# Green missing spots: Information entropy on greenhouse gas emission disclosure by Brazilian companies

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## Abstract

This study aims to address a critical gap in the literature by examining the incorporation of uncertainty in measuring carbon emissions using the greenhouse gas (GHG) Protocol methodology across all three scopes. By comprehensively considering the various dimensions of CO2 emissions within the context of organizational activities, our research contributes significantly to the existing body of knowledge. We address challenges such as data quality issues and a high prevalence of missing values by using information entropy, techniques for order preference by similarity to ideal solution (TOPSIS), and an artificial neural network (ANN) to analyze the contextual variables. Our findings, derived from the data sample of 56 companies across 18 sectors and 13 Brazilian states between 2017 and 2019, reveal that Scope 3 emissions exhibit the highest levels of information entropy. Additionally, we highlight the pivotal role of public policies in enhancing the availability of GHG emissions data, which, in turn, positively impacts policy-making practices. By demonstrating the potential for a virtuous cycle between improved information availability and enhanced policy outcomes, our research underscores the importance of addressing uncertainty in carbon emissions measurement for advancing effective climate change mitigation strategies.



Keyword: Greenhouse gas emissions, Information entropy, TOPSIS, Brazil.


Word count: 6206

## 1. INTRODUCTION

The broad consensus of the scientific community on the problem of global warming has led to a series of initiatives worldwide to improve the measurement of greenhouse gas emissions (henceforth, GHG) (Hsieh et al., 2021; Cui & Cao, 2024). This aims to enable better policies and decision-making across public and private sectors and multilateral organizations. Efforts to refine various methodologies seek to reduce the degree of uncertainty associated with available information. Yet, the specific ways organizations account for and report their carbon emissions remain understudied (Iamda et al., 2024; Oyewo et al., 2024). In this context, each organization develops its methodology for evaluating actions and projects, complicating the task of comparing and assessing the social, environmental, and economic outcomes of companies. The efforts to standardize social and environmental reports, such as those by the Global Reporting Initiative (GRI) and the Dow Jones Sustainability Index (DJSI), are particularly noteworthy (Puppim de Oliveira, 2008). One of the most accepted methodologies for measuring and reporting carbon emissions is the GHG Protocol, which provides standardized frameworks for public and private organizations (García & Freire, 2014). This metric is increasingly regulated in various countries, with sanctions and benefits for reporting bodies based on observed results. Therefore, sustainability literature is now focusing on understanding and evaluating the merits and demerits of this system in the details of its three scopes.

Furthermore, it is imperative to acknowledge the multifaceted influences shaping greenhouse gas (GHG) emissions beyond organizational boundaries. Regulatory pressures and environmental policies exert significant influence on emission reduction and reporting practices. Green practices, such as renewable energy adoption and carbon offsetting initiatives, play a pivotal role in mitigating emissions and fostering sustainability. Additionally, societal expectations and stakeholder demands increasingly drive organizations to integrate environmental considerations into their operational frameworks. By delving into these broader contextual factors, our study seeks to provide a holistic understanding of how environmental policies, regulatory frameworks, and organizational practices interact to shape GHG emissions measurement and management strategies. Through this approach, we aim to offer nuanced insights into the challenges and opportunities associated with enhancing carbon emissions measurement methodologies and advancing sustainable practices in both public and private sectors.

This article aims to contribute to the literature by analyzing the degree of uncertainty involved in measuring carbon emissions with the GHG Protocol methodology across direct and indirect emissions from company activities, energy consumption, and supply chains. Since the three scopes represent different dimensions of carbon emissions in the broad context of organizations' productive activities, our study seeks to measure the sources of uncertainty using the entropy of information. To accomplish this, the study makes a general comparison over time and across scopes, considering missing values and incompleteness of information. To our knowledge, no previous studies have employed this approach in the literature.

The research presented in this manuscript addresses a critical gap in the literature regarding the measurement of carbon emissions using the GHG Protocol methodology, focusing particularly on the uncertainties associated with direct and indirect emissions across various scopes. This research has significant practical applications, informing policymakers, regulatory bodies, and organizations in both the public and private sectors, as well as multilateral institutions, about the challenges and uncertainties inherent in current carbon emissions measurement practices. By employing the novel approach of information entropy to analyze sources of uncertainty within the GHG Protocol framework, this study offers insights that can guide the refinement and improvement of carbon emissions measurement methodologies. These insights are invaluable for enhancing the accuracy and reliability of carbon emissions data reported by organizations, thereby facilitating better-informed policy decisions, more effective regulatory measures, and improved corporate sustainability practices. Ultimately, this research contributes to global efforts to mitigate climate change by providing stakeholders with a clearer understanding of the complexities and challenges associated with measuring and reporting carbon emissions.

The study is structured in four parts, in addition to this introduction. In the next section, we present the theoretical background, which includes an analysis of the GHG Protocol methodology and a review of similar entropy studies related to our approach. Following that, we detail the database used and explain and discuss the method employed to assess the entropy of information within the Brazilian context. Subsequently, we present and discuss the results of the analysis. Lastly, we offer our final considerations based on the insights gained from this study.

## 2. THEORETICAL BACKGROUND

Some methodologies gain prominence as they prove to be more robust and broadly applicable to the diversity of economic sectors, regions, and climates. In this context, the GHG Protocol is a methodology widely accepted by a variety of stakeholders involved in efforts to measure and report carbon emissions (Phupoadtong et al., 2023). Originating at the beginning of the 21st century, the GHG Protocol establishes standardized frameworks that are customizable to the reality and context of each country, creating metrics to measure and manage GHG emissions in both the public and private sectors.

In Brazil, the GHG Protocol was implemented in 2008 when the Center for Sustainability Studies of Fundação Getúlio Vargas (FGVces), in partnership with national and international actors such as the World Resources Institute (WRI) and the World Business Council for Sustainable Development (WBCSD), adapted the GHG Protocol to the Brazilian context (Mariana et al., 2016). Since then, FGVces has provided tools and support for companies to adopt the GHG Protocol, though the number of companies has been growing at a slow pace. One of the center's purposes is to encourage a culture of reporting CO2 emissions following the GHG Protocol. Mariana et al. (2016) state that the center "organizes workgroups with participating companies for the improvement of the methodology and for the development of new tools to account for GHG emissions according to the prevalent reality in Brazil."

