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The Great Financial Transformation: Toward a Unified Theory of Climate Risk in Global Capital Markets

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Abstract

This synthesis examines 1,150 empirical investigations exploring how planetary ecological disruption cascades through global financial architecture. Drawing upon the theoretical heritage of Knightian uncertainty, Polanyi's double movement, and the emerging paradigm of Earth Systems Finance, we develop a unified framework for understanding climate-induced financial transformation. Our analysis reveals four fundamental insights that challenge conventional financial theory. First, the "carbon premium" manifests not as a stable risk-return tradeoff but as an emergent property of socio-ecological systems undergoing punctuated equilibrium shifts, exhibiting phase transitions that mirror thermodynamic irreversibility. Second, physical climate impacts operate through complex adaptive system dynamics wherein localized environmental perturbations propagate through financial networks via nonlinear amplification mechanisms, producing what we term "ecological contagion." Third, regulatory ambiguity generates valuation bifurcations that reflect competing temporal discounting regimes—what Keynes might recognize as "animal spirits" now channeled through climate consciousness. Fourth, institutional absorptive capacity—encompassing state effectiveness, informational transparency, and cognitive frameworks—modulates the velocity of climate risk internalization, revealing profound disparities between jurisdictions that approximate differential equations of institutional inertia. Environmental-certified instruments demonstrate countercyclical protective characteristics during ecological anxiety episodes. We identify critical lacunae concerning biodiversity collapse thresholds, systemic financial cascades, and distributional justice imperatives embedded in energy transition pathways.

Keywords: Climate finance; Earth Systems Theory; financial contagion; ecological economics; asset pricing anomaly; institutional economics; complex adaptive systems

1. Introduction: The Financialization of Planetary Boundaries

The Anthropocene's defining paradox confronts contemporary finance with unprecedented urgency: the very economic activities that generate capital accumulation simultaneously erode the biophysical foundations upon which all economic production ultimately depends. This dialectical tension—capital's simultaneous dependence upon and destruction of its ecological substrate—demands theoretical sophistication beyond conventional risk-return frameworks. What was once

dismissed as the moral preoccupation of ethically motivated investors has become the central problematic confronting institutional capital, sovereign wealth funds, and monetary authorities across the developed and developing worlds (Campiglio et al., 2023). This transformation reflects not merely shifting preferences but an ontological recognition: ecological dynamics now constitute foundational parameters determining the possibility conditions for future value creation.

The intellectual lineage of climate-finance scholarship draws from multiple traditions that remain insufficiently integrated. From Knight (1921), we inherit the crucial distinction between calculable risk and genuine uncertainty—a distinction that becomes operative when dealing with non-ergodic ecological processes characterized by tipping points and irreversible thresholds. From Keynes (1936), we derive insight into how cognitive frames and conventional judgment shape asset valuation under conditions of fundamental indeterminacy. From Polanyi (1944), we understand the historical tendency toward "double movement"—society's protective counter-mobilization against the destructive consequences of unregulated market expansion—now manifesting through climate policy, carbon pricing, and regulatory intervention. Contemporary scholarship has added crucial dimensions: the recognition of non-linear dynamics from ecological economics (Georgescu-Roegen, 1971; Daly, 1991), the institutional analysis of common-pool resource governance (Ostrom, 1990), and the emerging paradigm of Earth Systems Science (Steffen et al., 2015).

Modern climate-finance scholarship has crystallized around two fundamental vulnerability categories that correspond to distinct causal mechanisms (Giglio et al., 2021; Campiglio et al., 2023). **Physical hazards** emanate directly from altering environmental conditions: agricultural system failure when thermal thresholds are surpassed (Pankratz et al., 2023); fixed asset depreciation when ocean levels advance (Goldsmith-Pinkham et al., 2023); supply chain fracturing when inundation disrupts transportation networks. These represent what we term **first-order biophysical impacts**—direct translations of ecological change into economic outcomes. **Transition hazards** emerge indirectly from collective socio-political responses to ecological change: carbon taxation elevates operating expenses for emissions-intensive enterprises (Bolton & Kacperczyk, 2021); technological displacement renders existing capital stocks obsolete (Flammer, 2023); evolving cultural frameworks diminish consumption preferences for carbon-intensive goods. These constitute **second-order institutional responses**—mediated through governance structures, cultural cognition, and policy implementation.

The 2015 Paris Agreement represented a critical juncture in this intellectual evolution. By committing signatory nations to constrain global warming to well below 2°C above pre-industrial baselines, it communicated a fundamental policy trajectory requiring financial actors to reassess portfolio vulnerability (Monasterolo & de Angelis, 2020; Birindelli et al., 2023). Subsequent scholarly investigation has expanded exponentially, yet the field remains characterized by fragmented methodologies, contested findings, and insufficient theoretical integration.

This systematic synthesis addresses three interconnected investigative questions that proceed from descriptive to analytical to prescriptive:

RQ1: How do diverse categories of ecological danger—physical, transitional, regulatory, and biodiversity-related—influence security valuations, price volatility, and investment returns across primary financial exchanges?

RQ2: Through what transmission mechanisms and conditioning elements—institutional frameworks, disclosure obligations, market psychology, policy environments—does the connection between ecological danger and financial systems operate?

RQ3: What protective, diversifying, or amplifying functions do sustainable financial instruments—environmentally certified bonds, sustainability indices, performance-linked loans—serve in the context of ecology-related financial vulnerabilities?

Our contribution operates at three levels. First, we provide comprehensive mapping of a substantially fragmented research territory, distinguishing the distinctive impacts of physical versus transition hazards through a theoretically informed lens. Second, through systematic review protocols (Paul et al., 2021), we offer transparent and reproducible evaluation of methodological patterns and empirical consensus. Third—and most significantly—we formulate an integrated theoretical framework grounded in Earth Systems Theory, institutional economics, and complex adaptive systems thinking, accompanied by a comprehensive future research blueprint that addresses identified lacunae.

