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**ESG and Systemic Risk:
Volatility and Tail Exposures in the S&P 500**

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ESG i ryzyko systemowe: Zmienność i ekspozycja na skrajne zmiany w indeksie S&P 500

Abstrakt

Niniejsza rozprawa bada, czy czynniki środowiskowe, społeczne i związane z ładem korporacyjnym (ESG) powinny być traktowane jako źródła ryzyka systematycznego, czy też jako mechanizmy stabilizujące, które ograniczają zmienność i ekstremalne straty na amerykańskich rynkach akcji. Analizuje ona, jak te dynamiki wiążą się z globalną integracją koncepcji zrównoważonego rozwoju w przedsiębiorstwach. W badaniu wykorzystano tygodniowe dane przedsiębiorstw z indeksu S&P 500 z lat 2014-2025. Zastosowano metody ekonometryczne i uczenia maszynowego, aby uchwycić zarówno liniowe, jak i nieliniowe powiązania między wynikami ESG a ryzykiem finansowym. Czynniki ESG są ekstrahowane za pomocą analizy głównych składowych i udoskonalane za pomocą filtru Kalmana w celu generowania dynamicznych, zmiennych w czasie sygnałów reagujących na zmiany warunków rynkowych i politycznych. Analiza przebiega w trzech etapach. Regresje Famy-MacBetha pokazują, że ekspozycja na ESG nie generuje istotnych premii za ryzyko, co wskazuje, że zrównoważony rozwój nie jest czynnikiem wycenianym w stopach zwrotu w stanie równowagi. Heterogeniczne modele autoregresyjne (HAR) ujawniają, że firmy o wysokim wskaźniku ESG cechują się mniejszą trwałością zmienności w krótkim, średnim i długim horyzoncie czasowym. Oznacza to, że firmy zrównoważone były mniej podatne na wstrząsy finansowe w badanym okresie. Z kolei wyniki uzyskane przez zastosowania narzędzi teorii wartości ekstremalnych (EVT) potwierdzają, że firmy o wysokim poziomie wdrożenia ESG charakteryzują się niższym wskaźnikiem wartości zagrożonej (VaR) i oczekiwanego niedoboru (Expected Shortfall), co pokazuje, że ESG pomaga ograniczyć ryzyko skrajne i kruchość systemu finansowego. Modele uczenia maszynowego, takie jak Lasso, Elastic Net i XGBoost, potwierdzają te ustalenia w warunkach nieliniowych i poprawiają dokładność predykcji nawet o 50% w porównaniu ze standardowymi metodami ekonometrycznymi. Badanie wykracza również poza amerykański indeks zrównoważonego rozwoju stosowany na rynku akcji. Opracowany globalny czynnik

ESG z filtrem Kalmana, pozwala bowiem śledzić, jak stabilność oparta na zrównoważonym rozwoju rozkłada się na wszystkie firmy z indeksu S&P 500 w badanym okresie (2014-2025). Wyniki pokazują, że stabilizująca siła ESG zależy od standardów ujawniania informacji i dostosowania regulacyjnego. Ogólnie rzecz biorąc, ESG działa jako warunkowy globalny stabilizator i czynnik systemowy, redukując zmienność i ekspozycję skrajną. Uzyskane w toku badań wyniki mogą być wykorzystane praktycznie do poprawy ocen stopnia zrównoważenia finansów spółek poprzez połączenie perspektyw wyceny aktywów, zmienności i ryzyka skrajnego z hybrydowymi podejściami ekonometrycznymi i uczenia maszynowego, uwzględniającymi zarówno krajowy, jak i globalny wymiar integracji ESG.

Słowa kluczowe: czynniki ESG, ryzyko systematyczne; trwałość zmienności, ryzyko skrajne; teoria wartości ekstremalnych, uczenie maszynowe, stabilność systemowa, wycena aktywów, integracja globalnej zrównoważoności, filtr Kalmana, regresja Famy-MacBetha; heterogeniczny model autoregresyjny.

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ESG and Systemic Risk: Volatility and Tail Exposures in the S&P 500

Abstract

This dissertation examines whether Environmental, Social, and Governance (ESG) factors act as priced sources of systematic risk or as stabilizing mechanisms that reduce volatility and extreme losses in U.S. equity markets. It explores how these dynamics connect to global sustainability integration. The study uses weekly data from S&P 500 firms between 2014 and 2025. Econometric and machine learning methods are applied to capture both linear and nonlinear links between ESG performance and financial risk. ESG factors are extracted using principal component analysis and refined through Kalman filtering to generate dynamic, time-varying signals responding to changes in market and policy conditions. The analysis follows three stages. Fama-MacBeth regressions show that ESG exposures do not yield significant risk premia, indicating that sustainability is not a priced factor in equilibrium returns. Heterogeneous autoregressive (HAR) models reveal that high-ESG firms experience lower volatility persistence across short, medium, and long horizons. This means that sustainable firms transmit fewer financial shocks over time. Extreme Value Theory (EVT) results confirm that high-ESG firms face lower Value-at-Risk and Expected Shortfall, showing that ESG helps reduce tail risks and systemic fragility. Machine learning models, including Lasso, Elastic Net, and XGBoost, support these findings under nonlinear conditions and improve predictive accuracy by up to 50-80 percent compared with standard econometric approaches. The study also extends beyond the U.S. sustainability index applied to stock market. A Kalman-filtered global ESG factor is developed to track how sustainability-driven stability spreads across S&P 500 firms in the same sample period (2014-2025). The findings show that ESG's stabilizing power depends on disclosure standards and regulatory alignment. Overall, ESG functions as a conditional global stabilizer and acts as systemic factor, reducing volatility and tail exposure rather than priced source of

return. The dissertation contributes to sustainable finance by linking asset pricing, volatility, and tail-risk perspectives with hybrid econometric and machine learning approaches capturing both domestic and global dimensions of ESG integration.

Keywords: ESG factors, systematic risk; volatility persistence, tail risk; extreme value theory, machine learning, systemic stability, asset pricing, global sustainability integration, Kalman filtering, Fama-MacBeth regression; heterogeneous autoregressive model.

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List of Publications

- 1) Abdullazade, Z. (2026). Chasing Ghosts: The Elusive Ambiguity Premium in U.S. Equities. Finance Research Letter; <https://doi.org/10.1016/j.frl.2026.109836>
- 2) Abdullazade, Z. (2026). Ambiguity and Market Returns: A Composite Index Perspective. Finance Research Letters; <https://doi.org/10.1016/j.frl.2025.109388>
- 3) Borkowski, P. & Abdullazade, Z. (2025). ESG Indicators and Sectoral Volatility: GARCH vs. Hybrid Machine Learning. Finance Research Letters; <https://doi.org/10.1016/j.frl.2025.108103>
- 4) Abdullazade, Z. (2020). Empirical Test of Pecking Order Theory for the US Listed Firms. SSRN network circularization; <https://dx.doi.org/10.2139/ssrn.3583126>
- 5) Abdullazade, Z. (2019). Pecking Order Model of Corporate Financing: Literature Review. SSRN network circularization; <https://dx.doi.org/10.2139/ssrn.3506239>

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Introduction

The integration of environmental, social, and governance (ESG) considerations into global financial markets has evolved from a marginal niche into a defining element of modern finance. What was once regarded as a moral screening mechanism used by ethical investors has now become a structural component of asset pricing, risk management, and macro-financial stability. This transformation has emerged from several converging forces, including growing awareness among institutional investors of the financial materiality of sustainability risks and recognition by policymakers of the systemic implications of environmental and governance externalities. Academic inquiry has increasingly demonstrated that non-financial factors influence equilibrium conditions within capital markets, linking sustainability with valuation and systemic risk transmission. The integration of ESG frameworks has also been reinforced by international commitments such as the Paris Agreement and the UN Principles for Responsible Investment (UN PRI), which have embedded sustainability considerations into regulatory and asset allocation mandates. The rise of sustainable assets under management, which now constitute a significant portion of institutional portfolios, illustrates that ESG is no longer an ethical preference but a structural realignment of capital markets themselves.

Over the past two decades, sustainable investing has expanded rapidly, supported by empirical evidence showing that ESG exposures carry material financial consequences (Pástor et al., 2021; Zerbib, 2022). These effects manifest in valuation adjustments, liquidity conditions, cost of capital, and firm sensitivity to macroeconomic shocks. Despite this progress, the academic debate remains divided regarding whether ESG represents a priced risk factor generating its own return premium or merely functions as a non-priced conditioning variable that alters volatility and downside risk structures. Early studies reveal that firms with higher corporate social responsibility, a precursor of ESG performance, face lower implied costs of equity, reflecting investors' perception of reduced risk (El Ghouli et al., 2011). Subsequent research supports this finding, showing that environmental responsibility diminishes litigation risk and enhances market valuations through reputational mechanisms (Chava, 2014; Chasiotis et al., 2024). However, large-scale cross-sectional studies relying on various ESG data providers frequently report weak or statistically insignificant ESG return effects after accounting for conventional risk factors and suggesting limited incremental explanatory power (Bang & Ryu, 2024; Alves et al., 2025).

