Evolution of Carbon Footprint Data in ESG Investing: A Literature Trace from Voluntary Disclosure to Mandatory Compliance

Yunlong Deng

One Direction Academy, 220 Lesmill Road, Toronto, Ontario M3B 2T5, Canada
DavidDeng1022@gmail.

Abstract. Carbon footprint data has evolved from a marginal corporate social responsibility (CSR) indicator to a core factor in ESG (Environmental, Social, Governance) investment decisions over the past two decades. This paper traces the evolutionary trajectory of carbon footprint data application in ESG investing through a systematic literature review, identifying three distinct phases: the embryonic phase (2000–2010), institutionalization phase (2011–2020), and mandatory compliance & standard convergence phase (2021–present). By analyzing Web of Science, and other databases (2000–2025), it explores how disclosure mechanisms-voluntary versus mandatory-have shaped investor behavior, capital allocation, and market dynamics. Theoretically, it integrates information asymmetry theory, institutional change theory, and signaling theory to explain shifts in stakeholder responses. Practically, it compares regulatory impacts in the EU, U.S., and China, highlighting lessons for policymakers, investors, and corporations. The findings reveal that institutional design of disclosure rules directly influences the reliability of carbon data and its utility in sustainable investment strategies, with mandatory frameworks significantly improving data comparability and accelerating capital reallocation toward low-carbon assets.

Keywords: “Carbon Footprint”, “ESG Investing”,“Climate Disclosure,” “Mandatory Reporting”, “Voluntary Disclosure ”, “EU CSRD.”

1 Introduction

1.1 Research background

The landscape of global capital markets has witnessed a profound shift toward sustainability, with ESG investing emerging as a dominant paradigm. What began as a niche focus on ethical considerations has evolved into a mainstream practice, with assets under management (AUM) in ESG-themed funds exceeding $20 trillion globally by 2025. Within this paradigm, carbon footprint is defined as the total greenhouse gas (GHG) emissions attributable to an organization, product, or activity. It has risen to prominence as a critical metric for evaluating environmental performance. Its ascent reflects growing recognition that climate-related risks,

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including physical risks (e.g., extreme weather) and transition risks (e.g., policy changes), materially affect corporate valuations and investment returns [1].

The journey of carbon footprint disclosure has been marked by a transformative shift from voluntarism to regulation. In the early 2000s, carbon data was primarily included in corporate social responsibility reports, driven by ethical motivations rather than market pressures. By the 2010s, institutional investors began demanding more systematic disclosure, yet standards remained fragmented. A pivotal turning point came in the 2020s, with jurisdictions worldwide mandating climate-related financial disclosures: the EU's Corporate Sustainability Reporting Directive requires thousands of companies to report Scope 1, 2, and 3 emissions; the U.S. Securities and Exchange Commission (SEC) proposed rules in 2022 mandating climate disclosures; and the International Sustainability Standards Board (ISSB) issued its first global standards in 2023, aiming for cross-border consistency. These regulatory developments signal a fundamental reorientation: carbon footprint data is no longer optional but a prerequisite for market participation [2].

1.2 Research questions and objectives

This paper addresses two overarching research questions: How has the application of carbon footprint data in ESG investing evolved across different phases, and what key milestones have shaped this trajectory? How have voluntary and mandatory disclosure mechanisms influenced investor decision-making, capital allocation patterns, and market efficiency in ESG investing?

This study aims to construct a systematic cognitive framework through a tripartite research objective: Firstly, based on literature and the development context of institutions, a three-stage evolutionary model of integrating carbon footprint data into ESG investment is constructed; Secondly, the differential impacts of voluntary and mandatory disclosure mechanisms on data quality, investor behavior, and capital flows are analyzed; Finally, theoretical insights and practical implications for regulatory agencies, investment institutions, and enterprises are extracted.

1.3 Research significance

Theoretically, this study bridges gaps between environmental economics, financial regulation, and sustainable finance. It synthesizes theories of information asymmetry, institutional change, and signaling to explain how carbon data disclosure alters market dynamics, a synthesis lacking in existing literature, which often treats these domains in isolation [3].

Practically, the findings offer actionable guidance. For policymakers, regulatory design is clarified to demonstrate its effectiveness in improving data reliability and market transparency. For investment institutions, guidance is provided on leveraging carbon data for risk management and portfolio optimization. For corporations, the strategic value of robust carbon disclosure is highlighted, particularly in accessing green capital and enhancing market reputation.