The document proceeds sequentially: Section 2 details our investigative methodology. Section 3 provides descriptive characterization of the literature corpus. Section 4 synthesizes physical hazard evidence through an ecological economics lens. Section 5 analyzes transition hazard and the carbon premium debate within institutional and behavioral frameworks. Section 6 examines environmentally certified bonds as institutional innovations. Section 7 addresses emerging hazard categories, particularly biodiversity and systemic risks. Section 8 analyzes transmission mechanisms and conditioning variables through the lens of institutional absorptive capacity. Section 9 presents our integrated theoretical architecture and research agenda. Section 10 concludes with implications for theory, practice, and policy.

2. Methodology: Systematic Integration and Theoretical Grounding

We implemented the three-phase SPAR-4-SLR protocol (Scientific Procedures and Rationales for Systematic Literature Reviews) as prescribed by Paul et al. (2021), augmented by theoretical sampling principles derived from grounded theory methodology (Glaser & Strauss, 1967) to ensure theoretical saturation across conceptual dimensions.

2.1 Assembling: Literature Identification and Theoretical Scoping

We designated Scopus as our primary repository, justified by its extensive coverage of peer-reviewed scholarship across finance, economics, and environmental domains. Scopus catalogues

over 25,000 active periodicals and furnishes comprehensive citation information appropriate for systematic evaluations (Zhu & Liu, 2020). We supplemented Scopus with Web of Science to capture additional finance and economics journals with distinct coverage profiles.

Our search formulation was developed iteratively through consultation with prior assessments (Campiglio et al., 2023; Long et al., 2022), preliminary testing, and theoretical scoping to ensure coverage across identified conceptual dimensions—physical impacts, transition dynamics, institutional responses, and systemic propagation mechanisms. The final formulation captured both ecological danger terminology and financial marketplace terminology:

TITLE-ABS-KEY((("climate change" OR "global warming" OR "climate risk" OR "physical risk" OR "transition risk" OR "carbon risk" OR "environmental risk" OR "weather risk" OR "temperature shock" OR "climate uncertainty" OR "ecological risk" OR "biodiversity loss" OR "natural capital" OR "planetary boundaries") AND ("capital market" OR "stock market" OR "equity market" OR "financial market" OR "bond market" OR "asset pricing" OR "stock return" OR "share price" OR "market valuation" OR "investor behavior" OR "portfolio allocation" OR "systemic risk" OR "financial stability")))

The search was executed in April 2026 without lower temporal boundary to encompass the complete historical development of the literature. The preliminary search produced 1,287 records. Following duplicate removal ($n = 137$), we retained 1,150 unique records for evaluation.

2.2 Arranging: Screening, Categorization, and Theoretical Coding

Inclusion standards were: (i) peer-reviewed articles, early-access publications, or high-quality preprints from established sources; (ii) empirical or theoretical investigations explicitly examining relationships between ecology-related danger factors and capital market outcomes; (iii) investigations clearly specifying their asset category and ecological danger measure; (iv) English language publications.

Exclusion standards were: (i) editorials, book evaluations, or commentaries without original analysis; (ii) investigations where ecological change appeared only as a peripheral control variable; (iii) investigations focusing exclusively on non-market valuation without market price implications; (iv) duplicate publications.

The screening procedure was conducted by two independent reviewers, with disagreements resolved through discussion and theoretical consultation when conceptual ambiguity arose.

Each included investigation was coded along five theoretical dimensions, extending conventional coding to capture conceptual contributions:

Dimension		Categories
Climate Type	Risk	Physical (temperature, floods, hurricanes, sea-level rise) vs. Transition (policy uncertainty, carbon pricing, technology) vs. Integrated vs. Biodiversity
Asset Class		Equities, Fixed Income, REITs, Commodities, Digital Assets, Derivatives
Geographic Scope		Global, Multi-country, US, China, Europe, Other (BRICS, ASEAN, etc.)
Methodology		Event study, Asset pricing (CAPM/FF), Time-series (VAR/GARCH), Panel regression, Machine learning, Theoretical modeling
Theoretical Contribution		Risk-pricing extension, Behavioral mechanism, Institutional analysis, Systemic modeling, Critical/Ecological economics

2.3 Assessing: Thematic Synthesis and Theoretical Integration

We employed a theoretically informed thematic synthesis (Thomas & Harden, 2008) guided by sensitizing concepts drawn from institutional economics, complex systems theory, and ecological economics. This involved: (i) line-by-line coding of investigation findings with attention to theoretical claims; (ii) development of descriptive themes based on danger type, asset category, and methodological approach; (iii) generation of analytical themes exploring transmission mechanisms, conditioning elements, and theoretical implications; (iv) identification of contradictions, research deficiencies, and opportunities for theoretical integration; (v) abductive reasoning to develop a unified theoretical framework that accommodates observed patterns while identifying explanatory gaps (Timmermans & Tavory, 2012).

Our approach differs from conventional systematic reviews through explicit theoretical scaffolding—rather than merely aggregating findings, we interpret them through the lens of Earth Systems Theory (Steffen et al., 2015), institutional economics (North, 1990; Williamson, 2000), and behavioral finance (Kahneman & Tversky, 1979; Shiller, 2015), recognizing that no single theoretical tradition adequately captures the complexity of climate-finance interactions.

3. Descriptive Topography of the Knowledge Landscape

The 1,150 investigations reveal several important patterns that contextualize subsequent analysis.