Empirical analysis of this dissertation is based on 246,976 firm-week observations between 2014 and 2025. This period encompasses a decade marked by major sustainability and systemic developments, including the implementation of the Paris Agreement, the COVID-19 pandemic, the 2022 energy shocks, and the introduction of enhanced U.S. climate-disclosure regulations. The inclusion of both expansionary and crisis phases ensures that the dataset captures diverse market conditions under which ESG factors could influence financial stability. Collectively, this time frame provides a comprehensive empirical foundation for examining how ESG exposures interact with systemic risk and volatility dynamics across macro-financial regimes.

A weekly frequency is adopted as a methodological compromise between daily and monthly data. While daily returns often suffer from microstructure noise, monthly data may obscure short-term fluctuations critical for understanding volatility transmission and tail-risk behavior. Weekly observations strike a balance by retaining sufficient temporal granularity to detect contagion effects while maintaining statistical stability. The final sample includes 454 S&P 500 firms, statistically indistinguishable from the full index ($N = 503$) based on a Welch two-sample t-test ($t = 0.285$, $df = 934$, $p = 0.776$), confirming sample representativeness. ESG indicators were sourced from LSEG Refinitiv, financial variables from CRSP, factor returns were obtained from the Kenneth French U.S. Research Data Library, and macroeconomic state variables have been imputed from the Federal Reserve's FRED database, providing consistent and high-quality data for empirical analysis. It indicates that ESG exposures explain less than 0.5 percent of the cross-sectional variation in expected returns (average $\beta_{ESG} = 0.021$, $t = 0.74$). These results confirm the absence of a significant risk premium associated with ESG. Nonetheless, firms with stronger ESG profiles demonstrate approximately 20 percent lower volatility persistence than their low-ESG counterparts. The evidence implies that sustainability influences market dynamics primarily through the stabilization of volatility rather than through excess returns. This finding establishes a conceptual foundation for defining ESG as a conditional systemic stabilizer and not a priced source of compensation. Such results highlight the broader macro-financial implications of sustainability, positioning it as an endogenous mechanism that moderates systemic fragility.

Classical frameworks such as the Capital Asset Pricing Model (CAPM) and the Fama-French three-factor model (Fama & French, 1993) assume rational investors and efficient markets where only systematic risk earns a premium. Under such paradigms, firm-specific attributes like ESG would remain unpriced unless they altered expected cash flows or

covariied with systematic factors. Recent theoretical developments have challenged this assumption by suggesting that sustainability preferences and perceived risks can reshape market equilibria. Emerging versions of sustainable CAPM and portfolio-weighting frameworks indicate that investor utility derived from sustainability modifies equilibrium pricing and alters the sensitivity of returns to aggregate shocks (Pástor et al., 2022). These models treat ESG as an element that influences the covariance structure and risk-return trade-offs, redefining how markets internalize externalities. Within this perspective, ESG becomes a modifier of systematic risk itself rather than a residual firm characteristic.

The ambiguity surrounding ESG's financial role is further complicated by the nonlinear and interdependent nature of modern markets, which are increasingly exposed to tail events such as climate disruptions, banking crises, and pandemics. These shocks have consistently revealed the inadequacy of linear equilibrium models in capturing the spread of systemic risks. Traditional metrics like Value-at-Risk (VaR) and Conditional Value-at-Risk (CVaR), despite their prevalence in both academia and regulations, rely on assumptions of normality and linear dependence failing under extreme market conditions (Adrian & Brunnermeier, 2016; Van Oordt & Zhou, 2016). The inability of these models to capture fat tails and structural breaks underscores a deeper limitation explained further. By all conventions, volatility is treated as an exogenous and stationary process rather than as an endogenous and state-dependent phenomenon. This shortcoming has motivated this dissertation and growing recognition by research literature that ESG-related characteristics, such as governance strength and social accountability, may reduce systemic fragility and moderate volatility transmission.

Empirical evidence suggests that firms with robust ESG practices exhibit greater resilience to shocks, lower volatility spillovers, and slower spread of financial distress. Conversely, weak ESG performance exacerbates systemic fragility through governance failures, environmental liabilities, and social controversies that heighten correlation during crises. Understanding this difference requires theoretical innovation beyond the linear factor models dominating traditional finance. ESG, as a conditioning variable, interacts dynamically with volatility persistence and influences how markets absorb and transmit shocks. Addressing this observation demands advanced volatility modeling capable of capturing asymmetry, heterogeneity, and state dependence, the features characteristic of real-world financial dynamics.

Volatility modeling provides a critical lens for examining the mechanisms through which ESG influences market stability. The development of volatility research has

followed two major directions: (i) the autoregressive conditional heteroskedasticity (ARCH) and generalized ARCH (GARCH) frameworks (R. Engle, 2001), and (ii) the heterogeneous autoregressive (HAR) model introduced by (Corsi, 2008). While ARCH and GARCH models capture volatility clustering, they treat persistence as a single latent process, neglecting structural differences between short- and long-term volatility. The HAR model, by contrast, decomposes realized volatility into distinct time horizons, namely, short, medium, and long and reflect investor heterogeneity by capturing how shocks travel through time (Christoffersen & Diebold, 2000). This decomposition enables an explicit assessment of how transient noise and structural uncertainty interact. Despite the growing sophistication of volatility models, few studies have incorporated ESG into volatility persistence analysis. Such omission leaves a notable gap in understanding how sustainability conditions influence the duration and spread of market disturbances.

The dissertation addresses the revealed gap by integrating ESG variables into the HAR realized volatility model using data from the S&P 500 between 2014 and 2025. The results indicate a decline in weekly volatility from 0.029 to 0.023 points after accounting for ESG-market interactions, while the long-memory parameter decreases from 0.74 to 0.58 ($p < 0.01$). The study findings should objectify the notion that sustainability attenuates the persistence of shocks across time horizons and functions as a state-dependent variable dampening volatility transmission. The interpretation of ESG positions it as an endogenous stabilizing force, aligning with macro-financial perspectives that conceptualize sustainability as a structural determinant of systemic resilience. The research evidence suggests that ESG-driven stability arises not through return enhancement but through reduced fragility, improved information processing, and moderated behavioral overreactions.

The theoretical implications extend beyond volatility modeling to the broader architecture of financial stability. When sustainability systematically reduces volatility persistence, it signals that ESG operates through informational and behavioral channels, reducing uncertainty, enhancing investor confidence, and signaling credible long-term strategies. Low-ESG firms may experience prolonged volatility through uncertainty amplification and reputational risks. The behavioral interpretation of ESG reframes volatility persistence as a reflection of adaptive market efficiency moderated by sustainability. Embedding ESG into volatility analysis allows financial researchers to reconceptualize stability as an endogenous outcome shaped by the interaction between

non-financial attributes and systemic dynamics. Sustainability thus emerges not as a passive descriptor of firm behavior but as an active determinant of financial equilibrium.

Traditional volatility frameworks typically treat macroeconomic and firm-level shocks as independent of ESG variables and underestimate the impact of sustainability on risk dynamics. The empirical results of this dissertation contradict such assumption by demonstrating that integrating ESG factors consistently reduces realized volatility and persistence. These outcomes highlight the function of sustainability as damping mechanism within financial systems, limiting the cross-horizon transmission of shocks and supporting the broader objective of macroprudential stability. The observed reduction in volatility persistence reinforces argument that ESG possesses systemic relevance extending beyond its ethical or reputational dimensions. The last proposition challenges the separation between firm-specific behavior and systemic outcomes and suggests that sustainability is functional component of risk architecture.

The dissertation contributes to the finance literature of sustainability by addressing theoretical, empirical, and methodological gaps limiting our current understanding of ESG. The conceptual premise positioned is that ESG may determine the financial resilience and not excess returns. This focus departs from traditional equilibrium pricing approaches by emphasizing volatility persistence and tail exposure as mechanisms through which sustainability influences systemic stability. The research combines econometric precision with adaptive machine learning techniques to ensure interpretability and to capture nonlinearity with dynamic interactions. The methodological synthesis bridges division between explanatory and predictive modeling and reflects the evolving landscape of financial econometrics in an era of complex, data-rich environments.

This approach calls for the formulation of the following research hypotheses:

H1: ESG exposures do not generate a systematic risk premium in the cross-section of U.S. equity returns.

H2: Conditional on market and macro factors, higher ESG exposure amplifies conditional realized volatility, indicating stronger reaction to aggregate shocks.

H3: Despite higher conditional volatility, higher ESG exposure reduces downside tail risk, leading to smaller VaR/ES losses and thinner left tails.

The above listed hypotheses provide integrated framework for assessing ESG's role in financial markets, organizing the investigation across dimensions of pricing, volatility dynamics, and tail risk.

The empirical framework of this dissertation is supported with two complementary procedures employed to estimate latent ESG factors. The first employs principal component analysis (PCA) on MSCI-based indices from LSEG-Refinitiv datasets and synthesizes multidimensional sustainability indicators into one single benchmark capturing cross-sectional variation in ESG performance. The second introduces a dynamic state-space representation utilizing the Kalman filter (Kalman, 1960) and constructing a time-varying ESG factor that evolves continuously with changing market and policy conditions. This specification accommodates volatility clustering and structural instability, enabling ESG exposures to adjust dynamically to investor sentiment and disclosure shifts. The synthesis of PCA and Kalman filtering approaches yields a flexible yet interpretable measure of sustainability dynamics, offering both cross-sectional consistency and temporal responsiveness. Such dual representation strengthens the empirical validity of the models, ensuring that ESG influences are not constrained to fixed combinations of static indicators and can adapt to real-time informational, regulatory transitions.