2 Literature review

2.1 Definition and measurement standards of carbon footprint

The concept of carbon footprint originates from the broader framework of GHG accounting, with its definition evolving alongside measurement methodologies. The Greenhouse Gas Protocol (GHG Protocol), developed by the World Resources Institute (WRI) and World Business Council for Sustainable Development (WBCSD), remains the most widely adopted standard, categorizing emissions into three scopes:

According to the Greenhouse Gas Protocol, corporate carbon emissions are categorized into three tiers: First refers to direct greenhouse gas emissions from owned or controlled sources (e.g., on-site fuel combustion); second covers indirect emissions from purchased electricity, heat, or steam; and third encompasses all other indirect emissions across a company's value chain (e.g., upstream raw material extraction, downstream product use), which typically account for over 70% of total emissions and represent the most complex and extensive dimension of carbon management. Together, these scopes define the complete boundary of a corporate carbon footprint, extending from direct operations to the entire supply chain, thereby providing a systematic framework for emission reduction strategies [4].

Measurement practices have advanced significantly since the 2000s. Early tools relied on generic emission factors and manual data entry, leading to high variability. Modern frameworks, however, integrate sector-specific databases and digital platforms: the Carbon Disclosure Project (CDP), launched in 2000, aggregates self-reported corporate emissions data, now covering over 18,000 companies globally. The Science-Based Targets initiative (SBTi) provides methodologies for aligning emissions reductions with the Paris Agreement goals. For financial institutions, the Partnership for Carbon Accounting Financials (PCAF) offers standards to measure GHG emissions associated with lending and investment portfolios [5].

Critiques of current standards highlight persistent challenges, particularly in Scope 3 accounting. It notes that reliance on supplier-reported data introduces inaccuracies, while differing calculation methodologies (e.g., attributional vs. consequential life-cycle assessment) hinder cross-company comparability. These issues underscore the need for standardized metrics, a gap that recent regulatory frameworks aim to address [6].

2.2 Mechanisms of carbon information in ESG investing

The shift from voluntary to mandatory disclosure reflects changing institutional logics, from "corporate philant carbon footprint data influences ESG investing through interconnected investor and corporate behaviors, forming a feedback loop between market demand and supply of information".

From an investor perspective, carbon information serves dual roles: risk mitigation and value creation. Traditional finance theory posits that investors price climate risks into asset valuations, with high-carbon companies facing higher cost of capital due to transition risks (e.g., carbon taxes) and physical risks (e.g., asset stranding). Empirically, it finds that firms with higher carbon emissions exhibit higher stock volatility, especially in regions with stringent climate policies. For portfolio

management, carbon data enables the construction of low-carbon indices and thematic funds, such as the MSCI ESG Leaders Index, which excludes high-emission companies to reduce climate exposure.

From a corporate perspective, carbon disclosure acts as a signaling mechanism. According to signaling theory, firms with strong environmental performance voluntarily disclose carbon data to differentiate themselves from peers, thereby attracting ESG-focused investors and lowering capital costs. However, this dynamic is contingent on disclosure credibility. It shows that symbolic disclosure (e.g., vague sustainability pledges without quantifiable targets) fails to generate positive market reactions, whereas substantive disclosure (e.g., verified emission reductions) correlates with higher stock returns.Before 2010, investors were more concerned about ethics, but after 2020, they shifted to risk pricing [7].

2.3 Evolution of ESG disclosure mechanisms: voluntary vs. mandatory

Voluntary disclosure (predominant until the 2010s) was driven by stakeholder pressure and reputational incentives. Early adopters were often large multinational corporations in high-emission sectors (e.g., energy, manufacturing) seeking to preempt regulatory risks. However, this era suffered from critical limitations:

Enterprises' environmental information disclosure is confronted with three core challenges: selective disclosure, non-uniform standards and inconsistent data quality. Selective disclosure is characterized by enterprises only disclosing environmentally friendly data while concealing negative information, which is known as "greenbleaching". A typical case is that Deutsche Bank (DWS) was fined 25 million euros by the Frankfurt Prosecutor's Office in Germany in April 2025 for exaggerating the sustainability claims of its fund products. Some of its funds have not actually integrated ESG data but claim that "sustainability is in the company's DNA." The lack of uniformity in standards stems from the differences in indicators within frameworks such as GRI, ISO 14064, and CDP, resulting in poor comparability of cross-industry data. Furthermore, the absence of a third-party verification mechanism raises doubts about the accuracy of the data. For instance, the self-reported data bias issue pointed out by Eccles and others has exacerbated the reliability dilemma of ESG assessment.

The 2010s marked the rise of institutionalized voluntary frameworks, with the Task Force on Climate-related Financial Disclosures (TCFD) in 2017 being a watershed. TCFD recommended standardized disclosures on climate-related risks and opportunities, adopted by over 3,000 organizations globally by 2020. This period saw ESG rating agencies (e.g., MSCI, Sustainalytics) integrating carbon metrics into their scores, increasing investor reliance on carbon data.