The GHG Protocol divides CO2 emissions into three scopes. Scope 1 encompasses all emissions generated directly by a company in its production process, considering only sources owned or controlled by the company. It includes fuel combustion, company vehicles, and fugitive emissions. Scope 2 addresses indirect GHG emissions from electricity, usually generated outside a company's physical facility. Scope 3, in turn, deals with other indirect emissions not considered in Scope 2, also known as Value Chain Emissions, generally representing the largest set of emissions by a company, both upstream and downstream of its activities (Lewandowski and Ullrich, 2023). It is worth mentioning that Scope 2 uses two different methods to account for emissions, considering the different risks and opportunities associated with electricity use: the Location-Based and Market-Based Methods. As the GHG Standard (2014) report explains, "a location-based method reflects the average emissions intensity of grids on which energy consumption occurs (using mostly grid-average emission factor data), while a market-based method reflects emissions from the electricity that companies have purposefully chosen (or their lack of choice)" (p. 4).

The growing consensus on the urgency of global warming has led to increased efforts in the public and private sectors to improve tools for measuring and reporting GHG emissions. This consensus has driven a notable evolution in both the quantity and quality of environmental reports from organizations worldwide. For example, Braga et al. (2014) noted significant improvements in the level of environmental disclosure among companies in the Brazilian electricity sector from 2006 to 2009.

Alshehry and Belloumi (2017) observed a positive relationship between per capita CO2 emissions and per capita GDP, suggesting that continuous growth in some countries may not be feasible without a significant increase in CO2 emissions, given a constant energy matrix and productive structure. A contributing factor could be the energy consumption in road transport, which could degrade environmental quality as these emissions are well above the average for those countries. In this regard, the private sector has the potential to actively implement mitigation mechanisms, such as reducing total GHG emissions. Effective tools for mapping, diagnosing, and reporting GHG emissions can enable companies to play significant roles in shaping both international agreements and national legislation, providing evidence to support their positions (Andrade & Puppim de Oliveira, 2015).

Efforts are converging on initiatives that range from establishing certifications by third-party agents specialized in best practices to employing technologies to trace these certifications in the supply chains of major GHG emitters. However, there is a risk that larger emitters may opt against seeking greater transparency for themselves or within their supply chains. This underscores the importance of specialized governance in issuing and measuring traditional certificates and promoting the use of innovative technologies for more effective social control of emissions, such as blockchain-based certificates (Diniz et al., 2021).

Existing literature indicates a negative relationship between GHG emissions and the dissemination of carbon disclosure information, suggesting that higher environmental performance correlates with increased levels of environmental disclosure (Giannarakis et al., 2017). Conversely, Lemma et al. (2020) found that while companies more exposed to carbon risk tend to have lower quality financial reporting, this relationship is partially mediated by the quality of the companies' voluntary carbon disclosures.

However, Hsueh (2019) points out the existence of efforts in voluntary carbon disclosure by some global companies, primarily driven by senior managers and executives at the high administration level, in addition to the adoption of Environmental, Social, and Governance

(ESG) principles. Furthermore, it is observed that companies that are well-endowed with "complementary assets", such as investments in environmental Research & Development (R&D) or ISO 14001 certification, are more likely to voluntarily disclose more information about their emissions than required by law. Additionally, Jaggi et al. (2018) note that substantial institutional shareholdings, with the power to influence stock prices, also motivate companies to disclose higher levels of information enabling investors to better assess risk when making investment decisions. In contrast, Wei et al. (2024) argue that environmental disclosure is significantly and negatively affected by institutional ownership and state ownership.

In this context, the role of regulators gains importance as an independent element of the production process aimed at mediating relations between producers and consumers to seek common well-being. Concerning GHG emissions, the regulator ensures the intermediation of these relationships by establishing and evaluating compliance with transparency and control goals, requiring, for example, the presentation of widely accepted certifications for each sector. Hermawan et al. (2018) demonstrated that the existence of a regulatory body has a significant effect on the disclosure of carbon emissions, in addition to the size and profitability of companies.

Regarding indirect emissions in general, Hickmann (2017) shows that, although there are incentives for greater transparency in GHG emissions, the efforts undertaken by companies are largely driven by the threat of external controls of their production. In this sense, the authors observe that companies prefer to wait for a context of greater clarity in the political field regarding the effective adoption of GHG regulations and appropriate policy instruments, and then move to determine and disclose their GHG emissions. This gains relevance in a context where indirect emissions are substantial and growing. Therefore, developing better approaches to these emissions more systematically points to an opportunity for improvements toward energy savings (Hertwich & Wood, 2018).

In light of this literature review, the problem of accounting for CO2 emissions is apparent and seems to be a recurring issue, regardless of its causes and the methodology used. Garcia and Freire (2014) applied four different methods – ISO/TS 14067, GHG Protocol, PAS 2050, and Climate Declaration – to examine biogenic CO2 emissions for wood-based panels. The authors noted significant differences in the results of CO2 emissions among the four methods applied. Even using the same methodology, but with a different approach, the results can vary due to heterogeneous carbon reporting practices. Herold and Lee (2018) compared two similar companies - FedEx and UPS - that, within the GHG protocol, chose different carbon

measurement methods and reporting arrangements for their carbon emissions. The different control approaches - “financial” or “operational” - influenced the amount of CO2 emission disclosure.

Data uncertainty is a significant issue in accounting for CO2 emissions (Yang et al., 2023). It is a relevant concern across various areas due to insufficient data, limited knowledge, and inadequate methods to address such challenges (Amini et al., 2021). Talbot and Boiral (2018) identified several problems related to CO2 emission information disclosure, including low-quality information, lack of consistency, validity issues, and missing data. Their study analyzed 105 GHG reports, identifying 93.3% nonconformities, which were categorized into three main groups. Firstly, uncertainties regarding measurement methods and emission calculations involve the chosen methodology for direct and indirect emissions with clear measurement protocols. Secondly, incomplete or unrepresentative information on performance indicators relates to measuring all items/categories of the protocol without mixing this information on different indicators. Thirdly, lack of information refers to not disclosing a performance indicator entirely (Talbot & Boiral, 2018).

Zhang and Liu (2020) provided a comprehensive overview of the literature on corporate carbon information disclosure, noting an increase in reporting companies but with low content and quality. They highlighted that carbon information disclosed through different channels varies, and data comparability is weak. Difficulty in comparison arises within companies (e.g., over time) or between companies due to information uncertainty (Talbot & Boiral, 2018).

In this context, establishing rankings and comparing companies in terms of corporate sustainability performance, even in the same activity sector, is criticized (Boiral et al., 2022). The authors argue that data in these reports is unreliable, making rankings less meaningful (Boiral et al., 2022). Through research in the car manufacturing industry, the authors analyzed several GHG indicators and identified four barriers for ranking: noncompliance and lack of standardization of reported data, fuzzy and eclectic measurement methods employed, unclear and heterogeneous scope of measurement, and inappropriate contextualization and inconsistencies in disclosed information. Wegener et al. (2019) also argue that information lacks completeness and credibility in studies of GHG emissions. Through an oil and gas company in Canada, they support the lack of comparability and commensurability (Wegener et al., 2019).

