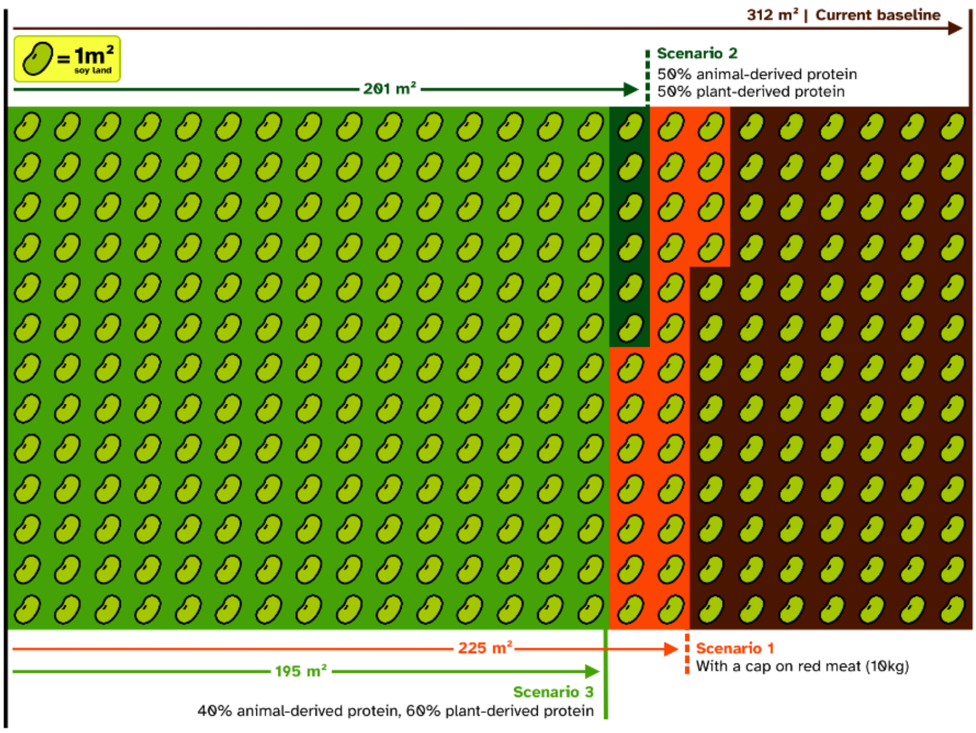

Figure 2: Soy land use for different dietary scenarios. All scenarios offer a significant reduction from current consumption patterns.

Reducing animal-based consumption leads to marked decreases in soy and total feed land demand. Under a red meat cap scenario (maximum 10 kg/person/year) soy feed land declines to 225 m²/person/year and total feed land to 660 m², while maintaining a protein intake of 22 kg/person/year through increased poultry consumption and 6kg less protein intake (28kg of protein in the current diet). Partial plant-based dietary shifts amplify these reductions: the 50/50 and 40/60 scenarios lower soy land use to 201 m² and 195 m² per person, respectively, corresponding to total feed land of 447m² and 399m² (Figure 2 and Figure A3 for total land use).

Product	Beef	Pork	Chicken	Other meat[1]	Dairy products	Eggs	Fish	Plant meat	Tofu	Soy milk
kg/person/year	14.90	35.10	22.00	2.50	123.37	5.84	5.48	0.57	0.09	2.61

Table 1: The Dutch consumption for animal products and chosen soy substitutes in kg/person/year.

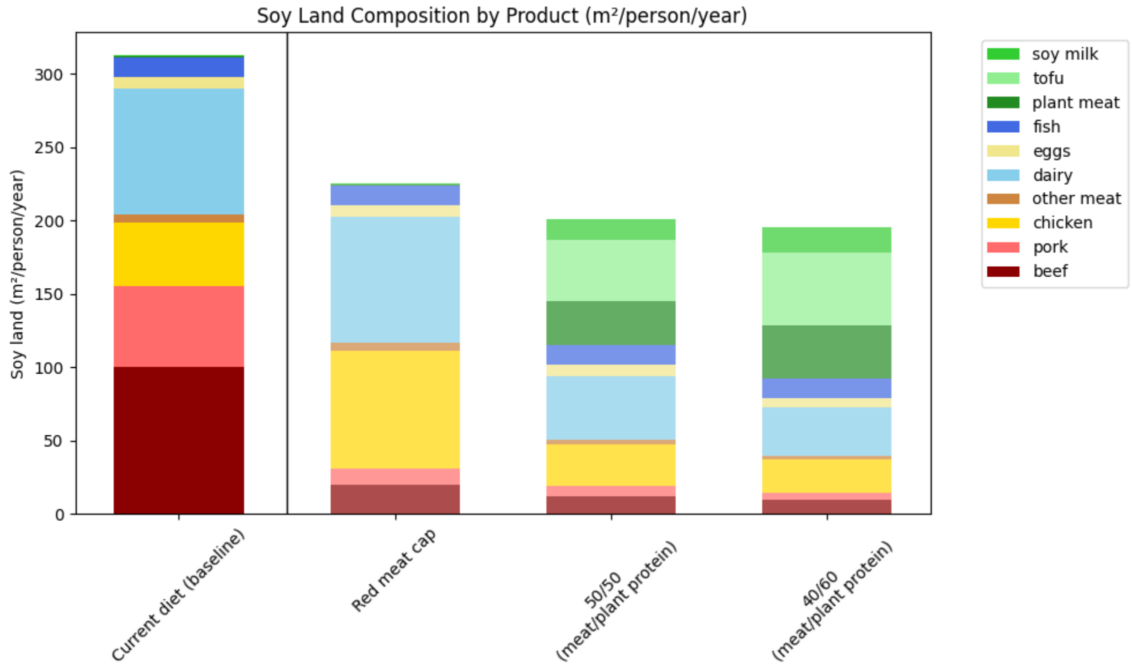

Figure 3: Soy feed land composition per person and year (m²/person/year), disaggregated by product and dietary scenario.

[1] Other meat consists of veal (1.4kg/person/year), sheep and goat, (1kg/person/year), and horse (0.1kg/person/year).

Figure 4 highlights strong differences in soy feed land requirements per kilogram of product. Beef is by far the most land-intensive product 6.7m² of soy land and around 20m² of total feed land to produce 1kg of beef due to high edible meat conversion ratios (EMCR), requiring substantially more feed than poultry (2m² soy land/kg; 5m² total feed land/kg) or pork (1.6m² soy land/kg; 6m² total feed land/kg), and orders of magnitude more than direct soy products such as tofu. Since soy is directly edible by humans, its use as livestock feed constitutes a clear case of food-feed competition. Approximately one-fifth of livestock feed consists of soy (Manceron et al., 2014), implying that reductions in animal protein demand also lower land use for other feed crops.

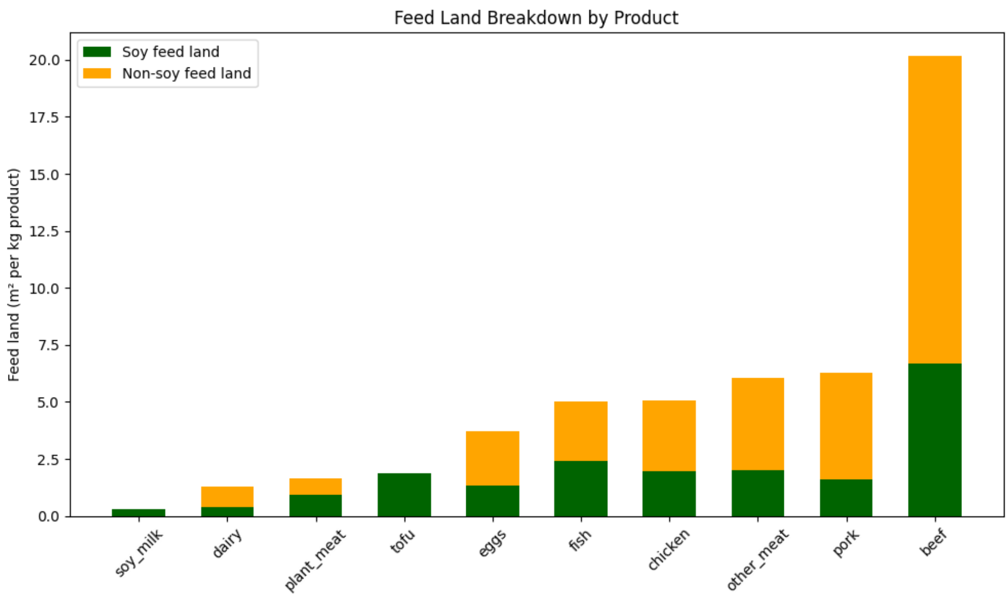

Figure 4: Soy and total feed land required per kilogram of product (m²/kg), based on edible meat conversion ratios and product-specific feed compositions.

The demand for meat products in the Netherlands thus increases pressure on soy feed production and reinforces large-scale, specialised production systems, which in turn tend to favour soy monocultures over more diversified agricultural landscapes (Kueppers, 2022). To understand how these concentrated production and export patterns can amplify risks to food security, the next section applies a social network analysis of global soy trade and market dominance.

