




Evaluating the Dynamics of Brazil's soybean trade: a comprehensive emergy analysis of resource dependencies

Cláudia Leão^a, Luiz C. Terra dos Santos^{a,*}, Biagio F. Giannetti^{a,b} , Feni Agostinho^{a,b} ,
Cecilia M.V.B. Almeida^{a,b} 

^a Post-graduation Program in Production Engineering, Paulista University, Brazil

^b State Key Joint Laboratory of Environment Simulation and Pollution Control, School of Environment, Beijing Normal University, PR China

ARTICLE INFO

Keywords:

Soybeans
Brazil
Emergy synthesis
Export dynamics
Non-renewable resources
Fertilizers
Pesticides
Commodity Trade

ABSTRACT

This study examines Brazil's soybean trade through the dual lens of economic and environmental considerations, employing emergy synthesis to reveal hidden resource dependencies and costs within production and export processes. It bridges ecological modeling and sustainability science by analyzing Brazil's soybean trade through the interplay of economic and environmental dimensions. By applying emergy-based indices—such as the Emergy Exchange Ratio, Emergy Benefit Ratio, and Opportunity Ratio - the analysis offers a nuanced understanding of trade dynamics between 2015 and 2019, particularly with partners like China and Europe. The trade with China showed an average EER of 0.27, meaning that for every unit of emergy value Brazil exported in raw soybeans, it received substantially more emergy in currency terms. In comparison, trade with European partners, such as Spain and The Netherlands, with $EE > 1$, was notably unfavorable for Brazil. The Opportunity Ratio is another key metric to indicate the potential economic gains from processing raw soybean commodities domestically. The analysis revealed that, on average, domestic processing could potentially lead to a GDP increase of 17 % from the soybean sector. Highlighting the environmental implications of reliance on non-renewable inputs such as fertilizers and pesticides, the study underscores the potential benefits of domestic soybean processing for enhancing GDP, reducing import dependency, and fostering equitable resource use. The research provides insights into sustainability through carefully integrating economic and ecological perspectives, informing strategies for addressing environmental costs while fostering balanced global trade practices.

1. Introduction

Soybeans represent a critical agricultural commodity in global trade due to their multifunctional use, including whole soybeans and derivatives such as protein concentrate, lipid extracts, and carbohydrate fractions, with production increasing by 145% since the 1990s, driven primarily by escalating demand from China (Mendes dos Reis et al., 2020; Xavier and Reis, 2022). Global cultivation is dominated by South American and North American agroecosystems, with Brazil, Argentina, and the United States collectively accounting for 80.5 % of global yields and 86.2 % of exports from 2012 to 2018 (FAO 2024). Brazil, contributing 28.8 % of global soybean yields, ranks second to the United States at 35 %, owing to its extensive arable land, conducive climatic conditions, and elevated photosynthetic efficiencies (Jia et al., 2020; Toloi et al., 2021). Strategic interventions by institutional and non-institutional entities have enhanced Brazil's agro-economic

infrastructure, establishing soybeans as a primary driver of its agricultural gross domestic product and trade surplus (Heron et al., 2018; Nassif et al., 2018). However, the sector exhibits high exogenous input dependence; approximately 60 % of phosphorus and 90 % of potassium fertilizers are sourced via transnational supply chains (AENDA, 2023; Medina, 2022). Such dependencies underscore the intricate fluxes of biogeochemical inputs within international agro-industrial networks, emphasizing the interconnectedness of economies reliant on agricultural export systems (Barbieri et al., 2022).

Understanding how ecosystems respond to intensifying agriculture is critical to mitigating the trade-offs between them. Conducting a thorough and robust evaluation when valuing globally traded resources needs more than just quantifying monetary transactions, as the pricing of exported resources frequently falls short of adequately covering the environmental costs incurred by the exporting nation (Bargigli et al., 2004; Huang et al., 2017). Including the genuine impacts on natural

* Corresponding author.

E-mail address: luiz.santos218@fatec.sp.gov.br (L.C. Terra dos Santos).

<https://doi.org/10.1016/j.ecolmodel.2025.111202>

Received 3 February 2025; Received in revised form 29 April 2025; Accepted 25 May 2025

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capital and ecosystem services may safeguard against countries depleting their essential resource bases without receiving suitable recompense. In response to this challenge, mechanisms aimed at accurately valuing traded resources, considering both the perspectives of the exporting and importing nations, were developed. [Kamp et al., 2019](#) argued that agricultural production needs to be optimized to develop within the constraints of planetary boundaries, and evaluating a system from multidisciplinary perspectives should be a prerequisite ([Zheng et al., 2023](#)). For [Samaniego et al. \(2017\)](#), this type of analysis can be performed for the entire grain sector because it can compare processing alternatives, resource qualities, and even future scenarios. These mechanisms offer a holistic view by integrating the relationship between the compensation received per monetary unit based on market price and the biophysical resource value ([Brown and Ulgiati, 2004](#)).

Numerous studies using emergy analysis have explored the ramifications of agricultural production, analyzing resource usage, economic outcomes, and social advantages. Various agricultural crops include rice ([Ting and Xiang, 2016](#)), wheat ([Zhao et al., 2019](#)), coffee ([Cuadra and Rydberg, 2006](#); [Giannetti et al., 2011](#)), crops integrated into production systems ([Cavalett et al., 2006](#)), and complex agribusiness ([Almeida et al., 2020](#)). [Eyni-Nargeseh et al. \(2023\)](#) analyzed different rice production practices by quantifying the total emergy required for each, revealing not only the costs visible in monetary terms but also the hidden environmental trade-offs. Across these diverse systems, emergy analysis offered a biocentric perspective for quantifying resource utilization, enabling researchers to visualize comprehensive resource flows and assess the systems' sustainability. [Yu et al. \(2016\)](#) emphasized that this approach elucidates the interconnectedness of socioeconomic systems within various contexts, facilitating resource use analysis and guiding the implementation of sustainable practices in agricultural systems. This approach considers how much emergy is produced and how it is traded or valued in monetary terms. By doing so, the method links the economic benefits (such as revenue from product sales) with the environmental costs (like resource depletion and ecosystem degradation) in a balanced manner ([Edrisi et al., 2022](#)).

In the context of emergy synthesis applied to trade analysis, the objective expands beyond just quantifying monetary trade values. It seeks to integrate these economic metrics with environmental indicators, aiming to identify equitable and environmentally sustainable patterns of resource exchanges. This approach transcends traditional economic assessments by incorporating essential ecological considerations, thereby providing a more holistic understanding of trade's impact. Among various assessment methods, the emergy synthesis approach ([Odum, 1996](#)) has thus far received relatively little attention as a policy support tool ([Cano-Londoño et al., 2022](#); [Mendez-Rodriguez, 2022](#)).

Given the economic significance of soybean exports for Brazil, studies have been conducted to assess the trade activities' advantages and disadvantages. [Cavalett \(2009\)](#) performed a comprehensive life cycle evaluation of soybeans produced in Southern Brazil, examining the production, transport, and processing stages. The findings revealed that the agricultural production stage is the most resource-intensive part of the lifecycle, particularly for soybean meal exported to Europe, as well as biodiesel and refined soybean oil. The study also showed that conventional soybean biodiesel production was not a sustainable energy alternative. In a subsequent article, [Cavalett and Ortega \(2009\)](#) assessed the quantity of emergy and nutrients exported to European countries. The study's primary findings indicated that farmers delivered approximately six times more emergy in the soybeans being sold than the value they receive in currency.

Globally, emergy synthesis has been utilized to analyze various trade aspects, such as the stability and equity of international bilateral trade between China and Japan ([Tian et al., 2017](#)), as well as to evaluate fair and environmentally balanced exchange of resources through examining mineral trade between China and the United States. [Wang et al. \(2018\)](#) utilized emergy analysis and the emergy exchange ratio indicator

to study crop production and trade in China, aiming to improve production processes. Their research recommended that China reduce its grain exports, especially to industrialized countries like Japan and the United States. By comparing the emergy-derived environmental support against the economic outputs, [Motakefi et al. \(2025\)](#) recommended more efficient and sustainable resource use, echoing the discussions on modifying trade practices to enhance domestic processing as seen in soybean production research.

