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Modern colonialism in carbon markets? Insights from emergy accounting

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A B S T R A C T

Climate change demands mitigation actions, and the international carbon credit market has emerged as a key strategy, as recognized by the Kyoto Protocol and, more recently, the Paris Agreement. However, carbon credit exchanges between developed and developing countries have increasingly reflected a pattern of Modern Colonialism, as market prices typically based on willingness-to-pay fail to capture the true value of ecosystem services provided by credit-generating countries. To address this imbalance, scientific tools that assess 'value' from the donor's perspective are essential, in which Emergy Accounting and its Emergy Exchange Ratio (EER) offers a promising approach. This study applies the EER to assess Brazil's carbon credit transactions from 2004 to 2019. Results show that Brazil exported between 25 and 43 times more emergy than it received in monetary return, indicating a significant ecological-economic imbalance. A biophysical value per ton of CO_2-eq. under the emergy perspective would be up to 40 times higher than market prices, resulting in an estimated cumulative loss of approximately USD 523 million for Brazil over the period analyzed. Although resolving the structural roots of unequal ecological exchange is beyond the scope of this study, our analysis contributes by focusing on one measurable dimension of that inequality. To tackle the disparities identified in Brazil's carbon credit trade, two main actions are proposed: (i) adjusting the price of carbon credits through diplomatic engagement, active participation in multilateral forums, and the establishment of minimum pricing based on biophysical metrics; and (ii) forming trade partnerships with countries that have higher Emergy per Money Ratios (EMRs), thereby enhancing emergy-based purchasing power. This study highlights the EER as a valuable tool for renegotiating equitable trade terms, guiding the valuation of ecosystem services, and promoting environmental justice. Future work should explore its integration into regulatory frameworks, including Brazil's upcoming Emissions Trading System, to foster more equitable carbon market dynamics.

1. Introduction

Concerns about the preservation and sustainable use of natural resources gained prominence in the 1990s, driven by growing awareness of climate change as a consequence of the increasing concentration of greenhouse gases (GHGs) in the atmosphere, associated with the technological, scientific, and socioeconomic advancements of the 20th century (IPCC, 2021; Parisa et al., 2022). In response to this scenario, the United Nations established the Framework Convention on Climate Change (UNFCCC) and began to promote regular forums with the participation of member countries, aiming to establish agreements focused on developing strategies to reduce GHG emissions. These meetings became known as the Conference of the Parties (COP), starting in 1991 with COP1, which centered on the pursuit of a more sustainable development model (Souza, 2012). In 2025, the COP will reach its 30th edition, which will be hosted in Brazil. A major milestone in this process took place during COP3, held in 1997 in Japan, with the signing of the Kyoto Protocol. This agreement established, among other guidelines, the carbon credit market, defined as the equivalent amount of CO_2 emissions avoided by a country or company as a result of public and private policies aimed at mitigating GHG emissions. According to Spilker and Nugent (2022), one of the key instruments of the Kyoto Protocol was the Clean Development Mechanism (CDM), which allowed more developed countries (38 nations defined by the UN) to purchase carbon credits generated by projects in developing countries. The objective was to enable these developed nations to meet their GHG reduction targets more efficiently, as established by the Protocol.

A carbon credit is a quantitative unit that represents the reduction or

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removal of one metric ton of carbon dioxide (CO_2) from the atmosphere. This reduction directly contributes to combating the greenhouse effect and to meeting the goal of limiting global warming to no >1.5 °C above 1990 baseline levels (Vargas et al., 2021). Currently, carbon credits function as tradable assets in two main types of global markets: the regulated market, in which prices and emissions are controlled by public authorities or institutional entities; and the voluntary market, operated by independent platforms where credits are traded directly between organizations and governments without the need for registration with the UNFCCC (Sobrinho, 2023). The trading of carbon credits began with the creation of the Clean Development Mechanism (CDM), which established a regulated market under the supervision of the UNFCCC. Starting in 2004, the mechanism led to the development of around 8000 projects in approximately 100 countries (Bittencourt et al., 2018). In Brazil, between 2004 and 2019, 345 projects were approved by the Clean Development Mechanism (CDMEB). However, the replacement of the CDM by the Paris Agreement in 2015 brought significant changes to the functioning of the global carbon market, creating uncertainty and requiring time for adaptation, standardization, and the creation of new control mechanisms. Specifically in Brazil, this transition left the country temporarily without a regulated carbon market until December 2024, when Law No. 182/2024 was finally approved and enacted, establishing the legal framework for the operation of the national carbon market.

The carbon market established by the Clean Development Mechanism (CDM) reflects the structural inequality between the economies of developed countries (with high GHG emissions) and less developed countries, which supply the carbon credits. The former, with urbanized economies and industrial sectors focused on resource-use efficiency, face complex and costly challenges in reducing emissions. The latter, with activities predominantly in the Energy and Agriculture, Forestry, and Other Land Use (AFOLU) sectors, have greater technical potential for emission reductions and credit generation (IPCC, 2014; Sobrinho, 2023). This asymmetry is also reflected in the monetary structure of the market, where transactions are carried out in strong international currencies (e.g., USD). In this context, credit-supplying countries - typically from the Global South - must exert significantly greater social, environmental, and biophysical effort to earn the same amount of hard currency, due to the systemic undervaluation of their ecosystem services. This reflects not just a disparity in purchasing power, but a deeper structural imbalance in how environmental contributions are compensated within global trade mechanisms. As highlighted by Hornborg (2009) and Martinez-Alier (2002), this configuration mirrors broader patterns of ecologically unequal exchange, in which the Global South delivers valuable environmental services and natural resources while receiving insufficient compensation, both in monetary and developmental terms. The CDM thus operates under the same logic as international commodity trade, where developing nations export low-value raw materials or ecosystem services underpricing conditions set by developed countries. In this context, Lyons and Westoby (2014) describe such dynamics as a form of 'carbon colonialism', whereby countries in the Global North offset their emissions through mitigation activities in the South, without properly addressing the environmental burdens or reinforcing structural dependencies embedded in such exchanges. This concept draws from broader critiques of modern colonialism in environmental governance, where global climate solutions reproduce historical patterns of appropriation and control (Svampa, 2015; Hornborg and Martinez-Alier, 2016), masking asymmetries behind ostensibly cooperative mechanisms. Rather than direct territorial domination, this form of colonialism operates through market-based instruments such as carbon trading, which mask structural asymmetries and enable the appropriation of ecological value without fair compensation.

An adequate determination of the appropriated value of carbon credits is essential for effective and fair carbon trading. However, traditional monetary valuations typically based on willingness-to-pay often fail to capture the full range of actors and processes involved in carbon sequestration. In particular, the role of Nature as the primary agent in the carbon capture process is largely overlooked, which reflects a broader tendency to evaluate ecosystem services through utilitarian or market-based lenses (Castree, 2003; McAfee, 1999). As a result, financial compensation for carbon credits may not reflect the ecological or biophysical effort embedded in their generation. From a biophysical perspective, 'value' can instead be interpreted in terms of the donor-side effort, i.e. the total energy and natural capital required to make a product or service available. This approach underpins Emergy Accounting, developed by Odum (1996), which quantifies the environmental support work in common biophysical units and provides a means of assessing whether the exchanges involved in mechanisms like the CDM are ecologically balanced. By incorporating emergy indicators such as the Emergy Exchange Ratio (EER), it becomes possible to expose systemic undercompensation and illuminate the invisible asymmetries of carbon markets that otherwise remain hidden under conventional economic metrics (Foster and Holleman, 2014; Gómez-Baggethun and Ruiz-Pérez, 2011).