3.2. Food Security Risks through a Trade Network Analysis

Betweenness Centrality and Brokerage

Betweenness centrality scores reveal an imbalanced intermediary structure in the global soy trade network. A small number of countries (excepting producers) occupy consistently central brokerage positions, indicating that soy trade connectivity depends on a limited set of intermediary nodes rather than being evenly distributed across countries.

Over the 2000-2022 period, several countries exhibit persistently high mean betweenness values. The Netherlands is the most central intermediary by a wide margin, reflecting its structural role as a trade and re-export hub. Other countries with strong intermediary functions include India, China, Germany, and a cluster of (Western-)European countries – Belgium, France, Italy, Spain, Denmark, and the United Kingdom. Outside Europe, Malaysia, South Africa, Russia, and Vietnam also play notable intermediary roles. There is a notable overlap with countries strongly associated with the shipping industry.

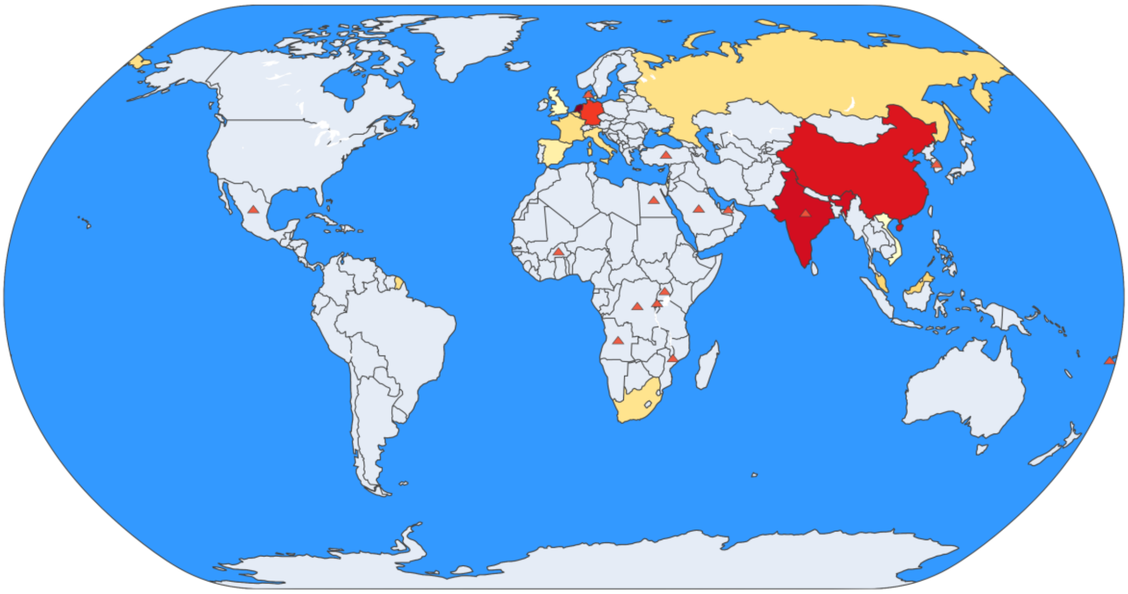

Figure 5. Countries with highest betweenness (shaded), and those with positive trends (△)

In addition to countries with stable and high betweenness, trend analysis highlights a group of rising intermediaries whose brokerage roles have increased over time. India shows the strongest growth, combining a high average betweenness with the steepest positive trend, indicating both a central and increasingly influential position in the network. Other countries with positive betweenness trends include Turkey, Saudi Arabia, the United Arab Emirates, and Egypt, alongside several smaller or emerging economies such as Mozambique, Angola, the Democratic Republic of Congo, Rwanda, and Fiji.

Overall, the results point to a dual network structure: a core group of entrenched intermediaries and a secondary set of countries with growing brokerage roles. While intermediary functions are concentrated among a few dominant nodes, new intermediary pathways have emerged over time, often outside traditional producer-consumer relationships. Figure 5 shows the betweenness on a map. For full lists of the countries with highest mean betweenness and strongest positive betweenness trends, please refer to Appendix B.

Trade Concentration

The Herfindahl-Hirschman Index (HHI) plotted over time – both for *soy weight* in tonnes and for *soy value* in dollar terms – indicates increasing concentration of soy trade over the study period, with trade value becoming more unevenly distributed across trade linkages. When considered alongside betweenness centrality, this suggests that trade is increasingly routed through a limited number of dominant trading pairs and pathways. While there is no clear “healthy” bound/guideline for the HHI, the upward trend reflects underlying systemic pressures that culminate in this kind of dominance.

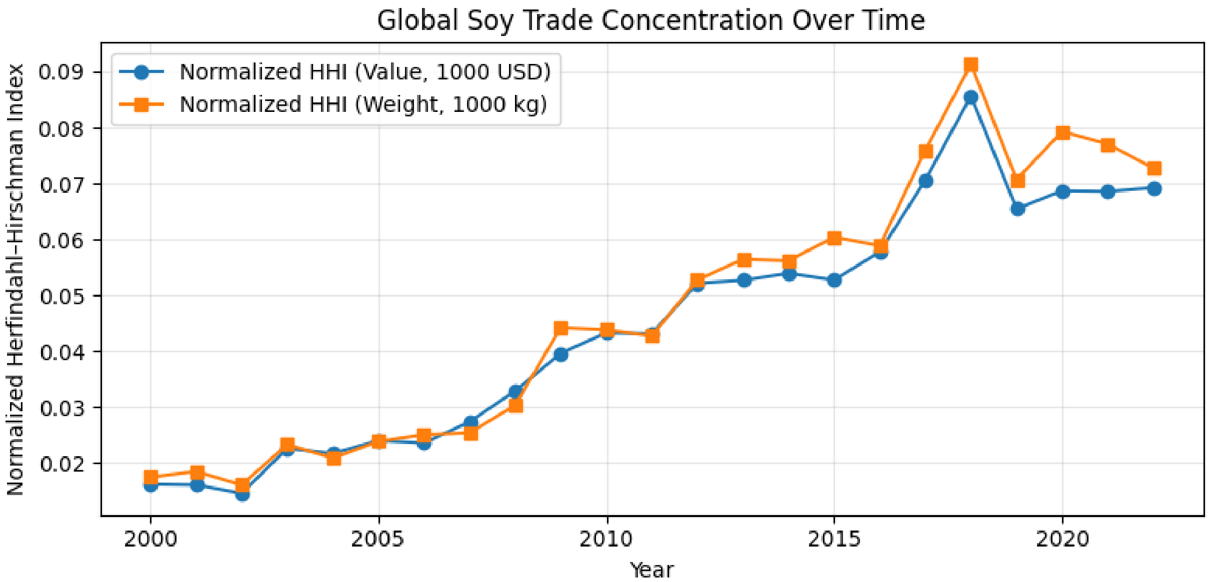

Figure 6. Plot of Herfindahl-Hirschmann Index of soy trade concentration over 2000-2022.

Taken together these findings indicate a concentration of the global soy trade network, characterized by both concentrated trade flows and growing reliance on key intermediary countries. Certain countries can be unduly affected by the failure of any of these trade connections, raising food security risks.

4.3. Climate-induced Risks in Soy-producing Regions of Brazil

Literature on soy production in Brazil highlights that monoculture expansion co-evolves with interacting climatic stressors, land-atmosphere feedbacks, and socio-ecological vulnerabilities. Across major soy-producing regions, climate change manifests primarily through rising temperatures, altered precipitation patterns, and deforestation-driven climatic disruptions (Yadav et al., 2023; Lawrence & Vandecar, 2015). Production practices such as intensive pesticide use further exacerbate environmental pressures by degrading soil and air quality and altering crop nutritional properties (Jia et al., 2020).

Rising average temperatures and an increasing frequency of heat extremes contribute to heat stress during sensitive growth stages of soybeans, reducing yields and contributing to long-term yield variability (Yadav et al., 2023). In parallel, rainfall regimes have become more variable, with shifts in wet season timing, more frequent droughts, and intense precipitation events, particularly in areas such as the Cerrado (Yadav et al., 2023; Lawrence & Vandecar, 2015; Piotrowski, 2018).

Soy monoculture expansion has been closely associated with deforestation and land conversion in the Cerrado and at the agricultural frontier of the Amazon (Rajão et al., 2020). The literature identifies reductions in evapotranspiration and increases in surface runoff as key biophysical pathways through which land-use change alters regional climate conditions. Native vegetation supports atmospheric moisture recycling through deep root systems and sustained transpiration, a function not replicated by soybean cultivation (Lawrence & Vandecar, 2015). As a result, land conversion contributes to declining rainfall, longer dry seasons, altered river flow regimes, increased flood risk during wet periods, and water scarcity during dry periods (Piotrowski, 2018; Lawrence & Vandecar, 2015).