Examining the trade between China and Africa, [Huang et al. \(2017\)](#) highlighted that Africa typically exports environmental and mineral resources at relatively low prices that fail to offset the depletion of natural capital while China exports manufactured goods to Africa. The results indicated that China benefits from both exporting manufactured goods and importing primary resources but emphasized that Africa misses out on opportunities by not developing local production and knowledge, by importing manufactured goods in exchange for exporting primary products. These authors recommended national policies should promote local processing of primary resources to foster greater economic opportunities within the continent.

Regionally, disparities in international trade among Chinese provinces were evaluated regarding the feasibility of processing resources within the country of origin by utilizing the Opportunity Ratio and examining regional economic disparities within China and the energy implications of interprovincial trade. Their analysis of international trade dynamics revealed that China's trade relationships tend to favor its partners more than China itself. Regarding the domestic market, the analysis suggested that Western Chinese provinces could significantly benefit by shipping processed goods to Eastern China, potentially resulting in an increase in GDP for these provinces ([Tian et al., 2018](#)). Similarly, in their study on the international trade of Argentine maize, [Rotolo et al. \(2018\)](#) discovered that using intermediary international grain traders resulted in a higher outflow of environmental resources from Argentina, creating an unfavorable emergy exchange situation for the country. On the other hand, when trade operations were facilitated through national trade organizations, a lower degree of disparity was observed. The study revealed a clear resource trade imbalance in emergy units, highlighting disparities that may not be as evident when transactions are evaluated solely in monetary terms.

The valuation in emergy brings justice to commodity trade because it can quantify the values on the supply side. By considering economic and environmental factors, the effectiveness of production systems is revealed ([Ali et al., 2019](#); [Ele et al., 2020](#); [Ortega, 2005](#)). The method ensures transparency since weighting factors, which are value judgments, are not employed ([Almeida et al., 2007](#)).

This study examines the dynamics of export activities involving Brazilian soybeans and their derivatives and the corresponding import patterns of non-renewable resources spanning the period from 2015 to 2019 to assess the environmental values of primary commodity flows in trade. The study focuses on the pre-pandemic period to capture a recent and relevant timeframe that reflects significant shifts in international soybean trade dynamics. This period provides a snapshot of trade practices during a phase of notable evolution in global markets, environmental concerns, and sustainability policies. Employing emergy synthesis principles ([Brown and Ulgiati, 2004](#); [Odum, 1996](#)), the analysis effectively encompasses energy and material flows, indirect environmental labor inputs, and the intricate human processes of trading this commodity to clarify and address the intricate relationships between trade, sustainability, and economic outcomes in Brazil's soybean sector.

- What are the specific environmental and economic impacts of Brazil's dependency on non-renewable resources, such as fertilizers and pesticides, in soybean production?
- How do the trade dynamics of Brazilian soybean exports and imports of non-renewable resources influence the overall sustainability of the agricultural sector?

- What are the potential economic benefits of processing soybean products domestically compared to exporting raw materials, and how can this shift impact Brazil's GDP?
- In what ways can emergy synthesis provide insights into the hidden environmental costs associated with Brazil's soybean trade, and how can these insights inform policy decisions?
- How can fair trade practices be integrated into Brazil's soybean export strategies to promote equity and sustainability in international trade?

This work aims to provide a more comprehensive framework for understanding the complexities of resource dependencies in the Brazilian soybean trade, ultimately guiding future research and policy development.

2. Methods

This study employs the emergy approach to evaluate Brazilian soybean exports and accurately assess the value associated with the exchanged resources. Emergy synthesis, which converts various forms of energy, materials, goods, and services into a unified unit. This approach mitigates the subjectivity inherent in other methods, facilitating the analysis and comparison between systems (Odum, 1996; Ulgiati and Brown, 2009), and considers the natural system's contribution to the human economy, essentially evaluating the "supply system of value" (Tilley and Brown, 2006).

By utilizing emergy synthesis, the accumulated embodiment across the entire supply chain in commodity trading can be assessed. This method interconnects the biosphere and the economic system to evaluate commodities' intrinsic values from a biophysical perspective (Tian et al., 2017; Zhong et al., 2018).

Defined as the total available energy directly and indirectly utilized by the natural system to create a product or deliver a service, emergy embodies the real value (Brown and Ulgiati, 1997; Odum, 1996) through the conversion of various energy forms, mass flows, labor, and services into solar energy joules (sej). This conversion is performed by multiplying the raw input flows by the unit emergy values (UEVs), updated to the emergy baseline (12E+24 sej/year) and the Emergy-Money ratio (EMR) that measures an economy's energy intensity by dividing the annually available energy by its GDP. This ratio gauges the efficiency of converting resources into monetary wealth, translating monetary values into the energy required to sustain them. Conversely, EMR reveals the average emergy a country obtains per unit of currency spent. The EMR allows for the conversion of the monetary worth of products, including the value of indirect labor (services), into the emergy of one form required to sustain them. The selected economies' EMRs (Emergy Money Ratio) are taken from the National Environmental Assessment Database (NEAD, emergy-need.com).

During commodity trade, what is transferred is both the emergy associated with the raw material and the emergy linked to the accompanying services. An emergy imbalance in trade indicates an unreciprocated acquisition of natural capital, ecosystem services, and technological and social knowledge by one of the trading partner countries. This imbalance signifies an unequal exchange of labor potential, environmental contributions to the economy, job creation opportunities, and the potential environmental consequences during resource processing. These complexities are often not adequately captured by monetary transactions and are obscured within the typically used framework of monetary terms of trade. Hence, emergy is a valuable tool to supplement economic assessments and recognize the underlying resource exchanges embedded within trade transactions.

To address the imbalances in the international trade of Brazilian soybean (Ali et al., 2019; Cavalett and Ortega, 2009; Wu et al., 2020), three emergy-based indices are used: the Emergy Exchange Ratio (EER, Odum, 1996), the Emergy Benefit Ratio (EBR) and the Opportunity Ratio (OR) (Tian et al., 2017). The energy diagram shows the flows and

interactions of the material cycle of the system under study and the scope of each indicator used to evaluate different stages of exchange within the Brazilian soybean exports (Fig. 1).

The Emergy Benefit Ratio (Eq.1) compares the emergy embodied in specific imported goods or commodities with the emergy associated with the money paid for those goods or commodities in all types of trade relationships (Huang et al., 2017). The currency exchanged is generated within the importing country's economy using its available resources. The EBR is predominantly contingent on the EMR of the importing nation and can show the extent of benefits realized from a trade dynamic. When $EBR > 1$, the emergy of the imported goods exceeds, the emergy returned to the exporting nation through the monetary exchange, indicating a favorable trade for the importer. Conversely, when $EBR < 1$, the emergy content of the traded item is higher than the emergy encapsulated in the money paid, suggesting an undervaluation of the commodity within the market.

$$EBR = \frac{\text{Imported emergy}}{\text{Money paid} \times \text{EMR of importing economy}} \quad (1)$$

The Emergy Exchange Ratio (EER) delineates the overall advantage within a trade relationship (Eq.2), highlighting the comparative advantage possessed by one party over the other (Giannetti et al., 2011). An EER of 1 indicates fair trade, while an EER greater than 1 suggests that the exporter receives fewer resources in the form of currency than it delivers in the form of the product (Odum, 1996).