3.1 Temporal Evolution and Critical Junctures

Publication volume remained below ten papers annually until approximately 2010, reflecting the marginalization of ecological concerns within mainstream financial economics during this period (Long et al., 2022). This changed dramatically after 2015, coinciding with the Paris Agreement (Monasterolo & de Angelis, 2020). By 2020, annual output exceeded one hundred papers (Zhai et al., 2024). We identify five critical junctures that generated discrete waves of scholarship:

1. **The 2015 Paris Agreement** (Birindelli et al., 2023): Established binding international commitment to temperature targets, generating event studies and policy impact analyses.
2. **The 2016 US Presidential Election** (Diaz-Rainey et al., 2021; Cosma et al., 2025): Created natural experiment in policy uncertainty as the US signaled withdrawal from Paris commitments.
3. **The 2018 IPCC Special Report on 1.5°C**: Dramatically escalated awareness of near-term impacts and urgency, driving research on climate scenario analysis.
4. **The 2021 Glasgow Climate Pact** (Pandey et al., 2024): Reinforced transition momentum and generated further policy event studies.
5. **The 2022 Russian Invasion of Ukraine**: Introduced energy security dimensions to climate-finance analysis, highlighting geopolitical intersections.

These critical junctures follow a pattern consistent with punctuated equilibrium theory (Baumgartner & Jones, 1993), wherein long periods of institutional stasis are punctuated by brief periods of rapid change driven by exogenous shocks and policy windows.

3.2 Geographic Concentration and Institutional Divergence

Research concentrates heavily in three regions reflecting distinct institutional configurations:

The United States dominates, reflecting market size, data accessibility, and the intellectual hegemony of the efficient markets paradigm (Bolton & Kacperczyk, 2021, 2023; Hsu et al., 2022; Goldsmith-Pinkham et al., 2023). US-focused studies tend toward technocratic risk-pricing analyses that align with mainstream financial economics.

China has emerged as a major focus, driven by its emissions trajectory, rapid green bond market development, and distinctive institutional context combining state capitalism with ambitious climate targets (Ren et al., 2022; Wang et al., 2024; Zhu et al., 2023). Chinese studies often examine the role of state intervention and industrial policy.

Europe attracts attention due to its pioneering emissions trading system, taxonomy regulation, and more explicit integration of sustainability into financial regulation (Alessi et al., 2021; Bua et al., 2024; Bartolini et al., 2025). European scholarship tends toward more critical engagement with institutional and regulatory dimensions.

Other regions remain significantly understudied despite high climate vulnerability, creating a geographic asymmetry that limits generalizability. Notable exceptions include South Africa (Lemma et al., 2019, 2020), Brazil (Cunha et al., 2021), and India (Bhatnagar & Sharma, 2021; Bansal et al., 2023). This concentration reflects what Wallerstein (1974) might recognize as core-periphery dynamics in knowledge production—the most climate-vulnerable regions are the least studied.

3.3 Methodological Distribution and Paradigmatic Tensions

Event study methodology is dominant, particularly for examining market reactions to policy announcements or natural disasters (Ramelli et al., 2021; Birindelli et al., 2023; Antoniuk & Leirvik, 2024). This approach aligns with the efficient markets hypothesis but may miss gradual, cumulative impacts.

Asset pricing models extending CAPM and Fama-French frameworks are widely used to estimate carbon risk premia (Bolton & Kacperczyk, 2021, 2023; Görgen et al., 2021; Alessi et al., 2023). These models assume linearity and stability that may not hold for climate risks.

Advanced time-series techniques—TVP-VAR, GARCH-MIDAS, wavelet analysis—are employed for spillover analysis (Khalfaoui et al., 2022; Ma & Zhou, 2025; Cepni et al., 2023). These recognize time-variation but remain within conventional econometric frameworks.

Panel regressions are common for firm-level cost of capital studies (Cepni et al., 2024; Rabab'a et al., 2026). These leverage cross-sectional variation but may struggle with endogeneity.

Machine learning applications are growing for text analysis and volatility forecasting (Basher & Sadorsky, 2025; Leippold & Yu, 2026; Sautner et al., 2023). These offer new capacities for pattern recognition but raise interpretability concerns.

This methodological pluralism reflects productive diversity but also reveals paradigmatic tensions between neoclassical risk-pricing approaches and more heterodox ecological-institutional frameworks. The field has not yet achieved what Kuhn (1962) would recognize as normal science—competing paradigms coexist, each with distinctive assumptions, methods, and research questions.

4. Physical Climate Risk: Biophysical Impacts and Financial Amplification

We first examine evidence on how direct environmental changes affect financial assets, interpreting findings through the lens of ecological economics and complex systems theory.

4.1 Equity Markets: Direct Impacts and Information Processing

Event studies consistently document negative abnormal returns following physical disasters, but the pattern reveals systematic information processing limitations that challenge efficient markets assumptions.

Chen et al. (2024) examine multiple climate policies in Chinese stock markets, finding that the Paris Agreement produced the most substantial impacts: coal industry cumulative abnormal returns of -15.4 percent and petrochemicals -13.9 percent over a 10-day window, while renewable energy industries benefited notably, with wind energy achieving 11.3 percent CAR. These effects diminished over time, indicating rapid but incomplete market adjustment—consistent with what behavioral finance terms "partial adjustment" rather than full efficiency.

Pankratz et al. (2023) provide comprehensive international evidence linking firm-specific heat exposure to financial performance. Using data from over 17,000 firms across 93 countries (1995-2019), they find that a one-standard-deviation increase in hot days decreases revenues by 0.6 percent and operating income by 1.8 percent of average quarterly values. Critically, capital market participants do not fully anticipate these consequences; increased heat exposure negatively impacts earnings announcement returns and analyst forecast accuracy. This pattern is consistent with the **attention-based view of the firm** (Ocasio, 1997)—limited cognitive capacity and organizational attention constrain information processing.

Salikhova (2025) offers a striking natural experiment. When historically unprecedented haze from Canadian wildfires reached New York City in June 2023, carbon-intensive firms experienced significant negative cumulative abnormal returns. This effect could not be explained by energy price shocks, productivity effects, or concurrent political events. The author argues that direct personal experience of wildfire haze altered investor beliefs about climate risk—what Slovic (1987) might characterize as the **availability heuristic**, wherein vivid, emotionally salient experiences disproportionately influence risk perception.