Taken together, heat stress, water stress, deforestation-driven feedbacks, and intensive production practices interact to increase yield variability and undermine production stability. Locally, this disproportionately affects rural communities dependent on soy production, exposing them to income volatility, land concentration, and displacement (Yadav et al., 2023; Jia et al., 2020; Mendes et al., 2025). At the global scale, climate sensitivity in Brazilian soy production translates into systemic food security risks through highly concentrated and interconnected supply chains, amplifying the transmission of climate shocks across borders (Lawrence & Vandecar, 2015; Rajão et al., 2020).

The climate-related risks identified in this analysis are synthetised in Table C1 of Appendix C. The table provides an overview of the main risk categories, their key drivers, underlying biophysical mechanisms, impacts on soy production, and broader systemic implications, complementing the qualitative discussion presented in this section. Furthermore, we produced a state-level spatial indicator of the Netherlands' soy sourcing intensity across Brazil (Figure C1). Import volumes from the soy trade panel were aggregated by Brazilian state and linked to official state codes (UF). We then normalized state-level import volumes by territorial area (km^2) to derive an import density metric (imports per km^2), enabling comparison across states of different sizes. Because densities were highly skewed, values were log-transformed ($\log_{10}$) prior to visualization. The resulting indicator was mapped as a choropleth using Brazilian state boundaries (GeoJSON), with missing observations rendered in grey to distinguish data gaps from low-intensity sourcing. This spatial layer provides a compact representation of where Dutch-linked soy sourcing is most concentrated, and can be interpreted alongside qualitative evidence on climate hazards and yield sensitivity in major producing regions.

4.4. System Integration through the Causal Loop Diagram

The causal loop diagram (CLD) integrates the demand-side modelling, trade network analysis and climate risk assessment into a systemic representation of the global soy-based feed system (Figure 7). Building directly on the quantified land-use results (Figures 2-4) and the concentration metrics from the network analysis (Figure 5; HHI in Figure 6), the diagram makes explicit how Dutch meat demand connects to monoculture expansion in Brazil and, ultimately, to food security risk.

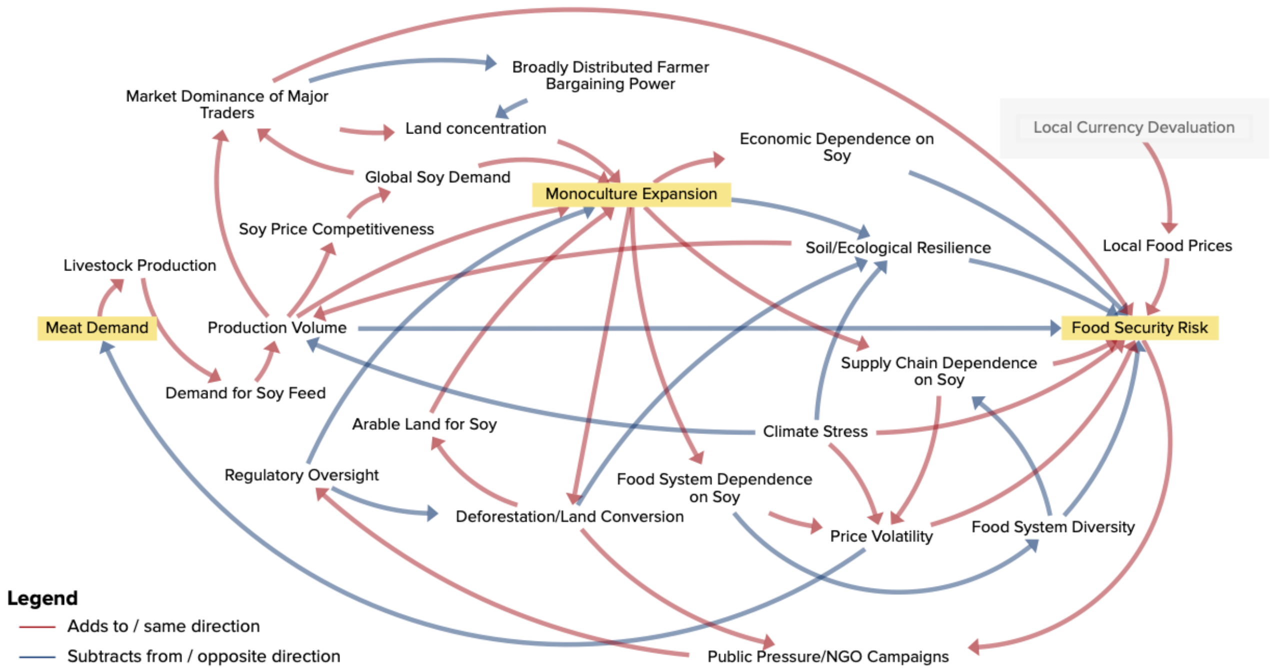

Figure 7: Causal-Loop-Diagram (CLD) mapping the global food-feed-system. Arrows indicate hypothesised causal links[2]; blue links denote positive reinforcement (+), while pink illustrates a negative relationship (-).Key variables are highlighted in yellow; depicted externality is portrayed with a grey shadow. For a version of this CLD accessible for people with visual impairments, see Appendix D1.

Monoculture expansion occupies the mediating position through which consumption patterns translate into ecological and systemic vulnerability. As shown in Section 4.1, higher meat demand increases livestock production and demand for soy feed. In the CLD this relationship forms a reinforcing demand-production loop: rising meat demand increases global soy demand and production volume, improves soy price competitiveness, and expands arable land for soy. This, in turn, accelerates deforestation and land conversion, directly strengthening monoculture expansion. The quantitative land-use reductions observed under the 50/50 and 40/60 dietary scenarios therefore correspond, in system terms, to a weakening of this reinforcing loop.

A second reinforcing loop operates through economic dependence. As production volumes increase, regions specialising in soy exports become increasingly reliant on the commodity for foreign exchange earnings. This economic dependence constrains diversification, both at farm and regional levels, reinforcing land concentration and further monoculture expansion. Trade concentration adds a further reinforcing dimension. Our network analysis shows that a limited number of intermediary countries and trade routes dominate the global soy system. As market dominance of major traders increases, farmer bargaining power declines. Reduced autonomy at the producer level limits

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[2] As this is the result and integration of the previous findings and due to amount of 123 present feedback loops in the CLD, we decided against labelling them within the figure and instead explained the most important loops in the main text.

incentives and capacities for diversification, thereby reinforcing large-scale, export-oriented monoculture production. Price volatility, amplified by concentrated trade flows, feeds back into production pressures, as producers attempt to stabilise income through scale rather than diversification (see Clapp, 2015). The network structure therefore reinforces the demand-driven loop identified above, linking trade concentration directly to land-use outcomes.

Ecological dynamics introduce another reinforcing mechanism. Deforestation and land conversion reduce soil and ecological resilience, increasing vulnerability to climate stress and weather variability. Rather than acting as a natural brake, declining resilience generates pressure to maintain output levels, encouraging further expansion into new land. As shown in Section 4.3, rainfall variability, heat stress and disrupted evapotranspiration cycles heighten yield instability. Food security risk emerges as the cumulative outcome of these interacting loops. It is shaped not only by exposure to climate stress but also by structural dependence on soy within the broader food system. Increased food system dependence on soy reduces food system diversity, which in turn heightens vulnerability to shocks.

Balancing feedbacks are present but comparatively weak. Rising food security risk and deforestation can stimulate public pressure and NGO campaigns, strengthening regulatory oversight and potentially constraining land conversion as well as monoculture expansion. Yet this balancing governance loop operates against multiple reinforcing economic, ecological and trade-based mechanisms. As long as meat demand remains high and trade concentration persists, regulatory interventions face structural counter-pressures embedded in economic dependence and supply chain configuration. The system appears robust under stable conditions because reinforcing loops sustain production and trade flows. However, the same tight coupling between meat demand, monoculture expansion and concentrated trade pathways renders it brittle under climatic or geopolitical disruption. The reductions in soy land use identified in Section 4.1 therefore represent not merely efficiency gains but potential leverage points capable of weakening the dominant reinforcing loops that currently drive systemic vulnerability.

Discussion and Limitations

The findings demonstrate how dietary demand, trade intermediation and ecological pressures interact to produce both efficiency and vulnerability within the global soy system. Dutch consumption of meat and dairy drives demand for soy-based livestock feed, translating domestic dietary choices into land-use pressures abroad, particularly in Brazil. Because soy is a human-edible crop largely diverted into feed channels this system exemplifies food–feed competition with substantial conversion losses. Even modest reductions in red meat consumption or shifts toward plant-based alternatives could therefore lead to significant reductions in soy-driven land use.

These demand-side effects gain their full significance within a tightly coupled systemic context. As a key intermediary in the global soy network, the Netherlands channels consumption through a limited number of highly connected trade routes. This concentration reinforces large-scale, export-oriented production systems in Brazil and incentivises standardisation and monoculture expansion. Monoculture expansion thus appears not as an anomaly, but as a rational response to a global system shaped by rising demand, cost competition and limited producer bargaining power. While deforestation and land conversion can sustain short-term productivity, they erode ecological resilience through biodiversity loss, soil degradation and altered hydrology, increasing sensitivity to climatic variability and long-term production risk.