When a country imports primary resources, such as soybeans, it avoids the necessity of domestic production, thereby conserving land, soil, water, and irrigation energy. Additionally, by importing unprocessed commodities, the importing country can integrate these resources into its local industrial processes, fostering job creation and income generation. Conversely, the export of primary resources implies a loss of economic opportunities that could arise from local industries processing and exporting value-added commodities. It is important to note that the EER does not distinguish between primary and processed resources; rather, it indicates "who wins" and "who loses" in the trade (Cavalett and Ortega, 2009).

$$EER = \frac{\text{Exported emergy}}{\text{Imported Emergy}} \quad (2)$$

The Opportunity Ratio (Eq. (3)) represents the potential increase in GDP that could be achieved if resources were processed within the exporting country rather than being exported in their raw form (Tian et al., 2017). This ratio helps to highlight and promote the potential benefits of alternative resource utilization. A country can create jobs and produce higher-value-added products by processing resources domestically, contributing to economic growth.

$$OR = \frac{(\text{Exported emergy} / \text{EMR of exporting economy})}{\text{Exported Trade Volume}} \quad (3)$$

While the economic evaluation of international trade centers around achieving monetary equilibrium, this set of indicators enables an examination of trade exchanges from an environmental perspective. This, in turn, aids in pursuing trade equity by preventing the uncompensated exploitation of resources (Huang et al., 2017). By considering environmental issues, these indicators provide a more comprehensive understanding of trade dynamics and may help to promote equity in global resource exchanges. The difference between the EER and OR indicators lie in calculating imported emergy. For the EER, the emergy of the country sending the money is used, whereas, for the OR, the emergy of the receiving country (Brazil) is utilized.

3. Results

The emergy associated with the exchange of soybeans and their derivatives between international partners, as well as the emergy linked to

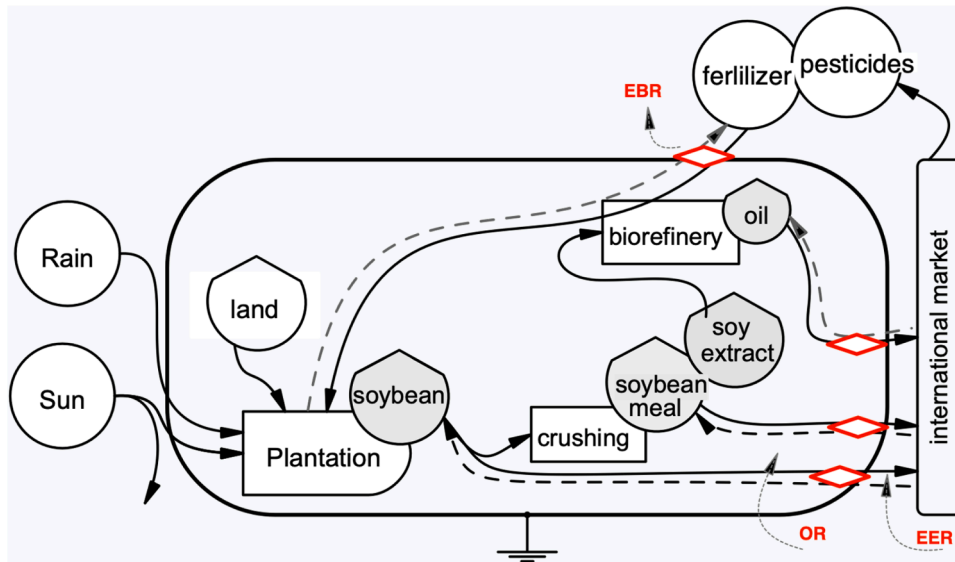


Fig. 1. Energy flows diagram of the Brazilian soybean showing sun, rain, fertilizers, and pesticides are needed for soybean production and processing. The exchanges studied in this work are highlighted in red diamonds.

the money received for these exchanges, constitutes the total emergy flows of trade between the partners. According to Geng et al. (2017), relying solely on economic assessments to evaluate trade can often lead to an incomplete picture of the trade balance. Industrialized countries have high currency circulation and low EMR, while developing countries exhibit high EMR due to low currency circulation, the amount of resources required to generate a unit of currency varies significantly between these regions. The different efforts to generate currency are particularly significant for the trade of primary resources, as the suppliers are often from developing nations, while the benefits typically accrue to developed countries.

3.1. Emergy benefit ratio

Import emergy flows (fertilizers and pesticides) among Brazil and its main trade partners (Belarus, Canada, China, Russia, and the US) for the years 2015 and 2019 are shown in Fig. 2, and detailed calculations are available in Supplementary Materials, Tabs. S1 and S2. Russia is the largest trade partner for Brazil, followed by Canada and US. in both years. The EBR for fertilizers imported by Brazil during the 5-year period shows that the country benefited in terms of emergy from all the key exporting nations analyzed, independently of the quantities and prices variations (Table 1). With an average EBR of 2, Brazil received twice the emergy from these countries than the emergy associated with the payments it made for these resources. The results suggest that importing low-transformed non-renewable inputs to support commodity

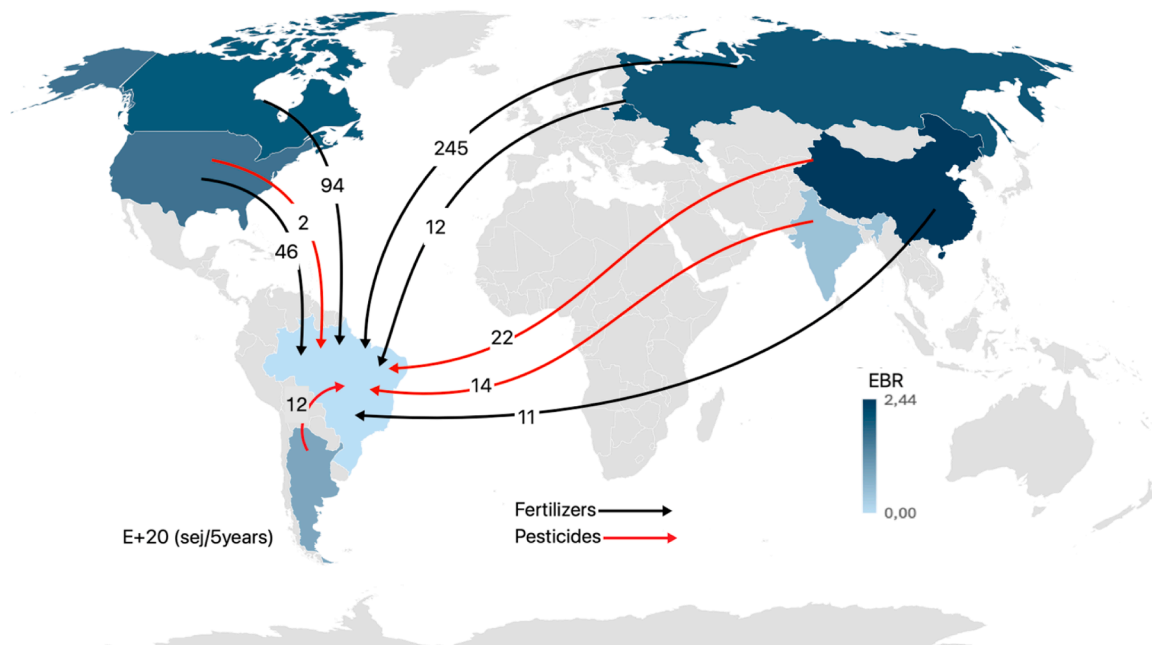


Fig. 2. Import flows of fertilizers and pesticides into Brazil from major trading partners for 5 years, along with the EBR values for each year. White cells indicate benefits to Brazil, while grey cells indicate benefits to the exporting partner.

Table 1

. Emergy Benefit Ratio of fertilizers and pesticides from major trading partners for 5 each year. White cells indicate benefits to Brazil, while grey cells indicate benefits to the exporting partner. Detailed calculations are available in Supplementary Materials, Tabs. S1 and S2.

	EBR								
	Fertilizers					Fertilizers			
	Russia	Canada	US	China	Belarus	China	India	Argentina	US
2015	1.69	1.74	1.43			0.54	0.47	0.79	-
2016	2.63	2.43	1.74			0.80	0.57	1.25	-
2017	-	2.22	1.81		2.14	0.64	0.48	1.07	-
2018	1.92	1.84	1.54			0.51	0.39	1.31	-
2019	1.86	1.66	-	2.44		0.40	0.32		0.15

production is a strategically sound decision. The detailed EBR calculation and statistical data of the three main fertilizer exporters are available in the supplementary materials.

On the other hand, the EBR calculated for pesticides imported by Brazil in the period pointed out that Brazil did not benefit in terms of trade relations with all countries except for Argentina 2016–2018. With a 5-year average EBR of 0.6, Brazil received 40 % less emergy from these countries compared to the emergy associated with the payments made for imported pesticides. These results indicate that importing transformed non-renewable inputs to support commodity production is not advantageous, particularly given that China and India control approximately 90 % of the total supply. Statistical data for the three main pesticide exporters and detailed calculations of the EBR can be found in the supplementary materials.