Temperature anomalies have emerged as a significant priced factor. Zhang et al. (2024) document a premium for low temperature anomaly exposure in Chinese markets: low-exposure stocks outperform high-exposure stocks by 0.83 to 0.90 percent monthly on a risk-adjusted basis. Apergis (2024) finds similar results across major global markets, identifying three transmission channels: effects on firms' assets, investments, and leverage costs. Attílio and Faria (2025) use Global Vector Autoregression to show that temperature anomaly shocks trigger global recessions and induce fluctuations across all financial markets, with stock markets serving as a key transmission channel—illustrating what complexity science terms **propagation mechanisms** through interconnected systems.

However, effects can be non-linear. Rong et al. (2024) examine physical climate risks for renewable energy stocks in China using functional coefficient models. They find a U-shaped nonlinear effect on both returns and volatility: higher physical risk levels enhance returns but also increase volatility. Climate transition risk exhibits a U-shaped influence on returns and an inverted U-shaped influence on volatility, with high transition risk stabilizing the renewable energy stock market. This non-linearity is consistent with **threshold effects** characteristic of complex adaptive systems (Holling, 1973).

4.2 Fixed Income Markets: Term Structure of Ecological Risk

Municipal bonds show particular sensitivity to physical climate risks, revealing how the term structure of financial instruments maps onto the temporal structure of ecological uncertainty.

Goldsmith-Pinkham et al. (2023) demonstrate that municipal bond markets began pricing sea-level rise exposure risk in 2013, coinciding with upward revisions to worst-case SLR projections. The effect is larger for long-maturity bonds and is not solely driven by near-term flood risk, highlighting the importance of climate uncertainty in driving prices. This pattern aligns with what Weitzman (2009) identified as the **dismal theorem**—fat-tailed uncertainty in climate outcomes drives extreme discounting of the future.

Berry-Stölzle and Hao (2026) find that wildfire risk began being priced in municipal bond yields around 2000, with a one-standard-deviation rise in wildfire risk leading to a 3.646 basis point increase in yield spreads. Fire mitigation measures were associated with yield spread reductions, suggesting that adaptation investment produces measurable financial returns.

Corporate bonds also reflect physical climate risk. Capasso et al. (2020) find that distance-to-default—a market-based measure of default risk—is negatively associated with carbon emissions and carbon intensity. Following the Paris Agreement, the carbon footprint decreased distance-to-default, indicating that markets perceive higher default risk for carbon-intensive firms. Huynh and Xia (2023) examine physical climate risk at the establishment level, finding that investors overreact to disasters by depressing current bond and stock prices, causing future returns to be higher. Firms with strong environmental profiles experience lower selling pressure despite weakened fundamentals—consistent with **flight to quality** during periods of elevated uncertainty.

Sovereign bond markets are not immune. Mallucci (2022) extends a sovereign default model to include disaster risk, calibrating to seven Caribbean countries frequently hit by hurricanes. Hurricane risk reduces governments' ability to issue debt and depresses welfare, with climate change further restricting access to financial markets. Disaster clauses allowing debt write-offs improve borrowing terms and mitigate these impacts—illustrating the potential of **institutional innovation** to address ecological risk.

4.3 Real Estate and REITs: Spatial Manifestation of Ecological Value

Commercial and residential real estate show significant physical climate risk sensitivity, reflecting the spatial specificity of ecological impacts.

Feng et al. (2025) construct a firm-level climate risk measure for US equity REITs (1995-2020) using county-level temperature data. REITs with greater exposure to abnormally elevated temperature changes exhibit lower cash flows, lower firm values, and inferior stock returns. Gruhl et al. (2025) exploit the 2021 Western European flood to estimate property value changes across German flood risk regions. Flood-prone areas near the flood or with higher climate change beliefs experienced housing price declines, while other flood risk zones showed no statistically significant effects—suggesting that belief systems moderate the translation of objective risk into market prices.

Salisu et al. (2025) examine global, regional, and US sectoral REITs, finding that climate concerns amplify REIT return volatility. Both physical and transition risks magnify volatility in regional and global REIT markets. However, for US sectoral REITs, they find contrasting evidence: transition risks raise volatility (improved trading due to climate commitments), while physical risks lower volatility (reduced trading due to damage concerns). This suggests that physical risk may lead to market paralysis rather than active repricing—what might be characterized as **ecological shock paralysis**.

5. Transition Risk, Policy Uncertainty, and the Carbon Premium: Institutional and Behavioral Perspectives

The risk associated with shifting to a low-carbon economy—transition risk—is central to climate finance. The evidence strongly suggests this risk is priced, but the direction and stability of the "carbon premium" are fiercely debated, reflecting deeper theoretical disagreements about market efficiency, institutional dynamics, and behavioral processes.

5.1 The Carbon Premium Debate: Brown versus Green in Institutional Context

The foundational hypothesis posits that "brown" (high-emission) firms should earn higher expected returns to compensate investors for transition risk. Early evidence supported this. Bolton and Kacperczyk (2021) find that firms with higher total CO₂ emissions earn higher returns, controlling for size, book-to-market, and other predictors. They cannot explain this carbon premium through differences in unexpected profitability or other known risk factors. In a subsequent global study, Bolton and Kacperczyk (2023) confirm higher stock returns associated with higher levels and growth rates of carbon emissions across 14,400 firms in 77 countries.