Given the complexity and uncertainty of information on CO2 emissions disclosure, this study focuses on the principle of information entropy. This principle is applied in various areas of science, academia, and practice. Claude Shannon introduced it through a multidisciplinary approach, which is a mathematical theory of communication (Shannon, 1948). Information entropy quantifies the 'amount' of information necessary to express an event. Since then, it has been applied to research in different ways, with information uncertainty being one of them. Moreover, we use information entropy as a measure of uncertainty (Han et al., 2018). According to Wanke et al. (2021, p.234), information entropy "provides the benefits of higher accuracy and superior objectivity" compared to other methods.

Research on different low-carbon operations in Brazil has used information entropy to propose models to reduce CO2 emissions and identify best managerial practices and performance (Wanke et al., 2021). Awasthi et al. (2011) generated an overall performance score (criteria weights) through fuzzy techniques for order preference by similarity to ideal solution (TOPSIS) and sensitivity analysis due to the information entropy of the data used in their research. This methodology provided the evaluation of the best options for sustainable urban transportation systems. Along similar lines, Zlaugotne et al. (2020) compared different alternatives based on GHG performance and proposed a rank of the EU countries that used the TOPSIS method. To address the complexity of carbon emission data uncertainty, this study adopts the approach of using information entropy and TOPSIS, supporting a better analysis of CO2 emissions.

## 3. DATABASE AND METHODS

### 3.1. RESEARCH SAMPLE AND DATA COLLECTION PROCEDURES

Data were collected from the Center for Sustainability Studies of Fundação Getulio Vargas (2022)(https://eaesp.fgv.br/en/study-centers/center-sustainability-studies). FGVces is a Brazilian project focused on the GHG Protocol. We collected data from the years 2017 to 2019, comprising 432 observations (139 in 2017 and 2018, and 154 in 2019). The dataset includes information from 56 companies across 18 sectors and 13 Brazilian states. The GHG Protocol is a well-established and widely accepted set of metrics. In Brazil, it was implemented in 2008 in partnership with representative national and international entities. Companies affiliated with FGVces are required to report their GHG protocol emissions and upload information to the FGVces platform. The CO2 emissions data (in metric tons of carbon dioxide) for each company on the platform includes detailed data from all three scopes.

Scope 1 represents direct GHG emissions sources owned or controlled by the organization and includes data from mobile combustion, stationary combustion, industrial processes, solid waste and liquid effluents, fugitive emissions, agricultural activities, and changes in land use. Scope 2 reflects indirect GHG emissions from sources owned or controlled by another firm, including emissions from purchased or acquired electricity, heat, steam, and cooling (transmission and distribution waste) – each of these items is considered in both location-based and market-based approaches. The location-based approach includes the grids on which energy consumption occurs, while the market-based approach reflects the electricity purchased by the company.

Scope 3, the corporate value chain, accounts for all emissions that the company is responsible for outside of its walls. This scope includes fifteen categories of CO2 emissions, divided into upstream (eight categories) – purchased goods and services, capital goods, fuel and energy-related activities (not included in scopes 1 and 2), transportation and distribution, waste generated in operations, business travel, employee commuting, leased assets – and downstream (seven categories) – transportation and distribution, processing of sold products, use of sold products, end-of-life treatment of sold products, leased assets, franchises, and investments. Additionally, scope 3 includes an 'other' category for any other CO2 emissions. For each scope, the total sum of emissions from that specific scope is calculated.

Based on our complete dataset, we treated 'zeros' as errors in how firms filled in the GHG protocol data. Since zero emission of CO2 is not possible, we replaced all 'zeros' with 'missing values' in our dataset. Moreover, we developed descriptive statistics (see Table 1) for our variables from Scopes 1, 2, and 3. It is important to note that the last column of Table 1 shows the missing values. Scope 3 exhibits the largest number of items with high rates of missing values. Scope 3 is the most recent and contains more items, relying on information from outside the company, making it the most challenging scope to obtain CO2 emission information.

**Table 1. Descriptive Statistics of variables (scopes) of our dataset**

| Variable | Min | Max | Median | Mean | SD | CV | Skewness | Kurtosis | Missing Values |
|---|---|---|---|---|---|---|---|---|---|
| Mobile combustion | 0.025 | 5612631 | 1138 | 119848 | 669560 | 6 | 7 | 48 | 6.02% |
| Stationary combustion | 0.091 | 47790987 | 1186 | 666913 | 4124825 | 6 | 10 | 99 | 14.12% |
| Company facilities | 0.005 | 18423997 | 7635 | 2121800 | 4268238 | 2011612 | 2 | 3 | 81.94% |
| Mix residues (solid waste and liquid effluents) | 0.241 | 1090268 | 184 | 38193 | 153530 | 4 | 6 | 33 | 66.20% |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Fugitive emissions | 0.001 | 2144090 | 530 | 23614 | 186156 | 8 | 11 | 115 | 13.66% |
| Agricultural activities | 0.246 | 1462533 | 9802 | 124689 | 311458 | 2 | 3 | 8 | 85.19% |
| Land use change | 8.9 | 399852 | 4721 | 36985 | 81877 | 2 | 3 | 8 | 87.73% |
| **Total scope 1** | **0.025** | **65650523** | **7862** | **1148719** | **5658066** | **5** | **9** | **91** | **2.08%** |
| Purchased electricity (location-based) | 0.058 | 651672 | 1960 | 29058 | 77426 | 3 | 4 | 22 | 2.08% |
| Purchased heat/steam (location-based) | 0.05 | 116156 | 259 | 16828 | 37854 | 2 | 2 | 2 | 95.37% |
| Transmission and distribution waste (location-based) | 261.743 | 533189 | 276446 | 255790 | 157802 | 1 | 0 | -1 | 93.98% |
| Total scope 2 (location-based) | 0.058 | 651672 | 2184 | 45576 | 104167 | 2 | 3 | 9 | 2.08% |
| Purchased electricity (market-based) | 3.313 | 295614 | 26236 | 44345 | 62697 | 1 | 2 | 6 | 93.29% |
| Purchased heat/steam (market-based) | 0.05 | 116156 | 318 | 17714 | 38678 | 2 | 2 | 1 | 95.60% |
| **Total scope 2 (market-based)** | **0.05** | **411771** | **3474** | **38633** | **75920** | **2** | **3** | **12** | **90.28%** |
| **Total scope 2** | **0.058** | **851963** | **2184** | **49412** | **114538** | **2** | **3** | **12** | **2.08%** |
| Upstream purchased good and services | 0.006 | 8426161 | 7658 | 402857 | 1437462 | 4 | 4 | 18 | 74.07% |
| Upstream capital goods | 0.674 | 435524 | 17276 | 85548 | 141966 | 2 | 2 | 1 | 97.92% |
| Upstream fuel and energy related activities | 0.006 | 13057598 | 12910 | 882797 | 2295652 | 3 | 4 | 16 | 86.81% |
| Upstream transportation and distribution | 0.069 | 9939846 | 8456 | 198290 | 958795 | 5 | 9 | 84 | 46.76% |
| Upstream waste generated in operations | 0.498 | 717920 | 507 | 17818 | 65689 | 4 | 7 | 68 | 53.70% |
| Upstream business travel | 0.277 | 28884 | 604 | 2016 | 4181 | 207395 | 4 | 19 | 24.07% |
| Upstream employee commuting | 0.069 | 139611 | 629 | 5824 | 16618 | 3 | 5 | 28 | 47.69% |
| Upstream leased assets | 392.55 | 34486 | 614 | 5398 | 12827 | 2 | 2 | 1 | 98.38% |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Downstream transportation and distribution | 0.291 | 6068066 | 4607 | 188922 | 684279 | 4 | 7 | 60 | 79.86% |
| Downstream processing of sold products | 739.33 | 13851577 | 5056696 | 5748083 | 5797167 | 1 | 0 | -2 | 97.92% |
| Downstream use of sold products | 10.02 | 437000000 | 138901 | 63080486 | 145000000 | 2 | 2 | 2 | 94.91% |
| Downstream end-of-life treatment of sold products | 61225.88 | 2697550 | 82474 | 828087 | 1082936 | 1 | 1 | -2 | 98.15% |
| Downstream leased assets | 333634.3 | 600821 | 531386 | 488614 | 136634 | 0 | 0 | -2 | 99.31% |
| Downstream franchises | 40.256 | 7132 | 3586 | 3586 | 5015 | 5015 | 0 | -3 | 99.54% |
| Downstream investments | 25647.37 | 156402 | 142197 | 108082 | 71743 | 1 | 0 | -2 | 99.31% |
| Other | 0.001 | 715971 | 8089 | 136320 | 261635 | 2 | 1 | 0 | 96.30% |
| **Total scope 3** | **0.277** | **457000000** | **11081** | **4433895** | **39911167** | **9** | **11** | **112** | **15.74%** |