3.2. Emergy exchange ratio

The EER results for soybean grains (Fig. 3), excluding China - which had an average EER of 0.27 and accounted for 61 % of the total flow - show that Brazil engaged in disadvantageous emergy trade with all its other trading partners (Spain, The Netherlands, and Thailand). Despite prices being practically the same across all countries (Table 2), as the volatility of the international market drives fluctuations, China’s EMR is significantly higher than those of other buyers. This indicates that China has a significantly higher available emergy to generate a unit of currency

and delivers more emergy in the form of currency than it receives in the form of products. Detailed calculations are available in Supplementary Materials, Tab. S3.

The results indicate that in terms of soybean meal exports, nearly equitable trade was achieved with The Netherlands and Germany in the last two years of the period, although both countries account only for 40 % of the soybean meal. Conversely, trade with France and South Korea was extremely disadvantageous (Supplementary Materials, Tab. S4).

As expected, trade with China and India, which together accounted for 85 % of the total trade, was beneficial for soybean oil. In contrast, trade with Bangladesh was found to be highly unfavorable (Table 2).

3.3. Opportunity ratio

If Brazil processed soybean grain (a primary commodity) domestically instead of exporting it, the sector’s GDP would increase annually. By dividing the exported emergy by the exporter’s EMR, one can estimate a virtual sectoral GDP increase, which can then be compared to the actual revenue generated from exports. On a 5-year average, an increase of 17 % could be achieved, meaning the country is missing out on opportunities to add value and create jobs through further processing and manufacturing. It is worth noting that the OR values have been increasing over the years (Table 3). This trend may be attributed to a decrease in the product’s price caused by fluctuations in the international market, which, in turn, makes domestic processing more

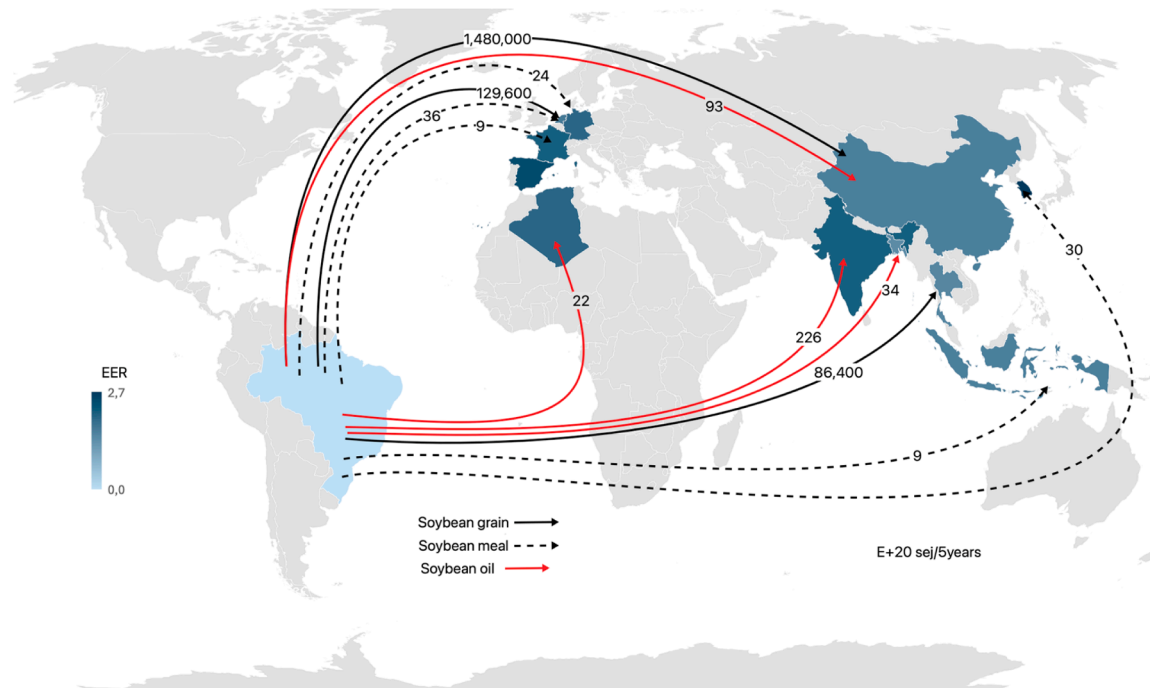


Fig. 3. Export flows of soybean grain, meal, and oil from Brazil to major trading partners.

Table 2

. EER values of soybean grain, meal, and oil for each year. White cells indicate benefits to Brazil, while grey cells indicate benefits to the importing partner. See detailed calculations in Supplementary Materials, Tabs. S3, S4 and S5).

	EER													
	Soybean grain				Soybean meal						Soybean oil			
	China	Spain	Netherlands	Thailand	Netherlands	South Korea	France	Germany	Indonesia	India	China	Argelia	Bangladesh	
2015	0.23	1.15		1.68		-		0.78	1.57	0.30	0.41	-	6.44	
2016	0.24	1.23		1.12		5.28		0.86	-	0.32	0.41	1.24	-	
2017	0.26	1.29	1.22		0.92	5.43		-	-	0.34	0.42	-	7.34	
2018	0.28	1.34	1.16		-	-		0.89	-	0.36	0.49	-	8.66	
2019	0.32	1.48	1.48		0.96	5.08	2.86	-	-	0.43	0.57	0.98		

Table 3

. OR values of each year’s soybean grain, meal, and oil. White cells signify benefits to Brazil when products are processed before exportation, while grey cells indicate no added benefits from processing the products. Detailed calculations are available in the Supplementary Materials, Tabs. S6 and S7.

	OR													
	Soybean grain				Soybean meal						Soybean oil			
	China	Spain	Netherlands	Thailand	Netherlands	South Korea	France	Germany	Indonesia	Thailand	India	China	Argelia	Bangladesh
2015	1.14	1.15	1.13	-	-	-	0.74	1.15	1.18	2.08	2.08	-	2.08	
2016	1.18	1.19	1.15	-	-	1.38	0.78	1.27	-	2.03	2.02	2.02	-	
2017	1.16	1.17	-	1.17	0.89	1.35	-	-	1.25	1.89	1.93	-	1.85	
2018	1.11	1.12	1.11	-	0.81	-	0.73	-	1.05	1.98	1.98	2.18	1.99	
2019	1.25	1.27	1.26	-	0.85	1.25	1.25	-	-	2.20	2.23	-	-	

appealing.

Given that commodities frequently undergo minimal processing prior to export, the next stage in the process is the exportation of soybean meal. The results indicate that selling soybean meal to The Netherlands and Germany remains attractive. This is primarily due to the prices offered by these countries, which are nearly double those offered by other countries importing soybean meal from Brazil (see Supplementary Materials, Tab. S6). For all other countries (South Korea, France, Indonesia, and Thailand), the sale of soybean meal could be discouraged since if the product were processed in the country, there would be a potential increase of 24 % in the sector’s GDP.

Finally, analyzing the OR of soybean oil, the results show that Brazil would benefit around two times if the oil exported was further processed domestically and used as a raw material in various industries. Soybean oil is essential to produce refined oil, hydrogenated fats, margarine, and mayonnaise, among other products. In addition to its culinary applications, soybean oil is used in industrial products such as paints, lubricants, solvents, plastics, and resins. A valuable component extracted from soybean oil is lecithin, an emulsifying agent used in manufacturing sausages, ice cream, cereal bars, food supplements, and more. Given this wide range of potential applications, in-house processing would not only create jobs but also enable the production of higher-value products that would be sold at increased prices.

In summary, the study analyzed energy flows in Brazil’s soybean trade, highlighting critical resource imbalances and economic inefficiencies. Using energy synthesis, which measures the environmental support required to produce traded goods, the research reveals that monetary metrics alone fail to capture the full cost of resource depletion, often masking trade imbalances.