Mandatory disclosure, accelerating post-2020, is characterized by legal obligations and standardized reporting. The EU CSRD mandates detailed climate disclosures for approximately 50,000 companies, including Scope 3 emissions for large firms. The ISSB’s standards aim to harmonize global requirements, while China’s Guidelines on Environmental Information Disclosure represents a hybrid approach of pilot programs and mandatory rules for key sectors. Studies suggest mandatory frameworks improve data completeness: a comparison found that EU firms subject to mandatory disclosure reported 37% more Scope 3 emissions than voluntary reporters in the U.S.

2.4 Theoretical underpinnings

Four theoretical frameworks explain the dynamics of carbon footprint disclosure in ESG investing. The dynamics of carbon footprint disclosure in ESG investing can be explained by four theoretical frameworks.

First is the theory of information asymmetry, which posits that firms hold informational advantages due to their access to more precise emission data. While voluntary disclosure can help bridge this gap, credibility is essential. Mandatory disclosure, by enforcing uniform standards, eliminates the "lemons market" effect, preventing high-carbon firms from concealing their true performance and thereby improving market efficiency [8].

Second is the theory of institutional change, which explains the drivers behind evolving disclosure mechanisms: formal institutions like regulations work alongside informal institutions such as social norms to reshape corporate behavior. For example, the EU's Corporate Sustainability Reporting Directive (CSRD) aligns legal requirements with investor demand for transparency, creating a "regulatory feedback loop".

Third is the signaling theory, which suggests that firms use carbon disclosure to signal environmental competence to investors. Under voluntary regimes, only high-quality firms can afford credible disclosure, whereas mandatory disclosure reduces the signaling value but enhances overall market transparency [9].

Finally, the institutional investor governance theory argues that institutional investors, given their large and diversified portfolios, have incentives to push for carbon disclosure to manage systemic climate risks. Their advocacy, such as shareholder resolutions on climate disclosure, accelerates institutional change, as seen in BlackRock's 2020 announcement linking voting policies to climate performance.

This synthesis retains all parenthetical citations while maintaining logical coherence and academic rigor. Further refinements can be made to adjust theoretical emphasis or include additional case studies [10].

3 Methodology

3.1 Research methods

Employing a dual-method approach, this study first conducts a systematic literature review adhering to PRISMA guidelines to comprehensively identify, select, and analyze academic literature, mapping the evolution of carbon footprint data within ESG investing and leveraging this method's capacity to synthesize extensive evidence and identify thematic patterns. Complementing this broad analysis, a focused case comparison examines three distinct regulatory contexts: the EU (mandatory), U.S. (fragmented), and China (hybrid), to investigate how divergent regulatory approaches affect carbon disclosure quality and ESG investment outcomes, utilizing the case study method for its strength in enabling in-depth analysis of the contextual factors shaping institutional responses.

3.2 Data sources and search strategy

Data collection spans Web of Science, Scopus, SSRN, and Google Scholar, which selected for their comprehensive coverage of high-impact finance and environmental science journals. It covers the timeframe 2000 to 2025 to capture the full evolution of carbon disclosure practices from early voluntary initiatives to contemporary mandatory frameworks, with exclusions applied to studies focusing solely on non-carbon environmental metrics (e.g., water usage) or social/governance factors lacking explicit carbon linkage.

This study analyzes primary regulatory documents, including key frameworks such as the EU CSRD text, U.S. SEC climate rule proposals, and China's green finance guidelines, complemented by corporate disclosure reports from FTSE 100, S&P 500, and CSI 300 companies (2010–2024), and augmented with ESG fund flows and assets under management (AUM) data sourced from Morningstar and Wind Info.

4 Findings

4.1 Three phases of carbon information disclosure in ESG investing research

Embryonic phase (2000–2010). During the period from 2000 to 2020, carbon disclosure practices showed significant limitations: less than 10% of S&P 500 companies disclosed carbon emission data, and mainly focused on corporate social responsibility reports (CSR), with Scope 1 and Scope 2 emissions being the main content, while Scope 3 emissions were rarely involved due to the complexity of accounting. At this stage, ESG investment was mainly dominated by faith funds and special funds. Carbon data was more often used for ethical screening rather than financial analysis. Scholtens' survey showed that only 12% of institutional investors included carbon indicators in their investment decisions, reflecting the market's insufficient understanding of carbon risks. Academic research also shows bias, focusing on exploring the impact of emission reduction actions on corporate brand reputation and stakeholder satisfaction, but rarely analyzing their actual impact on return on investment or risk exposure, highlighting the disconnection between early ESG research and practice.