All units in tons of Carbon dioxide ($tCO_2$)

The standard deviations observed in Table 1 reveal the variability of greenhouse gas emissions across different scope categories within an organization. A high standard deviation indicates a greater dispersion of data around the mean, suggesting significant variability among operational units or different activities within the organization. For instance, a high standard deviation in Scope 3 may indicate that indirect emissions, influenced by external activities such as third-party acquisitions and product use, are highly variable and challenging to control and predict. Conversely, a lower standard deviation in Scopes 1 and 2 suggests that direct emissions and those resulting from purchased energy generation are more consistent and predictable, facilitating the planning and implementation of reduction measures.

The standard deviation in Scope 3, at 4.75, underscores the complexity and uncertainty associated with managing indirect emissions. This value indicates significant challenges in quantifying emissions not directly controlled by companies, such as those from their supply chain. In contrast, the lower standard deviation observed in Scope 2 (Market), at 6.59, may reflect greater consistency and predictability in emissions resulting from market-purchased energy, suggesting relatively homogeneous energy purchasing practices among the units analyzed. Overall, Table 1 demonstrates a notable dispersion in standard deviation, attributable to the pronounced heterogeneity within our sample. This heterogeneity arises from including companies of various sizes and operating within diverse sectors, resulting in substantial variance in greenhouse gas emissions across the dataset.

In a further stage of our research, we included contextual variables (Table 2).

**Table 2. Descriptive Statistics of contextual variables**

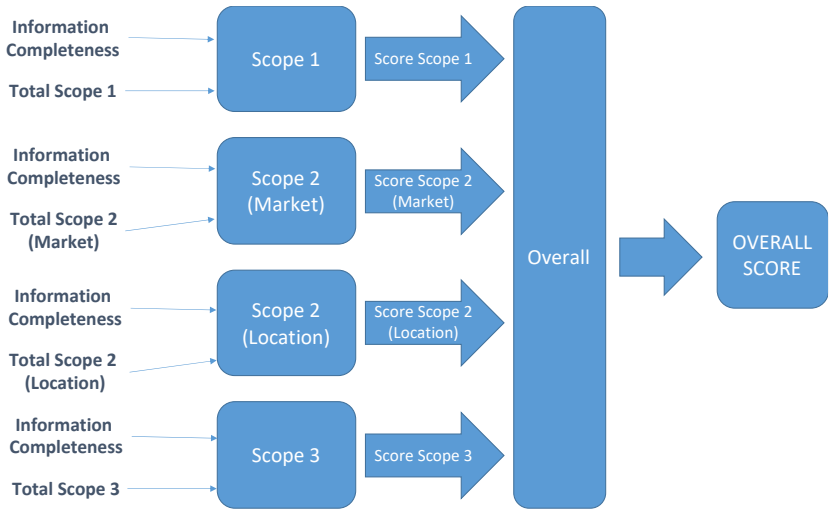
| DESCRIPTIVE STATS | PIB (R$) | GINI | ILLITERACY (%) | UNEMPLOYMENT (%) | POPULATION | AGE |
|---|---|---|---|---|---|---|
| MIN | 9.640E+10 | 0.676 | 1.900 | 6.200 | 2713147 | 1 |
| MAX | 2.348E+12 | 0.873 | 12.700 | 17.000 | 45919049 | 325 |
| MEDIAN | 7.799E+11 | 0.850 | 2.400 | 12.400 | 21168791 | 40 |
| MEAN | 1.361E+12 | 0.834 | 3.101 | 11.939 | 29507725 | 47.238 |
| SD | 8.714E+09 | 0.044 | 1.575 | 2.410 | 16317801 | 42.755 |
| CV | 0.640 | 0.052 | 0.508 | 0.202 | 0.553 | 0.905 |
| SKEWNESS | -0.028 | -1.030 | 2.964 | -0.778 | -0.153 | 2.175 |
| KURTOSIS | -1.882 | 0.540 | 11.615 | -0.348 | -1.752 | 12.367 |

The analysis of descriptive statistics reveals significant socioeconomic disparities among the studied regions, as indicated by data on Gross Domestic Product (GDP), Gini coefficient, and rates of illiteracy and unemployment. GDP varies considerably, ranging from approximately R$ 96.4 billion to R$ 2.35 trillion (Table 2), with a mean of around R$ 1.36 trillion and a median value significantly lower, suggesting a skewed distribution indicative of wealth concentration in certain areas. Additionally, the Gini coefficient, which measures income inequality, shows a wide variation between 0.676 and 0.873 (Table 2), emphasizing the significant economic inequality between regions. Such indicators are crucial for understanding the varied economic and social conditions among the populations studied, highlighting the need for differentiated policies that address the specificities of each region. The age distribution of the companies also exhibits considerable variation, ranging from 1 to 325 years. Notably, certain Brazilian companies boast a rich historical legacy spanning centuries, exemplified by Casa da Moeda, which celebrates a remarkable 325-year history.