For imported pesticides, the Energy Benefit Ratio over a five-year period was approximately 0.6, indicating that Brazil received 40 % less energy than the resource value embedded in the pesticides it paid for. This demonstrates an unfavorable trade condition, where expenditures exceed the environmental and resource benefits received. Such inefficiency contributes to higher production costs, environmental degradation, vulnerability to price fluctuations, and deteriorating soil and ecosystem health.

In the soybean trade, the analysis indicates energy losses for grain exports. Brazil exported more environmental resource support than it

recovered through monetary payments in most cases, with China as an exception. For soybean meal exports, trade conditions were closer to equitable with countries like The Netherlands and Germany, though these accounted for a smaller share of overall trade. The findings suggest that soybean commodities are systematically undervalued from Brazil’s perspective, with imbalances favoring trade partners.

The Opportunity Ratio analysis underscores the economic benefits of domestic soybean processing. If Brazil processed soybeans locally instead of exporting raw grains, its GDP could grow by an average of 17 % over five years. For soybean oil specifically, domestic processing could nearly double economic gains, illustrating the high potential for value addition through local manufacturing. Such a shift toward internal utilization would create jobs and foster stronger economic outcomes.

4. Discussion

Table 4 summarizes the 5-year balance for the period, considering the trade from the Brazilian exporter’s perspective and the calculated indicators for each case.

According to the literature, over-reliance on commodity imports can

Table 4

. Summary of the soybean Brazilian trade considering the benefits and losses according to the energy-based indicators: (EBR for imports, EER and OR for exports).

		2015–2019			Potential sector’s GDP increase (%)
		Beneficial trade (sej/ 5years)	Detrimental trade (sej/ 5years)	Total (sej/ 5years)	
Imports	Fertilizers	7.73E+22	-	7.91E+22	
	Pesticides	1.10E+19	1.77E+21		
Exports	Grain	1.09E+26	7.03E+25	2.49E+26	17
	Meal	6.99E+21	7.03E+25		24
	Oil	1.96E+22	2.65E+22		104
	Imports/ Exports			0.03 %	

hinder economic diversification and resilience, making countries vulnerable to economic shocks when global commodity prices fall or demand decreases (Barbieri et al., 2022).

While the ratio of imports to exports of Brazilian soybeans (0.03 %) may suggest that, in emergy terms, the contribution of the international market in supplying fertilizers and pesticides is insignificant, this perspective contrasts with Medina (2022). Medina argues that a significant portion of domestically produced fertilizers depends on foreign raw materials, highlighting the complex global interdependencies in agricultural inputs. Furthermore, soybean cultivation, as a major consumer of agrochemicals (AENDA, 2023), reinforces resource dependencies among nations, particularly in economies heavily reliant on agricultural trade (Barbieri et al., 2022). Medina's focus on fertilizer illustrates that even locally manufactured inputs rely on international supply chains. However, refining this argument by distinguishing between fertilizer and pesticide dependencies is important. While the international market is crucial for domestic fertilizer production, the research findings reveal that reliance on imported pesticides creates a more disadvantageous trade scenario. This underscores the need to assess agricultural inputs separately, recognizing their distinct economic and sustainability implications to better inform policy decisions.

However, the 5-year trade balance indicates that 33 % of Brazil's soybean exports occur under trade relationships where the country is disadvantaged, receiving less value in return than the environmental and resource costs embedded in the exported commodities. This economic imbalance signifies that Brazil effectively exports more resource value than the monetary compensation justifies, akin to trading high-quality products for undervalued returns. The environmental impact is equally concerning, as the hidden production costs, such as soil degradation and resource depletion, are not adequately compensated, effectively subsidizing buyers' benefits. This trade disparity exposes Brazil to economic vulnerabilities, as lower returns in emergy terms undervalue the nation's natural resources, leaving it at risk from market price fluctuations. To address this, Brazil could focus on domestic soybean processing to add value and achieve fairer exchange ratios while advocating for trade policies that recognize the environmental and economic costs of agricultural production.

These findings align with most previous emergy studies concerning soybean exports. Cavalett and Ortega (2007) assessed the emergy exchange in Brazil's soybean production, trade, and its industrialized derivatives to determine equitable exchanges regarding emergy/currency with the global market. They concluded that Brazilian farmers provided five times more emergy in the soybeans they sold than the monetary value they received in return. Furthermore, Cavalett (2007) and Cavalett and Ortega (2009) sequentially analyzed the soybean trade with European countries and discovered that soybean producers were delivering nearly 3 to 6 times more emergy in the exported soybean grain than the monetary value they were receiving in return. While their results are not directly comparable to the present research—given that their studies took a macro approach by evaluating trade with all countries and Europe in different years—the current investigation focuses on the three countries with the highest trade flow. Despite these methodological differences, the current findings indicate that Brazil continues to experience a net loss in soybean grain exports with all analyzed countries, except for China, even a decade later.

Studies analyzing other crops (Cuadra and Rydbeg, 2006; Giannetti et al., 2011) and various regions of the world (Huang et al., 2017; Tian et al., 2018) have reached similar conclusions. Giannetti et al. (2011) evaluated the emergy exchange ratio for coffee production in the Brazilian Savannah and observed that, with an EER value of 2.69, the farm exported almost three times more emergy to buyers than the amount received for green coffee. For Nicaragua, the EER for green coffee sold to various European countries and the United States suggests that these trade relationships require closer examination, as the countries appeared to benefit the most in emergy terms from trading with Nicaragua (Cuadra and Rydbeg, 2006).

Regarding studies related to different regions and trade partners, Huang et al. (2017) assessed the China-Africa trade relationship using the EBR and the EER indicators to quantify the exchange of natural capital and ecosystem services between these partners. They found that Africa exports its natural resources at low prices, which cannot compensate for the depletion of its natural capital. Conversely, China exports manufactured products to Africa, effectively offsetting African internal development in terms of labor and industrial development. This trade dynamic benefits China monetarily by both selling manufactured goods and importing primary resources needed to support its basic industry. Tian et al. (2018) investigated the trade in primary products between China and its main trading partners, confirming that trade advantages for economies should not depend solely on capital flows. Their results indicated that although the monetary value of China's imports far exceeds that of its exports, China receives more emergy in trade than it provides and this dynamic benefits China's economy by leveraging the primary resources it imports.

This work aligns with existing literature in concluding that the continuous export of commodities can lead to environmental degradation and resource depletion, thereby compromising the sustainability of exports and the health of local ecosystems. This happens because importing primary resources generally benefits developed economies, while the environmental impacts and natural resource losses experienced by exporting countries are frequently overlooked (Geng et al., 2017). Benefits from international trade can occur, but they depend on a combination of prices and emergy indicators. For example, the trade of Brazilian soybean meal with The Netherlands and Germany showed favorable EER values for Brazil. On the other hand, Brazil, with a lower EMR than China, can benefit more from trading primary commodities with this country. However, in general, developing and underdeveloped economies that have higher EMRs often experience a net loss in environmental support due to such trade. This dynamic highlights a potentially unsustainable trade imbalance, as exemplified by the trade relationships between Brazil and China with European countries.

Another key point highlighted in this work, when examining the relationship between developed and developing countries from the opportunity ratio perspective, is that the optimal strategy for developing nations is to add value to their raw materials before exporting them. This finding aligns with the results of Tian et al. (2017), who contrasted Chinese exports of soybean grain with the potential benefits of processing soybeans in their producing regions. Their analysis highlighted that local processing could generate jobs and add value. They also assessed regional disparities within the Chinese economy and the emergy involved in interprovincial trade, pointing out that less developed provinces should consider sending already processed products to the more developed eastern provinces. However, it is acknowledged that fully processing resources within the country of extraction is not always feasible and can lead to conflicts regarding global market freedom.

What are the options to achieve fair trade?