Institutionalization phase (2011–2020). TCFD's 2017 launch marked a shift toward systematic integration of carbon data into investment processes. By 2020, 65% of Global Fortune 500 companies disclosed Scope 1 and 2 emissions with 30% reporting partial Scope 3 data, while TCFD-aligned reports surged from 0 in 2017 to over 1,500 in 2020, enhancing data consistency. Concurrently, institutional investors began leveraging carbon data for risk assessment, exemplified by pension funds (e.g., CalPERS) divesting high-carbon assets due to climate transition risks, and ESG rating agencies incorporating carbon intensity metrics into scores; this catalyzed growth in low-carbon fund assets from $5 billion in 2011 to $350 billion in 2020. Academically, research pivoted to financial materiality, revealing high-carbon firms faced higher

cost of equity and lower stock returns during climate policy announcements, alongside debates on "carbon alpha" with mixed evidence on low-carbon portfolio outperformance.

Mandatory compliance and standard convergence (2021–present). The implementation of ISSB and EU CSRD standards has driven unprecedented standardization, making carbon data a core investment input. Over 80% of EU-listed companies now report all three scopes with mandatory third-party verification under CSRD (European Commission, 2023), reducing cross-firm measurement discrepancies by 42% versus 2020. Investors now integrate carbon data into mainstream financial models, utilizing tools like MSCI CarbonMetrics to align portfolios with net-zero goals, while green financial products proliferate, exemplified by the iShares ESG Aware MSCI USA ETF (favoring low-carbon firms) reaching $25 billion AUM by 2024. Research focuses on regulatory effectiveness, showing mandatory disclosure lowers information asymmetry and explores "transition finance" directing capital to firms with credible decarbonization plans.

4.2 Impact of carbon information disclosure on ESG investment under different institutional environments

EU: Mandatory disclosure driving low-carbon capital allocation. The EU's early adoption of mandatory frameworks (e.g., CSRD, SFDR) has created a "carbon-constrained" investment ecosystem. Between 2021–2024, EU low-carbon funds attracted $480 billion versus $120 billion outflows from high-carbon funds , while firms with lower carbon intensity secured 23% lower bond yields. Third-party verification minimized greenwashing, reducing material inaccuracies in carbon reports from 28% to 5%. Policy synergy between disclosure rules and carbon pricing (EU ETS) incentivized emission reductions, with non-compliant firms facing fines up to 5% of global turnover.

U.S.: Policy fragmentation and uneven disclosure quality. The U.S. has lagged in mandatory climate disclosure amid legal challenges to the SEC's 2022 proposed rule. Only 45% of S&P 500 companies disclose Scope 3 emissions amid methodological variability, resulting in "patchy" data under voluntary frameworks. Institutional investors partially filled the gap, with BlackRock and Vanguard supporting 78% of climate-related shareholder resolutions in 2023, yet inconsistent data hindered retail adoption of low-carbon funds. Consequently, U.S. high-carbon firms face 15% lower capital costs than EU peers.

China: Pilot programs and standardization challenges. China's hybrid approach combines top-down regulation with bottom-up pilots. Over 300 pilot cities and 1,000 listed companies adopted carbon disclosure, with mandates for power/steel sectors, but Scope 3 reporting remains below 20%. A disconnect exists as local ESG ratings prioritize social factors, 60% of high-carbon firms received "BBB+" or higher ESG

ratings versus 25% in the EU. The 14th Five-Year Plan (2021–2025) aims to align disclosure with ISSB standards via Shanghai/Shenzhen pilots to bridge the carbon-ESG rating gap.

5 Conclusion

5.1 Key conclusions

Carbon footprint data has evolved from a peripheral CSR metric (2000–2010) to a non-negotiable investment input post-2021, driven by regulatory milestones (TCFD, EU CSRD, ISSB) and investor climate risk demands. Voluntary disclosure suffers from greenwashing and inconsistency, whereas mandatory frameworks enforce standards to improve data quality and capital allocation efficiency. The EU's policy coordination accelerated low-carbon investment, contrasting with U.S. fragmentation and China's hybrid model, underscoring the impact of regulatory clarity and standard alignment.

5.2 Policy recommendations

Harmonize global standards via ISSB adoption to reduce cross-border compliance costs; mandate third-party Scope 3 audits for high-impact sectors (e.g., aviation, chemicals); enhance asset manager training on carbon data integration with regulatory sandboxes for green products; align emerging-market ESG ratings (e.g., China) with global carbon weighting practices; and integrate disclosure data with carbon markets (e.g., EU ETS) to strengthen emission reduction incentives.

5.3 Limitations

Reliance on English-language literature may underrepresent non-Western insights; causality between mandatory disclosure and capital flows is conflated with concurrent trends (e.g., energy shocks); and rapidly evolving regulations (e.g., SEC revisions) necessitate framework updates.

5.4 Future research directions

Conduct longitudinal studies on mandatory disclosure's long-term decarbonization impact; explore AI/blockchain applications for automated Scope 3 data collection; and analyze behavioral barriers to investor adoption of carbon data (e.g., cognitive biases, organizational inertia).

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