Emergy is defined as 'the available energy of one kind previously used up directly and indirectly to make a service or product' (Odum, 1996). It is a tool with a biophysical approach that understands the concept of 'value' from the donor's perspective, rather than from the receiver's - as typically adopted by economic science methods. Emergy considers the effort exerted by nature to produce and make a good or resource available. Given these characteristics (its biophysical basis that which avoids subjective or market-based valuations, its donor-side perspective in assessing value, and its capacity to account for the quality and hierarchy of different energy forms), emergy accounting emerges as a particularly suitable tool for evaluating exchanges. This makes it highly relevant for assessing fairness and transparency in carbon market transactions, from a biophysical approach. Among its various indicators, the Emergy Exchange Ratio (EER) stands out, whose equation relates the emergy delivered to the emergy received. This is the most appropriate indicator for studying exchanges, including the trade of carbon credits. EER has already been used in several studies on exchanges between countries and regions. For example, when studying the production and trade of coffee in Nicaragua, Cuadra and Rydberg (2006) concluded that all purchasers benefit up to 3 times (depending on the trading partner) when buying green coffee from Nicaragua; on the other hand, sales to the local market represented a more equitable exchange for Nicaragua. Cavalett and Ortega (2007) evaluated soybean exports from Brazil and found that the country delivers about 5 times more emergy in exported soybeans than it receives in monetary return. Tian et al. (2017) analyzed regional disparities in the Chinese economy between 1993 and 2012, focusing on the provinces. The authors concluded that external trading partners gained more advantages than their Chinese counterparts, although the eastern provinces of China performed significantly better than those in the central and western regions. Rótolo et al. (2018) investigated Argentina's corn exports and concluded that, whether considering international traders or national trading organizations, there was a disadvantage for Argentina. The EER values were 1.96 and 1.09, respectively, indicating that the country exports more emergy in the form of corn than it receives in monetary compensation; however, the value of 1.09 suggests a nearly balanced exchange. These and other studies that used EER as the main indicator to assess exchanges demonstrate its relevance as a more objective biophysical approach, in contrast to the subjective methods of neoclassical economics such as willingness-to-pay.

Recognizing the importance of carbon credit trading as one of the strategies to mitigate climate change, and also acknowledging that current pricing practices are often grounded in business-as-usual approaches that fail to adequately reflect the biophysical effort of Nature in supporting these credits, this study applies the EER emergy-based indicator to quantify and discuss more equitable pricing for carbon credits. The objective is to assess, in biophysical terms, the effort of natural ecosystems in credit-supplying countries, thereby avoiding a commercial dynamic that may be characterized as a form of modern colonialism. Using Brazil as a case study, this research analyzes all carbon credits issued under the CDMEB between 2004 and 2019, across multiple sectors as defined by the UNFCCC. While the analysis centers on Brazil, the proposed approach is applicable to other countries as well.

2. Theoretical background: unequal ecological exchange and environmental value appropriation

Although the primary focus of this article is not to explore the structural, historical, or institutional causes of global trade asymmetries, it is essential to situate our biophysical analysis within the broader theoretical frameworks that have long examined these imbalances. The literature on Ecologically Unequal Exchange (EUE) provides a critical context for understanding why certain countries systematically receive less in return for the environmental services and resources they export. By briefly reviewing this literature, we aim to frame our emergy-based findings as part of a larger discussion on environmental justice and systemic inequality.

In recent decades, the concept of Ecologically Unequal Exchange (EUE) has become central to explaining the persistent asymmetries in global trade of materials, energy, and ecosystem services. Drawing from world-systems theory and ecological economics, Hornborg (2009) contends that industrialized nations uphold their high levels of material consumption by systematically displacing environmental burdens to less affluent nations, including pollution, resource depletion, and land degradation. The author emphasized that global sustainability discourse often conceals these structural inequalities, promoting the illusion that technological and market-based solutions can resolve what are, in fact, deeply political and systemic problems. Extending this critique, Hornborg and Martinez-Alier (2016) highlighted how EUE is not merely a pattern of uneven material flows but a historical and political process through which core countries externalize environmental costs while benefiting economically. The authors argue that this process has created a condition of ecological debt, wherein the Global North owes a form of compensation to the Global South for the cumulative appropriation of ecological capacity (such as carbon sinks, biodiversity, and land) and for the unpaid labor embodied in resource exports. Martinez-Alier (2002) developed the notion of ecological debt by linking it to environmental justice struggles across the world, especially in Latin America, Asia, and Africa. The author demonstrated how local and Indigenous communities have historically borne the brunt of resource extraction, pollution, and biodiversity loss, all while receiving limited or no economic returns. Together, these contributions frame EUE not only as a matter of physical imbalance, but also as an ethical and political issue, central to any meaningful dialogue on sustainability, environmental justice, and global responsibility.

Dorninger et al. (2021) conducted a global analysis of material flows and found consistent patterns of net appropriation of biophysical resources by core countries from peripheral ones. Their findings demonstrate that these flows are not random but are structurally embedded in the global economy. Similarly, Hickel et al. (2022) used trade and labor data to estimate the monetary value of these asymmetric exchanges, concluding that countries of the Global South lost approximately USD 152 trillion between 1990 and 2015 through unequal exchange. This value results from the systematic undervaluation of exported raw materials and labor-intensive goods, relative to the value of imports from the Global North. According to the authors, this drain amounted to an average annual net outflow of USD 6.2 trillion, which is several times greater than the total aid received by the Global South in the same period. These figures underscore how unequal exchange not only perpetuates underdevelopment but also undermines the very notion of global economic convergence.

The role of Latin America in these dynamics has been especially prominent. Dorninger and Eisenmenger (2016), in their study of Argentina, Bolivia, and Brazil, demonstrated how these countries are deeply entangled in unequal exchange relations, acting as net exporters of materials while importing goods of higher monetary value. Corsi et al. (2024) argue that this pattern reflects a structural dependency, where peripheral economies are locked into roles as resource suppliers, despite discourses of development and modernization. Bruckner et al. (2023), focusing on EU consumption between 1995 and 2019, found that while >85 % of the economic value added from production remained within the European Union, large shares of the associated environmental pressures (including greenhouse gas emissions, material extraction, land use, and air pollution) were outsourced to other regions, particularly the Global South and Eastern Europe. The study showed that the highest environmental pressures per unit of GDP induced by EU consumption occurred in Eastern European countries such as Bulgaria and Romania. Moreover, over the 25-year period analyzed, the environmental footprint of EU consumption decreased within EU borders but increased abroad, underscoring a clear externalization of ecological costs. These findings reinforce the idea that ecological and economic benefits are asymmetrically distributed in global trade, a core concern of EUE theory.

Hornborg (2009) highlighted how mainstream sustainability discourse often ignores or actively conceals the structural inequalities underlying global environmental relations, favoring technocratic and depoliticized solutions that do not challenge the existing distribution of power. According to the author, prevailing narratives tend to treat sustainability as a technical problem of efficiency or innovation, rather than a political problem of access, responsibility, and historical debt. The study identified a series of ideological illusions that help maintain this status quo, including the belief that market prices reflect reciprocity, that technological development is neutral and universally accessible, and that sustainability can be achieved without confronting systemic global asymmetries. By relying on concepts such as 'green growth' and voluntary carbon markets, mainstream approaches often repackage inequality in the language of progress, sidestepping the deeper issues of resource appropriation and environmental injustice.

This critique directly connects to the concept of 'modern colonialism', also referred to as 'carbon colonialism', which has gained traction in recent debates over global climate governance. Lyons and Westoby (2014) used the term to describe how carbon offset mechanisms (such as those promoted under the Clean Development Mechanism) allow developed countries to maintain high emissions domestically while outsourcing mitigation responsibilities to the Global South. These arrangements are often justified as 'win-win' solutions but in practice reinforce asymmetries in power, land control, and environmental responsibility. Similarly, Svampa (2015), analyzing the extractivist model in Latin America, argues that even progressive governments have perpetuated colonial dynamics by intensifying large-scale resource exploitation in the name of development and fiscal revenue. This process, framed as part of the 'commodities consensus', deepens territorial dispossession and socio-environmental conflict, especially for Indigenous and rural communities.

A critique in the ecologically unequal exchange literature is the commodification of nature, i.e. the process by which ecological functions and elements are transformed into marketable goods, often stripped of their ecological complexity and social significance. For instance, Castree (2003) reviewed how capitalist economies systematically reframe nature as a set of discrete commodities, making them legible to markets but alienated from their original contexts. McAfee (1999) critiqued the emergence of green 'developmentalism', in which biodiversity and ecosystems are economically valued under the justification of conservation, yet in practice tend to consolidate benefits among global elites while marginalizing local communities. Similarly, Gómez-Baggethun and Ruiz-Pérez (2011) warned that the growing reliance on economic valuation of ecosystem services risks promoting unintended consequences, such as reinforcing privatization, commodification, and unequal access to natural resources, particularly in vulnerable populations. These critiques suggest that market-based environmental instruments, while well-intentioned, can inadvertently reproduce or even intensify the very injustices they aim to address.