The dissertation's empirical design follows a triangular methodological structure, integrating pricing, volatility, and tail-risk analyses. The first analytical dimension (section 3.1) revisits the classical question of whether ESG qualifies as a priced factor in cross-sectional asset pricing. Using Fama-MacBeth regressions (Fama & MacBeth, 1973), the study tests the explanatory power of ESG betas across 246,976 firm-week observations, finding an average β_{ESG} of 0.021 with a t-statistic of 0.74, confirming the absence of a risk premium. These results remain robust under specifications that address endogeneity, aligning with theoretical perspectives that link return premia to aggregate consumption and investment opportunity risks (Merton, 1973; Bansal & Yaron, 2004). The empirical evidence supports interpretation that ESG does not directly covary with market-wide risk factors but rather influences financial dynamics indirectly through volatility moderation and conditional risk adjustments. Hence, sustainability functions not as an independent risk source but as a stabilizing modifier embedded within systematic exposures.

The second analytical stage investigates volatility transmission across time horizons through the ESG-extended heterogeneous autoregressive (HAR) model. This framework decomposes realized volatility into short-term (daily-to-weekly), medium-term (weekly-to-monthly), and long-term (monthly-to-quarterly) components, incorporating ESG-market interaction term. It assesses how sustainability modifies the volatility persistence. Empirical results reveal that high-ESG firms experience faster dissipation of shocks,

reduced cross-horizon feedback, and lower volatility spillovers compared with low-ESG peers. Such findings reinforce the interpretation of ESG as stabilizing variable mitigating the continuation of shocks beyond transient trading cycles. The persistence of volatility is shown to be not merely a statistical phenomenon, but a behavioral and structural process conditioned by sustainability factors. The interpretation of ESG expands understanding of long-memory dynamics in finance by incorporating non-financial state variables as determinants of systemic behavior.

The third analytical stage examines downside risk, recognizing that volatility persistence alone does not fully capture the magnitude or frequency of extreme losses. The analysis employs Value-at-Risk (VaR) and Expected Shortfall (ES) measures, complemented by extreme value theory (EVT) via the Peaks-Over-Threshold (POT) method, isolating tail behavior in return distributions above the 95th percentile. Empirical estimates indicate that ESG exposures are associated with both lower tail thickness and smaller scale parameters, reflecting reduced likelihood and severity of extreme downside events. High-ESG firms exhibit approximately 15 basis points improvement in 95% VaR compared to low-ESG firms (-3.42% versus -3.57%), with effects persisting across subperiods and robust under rolling regressions. The study results substantiate ESG' interpretation as factor contributing to structural resilience, moderating risk transmission and reducing extreme loss. Quantile regressions of returns indicate a negative ESG-market interaction in the left tail, although the coefficients are not statistically significant at conventional levels, while EVT-based VaR and ES regressions do show statistically significant reductions in tail losses for high-ESG firms.

The inclusion of dynamic ESG factors estimated through Kalman filtering distinguishes this study from static cross-sectional analyses. The dynamic approach ensures that ESG exposures evolve with information flows, capture temporal asymmetries and allow volatility and tail-risk relationships to adjust endogenously. This framework enhances understanding of sustainability's stabilizing influence and models ESG as time-dependent attribute that interacts with shifting macro-financial regimes. The findings suggest that ESG may serve as conditional stabilizer, exerting stronger influence during periods of uncertainty or systemic distress, thereby integrating sustainability into the broader context of adaptive financial resilience.

To validate the robustness of empirical results in the dissertation, machine learning (ML) frameworks are applied along with traditional econometric techniques. The ML models, including Lasso, Elastic Net, and XGBoost, serve as benchmarks testing

predictive consistency and nonlinear relationships. The Lasso regression introduces L1 regularization to perform variable selection and prevent overfitting. It combines L1 and L2 penalties for balanced sparsity and stability analysis. XGBoost functions as ensemble learner iteratively minimizing the prediction error and capturing the complex nonlinear dependencies often missed by parametric approaches. Across all ML implementations, ESG-market interaction term improves the predictive accuracy, with XGBoost reducing the mean squared error by nearly half relative to the penalized linear models. Such results confirm that ESG enhances the predictive representation of financial risk even when it does not generate a risk premium. They demonstrate that sustainability integration refines model accuracy and aligns risk modeling with systemic stability objectives.

The deployment of ML in this research is guided by methodological intent rather than algorithmic substitution. The goal is to illustrate that stabilizing effects of ESG persist across both interpretable econometric frameworks and flexible data-driven architectures. This hybrid design reflects a growing consensus in empirical finance that predictive methods and economic theory should coexist rather than compete. The synergy between econometric interpretability and ML adaptability produces results that are both statistically rigorous and theoretically meaningful. It also positions ESG research at the frontier of methodological innovation, bridging the explanatory clarity of traditional finance with the analytical precision of modern data science.

Extending beyond the U.S. context, the dissertation situates ESG dynamics within global sustainability agenda. The study covers the 2014-2025 period, encompassing critical milestones such as Paris Agreement, COVID-19 pandemic, and evolving regulatory reforms in ESG disclosure. Each event has altered financial expectations and redefined sustainability's importance in risk assessment. By structuring the dataset around event windows rather than arbitrary time intervals, the study captures temporal heterogeneity in ESG relevance and identifies when sustainability exerts stronger stabilizing effects. The research findings reveal that ESG's influence is not static but conditional on macroeconomic regimes, institutional alignment, and policy transitions, reinforcing its interpretation as a state-dependent variable in systemic stability.

A key innovation of this research lies in the construction of forward-looking ESG factors using the Kalman filter framework. The dynamic specification continuously updates estimates of sustainability conditions as new information emerges. It transforms ESG from a static attribute into a latent and evolving state variable. Such design captures shifts in disclosure standards, investor sentiment, and regulatory priorities as structural

transitions rather than statistical noise. The resulting time-varying ESG series provide realistic representation of the sustainability-finance connection, offering a foundation for real-time monitoring of systemic risk through sustainability metrics. Flexibility of the Kalman filter ensures that ESG factors reflect both gradual and abrupt market changes, accommodating nonlinearity and structural adaptation within financial systems.

By treating ESG as a continuously evolving process rather than a fixed characteristic, the research introduces a temporal dimension to the understanding of financial resilience. The findings show that stabilizing effect of ESG intensifies during market stress but weakens during stable conditions. Such conditional asymmetry aligns with adaptive market efficiency theory, describing financial structures as evolving in response to changing environments. The empirical evidence also supports this proposition of sustainability, strengthening market resilience and moderating overreactions in turbulent periods.

The study results converge toward consistent conclusion - ESG does not generate a distinct risk premium in equilibrium asset pricing but significantly influences volatility persistence, tail behavior, and predictive accuracy. The absence of a premium does not denote irrelevance; rather, it reveals that ESG operates through channels affecting higher-order moments of return distributions and not their means. Sustainability functions as the systemic stabilizer enhancing resilience without altering expected returns and offering model shift in asset pricing theory. This reconceptualization implies that ESG should be viewed as conditioning variable that shapes structure and dynamics of risk transmission instead of as direct source of compensation.

From a practical perspective, these insights carry profound implications for investors, regulators, and policymakers. The consistent reduction in volatility persistence and tail exposure among high-ESG firms indicates that sustainability integration serves as an implicit form of insurance against systemic stress. Financial institutions seeking to strengthen stability can thus regard ESG not merely as a disclosure requirement or reputational consideration but as an endogenous contributor to macroprudential robustness. Firms exhibiting sound governance, transparent practices, and long-term strategic orientation demonstrate reduced operational uncertainty. They contribute collectively to more stable volatility structure at the level of financial system. This mechanism may explain why ESG considerations have become increasingly central to central bank guiding principles, regulatory frameworks, and macro-financial policy initiatives.

Theoretical contribution of the dissertation lies in reframing systemic resilience as endogenous property of financial networks shaped by sustainability-linked behavior. Such reorientation challenges the traditional view of resilience emerging exogenously through capital buffers or diversification. Instead, resilience can arise internally when sustainability influences investor expectations, firm behavior, and information diffusion. By embedding ESG into asset pricing and risk modeling, this research establishes a conceptual bridge between firm-level characteristics and macro-level stability. It shows how sustainability can modify systemic risk transmission. The empirical results demonstrate that high-ESG entities contribute to dampening of volatility cycles, reduce loss potential, and enhance adaptive capacity in the financial systems.

Thus, collective evidence presented across analytical stages of this dissertation confirms three central propositions. First, ESG exposures do not yield statistically significant risk premia, reinforcing the conclusion that sustainability is not a priced factor within equilibrium returns. Second, ESG integration consistently lowers volatility persistence and tail-loss exposure, underscoring its role as a stabilizing variable in financial markets. Third, the stabilizing influence remains robust across econometric and machine learning frameworks, supporting the conceptualization of ESG as a systemic resilience mechanism and not a source of excess returns. Together, these findings resolve long-standing debates over ESG's financial materiality and demonstrate the economic significance of ESG lies in its moderating systemic risk rather than generating alpha.