### 3.2. SELECTION OF METHODOLOGY

The methodological approach of this study is shown in Figure 1. We initially conduct TOPSIS analysis by considering information completeness and the total CO2 emissions of each scope (Figure 1). Furthermore, we apply the artificial neural network method to analyze the contextual variables.

Figure 1: Methodology




### 3.2.1. Information entropy and TOPSIS

Information entropy is commonly used in the sustainability field, with previous research applying this method to sustainable transportation (Awasthi et al., 2011) and low-carbon operations management practices (Wanke et al., 2021). In our study, we employ information entropy as a measure of uncertainty, a probabilistic concept used to calculate the randomness and dispersion of a criterion based on its entropy attributes. A higher information entropy value indicates greater randomness and dispersion of the criterion or construct weight (Núñez et al., 1996).

The information entropy weight (Zhang et al., 2011) is one of several techniques for order preference by similarity to the ideal solution (TOPSIS), a frequently used method in multi-criteria decision-making (MCDM) research in various fields, including business (Behzadian et al., 2012; Daugavietis and Ziemele, 2024). TOPSIS determines the best alternative outcome by minimizing the Euclidean distance (Paz et al., 2021). In our study, information entropy serves as a measure of uncertainty and is utilized to determine the weightings of criteria in our model. We apply TOPSIS considering information completeness and total CO2 emissions to generate improved scores for each scope and overall CO2 emission assessment.

### 3.2.2. TOPSIS and Artificial Neural Network (ANN)

TOPSIS can be used in combination with other techniques, such as artificial neural network (ANN). ANN is a non-linear regression technique based on the principle of how the brain processes information through neural networks (Bishop, 1995; Wu & Feng, 2018; Gao and Cui, 2022; Cui et al., 2024; Dar et al., 2024). Thus, through resampling procedures, we conducted bootstrap with 1000 replications to determine the sensitivity analysis on the

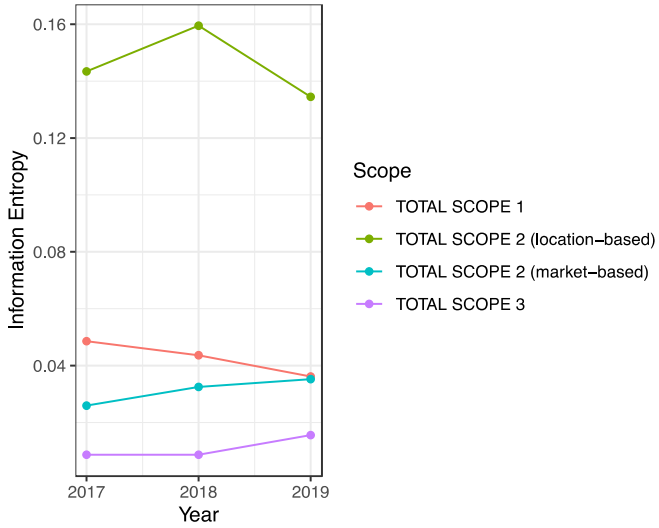
importance of our variables, including the contextual variables (Olden & Jackson, 2002). The results of TOPSIS in combination with ANN (Figure 8) illustrate the variables with positive or negative coefficients and identify the most relevant ones in our efficiency analysis.

## 4. Results and Discussion

### 4.1. Information entropy per year

This section aims to discuss how information entropy varies over the years, across states, and among sectors. In general, the results reveal a high percentage of missing values, leading to high information entropy, especially in scope 3. We expected that information entropy would decrease over the years. However, there was an increase in scope 2 location-based emissions from 2017 to 2018, while scopes 1 and 2 showed a decrease (Figure 2). Considering that these scopes represent more consolidated measurements of CO2 emissions, the results were as expected. In contrast, scope 2 market-based and scope 3 showed a slight increase in information entropy over the years, as indicated in Figure 2.

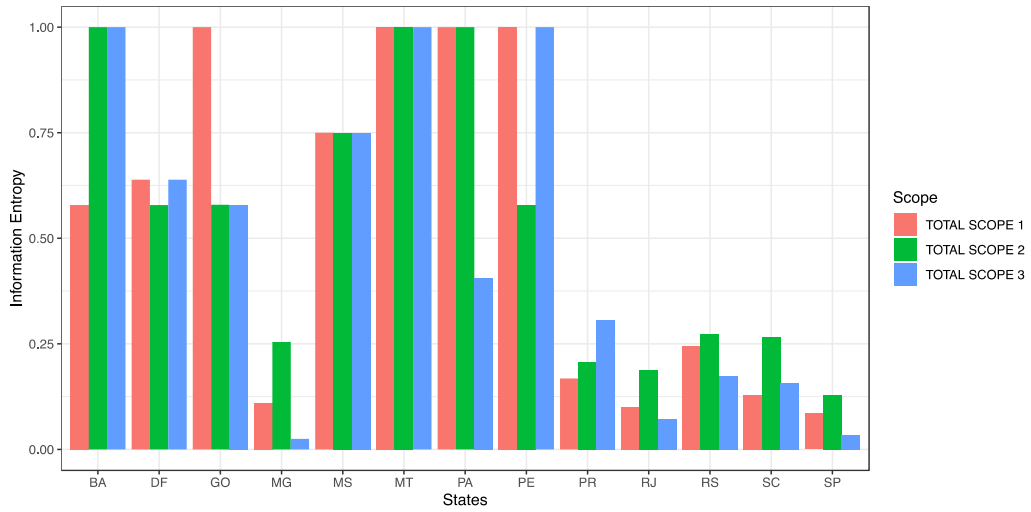
**Figure 2: Information Entropy Scores per Year**




### 4.2. States

Examining information entropy by states (Figure 3), we observed lower levels in six states located in the South and Southeast regions of Brazil. These states, especially São Paulo, are more economically developed, concentrating larger industries. With larger companies in more consolidated industries, there is greater completeness of information about GHG emissions. On the other hand, there is a high entropy of information in all scopes for the states of the North and Northeast regions, stemming from several missing values, as indicated in Figure 3.