1. Raising the prices of exported commodities represents the most straightforward and potentially easiest way to improve the emergy exchange ratio in favor of the disadvantaged country. By increasing commodity prices, exporting nations could better compensate for the depletion of their natural resources, contributing to more environmentally just trade. However, while this strategy could theoretically address environmental costs incurred by the exporting nation (Bargigli et al., 2004; Huang et al., 2017), it remains largely impractical. This is because developing countries often have limited influence over global commodity prices, making it difficult to implement such changes effectively in the international market.
2. Another approach focuses on forming trade partnerships with countries with similar emergy-to-money ratios. National public policies could promote these collaborations, fostering stronger economic ties among nations with less developed economies. By doing so, these countries could support each other's development through

a more balanced exchange of environmental resources and economic benefits. This strategy aims to achieve more equitable and sustainable trade practices, enabling these countries to grow together and minimize the disadvantages typically faced in trade with more developed nations.

A third option, also explored in the literature, is to decrease the reliance on labor - a significant energy input in commodity production (Cuadra and Rydberg, 2006) - and instead increase the use of fertilizers, advanced irrigation systems, and machinery, effectively transitioning to more automated, technology-driven processes. For example, machinery can perform tasks faster and potentially at a lower cost than a large workforce, improving production efficiency, particularly when labor costs are high or unstable. While this approach could lead to a more favorable trade, it would likely increase unemployment and subsequent social issues, especially in rural areas where agriculture is a major employer. When people lose their jobs, the local economy may suffer, and social challenges such as poverty and inequality might increase.

Under such circumstances, even if multilateral trade is balanced in monetary terms and has the capacity to promote appropriate compensation, the transfer of environmental wealth between trading partners appears to have the potential to undermine efficiency and equity in access to natural resources, potentially harming long-term sustainability (Geng et al., 2017; Liu et al., 2016). Despite SDG target 17.10 emphasizing promoting an equitable and fair multilateral trading system, biophysical trade imbalances persist (Geng et al., 2017; Liu et al., 2019). In an attempt to justify equity and improve global sustainability, the promotion of fair trade can be seen as a way to seek a harmonious coexistence of humanity within the natural limits of the planet (Kanashiro Uehara, 2024). In this regard, the International Fair-Trade Charter (IFTC) highlights that protecting the environment and the long-term viability of natural resources and biodiversity are fundamental pillars of Fair Trade (The International Fair Trade Charter 2018). Furthermore, since countries possess different natural resources and occupy varied roles in the international scenario, exploiting these resources can harm their long-term sustainability (Liu et al., 2016).

At the same time, ecological sustainability and environmental equity remain secondary to monetary considerations, and emergy assessment provides fruitful insights to improve terms of exchange between countries or balance the emergy of traded commodities (Cristiano, 2021; Geng et al., 2017). According to Du et al. (2022) and Guo (2023), fair trade can help improve the sustainable development of agriculture worldwide, contributing to the debates about the ecological and environmental consequences that still persist.

In summary, the study highlights Brazil's current trade practices' uneven environmental and economic impacts. While fertilizer imports may offer relatively favorable trade conditions, pesticide imports and raw soybean exports reflect systemic inefficiencies. To enhance sustainability, Brazil could prioritize policies that promote domestic processing, equitable trade practices, and stronger valuation of its natural resources.

5. Conclusions and recommendations

International trade can boost a country's economic development and generate additional advantages from internationally traded resources. A fair-trade relationship must consider economic and ecological aspects, promoting additional criteria for the value of resources and, consequently, for their efficient use. Consequently, trade policies should favor an appropriate balance between primary and manufactured flows and prevent countries from becoming impoverished by exporting only high-emergy resources without adequate compensation. Furthermore, national policies should implement the processing of primary resources locally to develop more economic opportunities within the country.

This research combined monetary and environmental assessments in a complementary approach, which could enable awareness of the

potential hidden support of resources beyond their market value. It aims to facilitate the development of policies for more balanced and equitable trade between developed and developing economies. Emergy synthesis is an alternative and complementary method for evaluating international trade. It quantifies the global environmental support provided by the biosphere that is embodied in trade flows, allowing for a fair assessment of the contribution of ecosystem services.

The results indicate that while Brazil appears to benefit from trade from an economic standpoint, it receives significantly fewer resources embodied in currency received from most bilateral exchanges. Particularly, Brazil benefits less when trading with more developed economies, whereas it is advantageous when trading with countries with higher emergy-to-money ratios.

From an academic perspective, this paper employs emergy synthesis to evaluate international trade, providing a broader perspective on the environmental support embedded in trade flows compared to traditional monetary evaluations. By focusing on the Brazilian soybean trade, it highlights the environmental and economic implications of exporting primary commodities and stresses the importance of incorporating environmental costs alongside market value in trade assessments. The research suggests that trade policies should aim to balance flows of primary and processed goods to prevent resource depletion and economic disadvantages. It advocates for local resource processing to improve sustainability and foster economic opportunities, supported by the Opportunity Ratio metric, which estimates potential GDP growth from domestic resource utilization. While the study underscores the economic benefits of internal processing and reveals trade imbalances—such as the costly reliance on imported pesticides and the undervaluation of raw soybean exports—it acknowledges emergy synthesis's limited acceptance as a mainstream tool, tempering its claims about reshaping trade policies. Nonetheless, by combining monetary and environmental assessments, the research offers valuable insights into trade strategies, aiming to guide equitable practices and address sustainability challenges in trade between developed and developing countries.

Returning to the research questions:

1. *What are the specific environmental and economic impacts of Brazil's dependency on non-renewable resources, such as fertilizers and pesticides, in soybean production?* The results indicate that Brazil's soybean production relies heavily on non-renewable resources, with an average dependency of 80 % on fertilizers and pesticides. This dependency can lead to negative environmental impacts, such as soil degradation and increased pollution. At the same time, economically, it may result in higher production costs and vulnerability to price fluctuations in global markets.
2. *How do the trade dynamics of Brazilian soybean exports and imports of non-renewable resources influence the overall sustainability of the agricultural sector?* The results suggest that while importing fertilizers can benefit Brazil, purchasing pesticides is disadvantageous. The export of soybean grains and meal is generally unfavorable, indicating that these trade dynamics may not support the sustainability of the agricultural sector. However, the soybean oil trade could significantly benefit the sector, potentially doubling the sectoral GDP, highlighting the need for strategic trade decisions.
3. *What are the potential economic benefits of processing soybean products domestically compared to exporting raw materials, and how can this shift impact Brazil's GDP?* The research emphasizes that processing soybean products domestically could lead to substantial economic benefits, including job creation and increased product value-added. The Opportunity Ratio indicates that internal resource processing could enhance GDP growth, suggesting that Brazil could achieve better economic outcomes by focusing on local processing rather than raw material exports.
4. *In what ways can emergy synthesis provide insights into the hidden environmental costs associated with Brazil's soybean trade, and how can*

these insights inform policy decisions? Emergy synthesis is highlighted as a valuable tool for quantifying the environmental support provided by the geobiosphere in trade flows. By revealing the hidden environmental costs associated with soybean trade, emergy synthesis can inform policymakers about the ecological impacts of trade practices, enabling them to make more informed decisions that promote sustainability and equity in trade. The proposed emergy synthesis method can be applied in various countries and in various time frames. Future research could focus on its application in different contexts to assist in public policy decision-making and to help countries select trading partners wisely.

5. *How can fair trade practices be integrated into Brazil's soybean export strategies to promote equity and sustainability in international trade?* The paper suggests that assessments incorporating both monetary and environmental evaluations can help ensure fair and environmentally sustainable pricing in trade. By integrating fair trade practices into export strategies, Brazil can promote equitable relationships with trading partners, ensuring that trade benefits are more evenly distributed and that environmental costs are adequately addressed.

The findings highlight the complex relationships between trade, sustainability, and economic outcomes in Brazil's soybean sector. Collectively, they advance our understanding of international trade dynamics, particularly in the context of environmental sustainability and economic development. The study's insights are highly valuable for policymakers, economists, and environmentalists who aim to promote fairer and more sustainable trade practices.