The dissertation contributes to financial economics in five interconnected ways. It empirically verifies the absence of an ESG premium even under endogeneity-robust, state-space specifications, advancing sustainable asset pricing theory. It extends volatility modeling by integrating ESG into HAR frameworks, validating that sustainability attenuates long-memory dynamics and moderates cross-horizon risk transmission. It expands extreme-risk literature through the incorporation of ESG into VaR, ES, and EVT frameworks, establishing that sustainability reduces both the frequency and magnitude of tail losses. It introduces machine learning as a methodological complement that enhances empirical robustness while maintaining interpretability. Finally, it places these findings within an international context by constructing a Kalman-filtered latent global ESG factor. The latter demonstrates that sustainability-driven stability may persist under the globally harmonized disclosure and regulatory conditions. Contributions of this dissertation aim at establishing groundwork for developing adaptive and sustainability-informed financial models capable of reflecting the dynamic nature of global markets. The presented

theoretical, empirical, and methodological advancements should build a foundation for future research aimed at constructing more resilient, equitable, and dynamically efficient financial systems.

Chapter 1. Conceptual Framework

1.1 ESG and Asset Pricing Models

The discussion surrounding ESG factors in finance has evolved from a peripheral ethical concern to one of the central debates in modern asset-pricing theory. Early in its development, financial economics regarded the market as a purely efficiency-driven mechanism in which all relevant information, including social and environmental factors, would be priced instantly if this information were financially material. However, as corporate behavior and investor preferences have become increasingly shaped by sustainability considerations, the question of whether ESG represents a priced source of risk or merely a conditional modifier of expected returns has gained prominence.

Enquiry into ESG debate in finance starts with its recognition as a priced factor. Traditional frameworks such as the Capital Asset Pricing Model/CAPM (Sharpe, 1964; Lintner, 1965) argue that only systematic risks or those risks correlated with the market portfolio, which are impossible to diversify away can be rewarded with premia. Within this framework, firm-specific characteristics such as ESG performance would be expected to influence asset pricing only if they altered aggregate risk exposures or cash-flow covariances with the market. Later extensions to asset pricing, most notably the multifactor models introduced additional factors such as size, value, and profitability (Fama & French, 1993, 2015). However, these factors were recognized as systematic precisely because they consistently explained variation in expected returns across broad samples.

The implication is clear, because for ESG to qualify as a priced factor, it must demonstrate systematic relevance rather than appear as an isolated firm-level trait. In other words, the classical logic of equilibrium pricing dictates that markets reward only those risks that cannot be diversified away. If ESG merely changes a company's idiosyncratic profile, let us say, by improving operational efficiency or reducing exposure to litigation, it would not, by itself, command a distinct risk premium. For ESG to matter at the level of equilibrium pricing, it must alter the covariance structure of returns or affect investors' aggregate marginal utility of consumption. This theoretical condition supports much of the subsequent debate, highlighting the tension between financial materiality and ethical materiality. ESG's relevance to risk and cash flow cannot be equated to its relevance for values and societal outcomes.

The Intertemporal Capital Asset Pricing Model (ICAPM) developed by Merton widens this discussion by embedding state variables that capture time variation in the investment

opportunity set (Merton, 1973). Within such a framework, ESG exposures could influence expected returns in two possible ways. They might serve directly as systematic risk factors, if they help predict shocks to the economy. Also, ESG could function indirectly by shaping investor hedging demands against evolving risks without commanding its own premia. This recognition led researchers to explore whether ESG should be modeled as a fundamental risk driver or as a conditioning element modifying exposures to traditional factors. A similar logic underpins the Arbitrage Pricing Theory (APT), which provides flexibility for multiple latent variables. Unlike CAPM, APT can incorporate ESG-related attributes such as reputational capital, stakeholder trust, or regulatory compliance as distinct influences on asset returns, making it theoretically well-suited for capturing non-traditional sources of value (Fabozzi, 2023).

Building on this theoretical foundation, recent research has sought to formalize the role of ESG within multi-period stochastic discount-factor frameworks. In such settings, ESG may appear either as a determinant of the conditional mean of returns (through its effect on expected cash flows) or as a determinant of conditional variance and covariance structures (through its effect on risk exposures). These distinctions are crucial because they determine if ESG is priced in equilibrium or merely relevant to conditional expectations. A growing literature places ESG within the broader class of intertemporal models, emphasizing that sustainability characteristics may act as proxies for macroeconomic state variables such as policy uncertainty, resource scarcity, or technological transition.

Empirical findings remain contested. On one side, meta-analyses and broad surveys suggest that firms with strong ESG profiles enjoy advantages such as lower capital costs, reduced financing constraints, and higher valuations (Clark et al., 2014; Friede et al., 2015). These outcomes are often explained by the view that ESG acts as a proxy for intangible asset development. Characteristics such as managerial quality, transparency, and reputational capital strengthen governance systems and employee trust while reducing agency costs (Malik, 2015). From a strategic perspective, such investments support “shared value” creation by enabling firms to pursue societal benefits alongside economic gains, further reinforcing long-term resilience (“Creating Shared Value,” 2019). This inconsistency can also stem from the behavioral segmentation of investors, where green-tilted institutions exhibit preference-driven demand even when no fundamental risk premium exists (Pedersen et al., 2021). Evidence of this type suggests that ESG may be integrated into market valuations not only for ethical reasons but also due to its role in

shaping firm capabilities. This view further implies that ESG performance functions as an informational signal that reduces uncertainty in capital allocation, consistent with models of heterogeneous beliefs and Bayesian learning, where investors update expectations based on observable governance strength.

The intuition behind the sustainability research findings rests on a broader reconceptualization of how markets process non-financial information. Traditional finance assumed homogenous beliefs and complete information, which rendered ESG immaterial unless directly linked to risk or cash flow. However, real-world markets are characterized by information asymmetry and behavioral heterogeneity. Firms with transparent ESG practices may face lower information risk, thereby improving investor confidence and compressing required returns. In Bayesian terms, ESG disclosures provide signals that help investors update posterior beliefs about managerial quality or default probability. Thus, even in the absence of a formal risk premium, ESG can influence prices through its informational role (Goldstein et al., 2022).

The opposing view emphasizes that consistent pricing of ESG factors has not been observed across all markets. Studies focusing on the United States, for example, often find that ESG does not systematically explain differences in expected returns, with coefficients in cross-sectional regressions frequently insignificant (Krüger, 2015; Jin, 2018). More recent evidence continues to highlight these inconsistencies. Some analyses demonstrate that ESG can behave like a priced risk factor under specific conditions, including through contingent claims analysis (Dobrick et al., 2025; Michopoulos et al., 2025), while others suggest that U.S. markets do not consistently reward ESG exposures (Gregory et al., 2021; Zumente & Bistрова, 2021). Much of this divergence can be traced to methodological differences, including how ESG ratings are constructed, which issues are deemed material, and how disclosure quality is assessed (Khan et al., 2016; Ademi & Klungseth, 2022).

This divergence underscores a methodological challenge that pervades the ESG literature, namely, the absence of standardized measurement and the potential for model misspecification. ESG metrics are inherently composite indicators built from numerous sub-dimensions, including emissions intensity, labor relations, board diversity, supply-chain transparency. Each rating agency employs distinct weighting and normalization schemes. Consequently, cross-study comparability suffers, and the true signal of ESG quality becomes obscured by noise. When combined with short historical data series and rapid methodological evolution, these inconsistencies make it difficult to establish whether ESG represents a persistent source of priced risk or merely a transitory preference effect.

The institutional and regulatory environment provides further clarity on why results vary. European markets, where mandatory disclosure rules and sustainability mandates are well established, often demonstrate significant ESG premia (Capelle-Blancard & Monjon, 2014; Cassola et al., 2024). By contrast, U.S. markets, operating under less stringent disclosure regimes, tend to reveal weaker or more transitory effects. This comparison suggests that ESG is not universally priced but becomes visible under strong institutional frameworks that reinforce transparency and accountability. Research from other countries (e.g. Poland) also shows that ESG is becoming a significant factor in investment decision-making and performance evaluation (Kluza et al., 2021). Similar findings are indicated for high-ESG Polish firms exhibiting lower systematic risk, and they are aligned with the volatility mitigation hypothesis tested in this dissertation (Mikolajek-Gocejna, 2022). Additional evidence suggests that ESG reporting enhances liquidity by reducing information asymmetry (Będowska-Sójka & Echaust, 2020). Sectoral variation may compound the issue, especially in high-carbon industries represented with Energy and Utilities. These industries frequently face valuation discounts tied to climate and regulatory risks, whereas industries like Technology or Healthcare, which are more naturally adapted to innovation and human capital, derive greater benefits from ESG integration (Bolton & Kacperczyk, 2021; Y. Wang et al., 2024).

These patterns highlight the essential insight of ESG's impact on pricing as conditional rather than universal. In jurisdictions with robust regulatory frameworks and mandatory disclosure, investors can differentiate high-quality sustainability performers from laggards, allowing ESG information to be credibly priced. In weaker institutional settings, where disclosure is voluntary and verification limited, ESG signals are noisy, and the market discounts them accordingly. The same logic applies across sectors, where sustainability issues are financially material, such as emissions in energy or data privacy in technology, the market integrates ESG rapidly. Where relevance is lower, ESG scores may have little or no pricing effect.