**Figure 3: Information Entropy Scores per States**




### 4.3. Sectors

Examining the entropy of information by economic sectors, we observe, as in the analysis by states, a great heterogeneity of the observed results (Figure 4). In the case of economic sectors, we observe that the sectors most traditionally associated with the ESG agenda are those with lower entropies of information. Whether due to the more polluting nature of their productive activity (such as the Oil and Gas sector) or the geographical proximity of the productive activity to regions of native forest (such as the agricultural sector), these sectors historically undergo greater scrutiny by society regarding the environmental impact of their activities. Over the years, this has led to greater regulation and attention to the accountability of their emissions. In short, sectors that are more regulated regarding the environmental impact of their activities have less entropy of information, while less polluting sectors have greater entropy due to less regulation, as shown in Figure 4.

### 4.4. TOPSIS

In this subsection, we discuss the results from the TOPSIS approach, considering the completeness of information and total emissions per scope. Taken together, the characteristics of Scope 1 - a more consolidated scope with well-established indicators that depend on the efforts of the company itself and some companies already have the culture of disclosure through corporate sustainable reports. As demonstrated in Figure 5, the results of TOPSIS on scope 1 show a low uncertainty weight and a higher weight attributed to the total emission of CO2. Scope 2 location-based shows similar results to Scope 1. However, Scope 2 market-based shows a high weight for information completeness (Figure 5). The option of purchasing energy

in Brazil is very recent. Scope 3 presents several complexities, such as a large number of categories; difficulty in measurement – supply chain; and a lack of knowledge and training of suppliers on how to account for data. Regarding these characteristics, scope 3 presents the higher weight of information completeness (high percentage of missing values), and the lowest weight for total scope 3 CO2 emissions as shown in Figure 5.

TOPSIS overall weights (Figure 6) show similar results for Scope 1 and 2 (location-based). Scope 2 market-based, as expected, shows a low overall weight. However, Scope 3 presents the highest weight, which was unexpected. A possible justification for this aspect is a limitation of the TOPSIS method when a large number of variables (as is the case with Scope 3) are considered in the model.