In response to these concerns, the emergy accounting method (Odum, 1996), although originally developed within systems ecology, offers a non-monetary, biophysical framework for visualizing systemic imbalances in the exchange of environmental goods and services. Rather than assigning 'value' based on market preferences or willingness to pay, emergy focuses on the donor-side effort, i.e. the total energy required by nature to generate a product or service. Its Emergy Exchange Ratio (EER) indicator has been applied in various contexts to assess unequal biophysical exchanges between nations, sectors, or production systems. However, the contribution of our study lies in applying the EER specifically to the Brazilian carbon credit market, a domain not yet examined through this lens. By quantifying the emergy delivered in carbon sequestration relative to the monetary compensation received through carbon credit transactions, we offer a novel perspective on how market-based climate mechanisms may continue to reinforce or even deepen ecological and economic asymmetries under the guise of environmental progress. Foster and Holleman (2014) argued that Odum's framework can be used dialectically to integrate ecological energetics with Marxian value theory, allowing a critique of capitalist appropriation of nature that is grounded in biophysical metrics. However, Hornborg (2014) warned against conflating energetic flows with economic value, noting that such equations can obscure the social and political dimensions of exchange. In line with this caution, we do not propose the EER as a pricing mechanism, but as a diagnostic tool that highlights the disparity between what ecosystems deliver and what is compensated monetarily.

In summary, while this study adopts a technical and diagnostic approach, it is conceptually anchored in the broader tradition of EUE scholarship. By quantifying an example of emergy-based environmental inequity in the carbon market, we aim to contribute empirically to debates on environmental justice and the structural conditions that sustain unequal ecological exchange. Our intent is not to provide a comprehensive socio-political analysis, but to supply robust physical evidence that can inform and support broader critiques of environmental appropriation and undercompensation in global trade. In the following section, we present the methodological approach used to quantify this imbalance, focusing on the Emergy Exchange Ratio (EER) as a diagnostic tool for evaluating Brazil's role in the international carbon market.

3. Methods

3.1. Emergy exchange ratio (EER) calculation procedure

Emergy accounting (Odum, 1996) is the scientific tool considered in this study to quantify and support discussions on carbon credit trading. It is an accounting tool in which all inputs and outputs of materials, energy, labor, and information are accounted for and then converted into solar emjoules (sej) using Unit Emergy Values (UEVs). In summary, its synthesized form is applied in three main steps: (i) Development of the energy diagram of the system being studied, using standardized symbols as suggested by Odum (1996); (ii) Preparation of the accounting table, which includes all input and output values of resources that support the functioning of the productive system, where they are classified as renewable, non-renewable, and those originating from the economy, and finally converted into sej units through the UEVs; (iii) Calculation of emergy performance indicators, which allow for comparative discussions between systems, management tools through sensitivity analyses, and even the development of alternative scenarios.

In this study, the traditional application of the method as presented in steps (i) and (ii) is not considered, since, unlike an evaluation of a production process, this study aims to quantify, in emergy units, the commercial exchanges related to carbon credits between countries. For this purpose, among the various diagnostic indicators provided by the method, the Emergy Exchange Ratio (EER) proves to be the most appropriate for this evaluation. As defined by Brown and Ulgiati (2004), the EER 'is always expressed relative to one or the other trading partners and is a measure of the relative trade advantage of one partner over the another". Odum (1996) dedicated an entire chapter in his book (Chapter 11) to presenting and discussing the EER, due to its macroeconomic importance and its value as a tool for decision-making on a large scale.

Fig. 1 presents a schematic representation of how the Emergy Exchange Ratio (EER) is calculated in this study. Brazil is used as a case study, but the methodological approaches applied here can be easily replicated, as long as relevant data are available. Basically, Brazil sells its carbon credits (after a rigorous process of verification and validation) to countries interested in purchasing them; the solid line arrow in Fig. 1 illustrates this sale of carbon credits. In return, the purchasing country pays Brazil in international currency (USD) for the acquired credits, and this payment must be used for purposes agreed upon in a contract; the dashed arrow represents the monetary payment for the purchased credits. The idea behind the EER is simple: for a balanced exchange, the emergy exported by Brazil in the form of carbon credits should equal the emergy received by Brazil in the form of money. As shown in the equation in Fig. 1, in the case of a balanced exchange, the EER would equal 1. When EER$>$1, more emergy is being delivered than received, meaning Brazil is at a disadvantage in the trade. When EER$<$1, Brazil would be at an advantage over the carbon credit purchaser, as a higher amount of emergy is being paid to Brazil in the form of money than what is being received in the form of carbon credits by the purchasing country. Further details on the use and applications of the EER indicator can be found in Odum (1996), as well as in other case studies including: Campbell and Tilley (2014), who developed the Eco-price to relate environmentally derived services and currency; Pan et al. (2024), who evaluated China-U.S.A. trade between 2001 and 2020; Dong et al. (2014), who assessed exchanges between the Xilinguole League region and the rest of China; Wang et al. (2018), who analyzed grain production and trade by China during 2000–2015; and Giannetti et al. (2023), who used the EER to discuss poverty traps in underdeveloped countries.

As shown in the EER equation in Fig. 1, although it has a simple algebraic form, its calculation requires a large amount of data for this study, since it considers Brazil's carbon credit exchanges with other countries between 2004 and 2019. For example, data on the amount of carbon credits traded, the countries purchasing the credits, the amount of money paid for the credits, the UEV of CO_2 and its meaning, as well as the Emergy per Money Ratio (EMR) of the purchasing country, are all essential for calculating the EER over the study period and achieving this study's objectives. For better understanding, each of these variables, along with their criteria and data sources, is presented separately in the following subsections.

3.1.1. Data on carbon credit trading

As carbon credit trading is still in its developmental stages - both in terms of defining criteria and standardizations, as well as in the establishment of regulatory bodies - at the time this study was conducted, there was no data source available on the transactions that had taken place. This situation is further complicated by the existence of both regulated and voluntary carbon credit markets. The absence of a central authority to regulate, arbitrate, and maintain a database on the volume of carbon credits, the values traded, and the parties involved (i.e., buyers and sellers), made it difficult to obtain data for the development of this study.

The carbon credit market began in 2004, following the regulation and definition of mechanisms under the Kyoto Protocol in 1997. At that time, the Clean Development Mechanism (CDM) was introduced - a voluntary flexibility mechanism that enabled developing countries to create projects aimed at reducing greenhouse gas emissions. These projects generated credits that could be traded with interested developed countries. According to Souza (2012), since 2004 Brazil has submitted projects for monitoring and approval by the Clean Development Mechanism Executive Board (CDMEB), managed by the United Nations

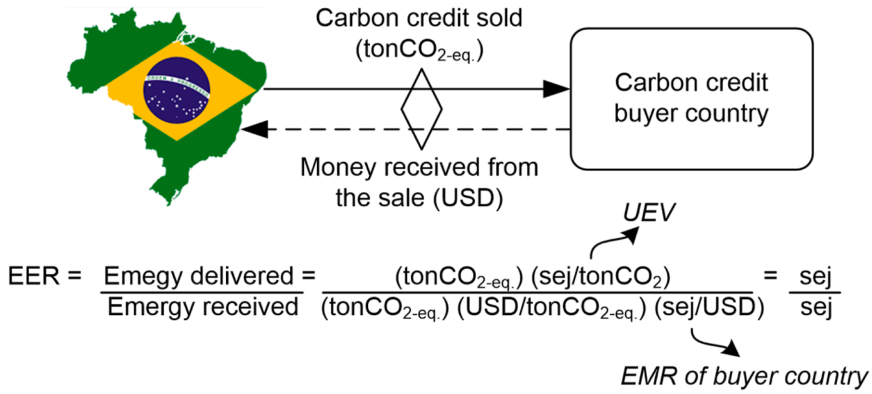

Fig. 1. Schematic representation of Brazil's carbon credit sales to purchasing countries, and the calculation of the Emergy Exchange Ratio (EER). UEV= Unit Emergy Value; EMR= Emergy per Money Ratio.

Framework Convention on Climate Change (UNFCCC). According to Silva Junior et al. (2010), the CDMEB was the body responsible for approving CDM projects, supervising their implementation, and issuing Certified Emission Reductions (CERs), the official documentation used for the commercialization of carbon credits. Due to rapid changes in global carbon credit trading negotiations and criteria, the CDM ceased to operate for new projects in 2021, marking a significant shift in the international approach to climate change mitigation.