Trade concentration further amplifies these vulnerabilities by increasing exposure to price volatility and supply shocks. The resulting system combines high efficiency with structural fragility: low redundancy, strong connectivity and reinforcing feedbacks characteristic of cascading failure risk. Ecological degradation is embedded within this logic. Yield losses linked to soil depletion or climate stress incentivise further expansion to maintain output, rather than self-correction through reduced production, challenging assumptions that degradation will naturally stabilise supply. Political-economic dynamics further shape these outcomes. Control over logistics, trade routes and capital constrains adaptive capacity and distributes risk unevenly, meaning that land-use decisions in Brazil are co-produced by distant consumption patterns and trade infrastructures. As a result, climatic, economic or geopolitical shocks can propagate rapidly through the network, affecting actors far from their origin.

The structure of the soy network mirrors vulnerabilities observed in other concentrated food commodities. Similar dynamics were evident during the 2022 disruption of wheat and sunflower oil exports following Russia's invasion of Ukraine, which exposed the fragility of systems reliant on a small number of critical exporters (Puma et al., 2020). While concentrated trade can enhance efficiency and affordability, it heightens exposure to correlated shocks (D'Odorico et al., 2014). Climate change further amplifies these risks, as large-area crop failures become more likely under increasing climate variability (Ray et al., 2015). At the same time, declining genetic diversity in globally traded crops, including soy, reduces the capacity to buffer against pests, diseases and climatic extremes (Khoury et al., 2014). This configuration delivers reliable provision under stable conditions but remains structurally fragile, characterised by path dependence, limited redundancy and reinforcing interdependencies between consumption, trade and ecology.

By linking dietary patterns, trade intermediation, and ecological change, this study contributes to the broader field by demonstrating that food security risk is co-produced across consumers, intermediaries, and producers. Previous research has examined soy-driven deforestation, food-feed competition, or trade concentration separately. Integrating them within a systems framework clarifies the feedbacks through which urban consumption patterns intersect with structural fragility in Brazilian agricultural landscapes. These findings extend work on global food system resilience and reinforce the view that sustainability challenges in agriculture cannot be resolved through production-side interventions alone but are embedded in the demand-trade-ecology nexus.

For the Amsterdam Institute for Advanced Metropolitan Solutions (AMS), these findings can be translated into policy leverage points helping to reduce Amsterdam's contribution to soy-driven monocultures[3]. Demand-side strategies are particularly promising, with low-effort, high-impact potential like the suggested red meat cap. Cities could reshape food environments in public institutions and retail by making plant-based options the default while keeping animal-based options opt-in. Pilot programmes can experiment with menu design, hybrid products, pricing, and in-store nudges to normalise plant-based diets. Transparency initiatives, such as publishing aggregated data on urban consumption impacts and feed intensity, can make hidden pressures visible to policymakers and the public. Together, these approaches leverage routine consumption patterns, social norms, and governance transparency to reduce reliance on feed-intensive products.

Several limitations should be noted. The dietary and land-use analyses focus on selected protein categories (meat, fish, dairy, eggs and plant-based substitutes) and exclude legumes, cereals and alternative plant-based foods. Feed-related land-use estimates capture crop inputs only and omit pasture, housing and infrastructure. Scenario assumptions rely on proportional scaling between animal and plant-based products and do not account for behavioural or regional variation. Soy is treated as a homogeneous crop, despite varietal differences, including genetically modified types, that may influence resilience. The causal loop diagram is a qualitative heuristic that captures the direction of feedbacks rather than their magnitude, timing or thresholds, and some links are literature-based rather than empirically verified. Boundary choices prioritise demand, trade concentration and ecological degradation, abstracting from geopolitical shocks, financial dynamics and local heterogeneity among producers. The analysis relies on global-scale data and therefore offers limited insight into regional Brazilian socio-economic conditions or distributional effects. Moreover, the quantitative impacts of ecological degradation and climate stress on yields and long-term resilience remain uncertain. Given the complexity of the global soy system, the study cannot establish direct causal chains between Dutch consumption and specific land-use or food security outcomes in Brazil. The results should therefore be interpreted as illustrating structural interdependencies and plausible causal mechanisms rather than predictive effects.

Conclusion

This study examined how Dutch imports of soy contribute to monoculture expansion in Brazil and how this expansion affects risks to food security. By integrating dietary demand modelling, trade network analysis, and a systems perspective, the research identified the mechanisms linking consumption, trade, and ecological change into a tightly coupled global system. The results show that food security risks emerge not from scarcity but from structural imbalances: concentrated demand, unequal power relations, and limited ecological resilience.

[3] The policy recommendations outlined here are not direct results of this report. They are included to provide context for the external partner's interest and to illustrate how the study's findings could inform potential interventions.

First, Dutch dietary patterns – particularly high consumption of red meat and dairy – generate substantial soy-driven land demand abroad. Even moderate dietary shifts toward plant-based proteins could substantially reduce feed-related land use. Second, network analysis revealed strong concentration within the global soy trade, centred on a limited number of producers and intermediaries. This concentration enhances short-term efficiency but heightens exposure to correlated shocks. Third, ecological degradation in major production regions further weakens system resilience, making yields increasingly sensitive to climate variability. The causal loop diagram integrates these findings, illustrating how global demand, economic dependence, and environmental decline reinforce each other through positive feedbacks.

For the Amsterdam Institute for Advanced Metropolitan Solutions (AMS), these findings highlight that interventions focusing only on production or monitoring deforestation are insufficient to address systemic vulnerability. Demand-side strategies – reducing reliance on feed-intensive products, diversifying protein sources, and fostering transparent food environments – offer higher leverage for mitigating risks while aligning urban consumption with global sustainability targets. As Amsterdam positions itself as a frontrunner in sustainable food governance within the Netherlands and Europe, its policies can serve as a testbed for approaches that connect consumption choices to global supply chain resilience.

Future research should deepen the systemic perspective introduced here by combining structural and empirical approaches. Key priorities include modelling how trade concentration and ecological stress translate into supply volatility and nutritional risk, as well as incorporating local perspectives from producer regions to better capture socio-economic and distributive dynamics. This could be achieved through quantitative modelling, scenario analysis under climate or trade disruptions, and locally grounded studies of producer decision-making, rural livelihoods and food affordability. Addressing the resilience deficit in global feed systems ultimately requires coordinated research and policy action across scales, linking consumer behaviour, trade governance and land-use transitions.

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Appendices

Appendix A: Dietary Demand and Feed-Land Modelling

Dietary Scenario Construction

To explore plausible transitions in Dutch protein consumption and their implications for soy-driven land use, we developed four dietary scenarios. These scenarios illustrate the impact of varying shares of animal- and plant-based protein sources while keeping total dietary protein intake approximately constant at 22 kg per person per year (except where plant protein is intentionally increased). The 22 kg baseline corresponds to the recommended protein intake of 0.8 g per kilogram of body weight per day, assuming a baseline adult weight of 75 kg. All scenarios maintain recommended fish intake of 15 g/day. The code framework allows the PROTEIN_TARGET to be modified, with the scenario logic automatically adjusting animal and plant protein contributions.

1. Current Diet

Represents recent Dutch averages for per-capita consumption of meat, dairy, eggs, fish, and plant-based substitutes. Protein intake is calculated directly from these amounts. Current protein intake: 28,43 kg/year.

- **Protein contributions (kg/person/year):**
  - Beef: 5.07 | Chicken: 5.06 | Pork: 8.07 | Other meat: 0.48
  - Dairy: 7.55 | Eggs: 0.72 | Fish: 1.26
  - Plant-based meat: 0.11 | Tofu: 0.01 | Soy milk: 0.08

2. Red Meat Cap

Beef and pork are capped at 10 kg per person per year combined, with reductions applied proportionally to their baseline consumption. The Dutch dietary guidelines (The Health Council of the Netherlands, 2025) recommend a maximum consumption of 10kg of red meat. Other animal products (chicken, dairy, eggs, fish) and plant-based substitutes remain at current levels unless additional protein is needed to meet the target. Any protein gap after reducing red meat is filled by increasing chicken consumption. No substitution with plant-based products occurs in this scenario.

- **Protein contributions (kg/person/year):**
  - Beef: 1.01 | Chicken: 9.37 | Pork: 1.61 | Other meat: 0.48
  - Dairy: 7.55 | Eggs: 0.72 | Fish: 1.26

    - Plant-based meat: 0.11 | Tofu: 0.01 | Soy milk: 0.08

3. 50/50 Diet (50% animal / 50% plant protein)

Animal products are moderately scaled down: beef, pork, and other meat reduced by 40%, dairy by 50%, eggs adjusted to fill gaps. Chicken fills the remaining animal protein to reach 50% of total protein. Plant-based substitutes are increased to cover the remaining 50% of protein using fixed shares: 25% tofu, 60% plant-based meat, 15% soy milk.

- **Protein contributions (kg/person/year):**
    - Beef: 0.61 | Chicken: 3.38 | Pork: 0.97 | Other meat: 0.29
    - Dairy: 3.77 | Eggs: 0.72 | Fish: 1.26
    - Plant-based meat: 6.60 | Tofu: 2.75 | Soy milk: 1.65

4. 40/60 Diet (40% animal / 60% plant protein)

All animal products are scaled down proportionally to achieve 40% of total protein from animal sources. Remaining protein requirements are met by increasing plant-based substitutes using the same fixed shares as above. Chicken contributes proportionally to reduced animal protein.