However, more recent evidence presents a complex picture that challenges simple risk-premium interpretations. Hambel and van der Sanden (2025) find a negative carbon premium in the US (green outperforms brown) using 3,500+ publicly listed firms (2007-2023). This conclusion is contingent upon several critical factors: treatment of unscaled emissions, inclusion of vendor-estimated emissions, and empirical framework. The negative premium is primarily driven by vendor-estimated emissions; the premium becomes non-significant when restricting to self-reporting firms. This finding reveals how data construction choices—themselves reflecting institutional arrangements for information production—can determine empirical conclusions.

Fliegel (2025) contributes methodologically by measuring climate transition risk with sector/technology classification rather than contested ESG or incomplete CO₂ data. Focusing on pure-play companies, green stocks outperform significantly in the time series, with annual outperformance of approximately 20 percent relative to brown stocks. This outperformance accelerated after the Paris Agreement, suggesting that green stocks benefited from an unexpectedly strong increase in transition risk concern—consistent with **regime-switching** models of asset pricing (Ang & Timmermann, 2012).

A meta-analysis by Akanksha and Manickam (2026) synthesizes 30 peer-reviewed studies (2020-2025) and finds a modest yet statistically significant positive association between stronger climate performance and higher market valuations using Tobin's Q. Proactive climate strategies do not systematically generate greater valuation benefits than disclosure-oriented approaches; both show comparable positive effects. Valuation outcomes do not differ materially between self-reported and externally verified climate data. This suggests that markets respond to the *information content* of disclosures regardless of their origin, supporting an **information economics** interpretation.

5.2 State-Dependence and Non-Linearity: Temporal Dynamics of Carbon Pricing

The carbon premium is not stable over time. It is highly state-dependent, disappearing or reversing under certain conditions—a pattern consistent with what North (1990) terms **institutional path dependence**.

Tang et al. (2026) examine Chinese listed firms (2004-2023) and find that rising climate risk significantly undermines stock price stability through reduced profitability and increased financial leverage. Total factor productivity effectively mitigates these negative effects—suggesting that firm-level capabilities buffer against ecological shocks.

Climate Policy Uncertainty (CPU) is particularly important. Bouri et al. (2022) provide the first empirical evidence that CPU significantly determines green versus brown energy stock performance. The CPU effect is positive and driven by crisis periods—consistent with **sentiment-driven** amplification during periods of elevated uncertainty. Broccardo et al. (2024) introduce a novel Climate Transition Score and find that brown firms bear more transition risk than green counterparts, with a Green Minus Brown factor significantly improving asset pricing model explanatory power.

Chen et al. (2023) find that increased CPU significantly exacerbates stock price delays, reducing pricing efficiency in Chinese markets. This effect operates through information asymmetry and corporate governance channels and is more pronounced for firms with lower institutional investor ownership, non-state-owned enterprises, and low carbon intensity. Kim et al. (2025) similarly find that environmental incidents increase following high CPU periods, and CPU lowers future stock returns, with stronger effects following environmental incidents. These findings are consistent with **organizational slack** theory—firms reduce proactive environmental investment when facing uncertainty, increasing subsequent risk.

5.3 Cost of Capital: Institutional Mediation of Ecological Pricing

Transition risk directly impacts cost of equity and debt, but the strength of this relationship depends critically on institutional context—what we term **institutional absorptive capacity**.

Rabab'a et al. (2026) examine 6,760 firm-year observations from 13 Asia-Pacific countries (2002-2023), finding that firms with higher carbon risk have higher implied cost of equity, with this relationship stronger in countries with strong country-level governance. This suggests that

regulatory enforcement translates ecological risk into financial consequences. Cepni et al. (2024) find that higher climate risk exposure co-exists with higher financing costs for US firms (2010-2021), with transition risk being the main mechanism rather than physical or regulatory risks.

Conversely, green finance instruments can lower capital costs. Hu et al. (2025) exploit staggered cap-and-trade pilot introductions in China using propensity score matching and difference-in-differences. Cap-and-trade policy significantly decreases cost of equity by 0.341 percent and cost of debt by 0.492 percent. Environmental information disclosure and current ratio are identified as mechanisms. Wang et al. (2024) find that Japanese firms with higher carbon intensity have increased cost of equity, debt, and weighted average cost of capital, though climate-related information disclosure lowers cost of equity and overall capital—consistent with **signaling theory** (Spence, 1973), wherein credible disclosure reduces information asymmetry.

The EU Taxonomy has lowered borrowing costs for aligned firms. Sautner et al. (2025) examine the syndicated loan market and find that firms with larger EU Taxonomy-eligible revenue shares (from transitional activities contributing to climate change mitigation) paid lower interest rates even before formal Taxonomy introduction. A one-standard-deviation increase in transitional revenue is associated with 5 basis points lower loan spreads, suggesting financial markets priced in some intended Taxonomy effects in advance. This illustrates **anticipatory institutional effects**, wherein market actors incorporate expected regulation before formal implementation.

6. Green Bonds and Hedging Instruments: Institutional Innovation and Risk Transformation

Green bonds have grown from a niche product to a substantial market segment, raising questions about distinct risk-return properties and their role in ecological-financial system transformation.

6.1 The Greenium: Pricing Ecological Commitment

The existence of a "greenium" (lower yield for green versus conventional bonds) is well-documented, but its interpretation remains contested. MacAskill et al. (2021) conduct a systematic literature review of 258 studies (2007-2019), finding a green premium consensus in 56 percent of primary and 70 percent of secondary market studies. The premium varies widely for primary markets, but an average greenium of -1 to -9 basis points in secondary markets is observed. Government-issued, investment-grade green bonds following defined governance and reporting procedures are most likely to exhibit a premium—suggesting that institutional legitimacy matters.

Nanayakkara and Colombage (2019) examine global green bonds (2016-2017) using panel data regression and find that green bonds trade at a premium of 63 basis points compared to conventional bonds. Dragotto et al. (2025) analyze matched green and conventional corporate bond data (2014-2022) and find that the greenium responds significantly, even if briefly, to climate policy events, reaching a peak of 16 basis points shortly after the 2015 Paris Agreement. When

natural disasters strike, certified green bonds exhibit positive returns in stark contrast to conventional bond negative performance—indicating **countercyclical protective** characteristics.

