Financial speculation and environmental valuation in carbon price formation in forest carbon markets: a systematic review

Especulação financeira e valoração ambiental na formação do preço do carbono em mercados florestais: uma revisão sistemática

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Abstract

The emergence of carbon markets can be interpreted both as a techno-economic innovation and as a climate governance mechanism that has gradually evolved into a speculative arena, where carbon credits are increasingly traded for risk and profitability rather than for their genuine environmental performance. The socio-environmental complexity of these markets demands a multidisciplinary analytical lens, given the high degree of economic myopia that speculation induces in price formation. This detachment between the ecological foundation of credits and their market equilibrium value highlights structural fragilities in valuation. Following the PRISMA protocol and the PICO framework, this study addresses the following research question: how does financial speculation influence equilibrium price formation in forest carbon markets? A systematic review was conducted using searches in the Scopus and Web of Science databases, carried out on 7 October 2025. The consolidated sample comprised 180 documents published in 97 journals and revealed a strong representation of energy economics, finance, and environmental policy. The findings indicate that regulatory shocks, liquidity conditions, and integrity narratives – both in Emissions Trading Systems (ETS) and in Voluntary Carbon Markets (VCM) – amplify volatility and speculative cycles, rendering prices highly sensitive to political and macroeconomic expectations, including oil prices, exchange rates, derivatives, and indices linked to climate and policy events. These dynamics unfold unevenly across territories, reflecting spatial asymmetries in governance capacity, regulatory enforcement, and the geographic distribution of mitigation potential. This speculation-oriented perspective exposes the implications of weak regulatory standardization and underscores the sensitivity of carbon prices to short-term interests, emphasizing the urgent need for market integrity and strengthened MRV+ mechanisms to realign price with ecological value.

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Resumo

A emergência dos mercados de carbono pode ser interpretada tanto como uma inovação tecnoeconômica quanto como um mecanismo de governança climática que evoluiu gradualmente para uma arena especulativa – na qual os créditos de carbono passam a ser negociados crescentemente em função de risco e rentabilidade e não de seu desempenho ambiental efetivo. A complexidade socioambiental desses mercados exige uma abordagem analítica multidisciplinar, dada a elevada miopia econômica que a especulação induz na formação de preços. Esse distanciamento entre a base ecológica dos créditos e seu valor de equilíbrio de mercado evidencia fragilidades estruturais nos processos de valoração. Seguindo o protocolo PRISMA e o *framework* PICO, este estudo investiga a seguinte questão de pesquisa: como a especulação financeira influencia a formação do preço de equilíbrio nos mercados de carbono florestal? Para tanto, foi realizada uma revisão sistemática com base em buscas nas bases *Scopus* e *Web of Science* (realizadas em 7 de outubro de 2025), resultando em um corpus consolidado de 180 documentos, publicados em 97 periódicos, com forte representação nas áreas de economia da energia, finanças e política ambiental. Os resultados indicam que choques regulatórios, condições de liquidez e narrativas de integridade – tanto em Sistemas de Comércio de Emissões (ETS) quanto em Mercados Voluntários de Carbono (VCM) – amplificam a volatilidade e os ciclos especulativos, tornando os preços altamente sensíveis a expectativas políticas e macroeconômicas (por exemplo, preços do petróleo, taxas de câmbio, derivativos e índices associados a eventos climáticos e regulatórios). Essas dinâmicas manifestam-se de forma desigual no território, refletindo assimetrias espaciais na capacidade de governança, na aplicação regulatória e na distribuição geográfica do potencial de mitigação. Essa perspectiva orientada pela especulação evidencia as implicações da frágil padronização regulatória e reforça a sensibilidade dos preços do carbono a interesses de curto prazo, destacando a necessidade urgente de integridade de mercado e do fortalecimento de mecanismos MRV+ para realinhar o preço do carbono ao seu valor ecológico.

Palavras-chave: Mercados de carbono florestal. Precificação do carbono. Governança territorial. Política ambiental; MRV+.

Códigos JEL: Q54, Q58, Q51, Q57, G12, R12, R14.

1. Introduction

In standard microeconomic price theory, financial speculation is recognized as a factor influencing market equilibrium, as agents assume risk by anticipating asset-price fluctuations in pursuit of efficiency and profit (Alaminos et al., 2024; Sabadini, 2013). The carbon market, by mirroring capital-market mechanisms, benefits from the liquidity generated by the short-term attractiveness of tradable carbon credits. Although it represents a technological and institutional innovation, this market retains a financial nature capable of internalizing the costs of negative externalities within its capitalist ecosystem, thereby contributing to climate-change mitigation (Berta et al., 2017). Its architecture – modelled on stock and over-the-counter exchanges – rests upon economic axioms that prioritize financial maximization. Consequently, financial speculation, as its structural guardian, has acquired an insidious and camouflaged character, distinct from other cycles of capital accumulation (Arrighi, 1996).

Although speculation itself is not illegal, its widespread practice can distort carbon credit prices (Azlen et al., 2022), contributing to speculative bubbles that alter market equilibrium and weaken the link between credit valuation and effective climate-mitigation outcomes. Such dynamics may erode trust and transparency, reflecting well-documented limitations of capitalist price systems (Kindleberger et al., 2023). As noted by Arrighi (1996), this decoupling corresponds to a broader historical transition in economic cycles, wherein commodities – such as carbon credits – increasingly assume abstract representations of value and price, often preceding environmental degradation and socioeconomic stress. Empirical evidence supports this interpretation, as illustrated by domestic policy effects on deforestation following the 2008 U.S. housing crisis (Motel et al., 2009) and by the energy sector's sensitivity to carbon-policy announcements (Morão, 2024).

From this perspective, financial speculation is no longer understood merely as a behavioral deviation within markets, but rather as a structural logic of dissociation between value, price, and ecological materiality. In light of Critical Geography, as formulated by Milton Santos, carbon markets operate within a technical–scientific–informational milieu that allows global financial decisions to become progressively detached from the places where climate mitigation effectively occurs (Santos, 1996, 2000). In this process, carbon is converted into a predominantly informational asset, whose circulation responds more to the dynamics of financial flows than to the underlying ecological processes that sustain it. In line with Giovanni Arrighi's historical interpretation of financialization as a recurrent stage in cycles of capital accumulation, this spatial abstraction contributes to the formation of prices that are increasingly sensitive to signals exogenous to environmental performance (Arrighi, 1996).

This dissociation materializes concretely in the price elasticity of carbon credits and in the anomalies associated with their price formation (Azlen et al., 2022; Berta et al., 2017). Situations of excess supply tend to intensify volatility and depress prices, while artificial restrictions arising from subsidized policies may raise marginal abatement costs, undermining environmental additionality and resulting in ineffective mitigation outcomes. Moreover, the strong linkage between carbon prices and energy-market dynamics (Ahmed et al., 2022; Giraudet et al., 2021; Tu et al., 2021), shaped by production shocks and the oligopolistic power of fossil-fuel sectors (Yeh et al., 2021) reinforces the sensitivity of carbon credits to speculative financial interests. The co-movement with Brent oil and thermal coal prices (Düsterhöft et al., 2023) thus highlights the persistent asymmetry between climate objectives and the logic of financialization, underscoring the need for regulatory oversight (Kindleberger et al., 2023).

To mitigate such distortions in both regulated and voluntary markets, pricing instruments – such as cap-and-trade systems and carbon levies – have adopted anti-speculation mechanisms and market-safety layers to stabilize supply–demand dynamics and avoid overvaluation (Berta et al., 2017). Their effectiveness depends on the regulatory capacity of states and international bodies to monitor, audit, and deter aggressive speculative practices. Within this environment of uncertainty, firms and markets react asymmetrically according to their position in the emissions hierarchy and carbon-finance cycle. Large corporations with greater market power and technological capacity often convert uncertainty into strategic advantage, while more exposed sectors face devaluations and increased risk, thereby amplifying inequalities and protectionist tendencies (Lamperti et al., 2021; Monasterolo & Raberto, 2018). The outcome is a pattern of shifting investment, rising volatility, and the financialization of nature – signs of macroeconomic disorder that hinder resource allocation and underscore the need for coordinated financial governance (Campiglio, 2016).