Future research should broaden the scope to include additional countries and diverse commodities, enabling a deeper understanding of the global applicability of emergy synthesis across various trade scenarios. Integrating ecosystem services into analyses, particularly for higher-value products, could offer a more comprehensive view of environmental contributions to trade while informing policies that balance primary and manufactured goods flows, preventing resource-rich nations from being undervalued in global exchanges. Building on findings about Brazil's dependence on non-renewable inputs like fertilizers and pesticides in soybean production, future studies should emphasize their ecological trade-offs, including soil degradation and deforestation. Explicitly linking resource dependency to environmental impacts would strengthen problem framing and support tailored policy recommendations. Critical areas of focus should include examining how chemical inputs impair soil fertility, organic matter, and microbial activity; exploring land-use changes driven by reduced productivity, such as deforestation; and implementing integrated emergy synthesis to assess economic and environmental trade-offs. These efforts can inform strategies to balance agricultural output with long-term ecological sustainability.

These findings may improve the understanding and application of emergy synthesis in international trade, thereby promoting more sustainable and equitable trade practices globally, despite the current limitations to its widespread acceptance. Despite these challenges, emergy synthesis offers significant potential to comprehensively understand the ecosystem's contribution to economic development. It can also aid in formulating more effective policies to ensure fair trade practices.

CRediT authorship contribution statement

Cláudia Leão: Writing – original draft, Conceptualization. **Luiz C. Terra dos Santos:** Writing – original draft, Conceptualization. **Biagio F. Giannetti:** Methodology, Conceptualization. **Feni Agostinho:** Writing – review & editing, Conceptualization. **Cecilia M.V.B. Almeida:** Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at [doi:10.1016/j.ecolmodel.2025.111202](https://doi.org/10.1016/j.ecolmodel.2025.111202).

Data availability

Data will be made available on request.

References

- AENDA (2023). Associação Brasileira dos Defensivos Genéricos, Associação Brasileira Dos Defensivos Genéricos (Brazilian Association of Generic Agrochemicals, Brazilian Association of Generic Agrochemicals). In Portuguese: <https://www.aenda.org.br/> (accessed on December 20, 2023).
- Ali, M., Marvuglia, A., Geng, Y., Robins, D., Pan, H., Song, X., Sun, H., 2019. Accounting for the emergy-based sustainability of crop production in India and Pakistan in the first decade of the 21st century. *J. Clean. Prod.* 207, 111–122. <https://doi.org/10.1016/j.jclepro.2018.09.236>.
- Almeida, C.M.V.B., Barrella, F.A., Giannetti, B.F., 2007. Emergy ternary diagrams: five examples for application in environmental accounting for decision making. *J. Clean. Prod.* 15 (1), 63–74. <https://doi.org/10.1016/j.jclepro.2005.07.002>.
- Almeida, C.M.V.B., Frugoli, A.D., Agostinho, F., Liu, G.Y., Giannetti, B.F., 2020. Integrating or disintegrating agribusiness systems: results of the emergy assessment. *Total Environ. Sci.* 729, 138733. <https://doi.org/10.1016/j.scitotenv.2020.138733>.
- Barbieri, P., MacDonald, G.K., Bernard de Raymond, A., Nesme, T., 2022. Food system resilience to phosphorus shortages on a telecoupled planet. *Nat. Sustain.* 5 (2), 114–122. <https://doi.org/10.1038/s41893-021-00816-1>.
- Barghili, S., Cialani, C., Raugei, M., Ulgiati, S., 2004. Unequal distribution of benefits and environmental burden. The use of environmental and thermodynamic indicators in support of fair and sustainable trade. In: *Proceedings of the IV Biennial International Workshop Advances in Emergy Studies*, pp. 16–19.
- Brown, M.T., Ulgiati, S., 1997. Emergy-based indices and ratios to evaluate sustainability: monitoring economies and technology toward environmentally sound innovation. *Ecol. Eng.* 9 (1–2), 51–69. [https://doi.org/10.1016/S0925-8574\(97\)00033-5](https://doi.org/10.1016/S0925-8574(97)00033-5).
- Brown, M., Ulgiati, S., 2004. *Emergy analysis and environmental accounting*. Encyclopedia of Emergy. Elsevier, pp. 329–354.
- Cano-Londoño, N., Heriberto, C., Krisztián, B., 2022. Integrated sustainability assessment: emergy, emergy, life cycle assessment frontiers in sustainability, 3, 921874. <https://doi.org/10.3389/frsus.2022.921874>.
- Cavalett, O., Ortega, E., 2007. Emergy and fair trade assessment of soybean production and processing in Brazil. *Manag. Environ. Qual.* 18 (6), 657–668. <https://doi.org/10.1108/14777830710826694>.
- Cavalett, O., Ortega, E., 2009. Emergy, nutrients balance, and economic assessment of soybean production and industrialization in Brazil. *J. Clean. Prod.* 17 (8), 762–771. <https://doi.org/10.1016/j.jclepro.2008.11.022>.
- Cavalett, O., De Queiroz, J.F., Ortega, E., 2006. Emergy assessment of integrated grain, pig and fish production systems on small rural properties in southern Brazil. *Ecol. Model.* 193 (3–4), 205–224. <https://doi.org/10.1016/j.ecolmodel.2005.07.023>.
- Cristiano, S., 2021. Organic vegetables from community-supported agriculture in Italy: emergy assessment and potential for sustainable, just, and resilient urban-rural local food production. *J. Clean. Prod.* 292, 126015. <https://doi.org/10.1016/j.jclepro.2021.126015>.
- Cuadra, M., Rydberg, T., 2006. Emergy assessment in coffee production, processing and export in Nicaragua. *Ecol. Modell.* 196 (3–4), 421–433. <https://doi.org/10.1016/j.ecolmodel.2006.02.010>.
- Du, H., Yang, L., Wang, W., Lu, L., Li, Z., 2022. Emergy theory to quantify sustainability of large cascade hydropower projects in the upper Yangtze. *Ecol. Modell.* 468, 109954. <https://doi.org/10.1016/j.ecolmodel.2022.109954>.
- Edrisi, S.A., Sahiba, S.A., Chen, B., Abhilash, P.C., 2022. Emergy-based sustainability analysis of bioenergy production from marginal and degraded lands of India. *Ecol. Modell.* 466, 109903. <https://doi.org/10.1016/j.ecolmodel.2022.109903>.
- Ele, S., Zhu, D., Chen, Y., Liu, X., Chen, Y., Wang, X., 2020. Application and problems of emergy evaluation: a systemic review based on bibliometric and content analysis methods. *Ecol. Indic.* 114, 106304. <https://doi.org/10.1016/j.ecolind.2020.106304>.
- Eyni-Nargeseh, H., Asgharipour, M.R., Rahimi-Moghaddam, S., Gilani, A., Damghani, A. M., Azizi, K., 2023. Which rice farming system is most environmentally friendly in Khuzestan Province, Iran? A study based on emergy analysis. *Ecol. Model.* 481, 110373. <https://doi.org/10.1016/j.ecolmodel.2023.110373>.
- FAO, 2024. FAOSTAT. Available online: <http://www.fao.org/faostat/en/#data> (last accessed on April 20, 2024).
- Geng, Y., Tian, X., Sarkis, J., Ulgiati, S., 2017. China-US trade: indicators for an equitable and environmentally balanced exchange of resources. *Ecol. Econ.* 132, 245–254. <https://doi.org/10.1016/j.ecolecon.2016.11.008>.