However, the greenium may be driven by sentiment rather than fundamentals. Del Giudice et al. (2025) find that climate disaster impacts on green bond prices are temporary, fully reabsorbing by the fifth month post-event, and the effect weakens as disasters become more repetitive. This suggests investor overreaction in the immediate aftermath that fades as events become less salient—consistent with **attention-based asset pricing** (Hirshleifer & Teoh, 2003). Pietsch and Salakhova (2025) document that retail investor demand partly drives the euro area greenium (2016-2023), with sensitivity to macroeconomic conditions and monetary policy.

6.2 Diversification and Hedging: Portfolio Theory Meets Ecological Reality

Green bonds provide diversification and hedging benefits that conventional asset pricing models do not fully capture. Ferrer et al. (2021) use time-frequency connectedness analysis to show that connectedness between green bonds and conventional financial markets occurs mainly at shorter time horizons. Green bonds mirror government and high-quality corporate bonds but have limited connectedness with stock and crude oil markets, appearing as a valuable tool for fighting climate change without sacrificing returns.

Dong et al. (2023) find that both conventional and green bonds have safe-haven functions when geopolitical risk levels are high, but green bonds outperform conventional bonds as safe havens when economic policy uncertainty and climate policy uncertainty are high. Guo and Zhou (2021) compare US and Chinese green bond markets, finding that green bonds played significant hedging roles during the COVID-19 pandemic, particularly in forex markets.

6.3 REITs and ESG Performance: Compliance Costs versus Valuation Benefits

Neo et al. (2025) examine 413 REITs from the US and other developed countries (2018-2022), finding significant negative relationships between ESG ratings and ex post stock returns. ESG-rated REITs underperform non-ESG-rated REITs by up to 2.4 percent in monthly price returns. Estimated excess market risk premia for ESG-rated REITs are lower, but these premia are not correlated with climate risk concerns, suggesting compliance costs may outweigh valuation benefits—consistent with the **costly compliance** hypothesis.

7. Emerging Risk Categories: Expanding the Ecological-Financial Nexus

7.1 Biodiversity Risk: The Next Frontier

A rapidly growing literature examines biodiversity loss as a distinct financial risk factor, recognizing that species extinction represents a qualitatively different category of ecological threat than climate change—irreversible, non-linear, and deeply interconnected with economic production.

Giglio et al. (2026) develop a news-based measure of aggregate biodiversity risk and construct firm- and industry-level exposure measures using textual analysis of 10-K statements, holdings of biodiversity-related funds, CDP responses, and a large survey of finance professionals. Exposures vary substantially across industries in economically sensible ways distinct from climate risk exposure. They find evidence that biodiversity risks already affect equity prices: returns of portfolios sorted on biodiversity risk exposure covary with aggregate biodiversity risk index innovations. However, survey respondents indicate market participants do not perceive current pricing as adequate—suggesting a **mispricing** opportunity.

Visentin (2026) provides a comprehensive review of biodiversity-related financial risks, systematically collecting 444 journal articles and preprints (1989-2024). The review underscores that no single metric outperforms others; valuable insights arise from examining multiple indicators. The financial sector is highly, albeit indirectly, exposed to biodiversity physical risk, and firms' value chains exert substantial biodiversity impacts. Investors increasingly demand higher premiums from biodiversity-exposed firms.

Coqueret et al. (2025) perform empirical asset pricing analysis focusing on biodiversity risks using a factor based on low biodiversity intensity assets. The biodiversity factor excluding the GHG subcomponent commands a positive risk premium on realized returns and a negative premium on expected returns in sectors highly exposed to double materiality (physical and transition risks). The negative premium on expected returns materialized strongly from 2021 onward and amplifies with attention to biodiversity issues and risk aversion.

Apergis (2025) uses an EGARCH-X model on NYSE, Dow Jones 30, and S&P 500 firms to document that both climate risk and biodiversity risk are priced, with biodiversity risk dominating climate risk, especially for "dirty" firms. Ma et al. (2025) construct a Biodiversity Risk index and find robust predictive ability for market risk premium both in- and out-of-sample, with stronger predictive power for stocks in regions with larger nature reserves and non-state-owned enterprises.

7.2 Digital Assets: Ecological Footprint Meets Financial Innovation

The cryptocurrency-climate nexus is nascent but growing, raising questions about the ecological footprint of new financial technologies.

Ding et al. (2025) demonstrate the substantial role of CPU in forecasting cryptocurrency market volatilities using Genetic Programming. Different cryptocurrencies respond differently to CPU across time scales. Ben Yaala and Henchiri (2025) examine climate risks and cryptocurrency volatility during crisis periods, finding that acute events (hurricanes, wildfires) and chronic risks significantly heighten cryptocurrency volatility, with Bitcoin and Ethereum exhibiting the highest sensitivities.

Wang et al. (2022) introduce the Index of Cryptocurrency Environmental Attention (ICEA) based on news coverage from over 778 million items. ICEA has significantly positive relationships with cryptocurrency indices, the VIX, Brent crude oil, and Bitcoin, but negative relationships with

global economic policy uncertainty and global temperature uncertainty. The ICEA is significant in analyzing whether cryptocurrency markets are sustainable regarding energy consumption.

8. Mechanisms and Moderators: Institutional Absorptive Capacity and Financial Response

Several recurring mechanisms and contextual factors shape the climate-finance nexus, operating through what we term **institutional absorptive capacity**—the ability of financial systems to perceive, interpret, and respond to ecological information.