Against this backdrop, this bibliometric systematic review (SR) aims to reveal the hidden role of financial speculation in price equilibrium and social welfare. In this context, carbon credits, sustainability-linked bonds, and green assets operate as speculative hedging instruments, enabling investors to exploit regulatory uncertainty for short-term gains while eroding productive investment and artificially inflating credit prices. These assets are classified across integrity and risk scales – ranging from "brown" to "high-grade" – according to certification quality, with voluntary markets exerting increasing pressure on regulated systems, especially in regions vulnerable to climate change.

Given the sectoral segmentation of the carbon market, this SR focuses on the forest-based segment, which generates credits through the restoration of degraded areas and the conservation of native and planted forests. Each certified credit represents one metric ton of CO_2 equivalent (tCO_{2eq}) sequestered or avoided, used to offset emissions within carbon projects (Guerreiro et al., 2021). Such projects, aligned with IPCC standards, reflect commitments established under the Kyoto Protocol and the Paris Agreement (UNFCCC, 2015).

In this sense, territory emerges as both the point of origin and the material limit of forest carbon markets. It is within territory that ecosystem services are realized and rendered certifiable, enabling the existence of carbon credits, and it is also there that the effects of volatility and instability associated with the financialization of these markets materialize in asymmetric ways. This spatial asymmetry reveals that processes of valuation and price formation tend to become progressively detached from the territorial conditions that sustain climate mitigation, shifting risks and uncertainties toward more vulnerable forest regions and conferring a structural – rather than incidental – character to territorial inequality within the functioning of carbon markets.

Considering the cyclical nature of financialization, where bubbles and transitions often precede structural economic shifts (Arrighi, 1996), we argue that correcting carbon-price signals requires the explicit valuation of ecosystem services. In forest markets, this can be operationalized through CO_2Flux, a complementary indicator to CO_{2eq} that captures carbon flow rather than stock, thereby improving accuracy, traceability, and auditability in pricing. By reducing information asymmetry and aligning market value with realized environmental performance, CO_2Flux can discourage speculative arbitrage and reinforce confidence in offset mechanisms, supporting the design of an Adjusted Environmental Budget for forest projects (Guerreiro et al., 2021, 2024). This analytical framework guides our hypotheses and subsequent empirical assessment.

In this context, the present study examines how financial speculation influences price equilibrium in forest carbon markets and how public policy frameworks mediate these fluctuations. By integrating bibliometric and systematic approaches, the review seeks to elucidate the mechanisms through which speculative behavior reshapes market efficiency, liquidity, and welfare outcomes. Beyond a mere description of volatility, the objective is to clarify how institutional design, integrity standards, and information asymmetries determine the extent to which carbon pricing reflects environmental value—rather than solely financial expectations. Ultimately, the question that arises is whether markets conceived to internalize ecological limits are able to fulfill this function when price signals respond more to the logic of speculation than to the territorial realities that sustain climate mitigation.

2. Methods

This study follows the PRISMA 2020 guidelines for systematic reviews (Page et al., 2021) and the PRISMA-S extension for search documentation (Rethlefsen et al., 2021). The central research question was formulated using the PICO framework (Population, Intervention, and Context), which structures analytical focus and eligibility criteria (Cooke et al., 2012), aiming to examine the effects of financial speculation on the carbon market.

While systematic reviews and meta-analyses are valuable for synthesizing quantitative evidence, they often fail to capture the complex and non-linear dynamics that characterize economic systems. Qualitative synthesis, in turn, enables a deeper understanding of actors' behavior, institutional design, and market failures, revealing mechanisms that quantitative asset-management approaches may overlook.

For these reasons, a mixed-methods approach combining quantitative and qualitative evidence was employed. Quantitative bibliometric mapping identifies structural patterns of research and citation, while qualitative analysis allows interpretation of market behavior, regulation, and integrity narratives. Together, these methods help uncover weaknesses in the carbon-credit system and support the formulation of more stable and equitable policy solutions for forest conservation and climate-change mitigation. This dual approach acknowledges the transitional nature of carbon markets, whose drive for profitability often persists independently of social and environmental outcomes.

The interdisciplinary scope adopted here represents a key analytical advantage for identifying gaps and designing effective strategies. Market failures are rarely visible through a single disciplinary lens; asymmetries linked to speculation, liquidity, and regulation can conceal externalities in both the short and long term, distorting equilibrium prices and encouraging environmentally inefficient policies.

3. Bibliometric Framework

The complexity of socio-environmental systems such as carbon markets demands a multidisciplinary approach. The intersection between financial, regulatory, and environmental dimensions creates multiple sources of uncertainty, frequently associated with the "economic myopia" introduced by speculative behavior (Sitarz et al., 2024).

Following the PICO framework (Cooke et al., 2012), the guiding question was defined as: How does financial speculation affect price equilibrium in forest carbon markets? The search and selection process adhered to the PRISMA 2020 and PRISMA-S standards (Page et al., 2021). Data were retrieved from Scopus and Web of Science on 7 October 2025, covering the period 2002–2025. The initial search identified 182 records (Scopus = 68; WoS = 114). After automated deduplication by DOI, title, author, and journal, two duplicates were excluded, resulting in a final sample of 180 articles.

The Boolean search strategy (applied in All Fields) focused on topic and price: ("carbon credits" OR "carbon market" OR "forest carbon") AND ("speculation" OR "speculative") AND ("carbon price" OR "carbon pricing"). The PRISMA flow diagram summarizing the screening process for the systematic review (2002–2025) is presented in Figure 1.

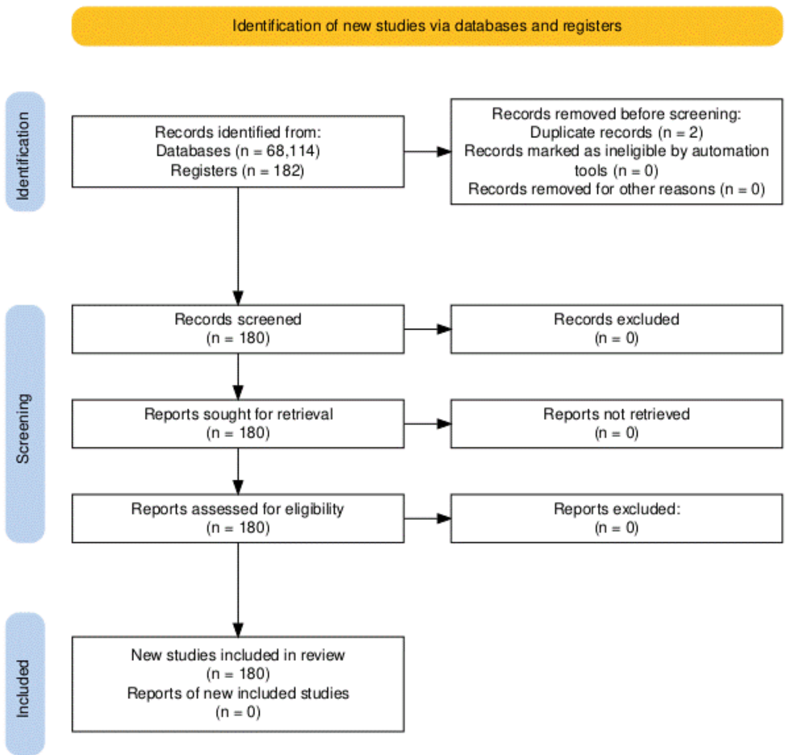

Figure 1. PRISMA 2020 flow diagram illustrating the systematic review process (2002–2025).
Adapted from Page et al. (2021), *The PRISMA 2020 statement: an updated guideline for reporting systematic reviews, BMJ*, 372: n71 (Haddaway et al., 2022; Page et al., 2021)

The PRISMA 2020 flow diagram (see Figure 1) ensures full traceability of the identification, screening and inclusion processes. Deduplication across Scopus and Web of Science yielded 180 valid records, guaranteeing thematic breadth and methodological consistency. The standardization of metadata fields and the combined use of Bibliometrix, VOSviewer, and R scripts enhanced reproducibility and comparability across databases, ensuring that the procedure can be replicated in accordance with the PRISMA (2020) guidelines.