The so-called "sin stock" anomaly offers a powerful counterpoint to ESG premia. Companies in industries such as tobacco or gambling consistently earn excess returns, not because of operational superiority but because they are excluded from ESG-sensitive portfolios. This exclusion reduces investor demand and forces higher expected returns, effectively producing a return premium for controversial firms (Hong & Kacperczyk, 2009; Dimson et al., 2020). In contrast, firms highly rated for ESG often experience elevated valuations and lower future returns, illustrating how investor preferences alone

can shape asset pricing outcomes. In combination, these findings suggest that ESG premia should be interpreted less as a consistent risk factor and more as a reflection of shifting demand and discount rates.

From a theoretical standpoint, the “sin-stock” literature introduces the idea of preference-based pricing, in which investors derive utility directly from holding certain types of assets or avoiding others (Heinkel et al., 2001). Here, the expected return differential arises not from differences in systematic risk but from non-pecuniary preferences. In equilibrium, assets disfavored by a segment of the investor population must offer higher returns to attract capital. This framework bridges classical utility theory with ethical investing behavior, providing a coherent explanation for why high-ESG firms may appear overpriced and low-ESG firms underpriced, even when fundamental risk is identical.

Theoretical advances have attempted to reconcile questionable sustainability patterns by embedding ESG into more general equilibrium and dynamic asset pricing models. It was demonstrated that ESG premia could be largely driven by utility considerations (Pástor et al., 2021, 2022). Investors accept lower returns for sustainability alignment, which creates temporary valuation premiums that diminish as ESG becomes fully incorporated into pricing. This view was expanded by modeling ESG premia as time-varying and dependent on shifts in investor preferences (Avramov et al., 2025). Similarly, a conditional “green CAPM” where ESG operates as part of the information set available to investors was proposed with another study of sustainability examined as a standalone factor (Galicia-Sanguino & Lago-Balsalobre, 2025). These frameworks collectively suggest ESG functions as a short-live but not persistent risk factor, thereby reshaping exposures to traditional drivers, particularly in times of systemic stress.

The implication of these dynamic frameworks is that ESG’s effect on expected returns is transient, contextual and state-dependent (Aydoğmuş et al., 2022). In equilibrium, as sustainable investing preferences diffuse throughout the market, any initial mispricing or temporary premium dissipates. Over time, ESG integration becomes part of the standard information set, leading to adjusted valuations but not persistent alpha. This perspective bridges the gap between earlier ethical-investment theories and modern behavioral finance, showing that sustainability considerations can be rationally accommodated within traditional utility-maximization models.

Multifactor approaches provide additional support for this interpretation. Evidence indicates that ESG acts as a latent variable influencing market betas, sectoral loadings, and

co-movement structures (Bessler et al., 2021). ESG disclosures also appear to affect abnormal returns in a time-varying fashion, particularly during reporting windows and policy interventions (Amel-Zadeh & Serafeim, 2018). These findings highlight that ESG influences market behavior in dynamic ways rather than serving as a fixed source of alpha. Moreover, firms with strong ESG often enjoy tangible benefits such as reduced litigation risk, fewer regulatory penalties, and improved funding conditions, which contribute to downside risk protection (Ashwin Kumar et al., 2016; Cai et al., 2024).

These observations imply that ESG operates through channels broader than simple cross-sectional return effects. Rather than directly generating excess returns, ESG modifies the sensitivity of firms to macroeconomic shocks, policy changes, and shifts in investor sentiment. For example, firms with robust governance and environmental oversight may respond more predictably to regulatory transitions, reducing uncertainty and stabilizing equity volatility. Similarly, strong social performance, manifested through employee satisfaction, supply chain ethics, or community engagement, can mitigate reputational risks, lowering equity beta during periods of market stress. This suggests that ESG functions as an amplifier or dampener of existing factor exposures, influencing how firms react to shocks rather than whether they experience distinct risk premia.

The growing evidence base thus calls for a more nuanced understanding of ESG's financial materiality. In equilibrium, sustainability characteristics appear to exert influence not by redefining the structure of risk pricing but by conditioning its transmission through the economic system. ESG performance can alter the responsiveness of firms to shocks, including financial, regulatory, or environmental waves, without fundamentally changing expected returns. Such a conditional view aligns with the emerging literature that treats ESG as part of a firm's risk mitigation architecture, much like diversification or hedging strategies (Jin, 2024).

Recent methodological developments also strengthen the case for treating ESG as a conditional rather than persistent factor. Existing models are based on quarterly or annual data and often miss short-term ESG-related effects. New approaches, incorporating weekly datasets and hybrid econometric-machine learning methods, are able to capture nonlinearities, regime shifts, and structural breaks in ESG-return dynamics (Page, 2023). Event studies conducted around major policy milestones such as the Paris Agreement reveal that ESG can lead to substantial repricing of high-carbon firms (Görge et al., 2025).

The introduction of high-frequency ESG data has marked a significant evolution in empirical finance. Previously, ESG information was updated infrequently, leading to sluggish model responses and low temporal resolution. However, the increasing availability of weekly or even daily sustainability indicators, derived from sentiment analytics, news media, and disclosure updates, allows researchers to observe ESG's interaction with financial variables at the same granularity as price and volatility data. These methodological advances make it possible to capture short-lived but economically meaningful reactions, such as investor repricing around climate-policy announcements or reputational crises.

Considered together, such insights indicate that ESG is best understood not as a conventional risk factor producing persistent premia, but as a dynamic and conditional influence on risk exposures, volatility, and investor preferences. Its effects are clearest when regulatory regimes are strong, and sectors face high material exposure, especially during periods of systemic stress. In this way, ESG may demonstrate financial materiality without conforming neatly to the classical definition of a priced risk factor. Rather than generating sustained alpha, ESG reshapes the structure of risk and returns in variations that may condition asset pricing outcomes over time.

The cumulative implication of the dissertation's literature review is that ESG acts as a contextual and state-dependent stabilizer of financial markets. Its influence emerges through behavioral channels, information transparency, capital allocation and risk management. ESG can be conceptualized as the "second-order factor", which is not directly priced but capable of altering response of priced factors to external shocks. This concept bridges traditional finance, seeking clarity in factor models, and behavioral economics, acknowledging preference heterogeneity and bounded rationality.

The academic debate on ESG and asset pricing has evolved rapidly, reflecting a model shift in financial economics. Initial skepticism grounded in the CAPM's risk-only framework has gradually conceded to conditional and multi-factor models, incorporating sustainability dimensions. The emerging frameworks recognize that, even in the absence of persistent risk premia, ESG factors can materially affect volatility, market resilience, and capital allocation. Consequently, these models extend the asset pricing theory by proposing that non-risk mechanisms can also produce systematic return variation.

1.2 ESG, Volatility Persistence and EVT

While the preceding section established that ESG may not consistently generate risk premia, its role in shaping risk dynamics, specifically volatility persistence and tail risk, has become a central focus of modern sustainable finance. Even if ESG is not directly associated with price premium, its potential to stabilize return distributions or reduce exposure to extreme outcomes carries substantial economic and policy implications. Understanding how ESG interacts with the statistical properties of volatility and extremes, therefore extends the debate in this dissertation from equilibrium pricing to systemic resilience.

Beyond return premia, a growing body of research highlights ESG's role in determining risk dynamics. Firms with positive ESG ratings tend to exhibit lower idiosyncratic volatility, greater stability, and superior performance during crises (Albuquerque et al., 2020; Hoepner et al., 2024). At the aggregate level, ESG-oriented capital inflows can reduce loss effects by dampening volatility spillovers across sectors and asset classes, thereby constraining the transmission of systemic shocks (Broadstock et al., 2021). Understanding these stabilizing properties requires theoretical tools capable of capturing two core dimensions of risk. The first is the persistence of volatility, which reflects the clustering and memory of market fluctuations. The second is the distribution of extreme outcomes, since systemic crises are driven not only by volatility clustering but also by rare catastrophic losses. Both dimensions must be addressed to assess whether ESG provides resilience in the face of systemic risk.

The dual structure of volatility, its persistence and tail behavior, represents the cornerstone of modern financial risk analysis. Volatility persistence captures how shocks to returns spread over time, generating sequences of heightened or subdued market activity. Tail behavior, in contrast, examines the probability and magnitude of extreme losses that occur outside the normal range of fluctuations. ESG factors may affect both dimensions simultaneously. They can dampen persistence by stabilizing investor expectations and improve tail behavior by reducing exposure to catastrophic firm-level or systemic events.

Volatility persistence has long been a defining characteristic of equity markets. The empirical observations that large changes in returns tend to cluster together, and that periods of calm are followed by continued tranquility, motivated the development of econometric models to describe this phenomenon.

The autoregressive conditional heteroskedasticity (ARCH) model formalized the insight of conditional variance evolving systematically with past shocks (R. F. Engle, 1982). This innovation bridged rational expectations with volatility dynamics by showing that risk is not constant but endogenous to the arrival of new information. However, ARCH required a large number of lags to capture persistence adequately, which spurred further refinements. The generalized ARCH (GARCH) framework incorporated lagged conditional variances. It has created a sound recursive process in which both recent shocks and past volatility could inform current expectations (Bollerslev, 1986). The innovation provided by GARCH is robust method for modeling volatility clustering, persistence, and mean reversion. This is also dominant tool for modern financial econometrics.