**Figure 4: Information Entropy Scores per Sector**

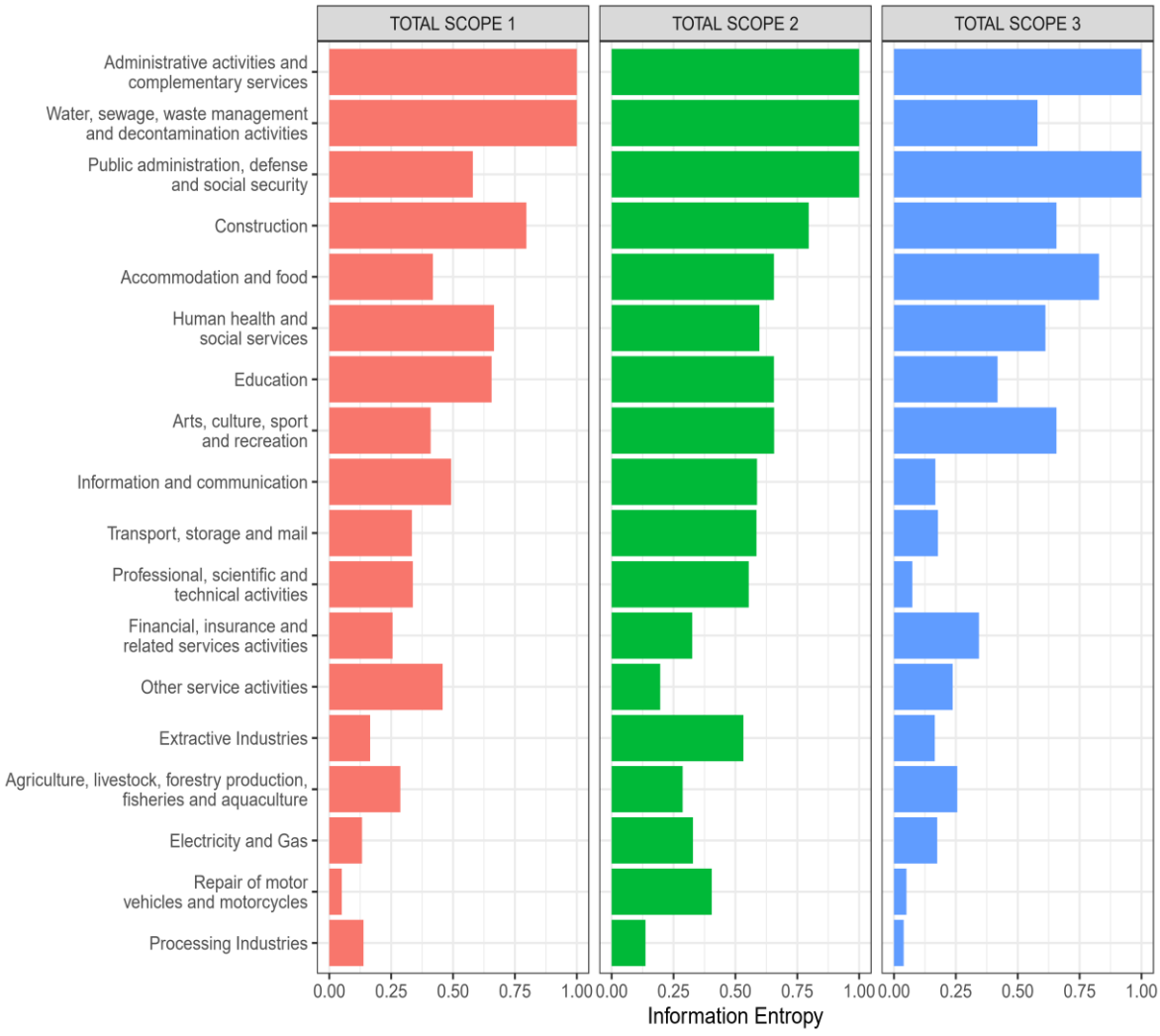


**Figure 5: TOPSIS Scope Weight**

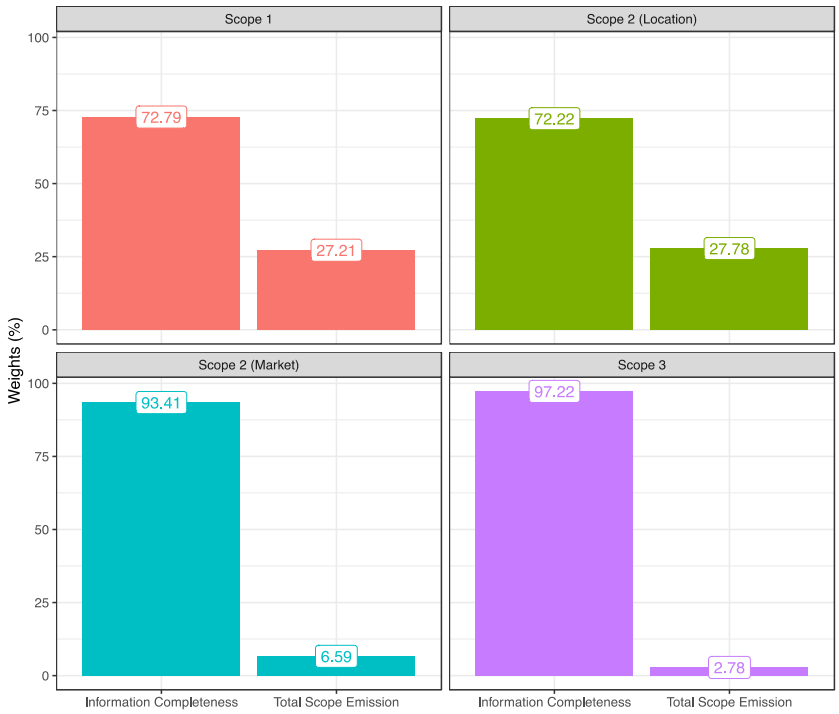
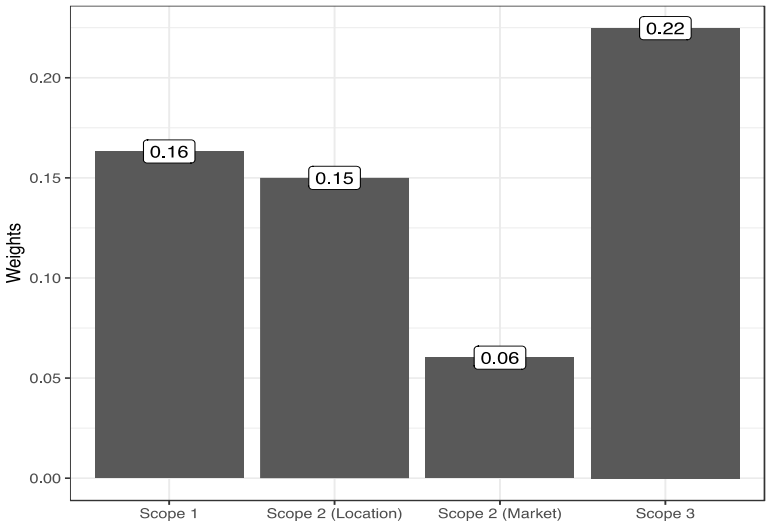


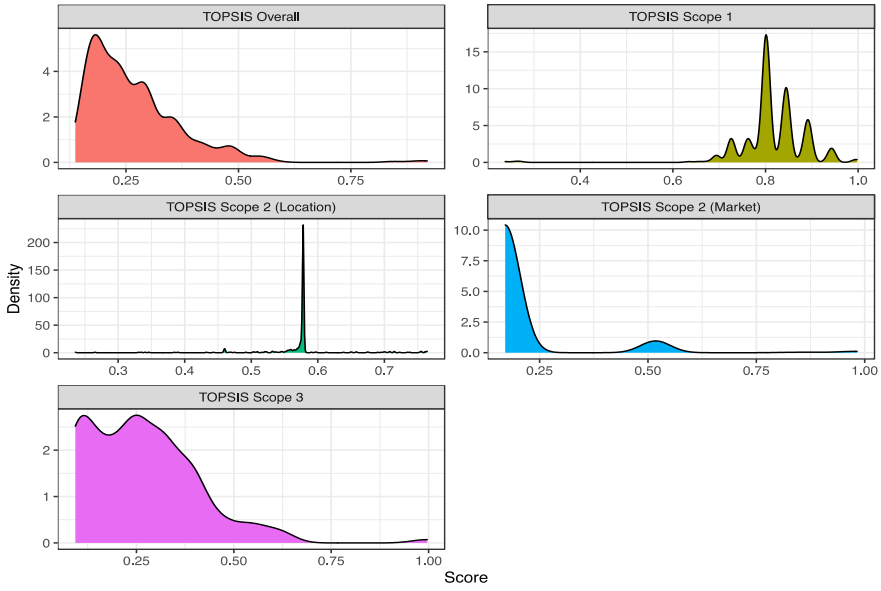

Figure 6: TOPSIS Overall Weight




Exploring TOPSIS results per Scope, we examine density plots to better visualize the results (Figure 7). In Scope 1, we observe the heterogeneity of the sectors - each peak concentrates on companies of a specific sector. Generally, Scope 1 presents high efficiency – most results are above 0.7. Results from Scope 2 location-based also show high efficiency (close to 0.6), as shown in Figure 7. However, it is a more homogeneous Scope compared to

the other scopes, probably due to the characteristics of our energy system in Brazil where companies usually do not have options or are extremely limited. The Scope 2 market-based graph (Figure 7) shows the lack of information and low efficiency. Finally, the Scope 3 chart (Figure 7) demonstrates its dispersion and extremely low efficiency.

Figure 7: TOPSIS Results Density Plot




Overall, Figures 5, 6, and 7 provided offer a detailed analysis of the heterogeneity and information completeness across greenhouse gas emission scopes, providing a critical view of the transparency and reliability of information disclosed by companies. In Scope 1, there is significant heterogeneity across sectors, which can be attributed to the diversity of industrial activities and their respective emission intensities. This variation underscores the need for specific sectoral policies that consider the peculiarities of each industry type regarding emissions.

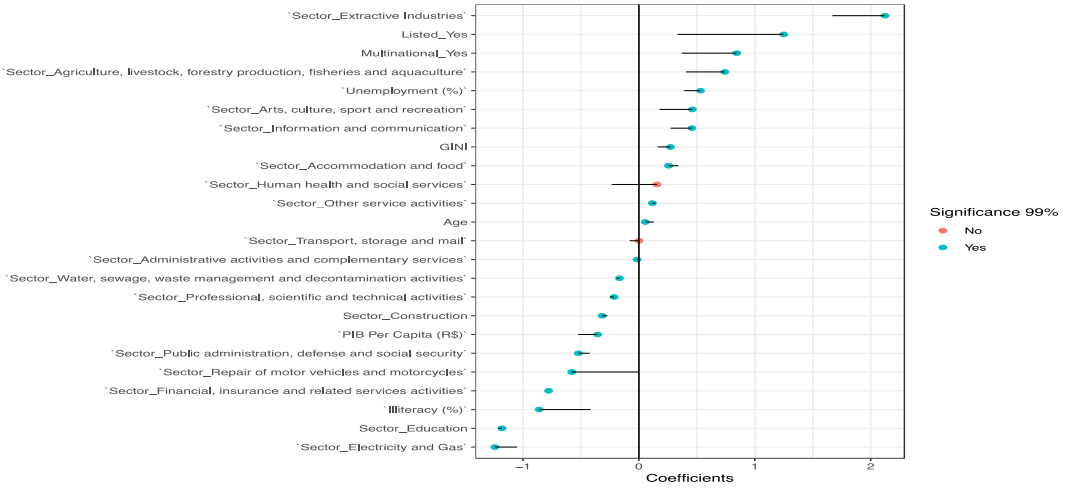
On the other hand, Scope 2 (Location) reflects uniformity in emissions characteristic of the Brazilian energy matrix. As previously mentioned, most companies in Brazil cannot freely choose their energy suppliers, resulting in homogeneity in reported emissions, limiting companies' ability to influence their carbon footprints through energy choices. This is slowly changing, but it remains a significant limitation. Additionally, Scope 2 (Market) and Scope 3 highlight a concern with 'information completeness,' where there appears to be greater interest from companies in disclosing their emissions rather than ensuring the accuracy and reliability of this data. Such a practice may undermine the effectiveness of emission mitigation strategies

and indicates the need for a greater focus on verifying and validating reported information, ensuring that transparency does not come at the expense of accuracy.