Two complementary methodological aspects merit attention. First, no open-access filters were applied in order to avoid availability bias and preserve representativeness across journals from different publishers and access models. Second, although no explicit language restriction was imposed, the requirement for English titles and abstracts resulted in a predominance of publications in that language, with occasional inclusions of studies in Portuguese, Russian, and Spanish that were also screened and included in the qualitative analysis. This linguistic scope, acknowledged as a structural limitation of the international literature, underscores the importance of extending future reviews to non-English sources.

4. Systematic Review Approach

Bibliometric networks – covering co-authorship, occurrence, and co-occurrence of authors and keywords – were analyzed using VOSviewer 1.6.20 and R (RStudio 2024.12.1) through the Bibliometrix package. Standardized data exports (.txt, RIS, BibTeX) ensured full replicability of the analytical process. For thematic classification, the Journal of Economic Literature (JEL) taxonomy of the American Economic Association was applied (Cherrier, 2017). Each of the 180 articles was coded in the master dataset using the field JELreported, with 42 codes provided by authors (Fornec, 23.3%) and 138 assigned through audit based on titles, abstracts, and keywords (JELsource, 76.7%). This classification procedure standardized economic indexing and improved comparability across studies.

5. Results and Discussion

5.1. Distribution and Trends in Scientific Production

The consolidated corpus (n = 180) comprises publications across 97 journals, with a pronounced concentration in high-impact outlets within energy economics, finance, and environmental policy. The most represented journals are Energy Policy, Energy Economics, Forest Policy and Economics, Ecological Economics, and Forests, together accounting for nearly one-third of the total sample. This distribution, illustrated in Figure 2, confirms the multidisciplinary character of the topic, bridging research on energy markets, financialization processes, and environmental policy instruments.

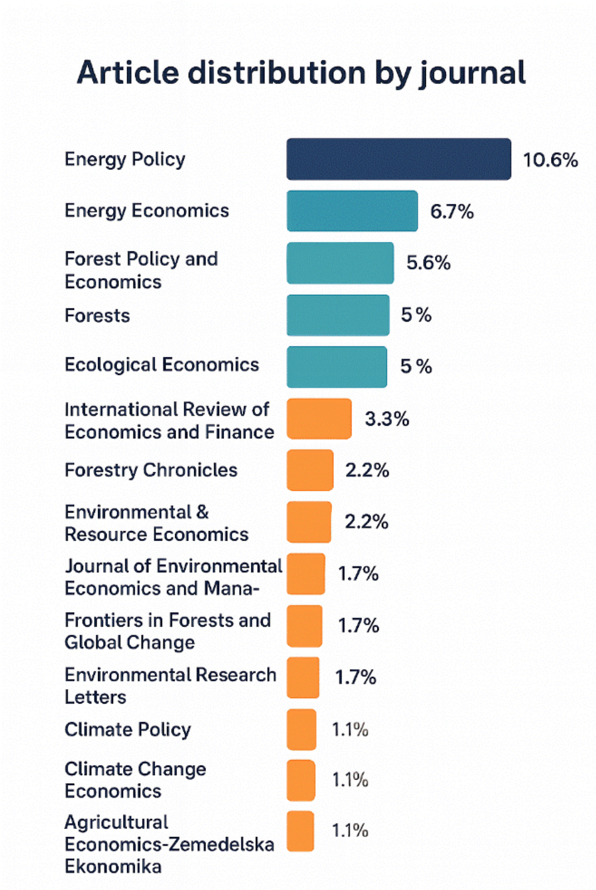

Figure 2. Top 15 journals publishing on speculation and carbon pricing (2002-2025). Source: Authors, based on Scopus and Web of Science data retrieved on 7 October 2025. Processing and visualization were performed using Bibliometrix/R (RStudio 2024.12.1).

Figure 2 shows that research on speculation and carbon pricing is mainly concentrated in energy and environmental economics journals, with a notable share of finance-oriented outlets. The debate therefore emerges at the intersection of price formation, market design, and risk across three analytical domains: energy (price formation and transmission), environment (integrity and policy), and finance (volatility and arbitrage).

This pattern reinforces the multidisciplinary character of the corpus (n = 180), which includes a wide array of aspects, from microeconomics to sustainable development. A pattern also clear from the analysis of attributes based on the JEL classification, which defines the analytical focus of the reviewed studies. As expected, category Q (environmental and resource economics) dominates (Figure 3), followed by G (finance) and C (methods), with additional support from H, O, and E, where public policy, innovation, and macroeconomic transmission are addressed. The following section applies the JEL taxonomy to structure this thematic mapping.

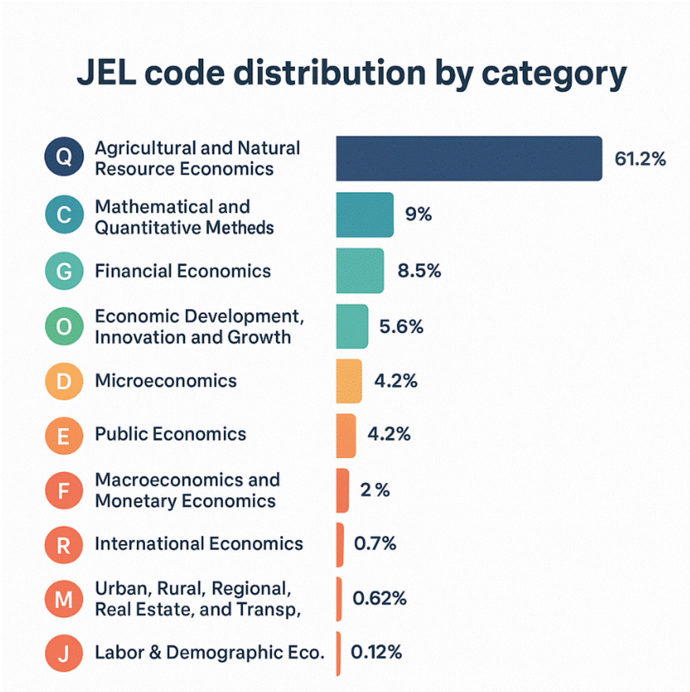

Figure 3. JEL code distribution by category for the analyzed corpus (n = 180).
Source: Authors, based on Scopus and Web of Science data retrieved on 7 October 2025. A total of 840 JEL codes were assigned. Processing and visualization were performed using Bibliometrix/R (RStudio 2024.12.1).

The thematic classification based on JEL codes (Figure 3) confirms the environmental orientation of the corpus, with Agricultural and Natural Resource Economics and Environmental and Ecological Economics as the prevailing categories. This predominance reflects the analytical focus on conservation, resource management, and environmental regulation.

The secondary representation of quantitative and financial domains highlights the methodological and speculative dimensions of the literature, linking econometric modeling, market behavior, and price dynamics. This distribution supports the transition to the next analytical stage, which examines how these thematic axes converge in studies on financial speculation and carbon pricing.

For qualitative analysis, the most frequent terms were prioritized, representing the core clusters of scientific production within the defined scope. This selection enabled an objective classification of the predominant thematic fields, forming the analytical foundation of the review through reference clusters. Following the methodological workflow, VOSviewer was used to identify keyword co-occurrences within the consolidated sample of 180 articles. A total of 169 valid terms were detected, connected by 4,130 links, yielding a total link strength of 6,064. The processing, conducted under full counting and normalized by association strength, produced six main clusters (Figure 4) that define the thematic structure of the field.