- Giannetti, B.F., Ogura, Y., Bonilla, S.H., Almeida, C.M.V.B., 2011. Accounting for emergy flows to determine the best production model for a coffee plantation. *Energ. Policy* 39 (11), 7399–7407. <https://doi.org/10.1016/j.enpol.2011.09.005>.
- Guo, Q., Ahmad, W., Sofuoğlu, E., Abbas, S., 2023. Testing the equity-pollution dilemma from a global perspective: does reducing consumption inequality impose environmental burdens? *Gondwana Res.* 122, 125–137. <https://doi.org/10.1016/j.gr.2023.05.022>.
- Heron, T., Prado, P., West, C., 2018. Global value chains and the governance of 'embedded' food commodities: the case of soy. *Glob. Policy* 9, 29–37. <https://doi.org/10.1111/1758-5899.12611>.
- Huang, S., An, H., Viglia, S., Buonocore, E., Fang, W., Ulgiati, S., 2017. Revisiting China-Africa trade from an environmental perspective. *J. Clean. Prod.* 167, 553–570. <https://doi.org/10.1016/j.jclepro.2017.08.171>.
- Jia, F., Peng, S., Green, J., Koh, L., Chen, X., 2020. Soy supply chain management and sustainability: a systematic literature review. *J. Clean. Prod.* 255, 120254. <https://doi.org/10.1016/j.jclepro.2020.120254>.
- Kamp, A., Ambye-Jensen, M., Østergård, H., 2019. Modeling matter and energy flows of local feed refined with grass clover protein as an alternative to imported soybean meal. *Ecol. Model.* 410, 108738. <https://doi.org/10.1016/j.ecolmodel.2019.108738>.
- Kanashiro Uehara, T., 2024. Planetary Wellbeing Principles for just and sustainable futures: a compass for system change, trade reforms, and transformations. *Sci. Pract. Policy* 20 (1). <https://doi.org/10.1080/15487733.2023.2300885>.
- Liu, X., Liu, G., Yang, Z., Chen, B., Ulgiati, S., 2016. Comparing national environmental and economic performances through emergy sustainability indicators: moving environmental ethics beyond anthropocentrism toward ecocentrism. *Renew. Sustain. Energy Rev.* 58, 1532–1542. <https://doi.org/10.1016/j.rser.2015.12.188>.
- Liu, Z., Wang, Y., Geng, Y., Li, R., Dong, H., Xue, B., Wang, S., 2019. Toward sustainable crop production in China: an emergy-based evaluation. *J. Clean. Prod.* 206, 11–26. <https://doi.org/10.1016/j.jclepro.2018.09.183>.
- Medina, Gabriel, da, Silva., 2022. The agribusiness economy in developing countries: areas of opportunities for a new development paradigm in the soybean production chain in Brazil. *Front. Sustain. Food Syst.* 6, 842338. <https://doi.org/10.3389/fsufs.2022.842338>.
- Mendes dos Reis, J.G., Sanches Amorim, P., Sarsfield Pereira Cabral, J.A., Tolo, R.C., 2020. The impact of logistics performance on Argentina, Brazil, and the US soybean exports from 2012 to 2018: a gravity model approach. *Agriculture* 10 (8), 338. <https://doi.org/10.3390/agriculture10080338>.
- Méndez Rodríguez, C., Salazar Benítez, J., Rengifo Rodas, C.F., Corrales, J.C., Figueroa Casas, A., 2022. A multidisciplinary approach integrating emergy analysis and process modeling for agricultural systems sustainable management—coffee farm validation. *Sustainability*. (Switz.) 14 (14), 8931. <https://doi.org/10.3390/su14148931>.
- Motakefi, M., Dahmardeh, M., Ghanbari, S.A., Asgharipour, M.R., 2025. A comparative study of production systems in the Goharkuh Taftan complex utilising emergy and economic analysis. *Ecol. Modell.* 500, 110947. <https://doi.org/10.1016/j.ecolmodel.2024.110947>.
- Nassif, A., Bresser-Pereira, L.C., Feijo, C., 2018. The case of reindustrialization in developing countries: towards the connection between the macroeconomic regime and industrial policy in Brazil. *Camb. J. Econ.* 42 (2), 355–381. <https://doi.org/10.1093/cje/bex028>.
- Odum, H.T. (1996). *Environmental accounting: emergy and environmental decision making*.
- Ortega, E., Cavalett, O., Bonifácio, R., Watanabe, M., 2005. Brazilian soybean production: emergy analysis with an expanded scope. *Bull. Sci., Technol. Soc.* 25 (4), 323–334. <https://doi.org/10.1177/0270467605278367>.
- Rotolo, G.C., Francis, C.A., Ulgiati, S., 2018. Environmentally sound resource valuation for more sustainable international trade: case of Argentine corn. *Resour. Conserv. Recycl.* 131, 271–282. <https://doi.org/10.1016/j.resconrec.2017.10.008>.
- Samaniego, P., Vallejo, M.C., Martínez-Alier, J., 2017. Commercial and biophysical deficits in South America, 1990–2013. *Ecol. Econ.* 133, 62–73. <https://doi.org/10.1016/j.ecolecon.2016.11.012>.
- The International Fair Trade Charter, 2018. <https://www.fair-trade.website/the-charter-1>. Accessed July 2, 2024.
- Tian, X., Geng, Y., Buonocore, E., Sarkis, J., Ulgiati, S., 2018. Discovering resource losses and gains in China's foreign trade. *J. Clean. Prod.* 191, 78–86. <https://doi.org/10.1016/j.jclepro.2018.04.210>.
- Tian, X., Geng, Y., Viglia, S., Bleischwitz, R., Buonocore, E., Ulgiati, S., 2017. Regional disparities in the Chinese economy. An emergy assessment of provincial international trade. *Resour. Conserv. Recycl.* 126, 1–11. <https://doi.org/10.1016/j.resconrec.2017.07.017>.
- Tilley, D.R., Brown, M.T., 2006. Dynamic emergy accounting to assess the environmental benefits of subtropical wetland stormwater management systems. *Ecol. Modell.* 192 (3–4), 327–361. <https://doi.org/10.1016/j.ecolmodel.2005.07.034>.
- Ting, Y.I., Xiang, P.A., 2016. Emergy analysis of rice cultivation in Hunan Province, China: a new perspective on sustainable agricultural development. *J. Integr. Agric.* 15 (10), 2426–2436. [https://doi.org/10.1016/S2095-3119\(16\)61375-8](https://doi.org/10.1016/S2095-3119(16)61375-8).
- Toloi, M.N.V., Bonilla, S.H., Toloi, R.C., Silva, H.R.O., 2021. Nääs, IdA Development indicators and soybean production in Brazil. *Agriculture* 11, 1164. <https://doi.org/10.3390/agriculture11111164>, 2021.
- Ulgiati, S., Brown, M.T., 2009. Ecosystem emergence and complexity. *Commun. Nonlinear Sci. Numer. Simul.* 14 (1), 310–321. <https://doi.org/10.1016/j.cnsns.2007.05.028>.
- Wang, X., Tan, K., Chen, Y., Chen, Y., Shen, X., Zhang, L., Dong, C., 2018. Emergy-based analysis of grain production and trade in China during 2000–2015. *J. Clean. Prod.* 193, 59–71. <https://doi.org/10.1016/j.jclepro.2018.05.072>.
- Wu, F., Geng, Y., Zhang, Y., Ji, C., Chen, Y., Sun, L., Fujita, T., 2020. Assessing the sustainability of soybean supply in China: evidence from provincial production and trade data. *J. Clean. Prod.* 244, 119006. <https://doi.org/10.1016/j.jclepro.2019.119006>.
- Xavier, D.L.D.J., Reis, J.G.M.D., 2022. Social network analysis on agricultural international trade: a study on soybean, soybean cake and maize exports. *Chem. Proc.* 10 (1), 37. <https://doi.org/10.3390/IOCAG2022-12319>.
- Yu, X., Geng, Y., Dong, H., Ulgiati, S., Liu, Z., Liu, Z., Sun, L., 2016. Sustainability assessment of an industrial region: a combined method of emergy analysis and IPAT (Human impact population affluence technology). *Energy* 107, 818–830. <https://doi.org/10.1016/j.energy.2016.04.092>.
- Zhao, H., Zhai, X., Guo, L., Liu, K., Huang, D., Yang, Y., Wang, K., 2019. Assessment of the efficiency and sustainability of wheat production systems in different climate zones in China using emergy analysis. *J. Clean. Prod.* 235, 724–732. <https://doi.org/10.1016/j.jclepro.2019.06.251>.
- Zheng, X., Liu, X., Pan, H., 2023. Assessment of the co-benefits of the integrated livestock and agricultural land system based on emergy, carbon footprint and economic return. *Environ. Sci. Pollut. Res.* 30 (3), 6117–6131. <https://doi.org/10.1007/s11356-022-22598-5>.
- Zhong, S., Geng, Y., Kong, H., Liu, B., Tian, X., Chen, W., Ulgiati, S., 2018. Emergy-based sustainability evaluation of Erhai Lake Basin in China. *J. Clean. Prod.* 178, 142–153. <https://doi.org/10.1016/j.jclepro.2018.01.019>.