The significance of the ARCH/GARCH models lies not only in their empirical success but also their theoretical implications. They provide mechanism through which memory, the dependence of present volatility on past shocks, can be quantified and forecasted. Persistent volatility suggests that risk does not dissipate immediately after a shock; instead, it decays gradually as information diffuses. ESG factors, insofar as they alter information diffusion through transparency, governance quality, or investor sentiment, can influence the degree of persistence itself. For instance, higher ESG transparency may accelerate information assimilation and reduce the persistence of uncertainty. Whereas opaque sustainability firms may exhibit prolonged volatility cycles due to their delayed resolution of ambiguity.

Subsequent developments within the GARCH family aimed to capture additional features observed in markets. Evidence showed that negative equity returns often generated disproportionately stronger volatility responses than positive returns, a pattern consistent with leverage effects and volatility feedback. The exponential GARCH (EGARCH) model addressed this by modeling logarithmic variance to account for asymmetry (Nelson, 1991). The threshold GARCH (TGARCH) specification explicitly differentiated between positive and negative shocks (Glosten et al., 1993). Although these models enhanced empirical realism, they continued to assume that autocorrelations in volatility decayed exponentially, a limitation inconsistent with the hyperbolic long memory found in realized volatility series. The fractionally integrated GARCH (FIGARCH) model addressed this by allowing fractional differencing, thereby capturing long memory more accurately (Baillie et al., 1996). FIGARCH represented an important theoretical advance, but its complexity and computational intensity limited its applicability to large datasets.

The expansion of the volatility models also provided conceptual foundation for studying the stability implications of ESG. By embedding ESG indicators within GARCH-type frameworks, researchers can test whether sustainability modifies the persistence parameter and high-ESG firms revert more quickly to their long-run volatility mean after shocks. If ESG enhances corporate adaptability or investor confidence, we should observe faster decay in conditional variance. Conversely, low-ESG firms may experience prolonged turbulence, reflecting higher perceived uncertainty.

The heterogeneous autoregressive (HAR) model proposed by Corsi offered a decisive breakthrough that shifted the focus from conditional variance to realized volatility derived from high-frequency data (Corsi, 2008). HAR decomposes realized volatility into daily or weekly, monthly, and quarterly components over this study. It provides simple but powerful approximation of volatility's long memory. Central insight of HAR is behavioral that describes a financial market as set of heterogeneous agents with distinct horizons, from short-term traders to long-term institutions. The agent interactions produce persistence across multiple timescales. Thus, HAR model combines econometric analysis with microstructural intuition.

Following Corsi's foundational insight, subsequent refinements of the HAR framework have significantly expanded its flexibility and empirical reach. Unlike traditional ARCH/GARCH models estimating latent volatility, HAR operates directly on observable realized measures, bridging econometric modeling with data-driven volatility estimation (McAleer & Medeiros, 2008; Guidolin & Liu, 2016). Later advancements introduced structural refinements such as HAR with component jumps (Corsi & Renò, 2012) and HAR-semivariance (Patton & Sheppard, 2015), which improved precision by isolating asymmetric and jump-related risks. Further innovations included HAR with quarticity for realized volatility to correct measurement error (Bollerslev et al., 2016) and HAR designed as an alternative risk metric in commodities' forecasting (Wen et al., 2016). More recent developments include flexible HAR using LASSO regularization to address overfitting (Audrino et al., 2019) and ensemble HAR approach, which averages across multiple volatility estimators to enhance predictive robustness (Lyócsa & Stašek, 2021). These model variations have transformed HAR into the versatile platform for modeling volatility persistence and market heterogeneity across assets and time scales.

Prior empirical research has consistently shown that HAR could outperform traditional GARCH-type models in forecasting realized volatility and replicating scaling properties of financial time series (Christensen & Prabhala, 1998; P. F. Christoffersen & Diebold,

2000). Extensions to HAR have incorporated models with jumps, macroeconomic influences, and leverage effects (T. Andersen, 2001). The linear additive structures of HAR make them uniquely well suited for embedding exogenous state variables such as ESG indicators. These features enable researchers to use HAR in testing whether sustainability may affect volatility spread across horizons and weaken persistence. The implications should provide a direct way to evaluate claims of ESG enhancing stability.

The combination of financial market realms and econometric flexibility makes HAR an especially valuable model for the study of ESG. It allows for the decomposition of volatility into different time-horizon components and reflects the behavior of heterogeneous investor classes. Short-term traders respond to immediate changes in financial markets, and long-term investors should adjust based on their sustainability considerations. By integrating ESG into the HAR structure, it is possible to test whether firms with higher sustainability indicators exhibit shorter shocks across all periods. This may suggest that ESG facilitates quicker recovery from crisis and potential loss.

Persistence is not the complete story. Systemic crises are characterized by not only lengthened volatility but also rare and extreme downside events. Traditional downside risk measures such as Value-at-Risk (VaR) became popular because they provided a standardized way to estimate maximum expected losses under normal conditions (Jorion, 1996). However, VaR suffers from a fundamental limitation - it says nothing about the size of losses beyond the cutoff. In stress environments, these limitations amplify mismeasurement of systemic fragility. ESG integration may, therefore, function not by altering mean returns but by reshaping the conditional tail distribution. It dampens the probability mass in the left tail through improved governance and investor signaling. Expected Shortfall (ES) was developed as a coherent alternative that measures the average loss once the VaR threshold is exceeded (Acerbi & Tasche, 2002). ES provides a more informative picture of tail exposure, and its growing adoption by regulators reflects clear conceptual advantages. Although, both VaR and ES often rely on distributional assumptions that underestimate fat-tailed risks (Cont, 2001).

Other systemic risk frameworks conceptualize volatility transmission through vector autoregressive (VAR) systems that quantify directional spillovers and feedback loops among financial markets (Diebold & Yilmaz, 2009, 2012; Diebold & Yilmaz, 2014). This connectedness-based perspective has substantially advanced the understanding of market interdependence and disturbance by illustrating how shocks are transmitted across financial networks. However, it rests on homogeneous autoregressive dynamics, assuming

that all volatility components evolve uniformly over time. Such models offer limited capacity to capture the multi-scale persistence that characterizes financial volatility. In contrast, the present study adopts HAR framework, which recognizes that volatility originates from processes operating at multiple temporal frequencies, ranging from rapid market adjustments to medium-term cyclical movements and long-term structural changes. Rather than imposing uniform autoregressive parameters, the HAR model integrates these heterogeneous influences within a single linear hierarchy. It allows the past volatility across horizons to exert differentiated and cumulative effects. Heterogeneity provides a richer representation of volatility memory and persistence and makes the HAR framework suitable for examining the conditioning and stabilizing role of ESG factors within systemic risk dynamics.

The limitations of variance-based measures highlight a deeper conceptual issue in finance. Risk is not merely about average variability, but it is about exposure to catastrophic extremes. Extreme outcomes, or so-called “black-swans”, shape investor behavior, liquidity provision, and systemic stability far more than small, frequent fluctuations. ESG factors may indirectly influence this tail behavior by improving corporate preparedness, operational resilience, and stakeholder trust, all of which mitigate vulnerability during market collapses. Thus, when viewed through the lens of tail risk, ESG should function as a resilience amplifier rather than a pure return driver.

Extreme Value Theory (EVT) offers a rigorous statistical framework for directly analyzing rare events. By focusing on asymptotic tail behavior, EVT allows estimation of the frequency and severity of catastrophic outcomes. The peaks-over-threshold (POT) method, which fits the generalized Pareto distribution to exceedances, has become a standard approach in financial applications (Embrechts et al., 1997; Danielsson & De Vries, 2000). EVT applications in finance show that conventional Gaussian-based methods systematically underestimate downside exposure, while EVT-based risk measures better capture loss, tail dependence, and systemic linkages across market segments (Longin, 2000; P. Christoffersen, 2004). This makes EVT a particularly powerful tool for evaluating systemic stability. Prior research evidence has demonstrated that ESG could influence tail outcomes as well. Firms with high ESG scores experienced fewer losses during the global financial crisis and the COVID-19 crash, in part because stakeholder trust and reputational capital buffered their performance (Lins et al., 2017; Ben Ameur et al., 2025). Emerging studies further confirmed that ESG reduced volatility

spillovers and could support portfolio diversification under turbulent conditions (Barson et al., 2024).

The appeal of EVT in the ESG context stems from its focus on extremes, the potential outcomes, most relevant to sustainability and systemic stability. While mean-variance frameworks capture day-to-day fluctuations, EVT isolates the behavior of the tails where financial distress concentrates. In practice, incorporating ESG information into EVT estimation can improve the prediction of tail thickness and exceedance frequency. For instance, firms with credible environmental risk-management practices may exhibit lighter left tails because catastrophic losses linked to environmental litigation, reputational collapse, or policy penalties become less probable (Zhang et al., 2021).

The integration of persistence models and tail risk frameworks has become an important area of research. Hybrid specifications that combine GARCH-type dynamics with EVT methods have been shown to improve the accuracy of conditional VaR and ES estimates (McNeil & Frey, 2000). More recently, realized volatility models like HAR have been embedded into EVT-based risk measures, producing accurate forecasts of downside exposure that account for volatility clustering as well as fat-tailed loss distributions (Patton & Sheppard, 2015). These approaches provide a natural bridge between volatility persistence and systemic tail outcomes.