The CDMEB's oversight includes information on registered projects, the quantity of carbon credits released for sale, and the countries interested in purchasing these credits for each project. However, there is no control over the actual amounts traded or the prices agreed upon by the parties involved. These specific details of the transactions were considered confidential and remained restricted to the project owners, buyers, and carbon credit brokers. In any case, the CDMEB database available through the UNFCCC (2025) was the only reliable and high-quality data source accessible for this study, even though it is understood that the data is likely underestimated to some extent, since not all carbon credit transactions during this period went through the CDMEB, particularly those in the voluntary market. The figures indicate a total of 345 Brazilian projects registered between 2004 and 2019, which together released approximately 50 million tons of CO_2 equivalent ($tonCO_{2\text{-eq.}}$) for commercialization. Table 1 shows the amount of $tonCO_{2\text{-eq.}}$ traded by Brazil each year, with the highest volumes recorded in 2012, 2006, 2005, and 2008, respectively. Our analysis includes all carbon credits issued to Brazil under the CDMEB framework between 2004 and 2019, regardless of sector. These credits span multiple sectors such as Energy, Land Use and Forestry, and Waste Management, as categorized by the UNFCCC.

Table 1
Annual amount and selling price of carbon credits traded by Brazil.

Year	Annual amount of carbon credits sold ($tonCO_{2\text{-eq.}}$)	Selling price of carbon credit ($USD/tonCO_{2\text{-eq.}}$)
2004	670,133.00	7.31
2005	6700,988.00	8.45
2006	8475,167.00	8.87
2007	1567,703.00	9.55
2008	2279,913.00	10.14
2009	1196,527.00	10.13
2010	1045,035.00	11.06
2011	1851,401.00	11.58
2012	21,636,671.00	11.85
2013	1988,893.00	12.27
2014	738,500.00	12.34
2015	292,952.00	11.83
2016	817,604.00	11.37
2017	Not Available	11.55
2018	31,595.00	11.73
2019	15,868.00	11.89

Fonte: Supplementary Material A, section A.1.

3.1.2. *Data on the revenue received by Brazil from the sale of carbon credits*

The price per ton of CO_2 equivalent ($tonCO_{2\text{-eq.}}$) during the period from 2004 to 2019 is another source of uncertainty in this study, as the UNFCCC (2025) does not provide information on the prices at which carbon credits were traded. Therefore, it was decided to use secondary data on average prices in $USD/tonCO_{2\text{-eq.}}$, as estimated in the study by Campoli and Feijó (2022). This report, issued by a major economic institution in Brazil, serves as an important reference for decision-makers.

In this report, the authors conducted a meta-analysis using studies that estimated the price of carbon through the Social Cost of Carbon (SCC) and the Marginal Abatement Cost (MAC) across different regions of the world. These data were related to variables based on the approaches of Integrated Assessment Models (IAMs), allowing the results to be extrapolated to the Brazilian context. The sample was built based on literature published between 2001 and 2019, with prices standardized to 2010 values. The explanatory variables, obtained from the World Bank, included GDP, land area, the industrial sector's share of GDP, and CO_2 emissions per capita, all of which proved to be relevant for estimating the carbon price applicable to Brazil. As shown in Table 1, the price per ton of CO_2 equivalent ranged from USD 7.31 in 2004 to USD 11.89 in 2019, displaying an overall upward trend, though it remained relatively stagnant over the last ten years.

3.1.3. *UEV of atmospheric carbon absorption by vegetal biomass*

As explained earlier, emergy flows (in sej units) are calculated based on the accounting table that integrates the inventory of the system being evaluated, along with the Unit Emergy Value (UEV; in sej/unit) of each flow accounted for in the inventory. By analogy, UEVs serve the same purpose as conversion coefficients used in Life Cycle Assessment (LCA), such as those found in various databases like Ecoinvent®. Currently, there are no standardized and controlled databases for UEV values, but efforts in this direction are being made by working groups from the International Society for the Advancement of Emergy Research (ISAER; emergysociety.com). Examples include the recently published databases by Arden et al. (2023) and De Vilbiss et al. (2024), as well as the National Environmental Accounting Data (NEAD). UEVs carry the memory - or emergy - of all the biophysical effort required along the production chain to make a given good or service available, and are considered the core of the emergy-based environmental accounting method.

The UEV for CO_2 was not found in any database, which made it necessary to estimate this value in order to meet the objectives of this study. Carbon credits can be considered the result of the ecosystem service known as carbon sequestration, which is generated by the planet's natural capital. According to Costanza et al. (1997), the term capital refers to the ‘set’ of materials and information that exists at a specific point in time and space. Every form of capital generates, either independently or in conjunction with services from other forms of capital, a flow of services that can be used to transform materials or their spatial configuration, with the aim of enhancing human well-being. From this perspective, ecosystem services can be understood as the flow of materials, energy, and information originating from natural capital, which, by combining with artificial and human capital, produces well-being. In the context of the carbon sequestration service, natural capital refers to each natural biome within a country that is capable of capturing carbon; agricultural production is not included in this accounting, as it involves biogenic carbon.

Calculating the biophysical value of these biomes is of fundamental importance for determining the biophysical value of each carbon credit, as measured by emergy theory. According to emergy algebra rules, the carbon sequestration service can be considered a co-product of each ecosystem as a whole, sustained by a given emergy input. In the case of natural Biomes, the main input considered is the average annual rainfall for each biome, converted into sej; the reason of ignoring solar radiation, geothermal heat, or other potential renewable sources is to avoid double-counting emergy from the same source. Therefore, the average value of a typical Brazilian carbon credit was calculated by dividing the average emergy input (sej/ha yr) of each Brazilian biome (Amazon Forest, Atlantic Forest, Cerrado, Pantanal, Caatinga, Pampa) by the average carbon sequestration of the aboveground vegetation in each biome (tonCO_2/ha yr), weighted by the total surface area of each Biome in Brazil. A value of 9.19E + 14 sej/tonCO_2 under the emergy baseline of 12E + 24 Sej/year was obtained, representing the effort of nature - or the emergy - in capturing one ton of CO_2 from atmosphere. This value was used as the environmental cost of each carbon credit, i.e., its UEV. Further details regarding the calculation procedures and data are provided in Supplementary Material B, section B.1.

3.1.4. Purchasing power of the countries that traded carbon credits

According to emergy theory, a macroeconomic approach to quantifying flows of materials, energy, and information can be carried out by using the relationship between the emergy that supports the development of a country or region and the gross domestic product (GDP) generated in that country or region. This relationship is known as the Emergy per Money Ratio (EMR), traditionally expressed in sej/USD. It serves as a measure of a country’s purchasing power, as it indicates how much emergy a country can buy or generate for each dollar invested. By its very nature, the EMR is an indicator that varies from year to year, possibly with less fluctuation in the demand for emergy (the numerator of the ratio) than in the GDP generated (the denominator). Exceptions occur during major global disruptions, such as the 2008 financial crisis driven by the real estate and stock market collapse in the U.S., the COVID-19 pandemic in 2019, and more recently, the economic policies of U.S. President Donald Trump.

Emergy-based environmental accounting is understood to still be in its early stages, with a growing number of researchers applying the method in their studies. In this context, standardization of the methodology and the development of a database with Unit Emergy Values (UEVs) and Emergy per Money Ratios (EMRs) would be highly beneficial, although such outcomes are expected in the medium to long term. Until a few years ago, working with EMRs in studies was a time-consuming task, as EMRs for multiple countries were not readily available across historical time series. Today, the National Environmental Accounting Database (NEAD), available at www.emergy-nead.com/home, has greatly simplified this task by providing EMRs for use by emergy analysts. In the present study, EMR data for the countries purchasing carbon credits from Brazil were extracted from NEAD on a year-by-year basis. It is important to highlight that, according to emergy theory, the EMR of the carbon credit purchasing country is used in the calculation of the Emergy Exchange Ratio (EER), since that country has a different purchasing power than Brazil, the carbon credit seller. In other words, each country has a different capacity to generate money per unit of sej invested. In a few isolated cases, the primary data from UNFCCC (2025) did not specify the country that purchased carbon credits from Brazil. In those instances, the EMR used was the average of the EMRs of the countries that purchased credits in that specific year.

3.2. Sensitivity analysis

To assess the robustness of the Emergy Exchange Ratio (EER) estimations, a univariate sensitivity analysis is conducted for the entire period between 2004–2019. As shown by the equation in Fig. 1, the EER is calculated as the ratio between the emergy exported (in the form of carbon credits) and the emergy imported (in the form of money). This analysis focused on three key parameters that influence the EER outcome: the amount of carbon traded (in ton$CO_{2\text{-eq.}}$), the Unit Emergy Value (UEV) of CO_2 (in sej/ton$CO_{2\text{-eq.}}$), and the emergy per money ratio (EMR) (in sej/USD). Each parameter was varied independently by ±10 %, ±20 %, and ±30 % around its base value, while the other two parameters were held constant. The selection of variation ranges was based on authors judgment, taking into account typical uncertainties associated with emergy assessments and market volatility in carbon pricing. Although conservative, this range is considered suitable for exploratory purposes in the context of this study. The sensitivity analysis is performed using a one-at-a-time approach, a standard technique in environmental accounting for examining parameter uncertainty. This approach allows the identification of the individual influence of each parameter on the final EER result.