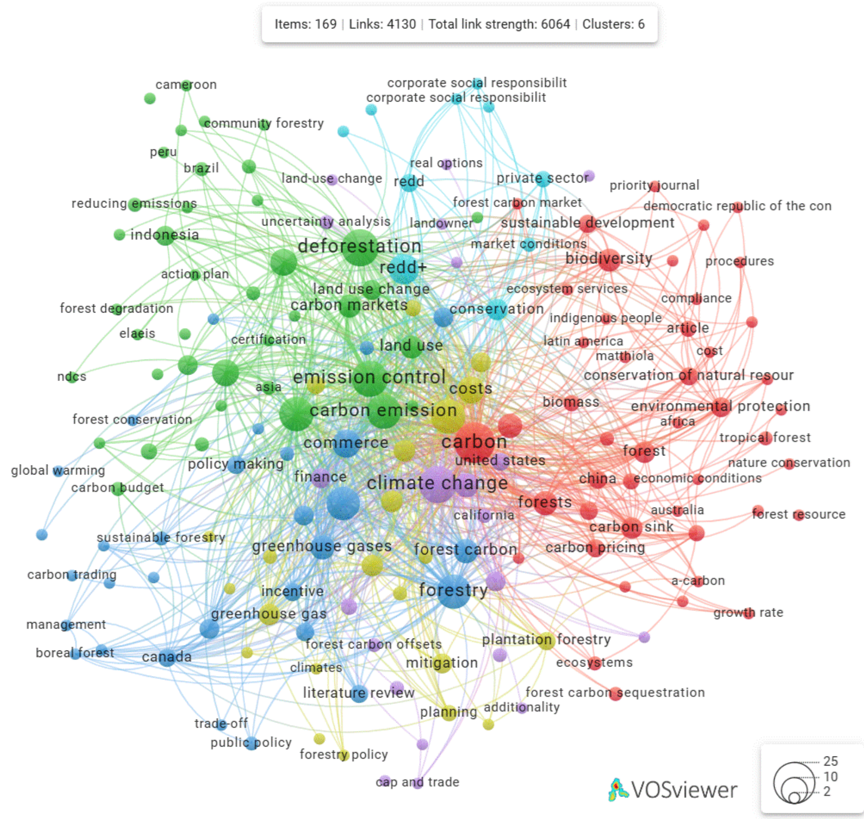

Figure 4. Keyword co-occurrence network (VOSviewer). Network map based on 180 articles, displaying six interconnected thematic clusters. The method used full counting; normalization by association strength; resolution = 1.0; total links = 4,130; and total link strength = 6,064. Colors denote conceptual groupings such as carbon pricing, environmental economics, climate policy, governance, and innovation.
Source: Authors, using VOSviewer (v1.6.20), based on Scopus and Web of Science data retrieved on 7 October 2025.

The spatial configuration shown in Figure 4 illustrates the multidisciplinary and cross-cutting character of the field. Central nodes such as forestry, carbon, climate change, and emission control structure the network, reflecting the strong ecological and governance orientation of the literature.

Market-related terms – including speculation, finance, and pricing – appear in adjacent clusters, indicating the emergence of a financial axis that connects environmental valuation to market mechanisms. This configuration suggests that the integration between ecological foundations and financial processes has become a recurring analytical focus in recent research agendas.

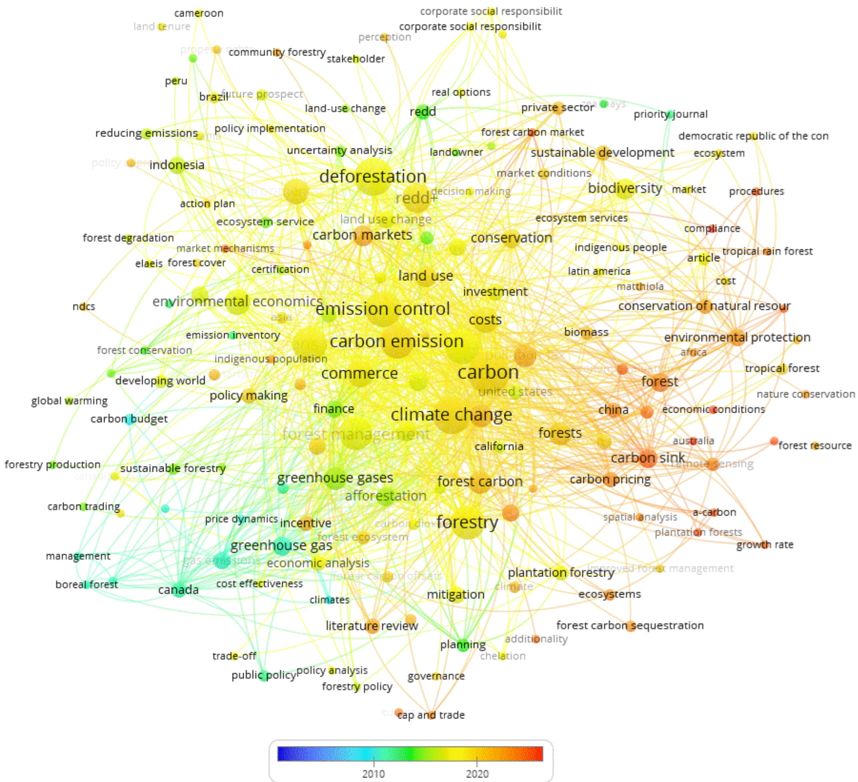

Figure 5. Temporal overlay visualization of keywords (VOSviewer). Chronological distribution of keywords from 2005 to 2025, showing the thematic evolution of the field. Warm tones (orange and yellow) represent recent research topics such as carbon pricing, emissions trading, and carbon sequestration, while cool tones (blue) indicate earlier conceptual foundations including climate change and global warming.
Source: Authors, using VOSviewer (v1.6.20), based on Scopus (n = 68) and Web of Science (n = 114) data retrieved on 7 October 2025.
Records published before 2005 are not displayed due to metadata limitations related to standardized keywords.

Figure 5 presents the temporal overlay visualization, illustrating the chronological evolution of keywords from 2005 to 2025. Warm tones (orange and yellow) identify the most recent research fronts, clustered around carbon pricing, emissions trading, carbon sequestration, and climate change mitigation. In contrast, cool tones (blue) depict the conceptual foundations consolidated in earlier decades, emphasizing themes such as climate, global warming, and tropical forest.

This chromatic gradient reflects a structural transition in the field—from theoretical and normative perspectives toward applied and economic analyses focused on carbon valuation, regionalized policy design, and the integration of environmental and financial metrics.

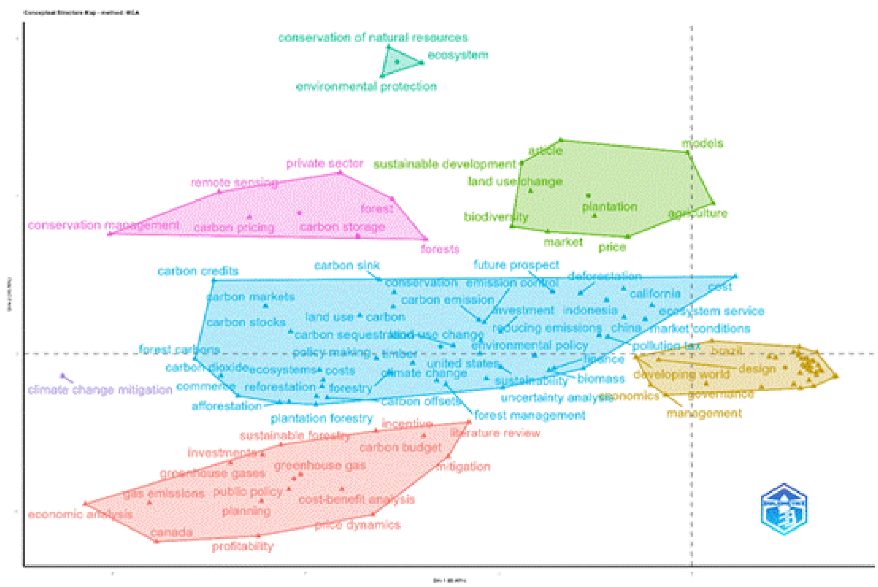

Figure 6. Conceptual structure map (MCA; Bibliometrix/RStudio). Two-dimensional projection of the keyword space using Multiple Correspondence Analysis with k-means clustering (k = 6). Axes: Dim 1 (50.49%) and Dim 2 (10.76%). Colors denote clusters; labels indicate representative terms.
Source: Authors, using Bibliometrix (R/RStudio 2024.12.1), based on Scopus (n = 68) and Web of Science (n = 114) data retrieved on 7 October 2025.