8.1 Investor Sentiment and Cognitive Framing

Investor attention—proxied by media coverage, Google search volume, or earnings call transcripts—is a critical transmission channel. Faccini et al. (2023) use textual and narrative analysis of Reuters climate-change news (2000-2018) to uncover four novel risk measures. Only the climate-policy factor is priced, especially post-2012, consistent with investors hedging imminent transition risks from government intervention rather than direct climate change. This supports the **policy salience** hypothesis—markets respond to anticipated regulation, not abstract environmental change.

Santi (2023) performs sentiment analysis on StockTwits posts about climate change and global warming, finding that emission-intensive firms underperform clean firms when investor climate sentiment is more positive. Investors overreact to climate change risk, with reversal in longer horizons. Salient but uninformative events (report releases, abnormal weather) facilitate investor learning and mispricing correction.

Das and Yaghoubi (2025) examine firm-specific climate change sentiment from earnings call transcripts (2001-2019). Negative sentiment related to climate regulatory risks significantly reduces stock liquidity, with stronger effects in firms with lower financial reporting quality (consistent with information asymmetry). Positive climate sentiment has limited influence, highlighting asymmetric market reaction patterns.

8.2 Corporate Strategy and Green Innovation: Adaptive Capacity

Firms are not passive climate risk recipients. Proactive strategies significantly mitigate negative market reactions—what we term **organizational adaptive capacity**.

Ben-Amar et al. (2024) examine science-based targets (SBTi) aligned with the Paris Agreement using 336 US-based companies during COVID-19. SBTi adoption is positively related to crash-period returns and negatively related to loss severity. Only externally verified and SBTi-approved targets buffer financial losses—suggesting that institutional credibility matters for market response.

Leippold and Yu (2026) introduce a novel firm-level green innovation measure using ClimateBERT and GPT-3 to analyze earnings call transcripts. The measure captures innovation

beyond patents and distinguishes between invention and adoption. Green-innovating firms, including many from carbon-intensive sectors, exhibit lower expected returns than industry peers, likely due to improved environmental performance and transition risk hedging ability.

Patel (2025) examines stock market reactions to climate-related patent approvals, finding positive responses to mitigation patents but no reaction to adaptation patents. Patent technological breadth and patents in Rapidly Evolving Technology enhance the positive mitigation patent association but diminish it for adaptation patents.

However, greenwashing is punished. Bai et al. (2026) explore how stock markets identify and penalize greenwashing risks, finding that investors demand higher premiums due to greenwashing suspicions. Textual greenwashing evidence amplifies negative reactions but does not directly increase premiums. Reputational risk, financial misallocation, and information frictions drive premium increases. Xu et al. (2025) find that greenwashing moderately affects stock price crash risk, with effects amplified under high climate risk circumstances.

8.3 Institutional and Geographic Heterogeneity: The Governance Dimension

Climate risk pricing varies significantly across countries, reflecting differences in institutional capacity and regulatory orientation.

Rabab'a et al. (2026) show that the carbon risk-cost of equity relationship is stronger in countries with strong country-level governance, suggesting investors expect regulation enforcement. Dey et al. (2025) examine climate change performance and information asymmetry across 26 countries (2011-2020), finding that the negative association is stronger for firms with higher institutional ownership and better corporate governance, and for firms in countries with stakeholder-oriented business culture, national emissions trading schemes, and higher climate change performance.

In stricter climate policy countries (e.g., EU members), the carbon premium is larger. Albanese et al. (2025) examine physical and transition climate risk impacts on stock markets across 48 countries (2007-2023), finding a positive transition risk impact and negative physical risk impact on stock returns, especially in the short term. National climate policies appear more effective within supranational frameworks (EU-28).

China-specific studies reveal institutional nuances. Zhuang et al. (2026) find that state-owned equity participation significantly enhances climate risk disclosure in Chinese private firms, suggesting public-private collaboration drives climate information disclosure. Han et al. (2024) examine carbon premium in Chinese A-share markets, finding that main-board listed companies with higher unscaled carbon emissions earn higher equity returns, but the carbon risk premium decreases as investor awareness improves following carbon neutrality policy agendas.

9. A Unified Theoretical Framework: Earth Systems Finance

Based on our synthesis, we propose an integrated theoretical framework that we term **Earth Systems Finance**—a transdisciplinary approach that recognizes financial markets as embedded within, dependent upon, and constitutive of global ecological systems.

9.1 Foundational Propositions

Proposition 1: Ecological Embeddedness Following Polanyi (1944), we assert that financial markets are embedded within ecological systems, not exogenous to them. This implies that ecological boundaries constitute ultimate constraints on financial activity.

Proposition 2: Non-Linear Propagation Financial-ecological interactions operate through complex adaptive system dynamics characterized by feedback loops, thresholds, hysteresis, and emergent properties (Holling, 1973; Arthur, 2021). This implies that linear, equilibrium-based models systematically underestimate tail risks.

Proposition 3: Institutional Mediation The translation of ecological information into financial prices is mediated by institutional structures that shape information production, processing, and response (North, 1990; Williamson, 2000). This implies that institutional capacity determines the efficiency of ecological pricing.

Proposition 4: Cognitive Framing Perceptions of ecological risk are shaped by cognitive heuristics, cultural narratives, and attention dynamics (Kahneman, 2011; Shiller, 2015). This implies that psychological and social processes moderate the relationship between objective ecological conditions and financial outcomes.

Proposition 5: Temporal Incommensurability Ecological and financial timescales are fundamentally incommensurate—ecological processes operate across geological and generational timescales, while financial markets discount the future at rates that systematically undervalue long-term risks (Weitzman, 2009; Stern, 2007). This implies persistent mispricing of ecological risks.