For the sensitivity analysis, instead of using statistical software, the ChatGPT artificial intelligence tool (OpenAI, 2025) was used to assist in writing the Python programming scripts required for the analysis; the scripts were validated by the authors using other cases and are available as Supplementary Material B, section B.2. Finally, the programming scripts were executed using the IDLE environment in Python version 3.13.

4. Results and discussion

4.1. Diagnosis of carbon credits commercialized by Brazil and its partners

It is important to begin by recalling that an Emergy Exchange Ratio (EER) greater than 1 indicates an unfavorable exchange for Brazil, as the country would be exporting more emergy than it is receiving in return. Fig. 2 presents the historical series of the EER for the carbon credits commercialized by Brazil between 2004 and 2019. The analysis of the results reveals a clear trend of imbalance in emergy exchanges. The highest values, observed between 2004 and 2009 indicate that the country delivered between 34 and 43 times more emergy than it

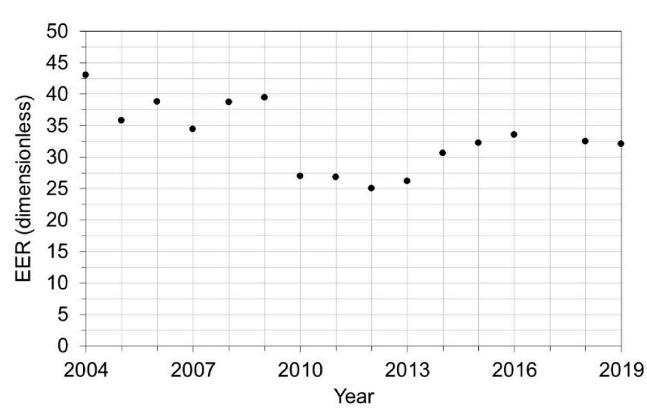

Fig. 2. Emergy Exchange Ratio (EER) resulting from Brazil’s annual sale of carbon credits and the monetary return received in exchange. Data available in Supplementary Material A, section A.2.

received. From 2010 onward, a decline in the EER is observed, with the lowest values recorded between 2011 and 2013 (ranging from 25.0 to 26.8). This decrease may reflect fluctuations in the international carbon price, changes in the composition of purchasing countries and their respective Emergy per Money Ratios (EMRs), or shifts in Brazil's bargaining power in the international market. To assess which variables most influenced the temporal variation of the EER throughout the study period, we analyzed the standard deviations of the log-transformed values of its components, using data from Supplementary Material A, section A.7. Since the EER shown in Fig. 1 is defined as the ratio of the UEV of CO_2 to the product of the carbon price and the EMR of the purchasing country, its variability is directly driven by these three components. The analysis revealed that the UEV remained constant over time and thus did not contribute to the observed variation. In contrast, the standard deviations of the log-transformed carbon price and EMR values indicated that the carbon price accounted for approximately 66 % of the variation in EER, while the EMR explained the remaining 34 %. These results highlight that fluctuations in international carbon market prices were the main factor influencing the changes in EER during the evaluated period; the social, cultural, political, and economic causes behind the variation in carbon credit prices and changes in the EMR are beyond the scope of this study.

Overall, the analysis of the EER in Brazil's carbon credit transactions from 2004 to 2019 reveals a consistently unfavorable exchange for the country. The high EER values indicate that, in emergy terms, Brazil provided 25 to 43 times more than it received in monetary return. This pattern suggests an undervaluation of Brazilian ecosystem services in the international carbon market, aligning with the findings of Giannetti et al. (2013), which point to the exploitation of natural resources without proportional benefits for the population. This can be interpreted as a 'drain' of environmental value, especially considering that carbon credits involve environmental and social externalities. This persistent imbalance, although analyzed here through a biophysical lens, is also rooted in broader structural factors. As discussed in the literature on Ecologically Unequal Exchange and carbon colonialism (e.g., Hornborg, 2009; Lyons and Westoby, 2014; Hickel et al., 2022) and earlier presented in Section 2, global trade systems often favor countries in the Global North by setting prices based on their own willingness to pay, rather than reflecting the true environmental costs borne by countries in the Global South. While exploring these causes is beyond the scope of this study, we acknowledge that the EER helps to quantify and reveal these asymmetries from a biophysical perspective, contributing to the broader discourse on environmental justice.

Although the EER stabilized around 30 starting in 2014, the values still indicate a substantially ecologically unequal exchange, with recurring advantages for the purchasing countries. The absence of sales in 2017 raises important questions about possible institutional barriers, changes in carbon market regulations, or internal political and economic instabilities. The persistence of EERs significantly greater than 1 throughout the entire time series reinforces the critique that the international carbon market, as currently structured, primarily benefits developed countries (which generally exhibit lower Emergy per Money Ratios (EMRs) than less developed nations) while systematically undervaluing the ecosystem services provided by countries in the Global South (Hornborg, 2009; Martinez-Alier, 2002). Since the major buyers of carbon credits are economically dominant countries, this pattern of emergy undercompensation reflects a broader logic of resource appropriation embedded in global trade, consistent with the literature (e.g. Dorninger et al., 2021) on ecological debt and systemic environmental asymmetry. This dynamic has been described as a form of 'modern colonialism', or, in the words of Brown (2003), 'resource imperialism'. In a study aligned with this perspective, Lyons and Westoby (2014) examined how land in Uganda was appropriated by companies from the Global North for reforestation projects and carbon credit acquisition, a process they define as 'carbon colonialism' and a case of 'neoliberal land grabbing'. Similarly, Coscieme et al. (2018) found that the appropriation of Brazilian land by foreign investors has resulted in significant environmental value appropriation, reducing the country's natural capital and its ability to provide ecological services. Using the ecological footprint as a metric, the authors estimated that 9.3 million hectares of Brazil's biocapacity have already been lost to this practice.

The persistence of high EER values throughout the time series underscores the need to question the assumptions on which current carbon-credit prices rest. We are not suggesting that exchanges be determined solely by emergy values; rather, we contend that biophysical indicators such as the EER can serve as complementary benchmarks when policy makers discuss price floors, compensation rules, or eligibility criteria for carbon-credit transactions. Recent studies illustrate this supporting role: Nascimento et al. (2025) used emergy metrics to guide food-security policies, while Campbell and Tilley (2014) advanced the Eco-price concept to illuminate the systematic undervaluation of ecosystem services. Such applications show that biophysical information can enrich, but not replace, economic and social considerations. At the same time, we recognize that the structural asymmetries revealed by the EER, most visibly the transfer of environmental value from the Global South to the Global North, cannot be resolved through price adjustments alone. As Castree (2003) and Gómez-Baggethun and Ruiz-Pérez (2011) argue, commodifying nature often reproduces existing power imbalances. We therefore present the EER primarily as a diagnostic tool: it brings hidden biophysical transfers to light and can inform broader institutional and political debates on environmental justice, while leaving room for additional social-equity metrics and governance reforms that go beyond pricing mechanisms.

As can be seen in Fig. 3, Brazil delivered much more emergy than it received in the carbon credit trade, as the market price established by the business-as-usual (willingness-to-pay) model fails to account for the effort that nature exerts to capture the carbon released by anthropogenic emissions. Through a simple exercise, the amount of emergy Brazil lost throughout the entire period analyzed (2004–2019) can be estimated. Fig. 3 reinforces the substantial mismatch between the market price for Brazilian carbon credits (traded price) and the price that would reflect an equitable exchange in emergy (equitable price), i.e., a scenario in which the Emergy Exchange Ratio (EER) would equal 1. Throughout the entire period analyzed in this study, the prices practiced ranged from 7.31 to 12.3 USD/t$CO_{2\text{-eq.}}$, while the equitable prices calculated based on the EER should have ranged between 296.2 and 399.8 USD/t$CO_{2\text{-eq}}$. This indicates that the carbon credits sold by Brazil were systematically undervalued, being sold at prices up to 40 times lower than those necessary to compensate for the emergy invested in the CO_2 absorption effort.