### 4.5. Contextual Variables

The relative importance of the contextual variables is presented in Figure 8.

**Figure 8: Coefficients of contextual variables**




With regard to contextual variables, as noted above, the highest coefficients are related to more polluting sectors (and therefore more regulated) or to larger companies with more consolidated control and governance structures. In this context, listed companies are subject to greater regulation and transparency, which leads to greater expertise in the verification and reporting of information related to their activities, including GHG emissions.

It is worth mentioning the coefficient found for the extractive industry, which is established much above the others, indicating a lower entropy for companies that declare themselves as belonging to this sector. As explained above, the extractive sector traditionally represents one of the biggest polluters (either in terms of GHG or solid waste), with a full range of instruments and monitoring and control bodies being observed on the negative impact of its activities. This profile is crucial for companies in the sector to be more prepared (and used) to provide detailed information on different dimensions of their production activity, including GHG emissions.

## 5. Conclusion

The severity of climate change problems and the relevance of reducing CO2 emissions are extensively explored in the literature. However, there is a lack of research on how the private and public sectors can present and improve CO2 emissions disclosure. The application of the

GHG Protocol proves to be a relatively complex task in practice, as it encompasses a wide diversity of heterogeneous sectors, with no possibility of broad standardization (Herold & Lee, 2018). On one hand, with the strong entry of ESG in the corporate environment, it is expected that ESG fosters sustainability. In theory, it would even promote more GHG Protocols. However, it is important to maintain focus on the central issue, which is to improve the quantity and quality of information for better and more accurate measurements of CO2 emissions.

Currently, the vast majority of companies are still not transparent in the disclosure of CO2 emissions, even though they are transparent and detailed concerning other corporate aspects. This problem stems from several factors. One of these factors would be related to the image of large companies that emit GHG, since these companies may choose not to pay attention to this dimension of their results. Under this criterion, there are also incentives to manipulate data for disclosure to stakeholders and investors. Since we observe the highest levels of information entropy in Scope 3, it is important to rethink how and if it makes sense to disclose CO2 of scope 3. Additionally, it is also relevant to seek strategies to deal with several issues on CO2 emissions disclosure. With regard to this, some questions emerge: How can a company cooperate and increase engagement with their supply chain on the disclosure of CO2 emissions? How can entities stimulate better CO2 disclosure? How can GHG group support improve training to promote better measurement and CO2 disclosures? How can companies be more transparent in their CO2 disclosure? Does it make sense to compare the performance of CO2 emissions disclosure across firms, cities, and countries?

In this context, public policies become important instruments for inducing better GHG disclosure by companies since governments (including regulators) represent neutral elements in market relations. As neutral agents, governments have the potential to act beyond the logic of market profitability, imposing sanctions and benefits that can lead other agents to act for the common good. An example of good practices that go beyond the economic logic of the market is precisely the improvement of the calculation and disclosure of GHG emissions resulting from the productive activities of companies. Sometimes, depending on the sector, these activities can be quite complex and costly, representing a disincentive for companies to adopt them. From this perception, and given the results found in terms of entropy originated from the poor quality of the companies' reports regarding their GHG emissions, it can be observed that public policies created to encourage better calculation of this information from companies would have significant impacts in terms of improving the availability of this information. This

improvement, in turn, can lead to a virtuous cycle of better evidence-based public policies for the establishment of mechanisms aimed at reducing emissions, such as better pricing in carbon markets.

In this study, due to the high level of uncertainty, low quality of data, and a large number of missing values, we used information entropy and TOPSIS to provide more quality in CO2 emissions analysis. The results demonstrate that the deepening of entropy analysis in the context of GHG emissions is a fundamental tool for methodological improvement since it makes it possible to direct efforts to identify the main information gaps. From this recognition, academia and practitioners must improve research and strategies to focus on initiatives around the suppression of these gaps. From our perspective, it would have a scalar effect of continuous improvement of the sources of information in the future.

On a practical level, our research sheds light on the formidable challenges surrounding CO2 emissions disclosure, particularly within the context of the private and public sectors. By elucidating the complexities and limitations inherent in current disclosure practices, we provide valuable insights for policymakers, regulators, and organizational stakeholders seeking to bolster transparency and accountability in emissions reporting. Moreover, our utilization of information entropy and TOPSIS techniques offers a methodological blueprint for enhancing the quality and rigor of CO2 emissions analysis, thereby advancing the analytical toolkit available to researchers and practitioners in the field of environmental sustainability. From a theoretical standpoint, our study contributes to the evolving discourse surrounding GHG emissions measurement and management by deepening our understanding of the factors driving uncertainty and data quality issues in emissions disclosure. By illuminating these underlying mechanisms, we pave the way for future research endeavors aimed at refining measurement methodologies and developing targeted interventions to address the identified challenges. Ultimately, our study serves as a catalyst for continued scholarly inquiry and practical interventions aimed at fostering greater transparency, accountability, and sustainability in organizational practices and public policies related to carbon emissions management.

However, we understand that the focus on Brazilian companies limits our conclusions and predictions to the Brazilian reality, making any observation based on the results in the context of other countries ambiguous. Additionally, it is worth mentioning that the information observed is concentrated on a base of medium and large companies, leaving out the context of

micro and small companies. This fact also represents a limitation in itself since the prognosis of public policies based on the observed results would have an impact on the entire universe of companies, and the context of micro and small companies has idiosyncrasies and particularities that make them somewhat disconnected from the reality of large companies. In this sense, a possibility for future improvement for this research would be to expand its scope to include companies from other countries and of all sizes. However, we understand that the low degree of institutional maturity of smaller companies makes the collection of information related to GHG emissions overly complex and costly for these companies.

## Data Availability Statement

The data that support the findings of this study are available from the corresponding author, Y, Tan, upon reasonable request.

## Conflict of Interest Statement

No potential competing interest was reported by the authors.

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