By merging HAR-style multi-horizon volatility with EVT's focus on extremes, these hybrid models capture both "ordinary" and "catastrophic" risk behaviors within one coherent structure. This integration is crucial when analyzing ESG because sustainability performance likely influences both dimensions. It can dampen medium-term volatility (via investor confidence) and reduce exposure to rare shocks (via governance quality or adaptive capacity). Empirical application of such hybrids enables quantifying ESG's stabilizing power more precisely than with traditional univariate models of tail risk. Subsequently, HAR specification improves conditional EVT frameworks in predicting market risk during periods characterized by extreme returns (Azliana Aridi et al., 2024).

The economic implications are significant. Standard asset pricing models such as CAPM assume normally distributed returns, focusing on variance as the primary risk measure. In contrast, both theoretical and empirical work show that investors are acutely sensitive to downside exposure, particularly when extreme losses threaten solvency or liquidity (Barro, 2006). ESG can be conceptualized in this light as a state variable that conditions exposure to systematic shocks. In favorable ESG regimes, investors perceive lower disaster risk, which translates into reduced sensitivity to tail events (Zerbib, 2022;

Pástor et al., 2022). Integrating this perspective with EVT provides a unified framework for testing whether sustainability reshapes both the persistence of volatility and the severity of extremes.

Viewed through the lens of extreme market events, ESG becomes both a behavioral and statistical moderator of systemic risk. Investors exposed to firms with credible sustainability commitments may anticipate milder losses during crises, adjusting portfolio weights accordingly (H. Wang et al., 2025). These expectations, in turn, influence market dynamics: capital flows toward sustainable assets act as a stabilizing feedback mechanism, cushioning the system against panic-driven sell-offs. EVT captures these dynamics empirically by measuring whether ESG-intensive portfolios exhibit thinner tails or lower tail-dependence coefficients relative to conventional benchmarks.

Considered together, HAR and EVT provide complementary frameworks for evaluating ESG's resilience potential. HAR captures the persistence of volatility across horizons and tests whether ESG weakens long-memory dynamics under normal conditions. EVT quantifies exposure to rare and catastrophic outcomes and allows for the assessment of whether ESG reduces vulnerability during crises. If ESG truly functions as a hedge against systemic risk, evidence should appear in both domains. Accordingly, empirical results indicate lower persistence in volatility and mitigation of tail exposure (Louzis et al., 2014; Azliana Aridi et al., 2024). The combination of HAR and EVT allows researchers to evaluate ESG's dual role as stabilizer of volatility dynamics and safeguard against systemic breakdowns. Such duality may reflect the two faces of sustainability itself - mitigation and adaptation. In terms of volatility persistence, ESG acts as a mitigation strategy by reducing the spread of shocks through markets. In EVT tails, it acts as an adaptation by buffering the magnitude of unavoidable extremes. These effects transform sustainability from a moral principle into a quantifiable risk-management attribute, embedding ESG within the architecture of financial econometrics.

1.3 Hybrid Risk Modeling Theories

As the statistical tools for volatility and tail analysis matured, scholars began exploring how to synthesize them with machine-learning methodologies capable of handling nonlinearities and regime shifts. The goal was not to replace econometric reasoning but to extend its reach in the face of complex ESG-finance interactions.

The increasing complexity of sustainability-linked financial dynamics has spurred the evolution of hybrid risk modeling frameworks that integrate econometrics, machine

learning (ML), and EVT (Peiris et al., 2024). While traditional econometric models remain indispensable for their interpretability and statistical rigor, they face limitations in accommodating non-linearities, regime shifts, and structural dependencies that characterize ESG-finance relationships. Sustainability indicators, influenced by heterogeneous investor behaviors, shifting regulations, and evolving disclosure norms, interact with market risk in ways that are often asymmetric and non-stationary. Capturing these intricacies requires hybrid approaches that extend beyond the confines of linear parameterization, combining the systematic structure of econometrics, the tail sensitivity of EVT, and the data-driven adaptability of ML (H. Wang et al., 2025). This synthesis provides a comprehensive methodological foundation to investigate how ESG modifies volatility persistence, tail behavior, and systemic risk transmission within increasingly complex financial systems.

The convergence of these approaches represents model shift in empirical finance. Traditional econometrics alone can capture persistence and causality but struggles with structural breaks or nonlinear feedback; machine learning alone can capture patterns but lacks interpretability. By merging them, hybrid frameworks combine statistical inference with predictive flexibility (De Lucia et al., 2020). Within the ESG domain, this is critical: sustainability signals are noisy, multidimensional, and context-dependent, requiring models that adapt while remaining explainable (Awijen et al., 2024).

Econometric approaches form the core upon which hybrid frameworks are constructed, offering interpretability and theoretical grounding essential for empirical validation. Advanced volatility models such as the Dynamic Conditional Correlation-GARCH (DCC-GARCH) specification enable researchers to examine how ESG-related shocks spread across sectors, markets, and time, identifying patterns of co-movement and volatility spillover that characterize systemic linkages (R. Engle, 2001). The use of realized volatility in models like HAR-RV allows for a more granular examination of multi-horizon persistence effects, capturing the interaction between short-term trading sentiment and long-term sustainability-driven adjustments in market risk (Corsi, 2008; Hansen et al., 2012). Further refinements, such as fractionally integrated GARCH, demonstrate that firms exhibit reduced long-memory in volatility, reflecting a structural dampening of risk persistence (T. G. Andersen et al., 2013). While econometric techniques provide transparency, they struggle to capture higher-order interactions, threshold effects, and the nonlinear spread of ESG attributed exposures through market microstructure, gaps that motivate the integration of machine learning and EVT-based extensions.

Econometrics thus remains the “language” of interpretation, essential for causal reasoning, but hybridization expands its expressive capacity. By embedding ESG into dynamic-correlation structures, researchers can detect whether sustainability metrics act as common shocks or diversifiers across sectors (Del Vitto et al., 2023). For instance, DCC-GARCH models augmented with ESG indices reveal whether high-ESG sectors move more synchronously during crises, indicating collective resilience, or more independently, indicating diversification benefits (Borkowski & Abdullazade, 2025). These insights cannot be captured with linear static models alone.

Machine learning methods have emerged as natural complement to many econometric frameworks, providing the capacity to uncover both non-linear and high-dimensional as well as regime-dependent relationships between ESG indicators and financial outcomes. Ensemble algorithms such as Random Forests, Gradient Boosting Machines, and Support Vector Machines identify complex dependencies among ESG attributes, firm-level fundamentals, and macro-financial indicators, frequently outperforming classical regressions in both in-sample fit and out-of-sample forecasting accuracy (Gu et al., 2020). Deep learning architectures, particularly Long Short-Term Memory (LSTM) networks, have proven powerful in modeling sequential dependencies in ESG-return dynamics. They capture how sustainability disclosures and policy developments influence volatility persistence and tail risk over time (Kim & Won, 2018). These models can recognize structural transitions, such as shifts following major regulatory events or environmental shocks, that econometric frameworks often miss. Moreover, recent advances in Natural Language Processing (NLP) extend ML’s reach to unstructured data by allowing to quantify textual ESG disclosures by translating qualitative sustainability narratives into measurable inputs for volatility and risk analysis (Du et al., 2024; H. Lee et al., 2024; Ong et al., 2025). Through such methods, ML offers a richer understanding of the behavioral and informational dimensions of ESG finance, complementing the quantitative focus of traditional econometric approaches (Alonso-Robisco et al., 2024).

The integration of machine learning (ML) into financial risk modeling represents one of the most significant methodological revolutions in empirical finance over the last decade. ML models differ fundamentally from parametric models in that they do not begin with fixed theoretical structures but instead discover relationships directly from data (Stempień & Ślepaczuk, 2025). This inductive nature makes ML particularly suited for studying ESG-financial linkages, which are characterized by complexity, high dimensionality, and dynamic context dependence. Sustainability factors are influenced by

multiple layers of variables, environmental performance metrics, governance quality, investor sentiment, regulation, and external shocks, interacting in nonlinear and often path-dependent ways (Spilak & Härdle, 2022). Traditional econometric tools struggle to capture such complexity without overfitting or misspecification. By contrast, ML algorithms adapt to these complexities through flexible function approximation, feature selection and hierarchical learning (Mullainathan & Spiess, 2017; Shi, 2025).

In the context of ESG, flexibility of ML models is useful for detecting subtle patterns that might otherwise remain hidden. For instance, Gradient Boosting Machines (GBMs) can iteratively combine weak learners to detect nonlinear thresholds in ESG-return relationships. They identify the point at which improvements in governance cease to yield marginal stability benefits and when environmental risk exposure triggers disproportionate volatility spikes (Soltani et al., 2024). Random Forests, through bootstrapped sampling, can handle the multi-collinearity inherent in ESG subdimensions, allowing estimation without the need for arbitrary dimensional reduction (Martín-Cervantes & Valls Martínez, 2023).

Deep learning models, particularly recurrent neural networks such as LSTM architectures, bring further advantages. Financial time series often exhibit long-term dependencies and feedback loops, where earlier ESG signals (like sustainability reports or policy commitments) influence investor behavior months later. LSTM networks are designed to capture these temporal dependencies, making them ideal for modeling ESG-driven return persistence or delayed volatility effects (Bhandari et al., 2024). Moreover, by incorporating external inputs, such as macroeconomic indicators, carbon price indices, or climate-risk news sentiment, LSTMs can approximate complex joint distributions that evolve dynamically over time (Rezaei et al., 2025).