Figure 6 illustrates the conceptual structure map generated through Multiple Correspondence Analysis (MCA) and k-means clustering (k = 6). The red cluster represents the microeconomic–analytical axis, including economic analysis, mitigation, investment, and cost–benefit modeling. The light-blue cluster integrates studies on carbon economics, encompassing emission control, carbon sequestration, and environmental policy. The green cluster groups the agro-forestry and market–price domain, with terms such as plantation, agriculture, biodiversity, and land-use change. The magenta cluster connects remote sensing, carbon pricing, and conservation management within the context of the private sector. Finally, the yellow/ochre cluster highlights governance and implementation issues in the Global South—particularly in Brazil—where design, management, and pollution tax emerge as key terms.

This configuration confirms the dual analytical core identified in previous figures: the intersection between economic–environmental valuation and governance/implementation. It consolidates carbon economics as a multidisciplinary field where financial, ecological, and policy dimensions converge.

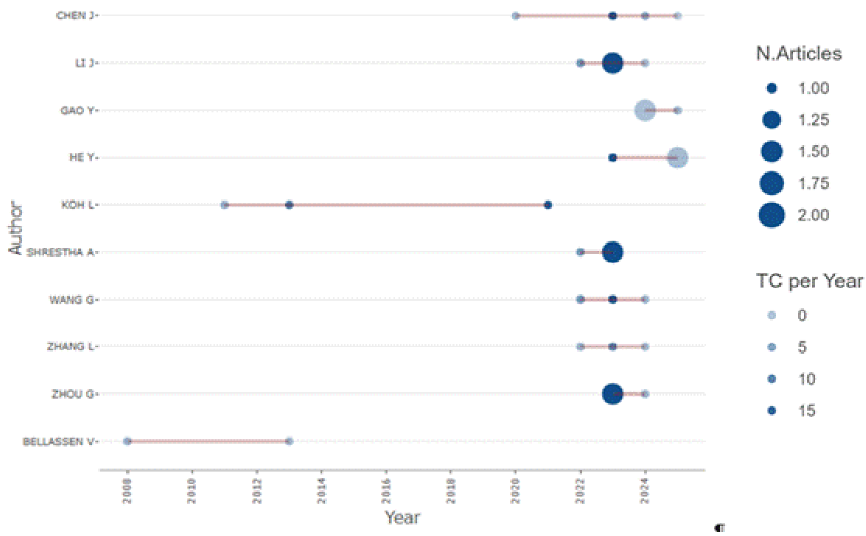

Figure 7. Authors' production over time (Bibliometrix/RStudio).
Source: Authors, using Bibliometrix (R/RStudio 2024.12.1), based on Scopus (n = 68) and Web of Science (n = 114) data retrieved on 7 October 2025. Lines represent each author's active publication period within the sample (2008-2025). Parameters: authorProdOverTime (M, k = 10); export resolution: 300 dpi.
Note: Although the systematic review covers publications from 2002 to 2025, the temporal visualization begins in 2008 due to metadata availability. Earlier records within the reviewed period lacked standardized author identifiers, preventing their inclusion in the longitudinal representation.

Figure 7 illustrates the temporal distribution of author productivity within the corpus, revealing three distinct patterns: (i) Long and continuous trajectories—authors such as Koh L. and Bellassen V. maintain extended publication lines over more than a decade, indicating seniority and cumulative citation impact; (ii) A recent post-2020 cohort—authors including Li J., Gao Y., and Chen J. display a sharp rise and larger bubbles between 2022 and 2025, reflecting accelerated visibility in topics such as carbon pricing, emissions trading, and market governance; and (iii) Authors with few but high-impact papers—isolated large bubbles denote synthesis or policy-assessment studies with strong citation performance despite limited output. Taken together, the time series confirms the renewal and geographical diversification of the field over the past decade, consistent with the trends observed in Figures 4-5 (the applied and economic turn) and the conceptual structure identified in Figure 6 (axes of governance, valuation, and conservation).

Table 1 presents the most productive authors in the sample between 2002 and 2025, highlighting the consolidation of a research core located primarily in the Global North—Western Europe, North America, and East Asia. Among the most influential contributors are Massimo Tavoni, Emanuele Campiglio, and Valentin Bellassen, whose work has shaped the integrated modeling of climate policy and carbon economics (Campiglio, 2016; van Vuuren et al., 2020). The temporal predominance of these authors after 2010 marks the consolidation of carbon economics as an autonomous subfield within environmental economics, grounded in price, risk, and governance metrics.

Table 1. Most productive authors in the sample (2002-2025). Ranking based on combined score; fractional count = 1/number of authors per article.

Rank	Author	Country	Affiliation	Active period	Span (years)	Articles (FC)	Total citations (TC)
1	*Zhang*	China	Tsinghua University	2022–2024	3	3.00	458
2	*Tanaka*	Japan	University of Tokyo	2012–2021	10	4.00	1722
3	*Campiglio*	UK	University of Edinburgh	2016–2016	1	2.00	1192
4	*Varun*	India	Indian Institute of Technology	2017–2023	7	2.00	140
5	*Franz*	Germany	Technical University of Munich	2021–2025	5	2.00	44
6	*Liu*	China	Peking University	2021–2022	2	2.00	86
7	*Massa*	Italy	University of Bologna	2016–2022	7	2.00	143
8	*Chen*	China	Shanghai Jiao Tong University	2024–2025	2	2.00	130
9	*Buttar*	UK	University of Birmingham	2009–2021	13	0.58	81
10	*Bellassen*	France	INRAE / Paris-Saclay University	2008–2013	6	2.00	850
11	*Peterson*	USA	Harvard University	2012–2024	13	2.00	83
12	*Lazzarini*	Brazil	University of São Paulo (USP)	2021–2025	5	2.00	152

Source / methodological note: Authors' elaboration using R/Bibliometrix. Fractional count prevents inflation due to multiple coauthorships. Total citations (TC) represent cumulative citations per author within the deduplicated sample (Scopus + Web of Science).

Figure 8 expands this analysis by showing the distribution of author production by country of affiliation, distinguishing single-country publications (SCP) from multiple-country publications (MCP). The figure highlights the dominance of the United States and China, which together account for over 40% of the total articles, as well as the growing prominence of European centers—Germany, France, and the United Kingdom—whose tradition in climate modeling and market regulation dates back to the establishment of the EU ETS (Ellerman & Buchner, 2007; Schippers & Massol, 2021). Conversely, the Global South remains underrepresented, with Brazil appearing among the top ten countries only after 2020, reflecting its delayed entry into the scientific debate on carbon pricing and offset mechanisms.

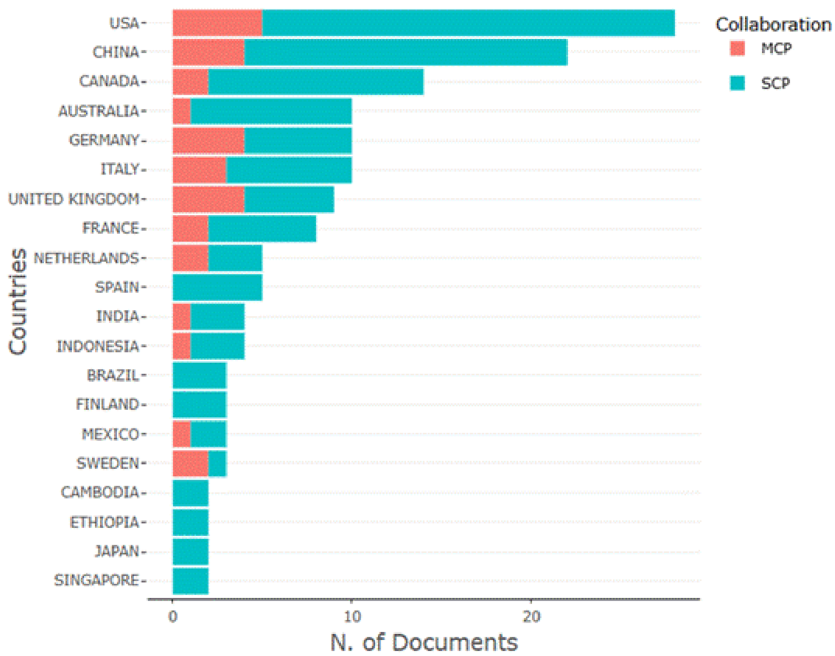

Figure 8. Authors' production over time and distribution by country of affiliation (SCP = single-country publications; MCP = multiple-country publications).
Source: Authors, using Bibliometrix (R/RStudio 2024.12.1), based on Scopus (n = 68) and Web of Science (n = 114) data retrieved on 7 October 2025.