- **Protein contributions (kg/person/year):**
    - Beef: 0.47 | Chicken: 2.62 | Pork: 0.75 | Other meat: 0.22
    - Dairy: 2.92 | Eggs: 0.56 | Fish: 1.26
    - Plant-based meat: 7.92 | Tofu: 3.30 | Soy milk: 1.98

Notes on Scenario Implementation

- For most scenarios, total dietary protein is held at 22 kg per person per year to ensure comparability across scenarios. In a balanced diet, additional protein sources such as legumes, nuts, and cereals would normally contribute to total intake. These sources are not included in the model for simplicity, as they do not affect soy-related land use. Therefore, the 22 kg protein target represents a conservative minimum baseline for dietary protein in this analysis.
- Feed land use: Calculated for all scenarios using EMCRs to account for edible parts only, combined with feed crop shares and crop-specific land footprints. Soy-driven land use is reported separately to highlight pressures from imported soy used in animal feed.
- Substitution logic: Ensures that decreases in animal products are offset by proportional increases in plant-based substitutes to maintain total protein intake. Poultry is treated flexibly,

filling remaining animal protein gaps without an upper limit. For example, in the 50/50 diet, beef, pork, and other meats are reduced to 60% of their current amounts, dairy is halved, eggs are adjusted if necessary, and chicken fills the remaining animal protein. In the 40/60 diet, all animal products are scaled proportionally to reach 40% of total protein from animal sources. Plant-based protein contributions are distributed according to fixed shares, with 25% from tofu, 60% from plant-based meat, and 15% from soy milk.

- Dairy conversion to milk-equivalent volumes: Average dairy consumption is 338 g/person/day, of which milk drinks account for 51%, yoghurt for 20%, and cheese for 9%. While this corresponds to approximately 123 kg of dairy products per person per year (0.338 × 365), cheese production requires around 10 L of milk per kg of cheese. The 9% share of cheese therefore corresponds to approximately 11 kg of cheese per person per year, equivalent to ~110 kg of milk. When combined with liquid dairy products, this results in a total milk-equivalent dairy demand of approximately 222 kg per person per year. Therefore, in the code calculations are made with 222kg, since EMCRs and feed ingredients correspond to dairy cows and therefore milk production.

In Table A1 the amount of kg/person/year consumed is summarised for the baseline and the different scenarios with Figure A1 visualizing the different consumption patterns.

Scenario	**Beef**	**Pork**	**Chicken**	**Dairy**	**Eggs**	**Fish**	**Other meat**	**Plant-based meat**	**Soy milk**	**Tofu**
Current diet	14.90	35.10	22.00	222.00	5.84	5.48	2.50	0.57	2.61	0.09
Red meat cap	2.98	7.02	40.72	222.00	5.84	5.48	2.50	0.57	2.61	0.09
50/50	1.79	4.21	14.71	111.00	5.84	5.48	1.44	33.00	51.56	22.18
40/60	1.38	3.26	11.39	85.93	4.52	5.48	1.11	39.60	61.87	26.61

Table A1: Annual per-capita food consumption (kg/person/year) by product for the baseline diet and alternative dietary scenarios.

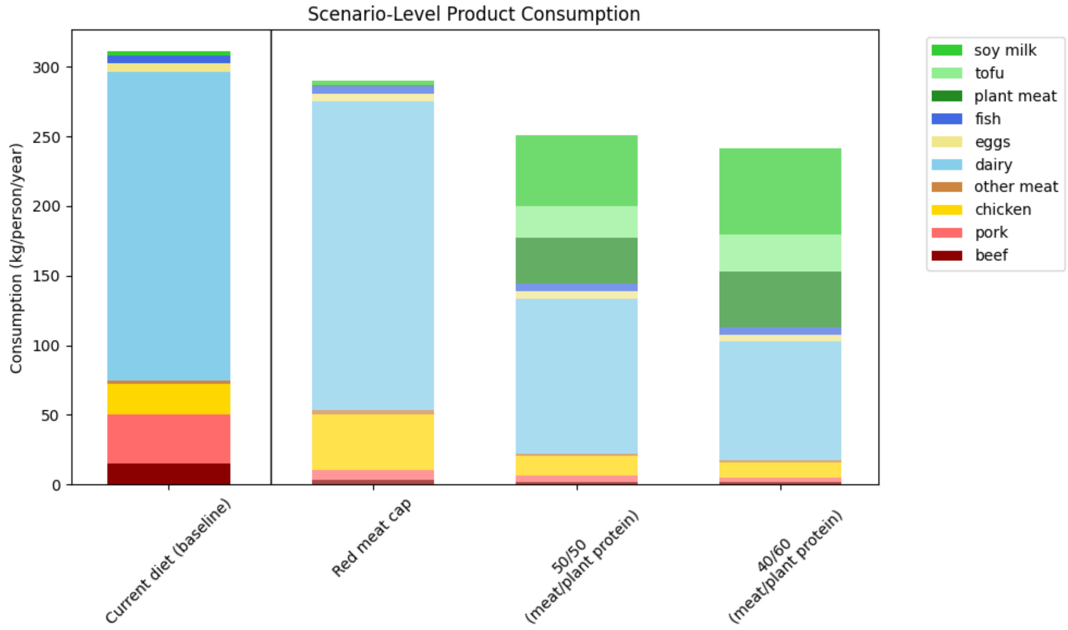

Figure A1: Visualization of per-capita food consumption patterns across the baseline and alternative dietary scenarios.

Since food products differ in their protein content, they contribute unequally to the annual protein target of 22 kg per person. This distribution of protein supply across products and scenarios is shown in Table A2 and visualized in Figure A2.

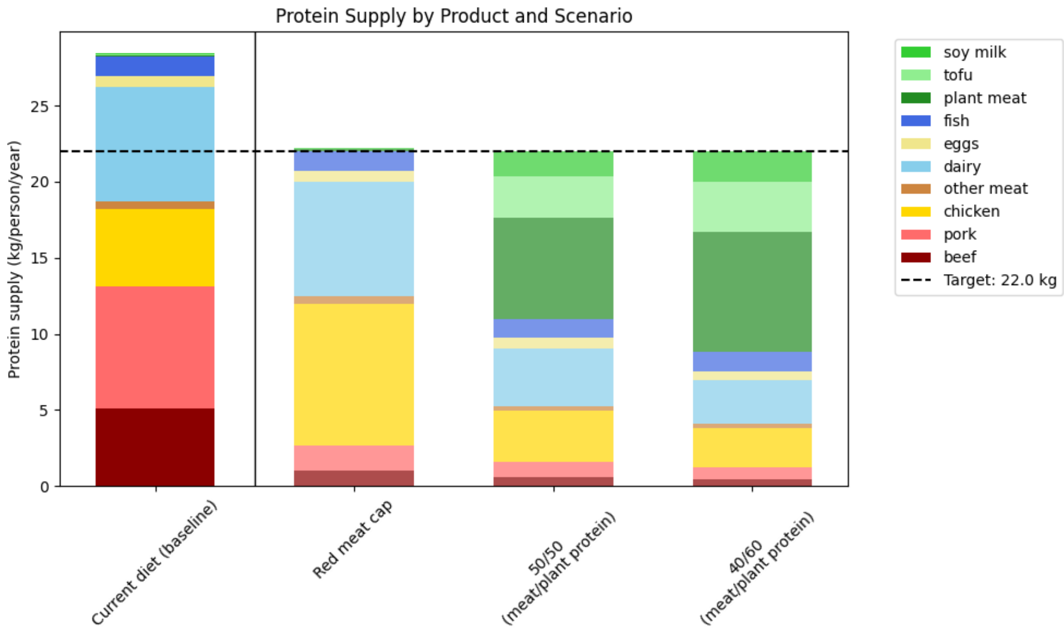

Figure A2: Visualization of per-capita protein contributions from each food product across the baseline and alternative dietary scenarios.

Scenario	Beef	Pork	Chi-cken	Dairy	Eggs	Fish	Other meat	Plant meat	Soy milk	Tofu
Current diet	5.07	8.07	5.06	7.55	0.72	1.26	0.50	0.11	0.08	0.01
Red meat cap	1.01	1.61	9.35	7.55	0.72	1.26	0.50	0.11	0.08	0.01
50/50	0.61	0.97	3.37	3.77	0.72	1.26	0.30	6.60	1.65	2.75
40/60	0.47	0.75	2.61	2.92	0.56	1.26	0.23	7.92	1.98	3.30

Table A2: Annual per-capita protein supply (kg/person/year) by product for the baseline diet and alternative dietary scenarios.

The contribution of different products to total feed land use varies by both soy and non-soy inputs, reflecting differences in production efficiency and protein content. This breakdown of feed land per product and dietary scenario is summarized in Table A3 and visualized in Figure A3.