According to Hornborg (1998), it is only by abandoning the pursuit of a definitive measure of value that aligns with market price, and

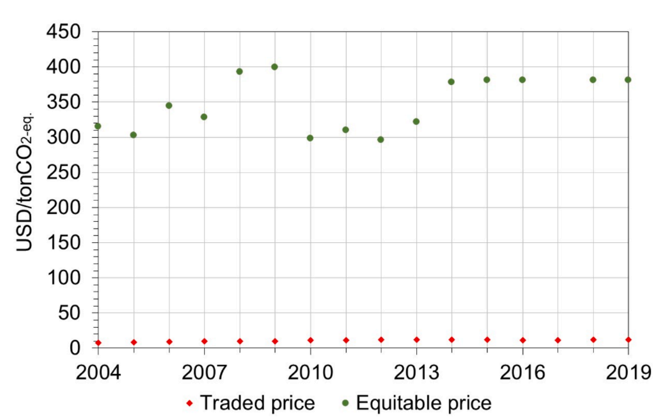

Fig. 3. Price of the carbon credit considering the actual traded price and the equitable traded price for an EER= 1. Data available in Supplementary Material A., section A.3.

accepting that such alignment is inherently unattainable, that we can fully grasp the depth of the issue and begin to envision ways to move beyond it. While acknowledging that this perspective implies structural changes in the social relations of exchange, it is also understood that short and medium-term actions, though not structural, are still important when they aim to rebalance exchanges from a biophysical perspective. With this goal in mind, other authors have been studying the pricing of carbon dioxide per tonne from a perspective more robust than simply willingness to pay. Although still grounded in traditional economic science approaches that now integrates climate sciences and social sciences, models such as PAGE09 and PAGE-ICE have been considered in estimating the social cost of carbon dioxide ($SCCO_2$), representing the total welfare loss across the globe caused by the emission of an additional tonne of CO_2. For instance, the study by Kikstra et al. (2021) estimated values ranging from 147 to 349 USD/-tonCO_2, with an average of 158 USD/tonCO_2; the authors themselves cited several other studies that also estimated the $SCCO_2$ using different models, finding values between 51 and 310 USD/tonCO_2. Included among these is the study by Pindyck (2019), who estimated values between 80 and 300 USD/tonCO_2 based on a survey approach with experts. Another important estimate was provided by Rennert et al. (2022), suggesting an average value of 185 USD/tonCO_2, using the Greenhouse Gas Impact Value Estimator model, based on the Resources for the Future Socioeconomic Projections.

For comparison purposes, it is observed that all these $SCCO_2$ estimates found in the literature, even though based on different models, are similar in order of magnitude to those obtained using the emergy-based EER, which shows variations between 300 and 400 USD/tonCO_2 in Fig. 3. These similarities lend credibility to the emergy approach as a valid framework for assessing the value of environmental compensation. However, emergy accounting offers more than just a comparable numerical result: it provides a biophysical foundation for understanding the flows of ecosystem services, independent of utility-based assumptions or willingness-to-pay criteria. Unlike conventional $SCCO_2$ models, the EER highlights donor-side ecological imbalances and allows for an explicit assessment of trade asymmetries in environmental terms. This makes the EER especially relevant for resource-exporting countries like Brazil, where undervaluation in international markets can result in significant net environmental losses that are not always captured in welfare-based approaches.

This discrepancy reveals a significant ecological-economic injustice: Brazil, as a provider of global environmental services, does not receive compensation proportional to the biophysical value of its contribution to climate change mitigation. This pattern is consistent with broader historical trends observed across Latin America, a region that has long functioned as a net exporter of low-value, resource-intensive goods while importing higher-priced manufactured products. As demonstrated by Infante-Amate et al. (2022), such trade asymmetries have resulted in enduring socio-environmental and developmental disadvantages for Latin American countries. Even in the most recent years of the series in Fig. 3, with slightly higher market values (around 11.8 to 11.9 USD/-ton$CO_{2\text{-eq.}}$), the biophysical value remains >30 times higher than the practiced value; in other words, the buyer countries of the carbon credit are paying 30 times less biophysical value than they received. By summing the total amount of carbon credits sold by Brazil over the entire period, as well as analyzing the traded and equitable prices, Brazil lost approximately 523 million USD during 2004–2019 if the EER had been equal to 1 throughout the period (Supplementary Material A, section A.4.). This money could have been used for cleaner production projects applied to production systems, as well as for reforestation projects in degraded natural areas to preserve natural capital and generate a greater quantity of environmental services.

Similar studies have also highlighted the emergy imbalance between products traded between less developed countries, referred to as 'rural' countries, and more economically developed ones. Among others, in evaluating the extraction and export of Ghanaian gold, Asamoah et al. (2017) concluded that a significant amount of resources are lost in this unbalanced export in terms of emergy. Updating the EER to reflect the ratio of emergy delivered versus received, the authors obtained EERs of 4.34 and 3.03 for two different gold mining systems evaluated. In another example, Viera-Romero et al. (2024) found that the production and export of shrimp by Ecuador reached an EER of 2.41, again indicating an emergy loss. Other examples include emergy imbalances in the export of coffee by Nicaragua (Cuadra and Rydberg, 2006), coffee in Brazil (Giannetti et al., 2011), soybeans by Brazil (Cavalett and Ortega, 2007), and maize grain by Argentina (Rótolo et al., 2018). These and other results, including those obtained in the present study, suggest that the international carbon market, as currently structured, operates under a logic of systemic undervaluation of natural resources and mitigation efforts from countries in the Global South. It is worth noting that such biophysical imbalances are not exclusive to international trade: other emergy studies have also documented similar patterns at regional and national scales, such as in agricultural systems where producers receive less emergy in return for their outputs (e.g., Giannetti et al., 2011). However, this study focuses specifically on international exchanges, given the global governance implications of carbon credit markets and Brazil's role as a provider of ecosystem services.

4.2. Sensitivity analysis

For the sensitivity analysis of the Emergy Exchange Ratio (EER) index, its three constituent variables (Unity Emergy Value (UEV), Emergy per Money Ratio (EMR), and the market value of a carbon credit (1 ton) in USD) were altered univariably by ±10 %, ±20 %, and ±30 %. The Python code was then executed using the IDLE environment in Python version 3.13, resulting in 270 combinations for EER values for the period of 2004–2019, with statistics briefly presented in Table 2. The results show how each variable impacts the magnitude of the EER while keeping all other variables constant. The results indicate that the variable with the greatest influence on the EER is the UEV. Variations of ±30 % in the UEV lead to significant changes in the EER, with an increase of + 50.92 % (from 28.50 to 43.01) and a decrease of −18.71 % (from 28.50 to 23.16). This suggests that this parameter has a direct and amplified impact on the EER, which is expected because the UEV is in the numerator of the indicator equation.

It can be observed in Table 2 that the variables EMR and USD have a negative influence on the EER, with the same magnitude. Both result in reductions of approximately −15 % (from 29.93 to 25.45) for positive variations of + 30 %, and increases of + 57.89 % (from 29.93 to 47.27) for negative variations of −30 %. The similar behavior of these two variables occurs because both are in the denominator of the EER equation, contributing equally to the reduction of the index. Increases in EMR or the market value of the carbon credit decrease the EER, while reductions in these variables increase it. The symmetry in the effects of EMR and USD reinforces that changes in either of these two variables produce a similar impact on the final result, thus making them strategic targets for manipulation of the index. On the other hand, in general, the EER response to UEV is more balanced and consistent than to EMR and USD, which is typical of a variable with more direct and controllable influence on the index.

As discussed in Odum (1996), one alternative to make the exchange

Table 2
Summary table with maximum, minimum, and average EER values obtained from the sensitivity analysis.