The joint interpretation of Table 1 and Figure 8 reveals a structural asymmetry that reflects not only scientific power but also the economic hierarchy between the Global North and the Global South. This configuration mirrors the uneven geographies of globalization and knowledge production described by Milton Santos (Santos, 1996, 2000) whereby technical–scientific infrastructures and decision-making capacities remain concentrated in core regions, while peripheral areas continue to depend structurally on them.

Empirically, this asymmetry is evident in the carbon-market literature, where most theoretical and methodological production is concentrated in the North—closely linked to the genesis and refinement of the EU ETS and to governance frameworks that privilege high-income regions (Gilbertson, 2021; Gren, 2024; Gren & Aklilu, 2016). Such centralization reproduces historical dependencies between scientific and economic capital, reinforcing the epistemic divide that limits Southern participation in rule-setting and valuation processes within global climate governance.

This imbalance supports the argument that the carbon market reproduces the same inequalities observed in the global financial system, wherein knowledge, capital, and measurement capacity are concentrated in the North, while mitigation potential largely resides in the South (Arrighi, 1996). Nevertheless, the growing participation of Latin American and Asian institutions indicates a positive inflection, suggesting the gradual emergence of an active scientific periphery within the international climate debate.

To strengthen this geographical reading, Figure 9 introduces an interpretive cartographic synthesis of the territorial architecture of compliance carbon pricing instruments, based on the World Bank Carbon Pricing Dashboard. This figure is not part of the bibliometric corpus itself; rather, it complements the systematic review by spatializing the institutional environment in which carbon pricing mechanisms are implemented. It distinguishes carbon taxes, Emissions Trading Systems (ETS), combined arrangements, and instruments under development or consideration, while also providing an interpretive reference to the Global North–Global South divide.

The map reinforces the argument that carbon pricing is not territorially neutral. Implemented instruments are more densely concentrated in Europe, North America, and selected Asia-Pacific economies, where regulatory capacity, market infrastructure, and institutional coordination are more consolidated. In contrast, several countries in Latin America, Africa, and other parts of the Global South appear through instruments under development or consideration, suggesting a more fragmented and still-emerging regulatory geography. This pattern helps connect the bibliometric asymmetry identified in Figure 8 with the broader spatial organization of carbon-market governance.

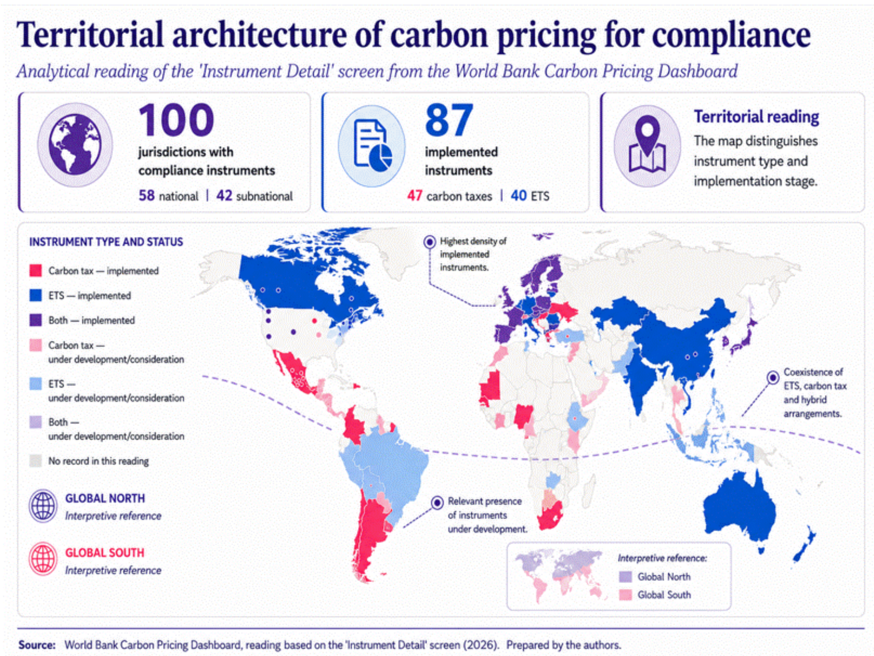

Figure 9. Territorial distribution of compliance carbon pricing instruments and North–South asymmetries. Interpretive cartographic synthesis based on the "Instrument Detail" screen of the World Bank Carbon Pricing Dashboard. The figure distinguishes implemented carbon taxes, Emissions Trading Systems (ETS), combined arrangements, and instruments under development or consideration. The Global North/Global South distinction is used as an interpretive geopolitical reference rather than as a strict geographic boundary.

This cartographic synthesis closes the geographical reading developed by connecting the uneven distribution of scientific production to the territorial architecture of carbon pricing. The next section advances from this spatial diagnosis to the thematic mechanisms through which speculation, regulatory uncertainty, and market design shape carbon price formation.

6. Thematic Insights from the Systematic Review

Financial speculation is not merely a transient anomaly in price fluctuations. It constitutes a structural phase within the broader cycle of capital accumulation, responding to the institutional and technological transformations of its time. In practical terms, oscillations and "manias" are not external noise to the carbon market but endogenous mechanisms that emerge when rules and expectations are reconfigured (Burtraw et al., 2009; Campiglio, 2016).

To interpret this phenomenon, the carbon market requires a combined quantitative–qualitative lens. Quantitative models, price regressions, volatility measures, and time-series analyses (Dou et al., 2022) capture short-term reactions to policy shocks and news cycles. Qualitative perspectives, in turn, reveal how rules, credibility, and enforcement shape expectations and market behavior (Ohlendorf et al., 2022; Zhang et al., 2024).

The systematic review indicates that speculation intensifies during periods of high volatility, when uncertainty and expectations amplify, and intertemporal myopia distorts price formation (Dou et al., 2022). Yet, speculative behavior is not confined to crisis peaks: post-reform stability does not eliminate speculation but conceals it. In contexts of gradual announcements or regulatory uncertainty, deviations may be camouflaged within the apparent regularity of aggregated expectations (Sitarz et al., 2024). Consequently, purely quantitative approaches tend to under-capture speculative behavior in "calm" regimes, making qualitative analysis of institutional design and incentive structures essential (Ding et al., 2025).

A recurrent theme in the literature concerns market intermediaries and architecture. In regulated markets, compliance obligations and monitoring mechanisms reduce direct manipulation, although banking, hedging, and compliance-cost structures still create space for strategic financial behavior (Campiglio, 2016; European Securities and Markets Authority (ESMA), 2024). In voluntary markets, where enforcement is diffuse, brokers and certifiers can widen spreads, transfer risk, and amplify speculation through expectations about eligibility, additionality, and integrity—a concern raised by Millard-Ball (2012) and reinforced in more recent governance analyses. In both contexts, liquidity and efficiency can be welfare-enhancing, but losses arise when market power sustains fees and redistributes risk without social return (Kangas & Ollikainen, 2023; Lessmann & Kalkuhl, 2024) .

The review also uncovers marked heterogeneity between ETS and VCM systems. In regulated schemes, adjustments in scope, cap design, allocation, and inter-system linkages transmit policy shocks to price and volatility (Burtraw et al., 2009). In voluntary systems, pricing depends on standards and narrative framing, making these markets more sensitive to news cycles and private governance (Millard-Ball, 2012). Across both, policy uncertainty—whether reform announcements, partial adjustments, or judicial decisions—emerges as a consistent determinant of speculative episodes, a finding strong across the 180 studies reviewed.