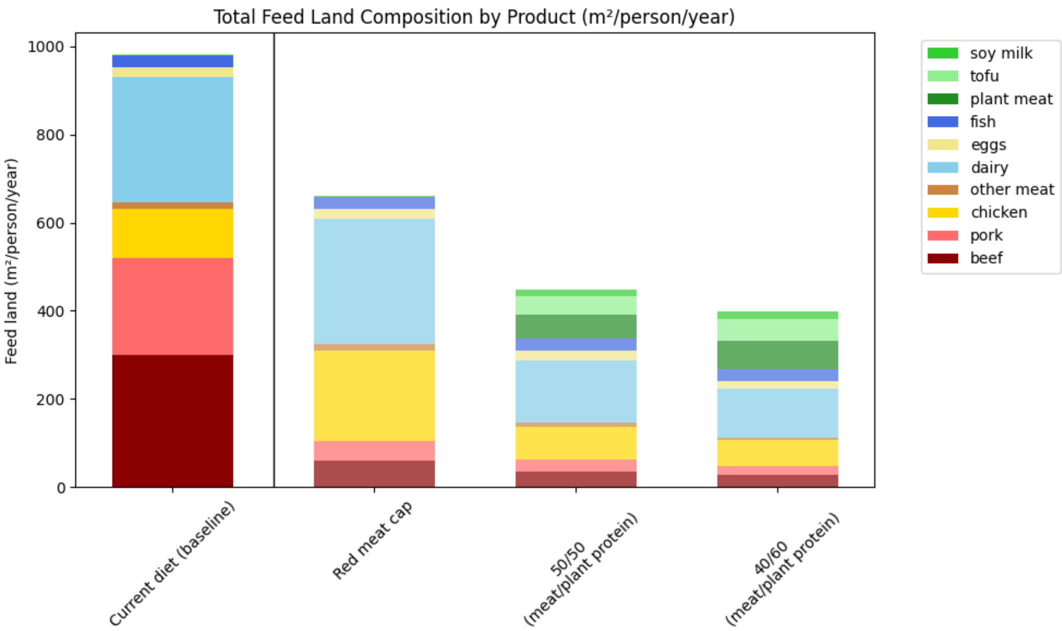

Figure A3: Total feed land composition per person and year (m²/person/year), disaggregated by product and dietary scenario.

Product	Soy share in feed	Soy land (m²/kg)	Non-soy land (m²/kg)	Total feed land (m²/kg)	Protein con-tent (g/kg)
Pork	0.12	1.581	4.680	6.261	230
Chicken	0.20	1.974	3.086	5.060	230

Beef	0.12	6.692	13.490	20.182	340
Other meat	0.12	2.002	4.035	6.037	200
Fish	0.25	2.432	2.566	4.998	230
Plant-based meat	0.33	0.917	0.740	1.658	200
Dairy (milk equivalent)	0.14	0.389	0.890	1.279	34
Eggs	0.18	1.316	2.406	3.723	123
Tofu	1.00	1.863	0.000	1.863	124
Soy milk	1.00	0.278	0.000	0.278	32

Table A3: Product-level soy share, feed land requirements, and protein content used in the model.

Scenario	Beef	Pork	Chicken	Dairy	Eggs	Fish	Other meat	Plant meat	Soy milk	Tofu
Current diet	99.71	55.50	43.42	86.40	7.69	13.32	5.00	0.52	0.73	0.17
Red meat cap	19.94	11.10	80.21	86.40	7.69	13.32	5.00	0.52	0.73	0.17
50/50	11.97	6.66	28.94	43.20	7.69	13.32	3.00	30.27	14.33	41.31
40/60	9.26	5.16	22.40	33.44	5.95	13.32	2.32	36.33	17.20	49.57

Table A4: Per-capita soy feed land (m²/person/year) allocated to each product across dietary scenarios.

The next table summarises how much soy and total feed land is used, and how much protein is entailed, for the different dietary scenarios.

Dietary scenario	Soy feed land (m²/person/year)	Total feed land (m²/person/year)	Protein intake (kg/person/year)
Current	312.26	981.24	28.41
Red meat cap	225.05	659.61	22.21
50/50	200.67	447.06	22.00
40/60	194.94	399.27	22.00

Table A5. Per-capita soy and total feed land, and protein outcomes across dietary scenarios.

To calculate scenario-specific protein supply, feed demand, and land use, product-level parameters and crop yield assumptions are required. Table A6 summarizes product-specific characteristics, including edible meat conversion ratios, feed ingredient shares, and protein content. Table A7 lists crop yields used to convert feed demand into land requirements, reflecting major production regions and assumptions for imported commodities.

Table A6. Product-level parameters and respective sources used in the dietary model

Product	**EMCR**	**Source**	**Feed ingredients (% soy / maize / wheat–barley / rapeseed)**	**Protein (g/kg)**	**Source (NEVO Database)**
Pork	4.74	Lanzoni et al. 2025; CVB 2023	12 / 45 / 25 / 8	230	NEVO 1418
Chicken	3.55	Lanzoni et al. 2025; Aviagen 2022	20 / 55 / 15 / 5	230	NEVO 1634
Beef	20.06	Lanzoni et al. 2025; FAO 2010	12 / 25 / 20 / 6	340	NEVO 1547
Other meat	6.00	Beef used as proxy	12 / 25 / 20 / 6	200	NEVO 1900
Fish	3.50	Lanzoni et al. 2025	25 / 20 / 30 / 5	230	NEVO 5527
Dairy	1.0	Ineichen et al., 2023	14 / 35 / 25 / 8	34	NEVO 270
Eggs	2.63	Li et al., 2024	18 / 50 / 20 / 6	123	NEVO 83
Plant meat	1.00	GFI Europe 2024	33 / 15 / 40 / 2	200	NEVO 2047 / 5554
Tofu	0.67	University of Bombay, nd	100 / 0 / 0 / 0	124	NEVO 5519
Soy milk	0.1	Soya.be/nl. 2025	100 / 0 / 0 / 0	32	NEVO 1381

Table A6: Product-level parameters used in the dietary model, including edible meat conversion ratios (EMCR), feed ingredient shares (% by mass), and protein content (g/kg).

Crop	Yield (t/ha)	Land use (m/kg	Region / assumption	Source
Soybeans	3.6	2.78	Brazil	USDA, 2024
Maize	10.27	0.97	The Netherlands	Our World in Data, 2023
Wheat	8.47	1.18	The Netherlands	Our World in Data, 2023
Barley	6.52	1.53	The Netherlands	Our World in Data, 2023
Rapeseed	3.78	2.65	The Netherlands	Our World in Data, 2023

Note: Since a lot of crops are imported from European Countries or from the Netherlands, crop yield data is used from the Netherland, soy is imported mainly from Brazil.

Table A7: Crop yield assumptions (t/ha) and resulting land-use factors (m^2/kg) applied in feed-to-land calculations, by crop and production region

Appendix B: Trade Network and Trade Concentration

ISO3	Country	Slope	Mean Betweenness	Max Betweenness
IND	India	0.013392	0.203011	0.452228
MOZ	Mozambique	0.001557	0.017096	0.054597
ARE	The UAE	0.001199	0.022246	0.050125
COD	Congo DR	0.001165	0.006401	0.037014
TUR	Turkey	0.001125	0.022596	0.076592
RWA	Rwanda	0.000981	0.00669	0.032084
FJI	Fiji	0.00098	0.016057	0.034647
SAU	Saudi Arabia	0.000927	0.030922	0.081414
EGY	Egypt	0.00082	0.009941	0.032977
AGO	Angola	0.00081	0.004412	0.023386

Table B1. Top 10 Countries with highest betweenness centrality trends. Slopes derived from regression over the years 2002-2022.