Variable altered	Variation (%)	Minimum EER	Average EER	Maximum EER
UEV	±30 %	23.16	28.50	43.01
USD	±30 %	25.45	29.93	47.27
EMR	±30 %	25.45	29.93	47.27

Complete data available in Supplementary Material A, tab 'Sensitivity'.

more balanced would be to avoid exporting raw materials and instead extend the production chain within Brazilian territory to transform the raw material into processed resources. In this case, the processed resource would have a higher market value and would result in more balanced EERs when traded, or could even be used internally to boost the national economy. However, carbon credits are not a good that can be transformed, instead, they can be considered a service provided, which makes their transformation into other goods impossible. Therefore, strategies to reduce the EER of Brazil's carbon credit sales to values close to or below 1 (which would reflect a more balanced exchange) should consider three main paths:

1) Reduce the value of the UEV of carbon absorption by natural biomes. Although the UEV has shown to be the variable with the greatest influence on the EER, it primarily depends on the average annual precipitation in the region of interest and the territorial extent of Brazil's natural biomes. Since there is no human direct influence over these factors – perhaps on the territorial area of the biomes, but in the long term – actions to reduce the UEV appear to be a somewhat impractical strategy.
2) Engage in transactions in a bull market scenario, maximizing the selling price of carbon credits. Market strategies that involve enhancing the climate agenda, such as international agreements, global awareness campaigns, and political pressure at events like the Conference of the Parties (COP), can help increase the market price of credits and, consequently, improve the EER performance.
3) Prioritize sales agreements with international buyers who have high EMR values, or at least values similar to those of Brazil. Selling carbon credits to countries whose economies demand more emergy per monetary unit implies that Brazil will be receiving more emergy per exported unit. This approach, already discussed by Odum (1996), is conceptually solid but faces practical limitations, as the main buyers, mostly developed countries, have low EMR ratios, making this path more challenging. In our simulation (Supplementary Material A, section A.6.), to achieve an EER equal to 1, the purchasing country (or group of countries) would need to have EMRs ranging between 7.45E13 sej/USD and 1.26E + 14 sej/USD during 2004–2019. However, it can be observed (Supplementary Material A, section A.1.) that the countries purchasing carbon credits from Brazil during this period had EMRs ranging from 1.01E + 11 sej/USD to 6.02E + 12 sej/USD, values 10 to 1000 times lower.

In summary, the sensitivity analysis showed that UEV is the variable with the greatest impact on EER, followed equally by EMR and USD. Practical strategies aimed at reducing the EER and benefiting Brazil should focus on favorable market conditions for carbon credit sales, as well as seeking to establish trade with countries that have high EMR values.

4.3. Insights and perceptions on the Brazilian carbon credits trade

4.3.1. Using the emergy exchange ratio (EER) as a tool for renegotiating minimum carbon credit selling prices

The EER can serve as a complementary instrument to conventional carbon pricing methodologies, introducing a biophysical perspective into economic valuation. While it is not intended to replace traditional economic models, the EER would offer a complementary and powerful lens through which market prices can be assessed more equitably, particularly in contexts involving environmental services such as carbon credits. By highlighting the emergy (i.e. the amount of available energy directly and indirectly required to generate a product or service), the EER can help recalibrate market values to reflect the biophysical environmental cost of carbon mitigation, contributing to a more equitable trade framework. This idea has been further developed by other authors in various contexts, including maize grain exportation in Argentina (Rótolo et al., 2018), coffee production in Nicaragua and Brazil (Cuadra and Rydberg, 2006; Giannetti et al., 2011), and assessments of regional performance (Tian et al., 2017).

In Brazil, significant investments have been made by companies to put in practice cleaner production projects to transition toward more sustainable processes. In some cases, this strategic management has yielded carbon credits that can be sold. However, the financial returns from selling carbon credits often fail to match the magnitude of these efforts. This disparity is particularly pronounced in the agribusiness sector, which is responsible for a large share of Brazilian carbon credits. Many of these credits stem from reforestation projects or the implementation and preservation of areas with natural vegetation. These preserved lands, while essential for carbon sequestration, represent an opportunity cost: they are often withheld from economically productive uses such as agriculture or cattle ranching. Thus, carbon credit revenues should be sufficient to at least offset the loss of economic utility, reinforcing the need for a more equitable pricing mechanism for international trade of carbon credits. Moreover, the application of the EER could be an important measure to counteract what has been called in this study as 'modern colonialism'. This imbalance occurs when developing nations are locked into environmentally beneficial practices without receiving commensurate compensation, perpetuating inequality under the guise of sustainability. As discussed in recent studies on the dynamic analysis of sustainable development (Giannetti et al., 2023), emergy-based indicators like the EER offer a path toward fairer international relationships by ensuring that environmental services provided by developing countries are properly valued.

As final remark, the use of emergy-based indicators such as the EER offers a compelling path to more equitable carbon credit pricing by accounting for the biophysical environmental and economic costs of mitigation efforts. Specifically for the Brazilian case, with the enactment of Law No 15,042/2024 (Brazil, 2024), which establishes the Brazilian Emissions Trading System (SBCE), there is a timely opportunity to integrate thermodynamic-based metrics like the EER into this regulatory framework. Such integration could enhance negotiation processes and help prevent unequal exchanges that resemble modern forms of colonialism. In this sense, it would be possible to prevent Brazil from remaining merely a supplier of resources - or the 'backyard' of the U.S.A. as it was referred to in April 2025 by the U.S. Secretary of Defense, Pete Hegseth - to economically stronger countries, without receiving due compensation.

4.3.2. Moving toward a global environmental fair trade system

The proposal to consider the EER as a benchmark for better evaluating exchanges between nations is theoretically well-founded by emergy theory, but its implementation presents a practical challenge. The idea of a globally regulated system for environmental exchanges (not exclusively for carbon credits) is not new, but it remains largely unrealized. Importantly, such a proposal does not originate from H.T. Odum himself, but from Scienceman (1987; APUD Odum 1996), a key contributor to emergy theory and one of its most active proponents. As highlighted by Odum (1996), Scienceman envisioned the creation of a pool of international funds, in which countries would convert their national currencies into 'Emdollars' based on their emergy per money ratios (EMR). Emdollar (usually noted as USD^{Em}) is a unit of emergy expressed in terms of money, using the emergy per money ratio to convert solar emjoules into equivalent dollars (e.g., sej * USD/sej = USD^{Em}). It represents the purchasing power of emergy and allows for expressing emergy flows in economic language, which facilitates comparison between classical economic and biophysical values. Scienceman's proposal aimed to facilitate more equitable international exchanges based on ecological effort, rather than market distortions driven by geopolitical or monetary advantages.

Although hypothetical, this suggestion could, in practice, take the form of a global environmental bank or a specialized arm of an existing institution, such as the World Bank. Given the urgency of the climate crisis, such a body could initially focus exclusively on carbon credit transactions, enabling a trial implementation of emergy-based accounting within a limited yet critical domain. As already at the center of climate negotiations, the United Nations may be the most suitable institution to manage this global environmental bank, ensuring transparency, inclusiveness, and the balancing of interests between developing and developed nations. This proposal aligns with the broader call for a global environmental fair trade system (e.g., Fairtrade America at fairtrade.net/us-en.html, and World Fair Trade Organization at wfto.com), in which countries are rewarded not only for reducing emissions but for the long-term environmental stewardship embedded in their national development pathways. Of course, turning such a proposal into reality would demand substantial political will, institutional creativity, and the integration of thermodynamic indicators like the EER into international climate and trade regimes.

Ultimately, moving toward a global environmental fair trade system demands not only financial mechanisms, but also new metrics like the EER to guide equitable exchange. The recently enacted Brazilian regulatory framework for carbon credit negotiations shows progress at the national level, but the construction of truly equitable environmental markets will depend on global cooperation and systemic shifts in how we understand and reward ecological contributions.

4.3.3. *International exchanges with emphasis on different scales*

Brazil's diverse ecological and economic regions may generate vastly different emergy flows and regional emergy per money ratios (EMRs), so it would be beneficial to explore the net emergy calculations at subnational scales. Utilizing state-level or even regional-level data could help identify contexts in which net emergy is particularly advantageous. In some cases, large-scale area may not appear beneficial for trade at the national level but could yield localized emergy gains that justify participation in emergy-based carbon credit systems. This idea is not new, since Odum (1996) discussed the case production and trade of shrimp aquaculture in Ecuador, illustrating how regional emergy advantages can influence international trade dynamics. This line of inquiry may be especially relevant for environmental governance and decentralized decision-making in countries with continental dimensions, such as Brazil.

To illustrate this idea, Table 3 presents the net emergy results based on data from 2007. The simulation was conducted only for that year due to data limitations: EMRs for Brazilian regions and states were available solely for 2007, which restricted the analysis for the full period between 2004 and 2019. It is suggested that additional analysis be undertaken in future studies as more data become available. It is important to note that this analysis assumes that all carbon credits traded by Brazil in 2007 originated exclusively from projects within the same region or state being evaluated. Based on the data presented in Table 3, it is evident that all Brazilian regions and states analyzed showed negative net emergy when trading carbon credits in 2007. This means that the emergy delivered, i.e. the environmental value embodied in the ecosystem services provided, was consistently higher than the emergy received in the form of money, regardless of the region or state in Brazil. States with greater forest cover and carbon sequestration capacity, such as Rondônia, showed especially high losses, indicating a substantial imbalance in exchanges when viewed through the lens of emergy.