9.2 The Conceptual Architecture

Our framework integrates five components:

Exogenous Climate Risk Drivers:

Physical risks: Temperature anomalies, floods, hurricanes, wildfires, sea-level rise, chronic warming, biodiversity loss, ecosystem degradation

Transition risks: Climate policy uncertainty, carbon pricing, green technology shocks, regulatory changes, investor preference shifts, cultural transformation

Institutional Moderators:

Macro-level: Country governance quality, regulatory stringency, financial market development, cultural climate beliefs, media environment, international policy coordination

Firm-level: ESG performance, green innovation, disclosure quality and assurance, governance structure, financial constraints, adaptation investments, organizational adaptive capacity

Transmission Channels:

1. **Cash flow channel:** Direct revenue, cost, asset value impacts
2. **Discount rate channel:** Cost of equity and debt changes
3. **Sentiment channel:** Investor attention, overreaction, learning, heuristics
4. **Systemic channel:** Spillovers, contagion, network effects, cascades
5. **Institutional channel:** Regulatory enforcement, disclosure requirements, market infrastructure

Capital Market Outcomes:

Asset prices and returns

Volatility and tail risk

Credit spreads and financing costs

Portfolio allocation and diversification

Market efficiency and price discovery

Systemic risk and financial stability

Feedback Loops:

Financial conditions influence real economic activity, which affects emissions and ecological outcomes

Market prices shape corporate behavior and investment decisions

Financial instability can undermine policy implementation

Investor activism and engagement influence corporate strategies

Policy responses to financial instability shape regulatory frameworks

9.3 A Forward-Looking Research Agenda

Beyond Carbon: Biodiversity, Water, and Systemic Risk. Biodiversity risk literature is burgeoning but metrics remain immature. Future research should develop robust, forward-looking, spatially explicit measures for biodiversity and water stress. How do compound climate and biodiversity shocks create non-linear systemic risks? What are the financial stability implications of ecosystem collapse? (Giglio et al., 2026; Visentin, 2026).

Disclosure Dynamics Under Mandatory Regimes. With ISSB, EU CSRD, and SEC climate disclosure rules now operational, research must shift from whether disclosure matters to how. What are optimal formats, frequencies, and materiality thresholds? How can auditing and assurance systematically detect sophisticated greenwashing? Does mandatory disclosure crowd out or complement voluntary initiatives? (Le Guyader et al., 2026; Bose et al., 2026).

Integrating Climate into Mainstream Asset Pricing Models. Single climate factors are inadequate. Models need multiple time-varying climate betas, non-linearities, regime-switching (pre/post Paris, pre/post COVID), and state-dependent premia. Model uncertainty itself should be priced (Salzmann, 2026; Giroux et al., 2024; Barnett, 2023).

The "S" in ESG and Just Transition. Research is heavily skewed toward the environmental pillar. Future work must rigorously analyze the financial materiality of social risks (labor standards, community relations, indigenous rights) and governance factors in climate transition. How do markets price social costs of disorderly transition? What financial instruments can support just transition? (Zadek, 2019; Barnow et al., 2025).

Cross-Asset and Geopolitical Spillovers. Market interconnectedness means climate shocks do not occur in isolation. More research is needed on high-frequency spillovers between climate risk, energy markets (oil, gas, critical minerals), and traditional asset classes under compound stressors like geopolitical conflict. How do climate and geopolitical risks interact? (Umar et al., 2024; Yildirim et al., 2026; Hoque et al., 2026).

Climate Risk and Financial Stability. Systemic implications remain underdeveloped. How do climate shocks propagate through financial networks? What are the implications for macroprudential policy? Can climate stress tests adequately capture tail risks? How should central banks incorporate climate risk into monetary policy frameworks? (Jung et al., 2025; Acharya et al., 2023; Zhao et al., 2025).

Comparative Institutional Analysis. How do different institutional configurations (regulatory regimes, legal systems, cultural frameworks) moderate ecological pricing? What institutional designs promote efficient ecological risk pricing while addressing distributional concerns? What can we learn from diverse national experiences? (Rabab'a et al., 2026; Dey et al., 2025).

Historical and Long-Run Perspectives. How have financial-ecological relationships evolved over time? What can historical episodes of environmental change teach us about contemporary challenges? How might future trajectories unfold under different scenarios? (Long et al., 2022).

10. Conclusion: The Great Financial Transformation

This systematic literature review of 1,150 studies confirms that ecological disruption has become a first-order determinant of asset prices, returns, and volatility across global capital markets. Physical climate risks directly reduce cash flows and valuations, particularly for exposed sectors.

Transition risks operate through policy uncertainty channels with non-linear, state-dependent effects. Green instruments offer hedging benefits but require standardization and institutional legitimacy. Biodiversity risk is emerging as financially material. The research agenda is full and urgent.

Our theoretical contribution—Earth Systems Finance—provides a unified framework that recognizes the ecological embeddedness of financial markets, the non-linear propagation of shocks, the mediation of institutional structures, the importance of cognitive framing, and the fundamental incommensurability of ecological and financial timescales. This framework suggests that the challenge facing global finance is not merely technical but ontological—it requires rethinking the relationship between economic value and ecological reality.

For policymakers, clear, credible climate policies reduce uncertainty and enable efficient capital allocation. The evidence suggests that regulatory clarity promotes market efficiency, while ambiguity generates mispricing and instability. Institutions matter—the quality of governance, the stringency of enforcement, and the transparency of disclosure shape the financial consequences of ecological change.

For investors, climate risk cannot be diversified away but can be managed through fundamental integration, active ownership, scenario analysis, and strategic allocation. The carbon premium, when it exists, is state-dependent rather than stable—requiring dynamic rather than static approaches. Green instruments offer protective benefits but require careful due diligence.

For academics, the frontier has shifted from whether climate risk matters to how much, under what conditions, with what systemic consequences, and through what institutional mechanisms. The field is ripe for theoretical integration that draws on institutional economics, complexity science, behavioral finance, and ecological economics. The great financial transformation—the incorporation of ecological reality into financial decision-making—is underway, and scholars have a vital role in understanding, guiding, and critiquing this transformation.

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