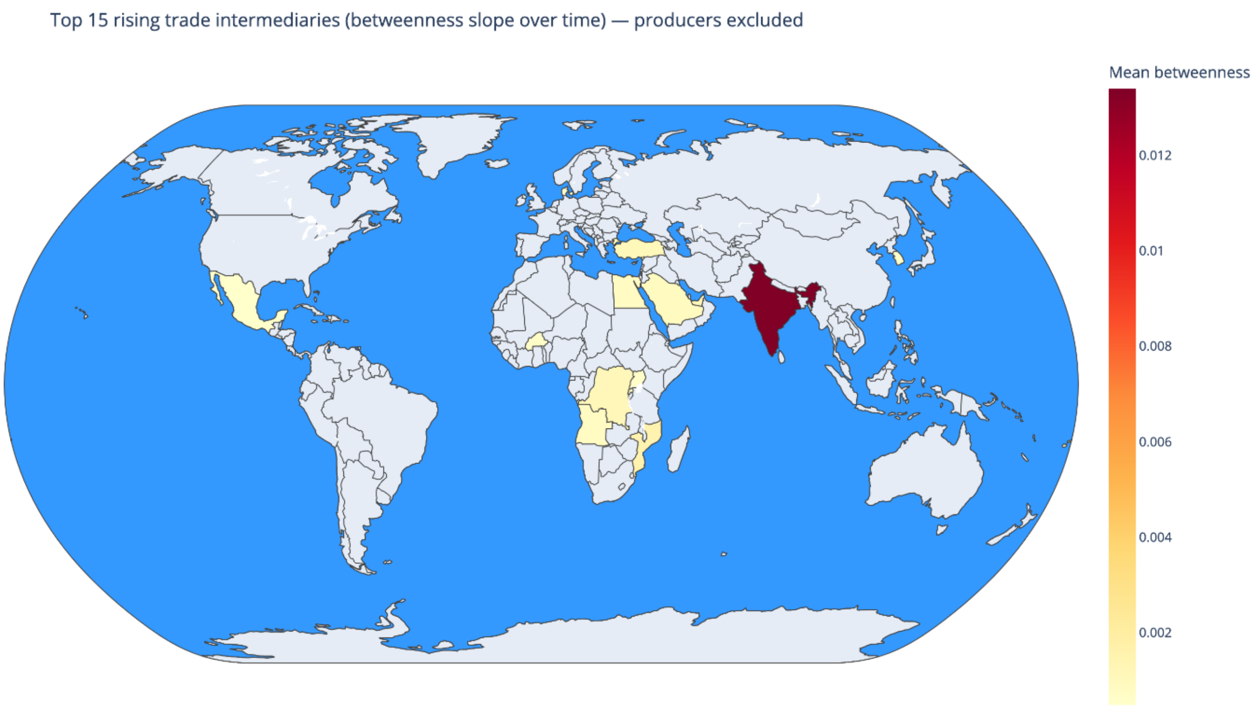

Figure B1. Map of Top 10 Countries with highest betweenness centrality trends. Data from Table B1.

ISO3	Country	Mean Betweenness	RUS	Russia	0.075094
NLD	The Netherlands	0.243861	ZAF	South Africa	0.071048
IND	India	0.203011	ITA	Italy	0.069855
CHN	China	0.195969	ESP	Spain	0.05451
DEU	Germany	0.175486	DNK	Denmark	0.036383
MYS	Malaysia	0.086492	GBR	The UK	0.034989
BEL	Belgium	0.077841	ISR	Israel	0.03392
FRA	France	0.076165	VNM	Vietnam	0.03315

Table B2. Top 10 Countries with highest betweenness centrality scores.

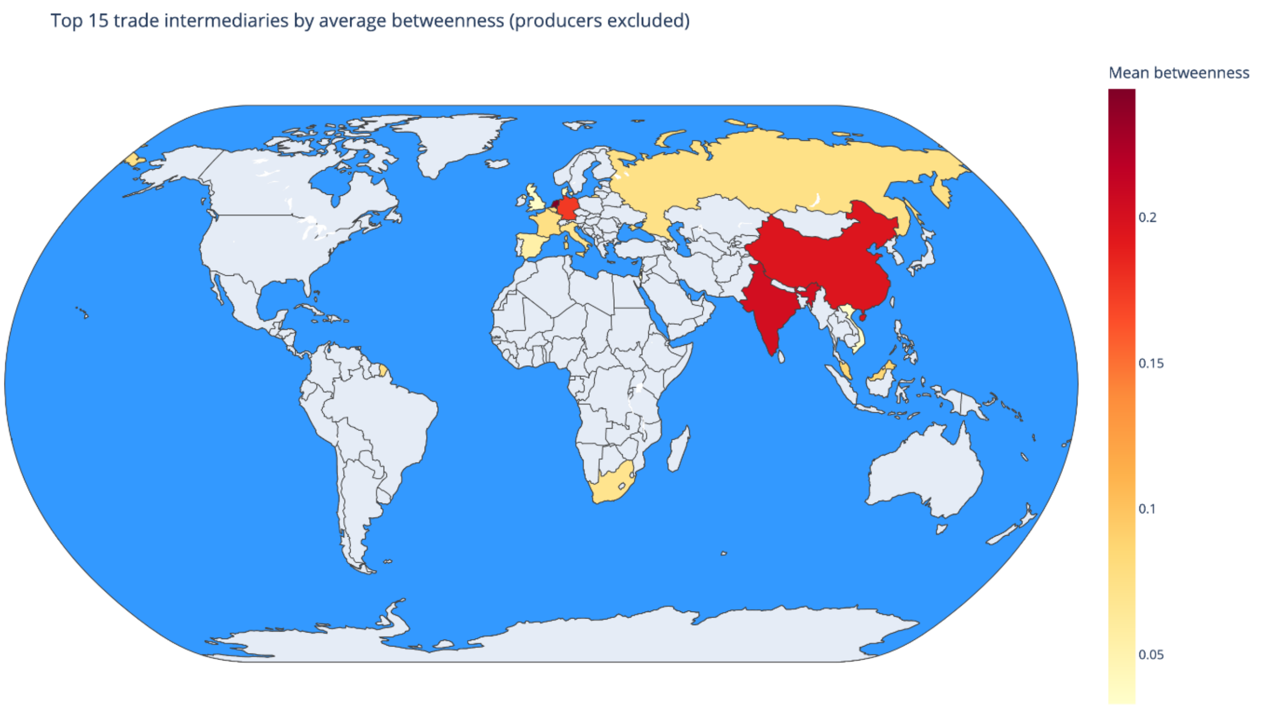

Figure B2. Map of Top 10 Countries with highest betweenness centrality scores.

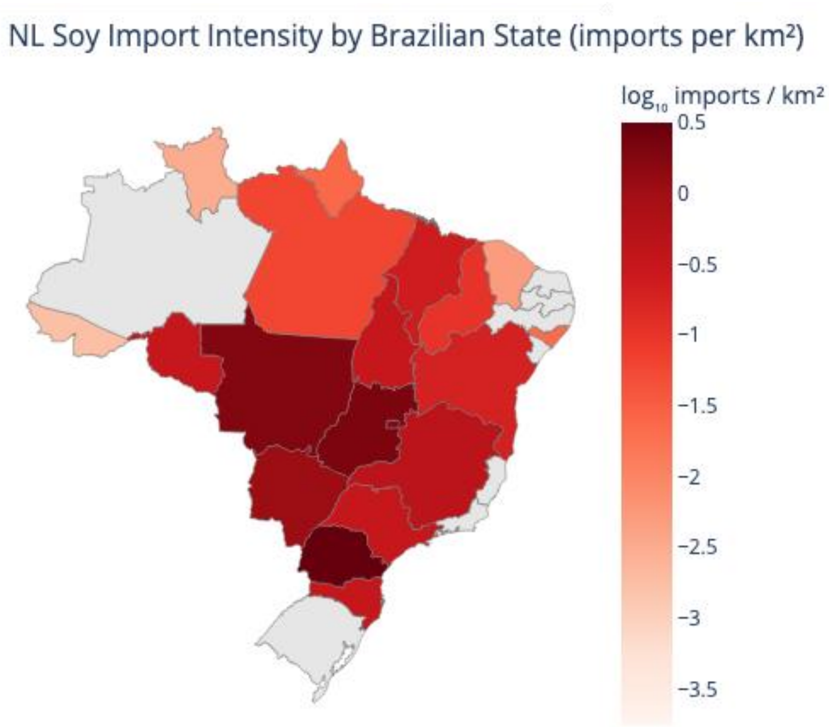

Figure B3. Soy Imports per Brazil state, normalized by the state's area. This plot ignores the proportion of arable land.

Appendix C: Climate Assessment & Modelled Impact of Climate Change on Soy Yields in Brazil