Table 3 shows that the EMRs of Brazilian regions and states range from 9.88E + 11 sej/USD to 3.56E + 13 sej/USD. Therefore, some values are lower than the average EMR of the countries that bought carbon credits from Brazil in 2007, which was 2.80E + 12 sej/USD. Specifically, the states of Pernambuco, Sergipe, Rio de Janeiro, São Paulo, Santa Catarina, and Rio Grande do Sul, as well as the Southeastern region, fall into this category. Thus, a more equitable trade or positive net emergy would be expected for these states and regions as carbon credit providers. However, the trading price of 9.55 USD/ton$CO_{2\text{-eq.}}$ in 2007 meant that the emergy delivered still exceeded the emergy received in the form of money, resulting in negative net emergy across all states and regions. The worst performances were observed in São Paulo and Rio de

Table 3
Net emergy estimation for different Brazilian scales (Regions & States), base year 2007.

Brazilian regions & states	EMR (sej/USD)	Delivered emergy as carbon credit (million USD^{EM}) [a]	Received emergy as money (million USD) [b]	Net emergy (million USD) [c]
1. Northern region	1.57E + 13	78.99	14.97	-64.02
Rondônia	6.90E + 11	173.92	14.97	-158.94
Acre	1.32E + 13	108.95	14.97	-93.98
Amazonas	2.27E + 13	63.61	14.97	-48.64
Roraima	7.95E + 12	50.42	14.97	-35.45
Pará	1.80E + 13	79.99	14.97	-65.02
Amapá	3.56E + 13	40.42	14.97	-25.45
Tocantins	1.19E + 13	121.52	14.97	-106.55
2. Northeastern region	7.80E + 12	256.17	14.97	-241.20
Maranhão	3.42E + 13	42.13	14.97	-27.15
Piauí	1.02E + 13	141.47	14.97	-126.50
Ceará	5.35E + 12	270.81	14.97	-255.84
Rio Grande do Norte	4.20E + 12	344.67	14.97	-329.70
Paraíba	3.13E + 12	462.36	14.97	-447.39
Pernambuco	2.26E + 12	631.89	14.97	-616.92
Alagoas	3.22E + 12	451.35	14.97	-436.38
Sergipe	2.78E + 12	512.35	14.97	-497.38
Bahia	4.92E + 12	291.64	14.97	-276.67
3. Southeastern region	4.65E + 12	631.89	14.97	-616.92
Minas Gerais	5.27E + 12	274.74	14.97	-259.77
Espírito Santo	1.11E + 13	130.74	14.97	-115.77
Rio de Janeiro	9.76E + 11	1458.22	14.97	-1443.25
São Paulo	1.28E + 12	1115.11	14.97	-1100.14
4. Southern region	3.15E + 12	440.86	14.97	-425.88
Paraná	4.27E + 12	338.51	14.97	-323.54
Santa Catarina	2.35E + 12	611.51	14.97	-596.54
Rio Grande do Sul	2.81E + 12	512.35	14.97	-497.38
5. Central-Western region	1.23E + 13	213.00	14.97	-198.03
Mato Grosso do Sul	1.20E + 13	119.98	14.97	-105.01
Mato Grosso	1.92E + 13	75.23	14.97	-60.25
Goiás	5.65E + 12	256.17	14.97	-241.20

[a] Emdollars (USD^{EM}) calculates as: (1.44E21 sej delivered as carbon credit in 2007; data from Supplementary Material A, section A.5.) / (EMR in sej/USD, column #2 of this Table).
[b] Received money calculated as: (9.55 USD/ton$CO_{2\text{-eq.}}$) * (1.565.703,00 ton$CO_{2\text{-eq}}$ traded). Both data from Table 1.
[c] Net emergy = (USD) - (USD^{EM}).

Janeiro (approximately –1400 and –1100 million Emdollars, respectively), which are the two strongest economic performers in Brazil. While all states and regions had negative net emergy, the best performances were seen in Amapá, Maranhão, Roraima, Amazonas, Mato Grosso, and Pará, respectively, all with negative net emergy below 65 million Emdollars. From an emergy perspective at different scales, it would have been more balanced for carbon credits to be traded between these six Brazilian states and foreign countries. Moreover, the revenue from carbon credit sales should have been reinvested in projects within those same states.

These results reinforce the perception that Brazil, even at regional or state levels, when selling carbon credits without adequately considering their emergy value, ends up helping other countries achieve their carbon emissions targets at the expense of its own natural capital. The analysis, therefore, highlights the importance of incorporating indicators such as the EER into carbon pricing discussions across different scales, especially following the recent regulation of the Brazilian carbon market (Law No 14.626/2023), which established the Brazilian Emissions Trading System.

4.4. Limitations and suggestions for future research

While the present study proposes the use of the EER as a valuable instrument in assessing and negotiating carbon credit, several limitations and opportunities for further research must be acknowledged. For example, there is a need to refine the emergy accounting associated with each carbon mitigation project. The amount of emergy delivered by a given project initiative may vary significantly depending on its geographic context, specifically related to the type and productivity of the local natural biomass involved. For example, projects based in regions with higher natural biomass productivity may offer greater carbon absorption and, thus, higher emergy contributions to the global system. A more granular (different scales) calculation of emergy inputs and outputs could yield more precise EER values, instead a national average as developed in this study.

Another aspect that deserves future attention is the uncertainty analysis for enhancing the robustness of Unit Emergy Value (UEV) calculations for CO_2 traded as carbon credits. In this study, the UEV was estimated based on the natural effort required to absorb CO_2 through biomass accumulation. However, alternative approaches, perhaps based on the effort required to implement cleaner production projects and reduce GHG emissions in both rural and urban areas, may offer different perspectives on the emergy content of CO_2. Future research should explore these alternatives and evaluate their implications across various contexts. This is particularly important since the sensitivity analysis indicated the UEV as the variable that most influences the final value of the EER.

5. Conclusions

The application of the Emergy Exchange Ratio (EER) revealed that Brazil's carbon credit trade between 2004 and 2019 was markedly unfavorable. In terms of emergy - that is, the environmental value embedded in ecosystem services - Brazil delivered between 25 and 43 times more emergy than it received in monetary return. This highlights a clear ecological-economic imbalance in the country's carbon credit transactions, where the biophysical wealth exported did not find a corresponding financial equivalent. Simulations estimating an equitable price for the traded carbon credits showed that market prices were up to 40 times lower than what would be considered equitable from an emergy perspective, resulting in an estimated cumulative loss of around 523 million USD for Brazil over the analyzed period.

Since the carbon credits sold by Brazil are a service rather than a good that can be transformed to attain higher added value, the suggested strategies to rebalance these exchanges include: (i) adjusting the price of carbon credits, and (ii) establishing strategic trade partnerships. We emphasize that these actions will not resolve the structural problems underlying unequal exchanges between the Global South and the Global North, but they are important steps toward addressing one measurable dimension of that inequality. To achieve (i), the market value of Brazilian credits could be enhanced through coordinated diplomatic actions, active participation in multilateral forums such as the COPs, the incorporation of environmental justice criteria in climate negotiations, and even the creation of negotiating country blocs that demand minimum prices based on biophysical metrics such as emergy. To achieve (ii), a strategic action would be to prioritize agreements with countries whose Emergy per Money Ratios (EMRs) are higher, as these countries represent greater purchasing power in emergy terms, thus reducing imbalances in trade. While this path faces practical challenges since many of the major buyers have low EMRs, Brazil could diversify its buyer portfolio by seeking out new emerging markets with more favorable ratios.

Recognizing the limitations of this study and the need for further efforts to strengthen the insights presented, this research suggested that the use of the EER can be a promising tool for renegotiating minimum selling prices, proposing international systems for more equitable environmental trade, and evaluating exchanges at different geographic scales; all of which could contribute to avoiding 'modern colonialism'. In this regard, further studies are recommended to explore the potential implementation of the EER in regulatory, subnational, and institutional contexts such as the new Brazilian Emissions Trading System (SBCE), to ensure greater environmental justice and the proper valuation of ecosystem services provided by Brazil and other countries that sell carbon credits.

CRediT authorship contribution statement

Pedro Pierucci: Writing – original draft, Investigation, Data curation, Conceptualization. **Feni Agostinho:** Writing – original draft, Supervision, Formal analysis, Conceptualization. **Federico Sulis:** Writing – original draft, Data curation. **Cecília M.V.B. Almeida:** Writing – review & editing. **Biagio F. Giannetti:** Writing – review & editing.

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.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.ecolmodel.2025.111327.

Data availability

All data used in this study are available within the article itself or as supplementary material.

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