Within the forest segment, the review identifies a distinct price regime conditioned by project ecology (permanence and leakage risk, measurement accuracy) and regulatory evolution. Recent studies examine risk premiums by country and practice, simulating trade gains when uncertainty is internalized (Gren, 2024). European debates on forest removals under the new CRCF have generated strong ex-ante market signals: projects and assets reposition even before eligibility pathways become operational—an archetype of "value anticipation" consistent with accumulation-cycle theory. Regulation (EU) 2024/3012, which formalizes certification for removals and carbon farming, reshapes incentives; the 2025 scientific advisory report further recommended separate targets for reductions and removals to prevent mitigation deterrence—both consistent with anticipatory pricing dynamics (European Union, 2024).

Within forest-based economies, carbon-price volatility reshapes rotation calendars and selective harvesting methods, influencing synergy zones between profitability and CO2 removal (Ekholm, 2020; Luo et al., 2023; Tee et al., 2014; van Kooten, 2023). The reintegration of AI and optimization tools into harvesting schedules, risk management, and eligibility assessment improves operational efficiency but also introduces new volatility channels, as technological expectations themselves become priced (Cong et al., 2024).

Although Australia is not a forest-based economy, its Eucalyptus species – widely introduced in tropical and subtropical regions – underpin the structure of planted forests across the Global South, particularly in Brazil. This genetic and silvicultural legacy connects Australian-origin forestry with contemporary carbon-market mechanisms, where plantation cycles and productivity models shape valuation and credit-generation dynamics.

From a geopolitical standpoint, the North–South asymmetry discussed in Section 3.1 re-emerges: theoretical and methodological output remains concentrated in the North, while most forest mitigation potential lies in the South, where institutional capacity and regulatory risk continue to shape pricing outcomes (Scherger, 2024). At the level of international negotiations, rule design and exception mechanisms may enable formal targets without substantive emission reductions, a recurring concern in governance analyses (Maraseni & Reardon-Smith, 2019).

In synthesis, the reviewed evidence suggests that the forest carbon market can operate both as a mitigation instrument and as a vehicle for financialization. When captured by short-term incentives, it dematerializes ecological value into financial operations of return, risk, and liquidity, turning the climate crisis into a new frontier of valorization, in line with accumulation-cycle theory. This process, however, does not unfold in abstraction but is inscribed in concrete territories, where the production of ecosystem services, institutional regulation, and exposure to risk are unevenly distributed across space. The transition from "forest value" to "expected financial value" thus reflects not only a shift in pricing logic, but also a geographical reconfiguration of climate mitigation, helping to explain why risk premiums, regulatory arbitrage, and integrity narratives have assumed a central role in the formation of carbon credit prices.

7. Comparative Synthesis of Market Mechanisms

Table 2 summarizes the conceptual patterns emerging from the 180 studies reviewed, classifying them by market type, speculative mechanism, and policy implication. The synthesis highlights how speculative behavior varies across institutional designs – from regulated Emission Trading Systems (ETS) to Voluntary Carbon Markets (VCM) and hybrid regimes – revealing that financial speculation is not an isolated phenomenon but a structural component of carbon price formation. This integrative overview bridges empirical evidence and regulatory insight, serving as a conceptual interface between Sections 3 and 4. These speculative mechanisms unfold unevenly across regulatory and territorial contexts, revealing that carbon price formation is inseparable from the spatial organization of markets, governance capacities, and the geography of mitigation itself.

Table 2. Comparative overview of speculative mechanisms and policy implications in carbon markets (n = 180)

Market Type	Speculative Mechanism	Policy Implication	Representative Studies
Emission Trading Systems (ETS) (EU ETS, KETS, California Cap-and-Trade)	Price volatility driven by allowance oversupply and inter-period banking. Speculative arbitrage exploiting allocation asymmetries. Short-term trading dominance by financial intermediaries.	Introduce adaptive price corridors linking marginal abatement cost and social cost of carbon. Limit speculative banking beyond compliance cycles. Strengthen transparency and disclosure within allowance registries.	Burtraw (2009); Campiglio (2016); Dou (2022)
Voluntary Carbon Markets (VCM) (REDD+, CORSIA, Gold Standard, Verra)	Forward pre-selling and low verification quality enabling speculative accumulation of underpriced credits. Liquidity asymmetry and off-balance sheet transactions detached from mitigation outcomes. Speculative expectations driven by ESG signalling and reputational arbitrage.	Implement MRV+ frameworks with independent auditing and real-time tracking. Introduce reversibility insurance to mitigate permanence risk. Harmonize certification standards to reduce information asymmetry.	Millard-Ball (2012); Kangas & Ollikainen (2023); Lessmann & Kalkuhl (2024)
Hybrid / Emerging Markets (China ETS, Brazil SBCE, Colombia, New Zealand)	Dual pricing during pilot-to-compliance transitions. Governance gaps and fragmented oversight allowing speculative spreads between regulated and voluntary instruments. Market inertia amplified by policy uncertainty and institutional experimentation.	Develop stabilization funds to absorb speculative liquidity shocks. Integrate fiscal tools (carbon floor prices, auction reserves) to align liquidity and integrity. Enhance international linkage protocols to reduce cross-market volatility.	Gren (2024); Scherger et al. (2024); Maraseni et al. (2019)

Source: Authors, based on systematic review (Biblioshiny and RStudio, 2025). Classification by market type (ETS / VCM / Hybrid), dominant speculative mechanism, and main policy implication.

As Arrighi (1996) observed, every financial cycle expands through speculation before regulation restores order. Carbon markets follow the same rhythm: speculation grows were price and ecology drift apart. In regulated systems, it is institutional; in voluntary ones, symbolic – echoing Pareto's logic of belief and profit. Kindleberger et al. (2023) reminds us that such waves are not anomalies but moments of renewal. Here, speculation becomes the mechanism through which capitalism converts ecological uncertainty into economic value – a transition explored further in Section

4, reaffirming the historical evolution of economic thought toward environmental integration Gullo (2010).

8. Conclusions

The systematic review of 180 articles demonstrates that the incorporation of financial instruments into the climate agenda has generated a growing disjunction between the environmental and market value of carbon credits. This divergence – where prices reflect cycles of liquidity, risk, and expectation rather than ecological externalities – characterizes an advanced stage of climate financialization. The result is a system in which policy shocks, regulatory news, and intermediation strategies shape price dynamics with sufficient intensity to influence real decisions in investment, mitigation, and land use.

The literature addressing carbon markets as financial assets converges around three main analytical strands, each grounded in the microeconomic logic of market equilibrium and price formation.

The first strand examines the relationship between carbon and energy markets, showing that carbon prices are significantly affected by fossil-fuel demand, particularly for oil and coal. Empirical studies such as Aslam et al. (2023) and Azlen et al. (2022) indicate that fluctuations in energy demand, especially during oil booms raise emissions and, consequently, the price of carbon credits. Energy-price volatility also exhibits strong predictive power for future carbon prices. This linkage transmits changes in fossil-fuel demand and energy-mix composition directly to carbon prices, propagating short-term volatility and expectation effects across the system.

The second strand focuses on price volatility and market dynamics, as noted by Disterhoft et al. (2023) and others (Billimoria et al., 2025; Chen et al., 2019). These studies highlight the effects of uncertainty in carbon trading, including outliers, abrupt shifts, and variance clusters. Endogenous volatility – expressed through jumps and regime breaks – indicates that carbon markets react nonlinearly to uncertainty. Speculative behavior becomes visible during stress periods but is often disguised under "stable" regimes, where it hides behind the regularity of expectations.

The third and most recent strand explores the role of carbon markets as investment vehicles and their implications for portfolio performance, showing potential diversification benefits, particularly during downturns. Studies such as Zhang et al. (2024) and Demiralay et al. (2022) demonstrate that incorporating carbon credits can reduce portfolio risk, though effects vary across markets and time horizons, especially within the EU ETS.