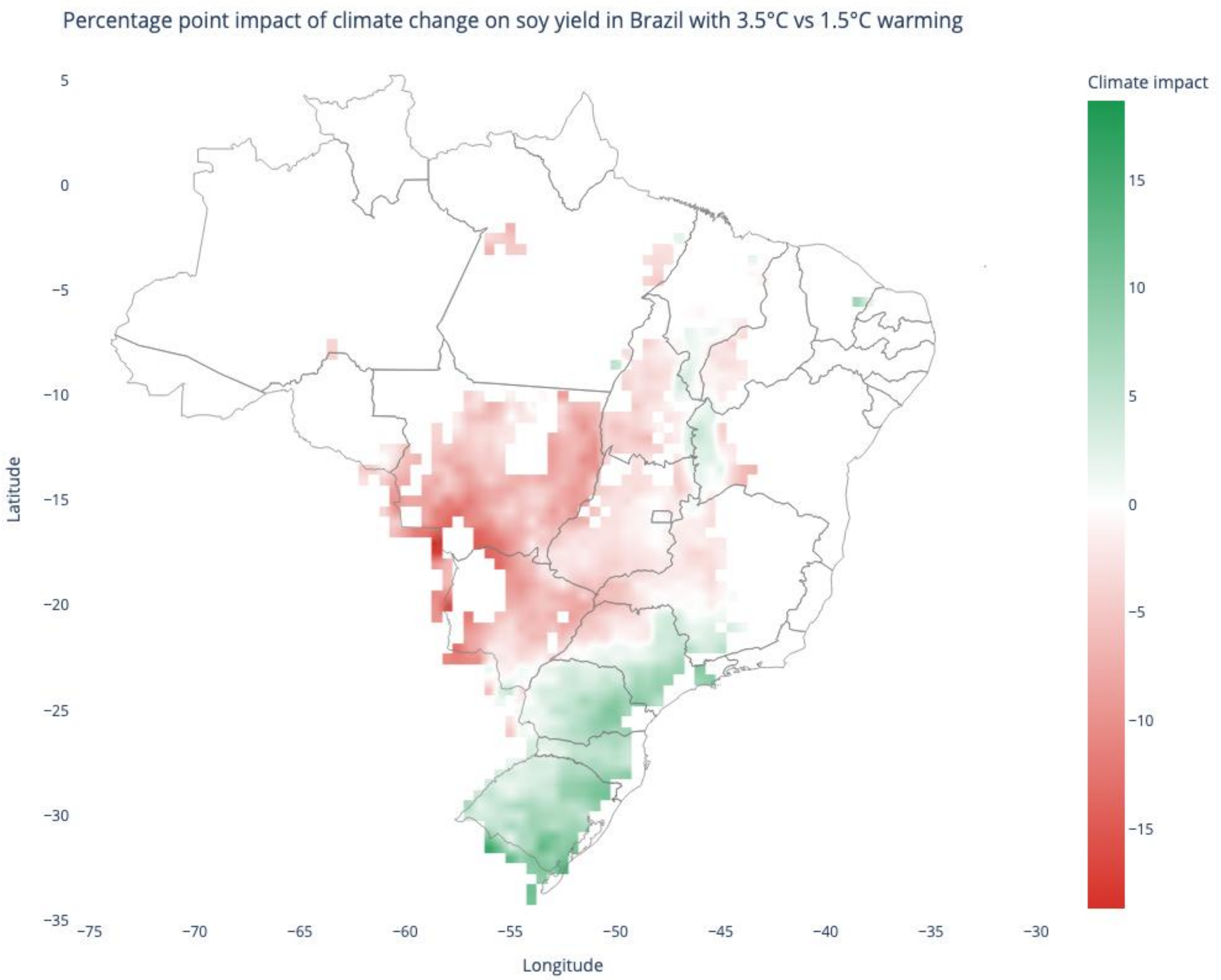

Figure C1: Modelled Impact of Climate Change on Soy Yields in Brazil with 3.5ºC warming, compared to 1.5ºC baseline.

Risk	Drivers	Biophysical mechanisms	Impacts on production	Systemic implications
Heat stress	Rising mean temperatures; increased frequency of heat extremes	Exceeding optimal temperature thresholds during crop growth	Declining yields; increased yield variability	Reduced production stability; heightened sensitivity to short-term climate shocks
Water stress	Rainfall variability; delayed or shortened wet season; drought frequency	Irregular precipitation; high evaporation rates; soil moisture deficits	Water scarcity during growth cycle	Higher risk of multi-year production losses
Deforestation	Soy monoculture expansion; land conversion in Cerrado and Amazon	Reduced evapotranspiration; weakened moisture recycling; altered atmospheric circulation	Lower annual rainfall; longer dry seasons; higher temperatures	Reinforcing feedback between land-use change and climate stress; regional climate destabilisation
Hydrological disruption	Land-use change; deforestation	Increased surface run-off; reduced soil infiltration and groundwater recharge	Flood risk in wet season; water scarcity in dry season	Destabilised river systems; reduced water security for agriculture and communities
Soil degradation	Intensive pesticide application; monoculture practices	Loss of soil structure and organic matter; reduced nutrient cycling	Lower soil resilience; increased dependence on external inputs	Long-term climate sensitivity; economic vulnerability to input price shocks
Socio-economic vulnerability	Yield instability; land concentration; input dependence	No mechanism; Interaction of other biophysical processes with market pressures	Income volatility; displacement of smallholders	Local livelihood insecurity; social inequity
Global food security risk	Export concentration; dependence on Brazilian soy	No mechanism; ripple effect of local climate shocks through trade networks	Feed shortages; rising livestock costs	Price volatility

Table C1: Synthesis of the climate sensitivity analysis. All supporting literature is referenced in the main text.

Appendix D: Causal-Loop-Diagram (Visually Impaired Version)

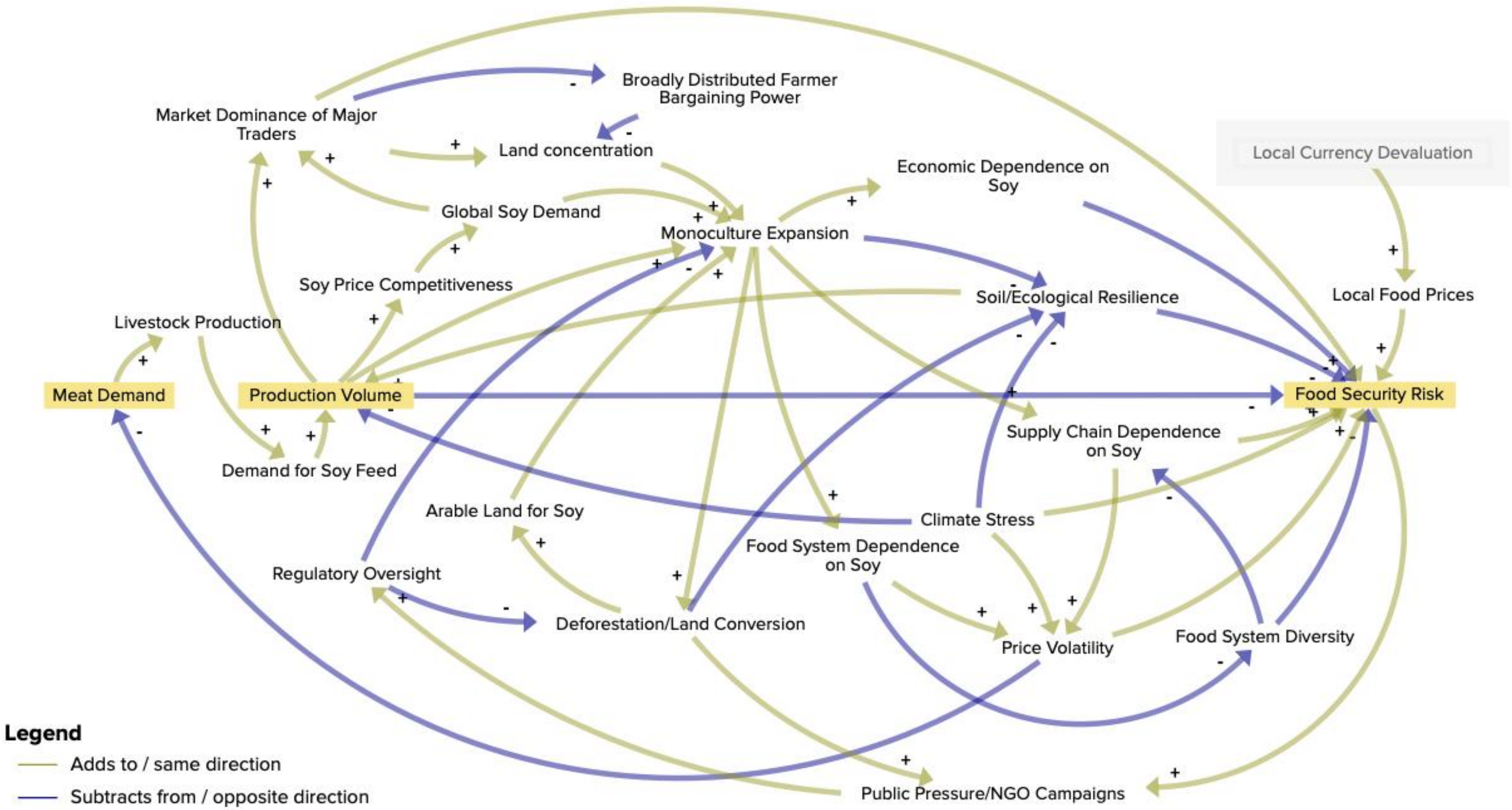

Figure D1: Causal-Loop-Diagram (CLD) mapping the global food-feed-system. Arrows indicate hypothesised causal links; blue links denote positive reinforcement (+), while pink illustrates a negative relationship (-).

Declaration of Independence

We have read and understood the University of Amsterdam's rules regarding fraud and plagiarism. We declare that this written paper is entirely our own work. All sources used have been carefully acknowledged and correctly cited according to academic standards. This paper has not been submitted, in whole or in part, for any other course or assignment. We have used AI tools solely for technical support – specifically for refining language (ChatGPT, DeepL Write, Grammarly) and for assistance with coding according to patterns already known to the authors (GitHub Copilot, ChatGPT). All research ideas, data analysis strategies, writing, coding logic, and final interpretative decisions were our own.

Authors' Contributions

All authors jointly formulated the research question, conceptualised the causal loop diagram, made collective decisions on scope and synthesis, and contributed to proofreading, feedback, and overall project coherence. Adi developed the trade network model and the quantitative portions of the preliminary climate data analysis, including all related coding, methodological design, and analysis, and contributed to the introduction. Eva designed and implemented the dietary demand model, including coding, methodological documentation, results analysis, and drafting the discussion and appendix. Simona led the climate impact component, including the methods and results sections. Franziska developed the conceptual framework, finalised the causal loop diagram and its methods and analysis section, and authored the conclusion.