Overall, the literature suggests that while carbon prices are shaped by multiple determinants, their interpretation within a microeconomic equilibrium framework reveals a duality: carbon, as a financial asset class, introduces diversification opportunities but also regulatory, temporal, and informational arbitrage windows that can erode social welfare when private value capture outweighs environmental benefit.

We argue that the imperfectly competitive structure of the carbon market provides fertile ground for speculative practices that inflate credit prices without ensuring proportional environmental returns. Early studies in this field often treated financialization superficially, without connecting it to price-equilibrium theory, capital-accumulation cycles, or the broader history of economic thought, focusing instead on indices, exchanges, and hedge fund activity.

From an institutional standpoint, the review confirms a persistent structural heterogeneity between regulated markets (ETS) and voluntary markets (VCM). In ETS, cap-and-trade frameworks, reform credibility, and banking/balancing rules limit direct manipulation but do not eliminate speculative incentives surrounding policy reforms and announcements. In VCM, the diversity of standards and private governance structures makes prices more sensitive to integrity narratives, amplifying information asymmetries and creating space for extractive intermediation. In both settings, intermediaries enhance liquidity and reduce transaction costs but may intensify financialization when market power, opacity, and fees detached from environmental performance prevail.

In the forest segment, the evidence is unequivocal: permanence, leakage, and measurement risk define a distinct price regime in which risk premiums vary by country, typology, and management practice. Debates over removals and regulatory eligibility generate ex-ante value signals that attract speculative investment even before normative consolidation. Nevertheless, rapid advances in technical solutions – such as MRV+ geotechnologies (LiDAR/SAR, CO2Flux, optical time series, growth and risk modeling), data standardization, and independent auditing – are improving accuracy, traceability, and transparency, thereby compressing uncertainty premiums and curbing opportunities for financial capture without environmental return. From a geographical perspective, this asymmetry is not merely economic or institutional, but spatially produced: regulatory capacity, measurement infrastructure, and financial decision-making concentrate in core regions, while mitigation activities, land-use transformation, and environmental risk remain territorially anchored in peripheral forest landscapes.

The North–South asymmetry once again emerges as a structuring axis: theoretical production and measurement infrastructure remain concentrated in the Global North, whereas forest mitigation potential and regulatory uncertainty are primarily located in the Global South. This imbalance affects price, liquidity, and risk: where institutional capacity and standardization are weak, carbon prices tend to reflect expectations rather than ecological value—precisely the conditions that foster speculation. Since 2008, there has been no empirical reason to assume that such market failures are less harmful than political intervention or scientific discredit, nor that carbon-credit markets have systematically achieved their stated objectives. The debate on the effectiveness and limits of carbon-credit policy thus remains open, and the evidence presented here raises as many questions as it answers. Ultimately, by articulating these analytical fronts, this systematic review offers a strategic lens to reassess the limits and promises of a carbon market still in formation—one in which the forest, as asset, symbol, and ecological infrastructure, occupies a central and contested position, while simultaneously emerging as lived territory and concrete space where global financial logics collide with local environmental realities.

9. Policy Implications

The findings suggest that the stability of carbon prices depends less on market maturity than on institutional design. Strengthening MRV+ systems—extending measurement, reporting, and verification to include social and ecological co-benefits—could reduce the informational asymmetry that fuels speculative volatility. Likewise, introducing reversibility insurance mechanisms would improve long-term credibility, ensuring compensation when carbon stocks are lost through fire, pests, or management failures. Finally, establishing price corridors, with minimum and maximum thresholds, may prevent speculative bubbles and reinforce allocative efficiency. From a systemic perspective, these measures align with Arrighi's interpretation of financial cycles: speculation and regulation are not opposites but sequential phases of the same dynamic, where governance transforms uncertainty into stability.

From a geographical standpoint, the effectiveness of these policy instruments is inherently uneven across territories. Institutional capacity, technical infrastructure, and governance density vary significantly between regions, shaping how MRV+ systems, insurance mechanisms, and price controls are implemented and enforced. In forest-based economies of the Global South, where mitigation potential is high but regulatory stability and monitoring capacity are limited, policy instruments tend to operate under greater uncertainty, amplifying spatial asymmetries in price formation and risk allocation. Consequently, carbon-market regulation cannot be treated as territorially neutral: its outcomes depend on the spatial distribution of institutions, knowledge, and enforcement capacity, reinforcing the need for geographically differentiated policy design.

10. Limitations and Future Perspectives

The forest carbon market presents structural limitations that constrain both its environmental effectiveness and its economic stability. The accelerating financialization of forest assets, as emphasized by Azlen et al. (2022) and Isah et al. (2024), reveals a widening disconnect between the ecological and financial valuation of forest credits. Price volatility—driven by market sentiment, liquidity conditions, and regulatory uncertainty (Wu & Qin, 2021)—undermines long-term investment horizons, discourages productive capital allocation, and weakens incentives for sustainable forest management. These limitations are not evenly distributed but manifest territorially, as carbon market risks, benefits, and governance capacities are spatially differentiated across landscapes, regions, and socio-ecological contexts.

Moreover, as Gilbertson (2021) cautions, the expansion of the forest carbon market risks reproducing historical inequalities by favoring large actors while marginalizing vulnerable communities. This concern is exemplified by Afro-Colombian populations affected by mining activities, whose territorial rights and governance participation are often disregarded. The proposed inclusion of forest removals in the EU ETS by 2030 (Bleuel & Müller, 2024) crystallizes the tension between ecological integrity and the pressure for liquid assets to fulfill Article 6 commitments under the Paris Agreement UNFCCC (2015).

Another critical limitation lies in the market's dependence on forests as a valorization infrastructure. While optimization and efficiency-oriented instruments can enhance allocative outcomes, they risk neglecting complex ecological dynamics—such as biodiversity and resilience—when scientifically validated environmental metrics are not fully integrated (Kovacs et al., 2021). In the absence of robust safeguards, market design may internalize financial risk while externalizing ecological risk, ultimately eroding the environmental legitimacy of the system.

Despite these constraints, the forest carbon market retains significant potential for evolution, provided that structural reforms are implemented. The integration of artificial intelligence and climate modeling (Zhang et al., 2024) opens promising avenues for evidence-based governance, reducing uncertainty and improving the valuation accuracy of ecosystem services. Fine-scale spatial modeling of carbon sequestration, as proposed by Kovacs et al. (2021), supports more efficient resource allocation and risk management at both project and landscape scales.

Among the most promising regulatory innovations, Gren (2024) proposes pricing forest-removal risks through adjusted secondary markets (e.g., reversal-risk instruments), thereby enhancing credit reliability and aligning environmental asset valuation with ecological fundamentals. However, the integrated analysis presented in this review suggests that financialization is likely to deepen, with speculation distorting the circulation between fictitious and real value, ultimately eroding trust in price-control mechanisms. In this dynamic, core economies may retain financial advantages by outsourcing environmental responsibility to peripheral countries without altering their own productive or energy structures—thus perpetuating an unsustainable pattern of consumption detached from ecological materiality. Avoiding such an outcome requires institutional redesign capable of reconnecting price with integrity, ensuring that valuation mechanisms reflect genuine ecological performance rather than speculative expectation.

Data Availability

The curated bibliographic metadata used in this systematic and bibliometric review, together with the documented search protocol, PRISMA materials, data dictionary, and associated R scripts, are available in the Zenodo replication package: https://doi.org/10.5281/zenodo.20781567. The public package excludes raw Scopus and Web of Science exports, full-text PDFs, full abstracts, and raw affiliation fields because of database, publisher, and copyright restrictions.

Code Availability

The R scripts included in the Zenodo replication package generate the public metadata dataset, the documented search-protocol files, the PRISMA materials, and the repository documentation. The package supports transparency and traceability of the preserved final corpus (n = 180). Available at: https://doi.org/10.5281/zenodo.20781567.

Declarations

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Consent for publication. Not applicable.
Human and Animal Rights. Not applicable.

Supplementary Material - (available upon request)

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