Despite their strengths, ML-based approaches are often criticized for their opacity. Purely data-driven models can achieve high predictive accuracy but provide little economic interpretability, making them ill-suited for policymaking or risk management without careful adaptation. Financial regulators and asset managers require not only accurate forecasts but also an understanding of why certain variables drive those forecasts. This need has spurred the rise of explainable AI (XAI) methods, such as SHAP (SHapley Additive exPlanations) and LIME (Local Interpretable Model-agnostic Explanations). Such methods help decompose complex ML predictions into interpretable contributions of input variables. Applied to ESG, these techniques reveal which sustainability

dimensions (e.g., emissions, board independence, diversity) most strongly influence volatility or tail risk predictions (Awijen et al., 2024).

ML models, while powerful in prediction, often suffer from limited interpretability and theoretical transparency, constraining their explanatory value in financial modeling. This limitation poses a barrier to wide adoption of ML-based systems in decision-making and regulatory contexts (Mullainathan & Spiess, 2017; Iskhakov et al., 2020). Consequently, researchers need to reconcile the predictive performance with the interpretive clarity by developing hybrid econometric-ML architectures integrating structural rigor of econometrics with the adaptive flexibility of ML. Frameworks such as GARCH-LSTM and HAR-LSTM combine the persistence-tracking strengths of volatility models with non-linear pattern-recognition capacity of deep learning networks. They are applied to improve modeling of regime-dependent and high-dimensional financial dynamics (Zhai et al., 2020).

Recent advances in machine learning have extended hybrid econometric frameworks into sustainability analytics, particularly for dimension reduction and tail-risk estimation. Techniques such as Principal Component Analysis (PCA) and Kalman filtering are increasingly employed to extract latent ESG factors and track sustainability exposures across markets and over time (B. Liu & Lai, 2024). These innovations reflect a broader methodological convergence in empirical finance, where diverse modeling is combined to resolve complexities of modern risk systems. Within such unified framework, econometrics provides theoretical structure and statistical inference, EVT contributes robustness in capturing extreme outcomes, and ML offers adaptive flexibility for modeling nonstationary and sustainability-linked risk environments.

The institutional uptake of hybrid models underscores their importance beyond academic research. Asset managers rely on ML-enhanced ESG scoring systems that synthesize structured and unstructured data in refining portfolio construction, risk management, and engagement strategies (Del Vitto et al., 2023). Central banks and regulators employ EVT-based approaches for the assessment of climate-related systemic risks and conducting stress tests under extreme but realistic sustainability scenarios. Supervisory authorities adopt ML techniques for detecting disclosure inconsistencies and identifying potential fraud related to greenwashing (Dao et al., 2024; X. Wang et al., 2025). The integration of hybrid methodologies into both market practice and policy evaluation demonstrates that their significance and practical applications extend beyond

empirical innovation (Alshahmy & Sahiner, 2024). Such methodologies represent the backbone of data-driven sustainable finance.

The institutional dimension of hybrid ESG modeling reflects the increasing recognition of sustainability as a systemic risk factor in global financial governance. Regulatory authorities such as the European Central Bank (ECB) and the Network for Greening the Financial System (NGFS) are now integrating climate and ESG-related indicators into their macroprudential frameworks (Bax et al., 2023). Hybrid models provide the technical infrastructure for these initiatives by linking micro-level corporate exposures to macro-level systemic vulnerabilities. ML-enhanced EVT models are being applied to stress test financial institutions under climate-transition scenarios, allowing supervisors to identify vulnerabilities not captured by linear stress-testing frameworks (Acharya et al., 2023). Simultaneously, asset managers use hybrid econometric-ML pipelines to process high-volume ESG disclosure data, improving risk assessment and engagement efficiency.

Hybrid risk modeling frameworks represent a decisive methodological and conceptual turning point in the study of ESG and financial stability. Hybrid models combine econometric interpretability, EVT precision, and machine learning flexibility to create an integrated framework for analyzing ESG-related risks. Their structure captures the complex and nonlinear relationships shaping ESG's financial relevance. Hybridization also introduces challenges of interpretability and overfitting, addressed through regularization, cross-validation, and systematic benchmarking across econometric and ML estimators. Within this integrated approach, ESG ceases to be treated as a static parameter and instead functions as a conditioning state variable that impacts on persistence and extremity of market risk (Castellano et al., 2024). Beyond methodological innovation, the synthesis of ML and econometrics embodies philosophical shift. It recognizes that financial risk is socially embedded, arising from complex adaptive systems where investor behavior, regulation, and firm strategy co-evolve. Hybrid frameworks merge mechanistic models with adaptive learning architectures. They provide stronger predictive accuracy by offering a more faithful representation of financial ecosystems under sustainability pressures.

1.4 Research Gaps and Contributions

Despite rapid advances in ESG research, several foundational questions remain unresolved. A central theoretical issue concerns whether ESG qualifies as a priced factor

within equilibrium asset-pricing frameworks such as the Intertemporal CAPM. While earlier studies document valuation benefits consistent with implicit ESG premia (Friede et al., 2015; Pástor et al., 2021), empirical evidence, particularly from U.S. markets, often fails to identify systematic compensation for sustainability exposures (Krüger, 2015; Zumente & Bistрова, 2021). These inconsistencies suggest that ESG functions less as a priced risk factor and more as a conditioning variable influencing exposure to conventional risks.

The continued pattern in research literature is the regional asymmetry of sustainability impactful results. European markets with strong disclosure regimes and regulatory incentives frequently display more pronounced sustainability premia, but U.S. market findings remain weaker and transient. Such divergence suggests that ESG's financial relevance depends less on intrinsic risk pricing and more on institutional quality, regulatory enforcement, and investor preferences - the conditions determining how sustainability information becomes embedded in market expectations.

These discrepancies reveal two key gaps. The first is contextual dependency, as the valuation effect of ESG appears contingent on institutional strength and transparency of disclosures. In well-regulated environments, sustainability information is efficiently priced; in opaque settings, it remains noisy and undervalued. The second is temporal instability, as ESG-return relationship shifts across market regimes. During expansions, investors prioritize short-term performance, whereas in downturns, ESG's resilience becomes more valued. However, only small number of models captured this dynamic behavior, often treating ESG as static explanatory variable. The dissertation addresses both issues by embedding ESG in dynamic econometric structures, HAR and EVT frameworks, to examine how sustainability influences persistence and extremity of market risk across regimes.

Beyond pricing risk, claim of ESG enhancing financial stability remains empirically unexamined. Although sustainable firms are found to exhibit lower volatility and greater resilience (Albuquerque et al., 2020; Hoepner et al., 2024), little work has been formally performed to test if ESG decreases volatility persistence, a key dimension of market dynamics captured by HAR processes. Likewise, the link between ESG and tail risk remains poorly understood. While EVT-based measures such as VaR and ES are common in risk management, limited investigation on sustainability factors affecting these extreme outcomes was conducted. This research shortcoming limits understanding of ESG,

whether it mitigates systemic fragility by reducing exposure to tail-risk of the return distribution.

Lack of integrated analysis across volatility and tail-risk domains represents a major empirical gap. Most studies investigate such risk dimensions separately, offering partial insights. Volatility analyses imply that ESG stabilizes returns, whereas tail-risk studies suggest lower crash probabilities for high-ESG firms. These findings have not converged within a single model capable of capturing both persistence and extremity. Financial resilience is multidimensional, as it involves both mean reversion of volatility (after shocks) and avoidance of catastrophic breakdowns. Combining HAR's multi-horizon volatility decomposition with tail characteristics of EVT, the present dissertation provides unified framework for the assessment of ESG's dual stabilizing role.

Additional limitation arises from ESG data itself. Commercial ratings by providers such as MSCI, Refinitiv, and Sustainalytics differ in scope, methodology, and weighting. They mainly lead to inconsistencies and distort research inference (Berg et al., 2022; De Giuli et al., 2024). Divergent ratings can make the same firm appear both sustainable and unsustainable, generating measurement error and attenuation bias. Such dilemma is addressed by constructing latent ESG factors using Principal Component Analysis and Kalman filtering extracting common signals. This approach harmonizes disparate datasets and captures time-varying nature of sustainability performance more effectively than raw ratings.

Another aspect, which is overlooked, concerns the nonlinearity of ESG-risk relationship. Most empirical models assume proportional effects, but evidence points to thresholds and diminishing returns. ESG may deliver limited benefits below the disclosure threshold but substantial stability once governance standards are met. Beyond that point, overinvestment in ESG may reduce its efficiency. Capturing the nonlinear effects may require hybrid econometric-machine learning model applications for adaptation to shifting functional forms.

The dissertation advances the sustainability-finance literature through an integrated framework that connects pricing, volatility, and tail-risk perspectives. First, it embeds ESG exposures within ICAPM-style pricing tests. This allows an evaluation of whether sustainability characteristics are systematically rewarded after controlling standard risk factors. Second, it investigates whether ESG performance reduces volatility persistence using HAR models. In doing so, it tests the role of sustainability in moderating long-memory dynamics. Third, it extends the analysis to the

extreme tails of return distributions. ESG exposures are incorporated into EVT-based estimates of Value-at-Risk and Expected Shortfall to assess whether sustainable firms are less vulnerable to severe market losses. Fourth, it improves ESG measurement reliability by constructing dynamic latent factors that harmonize ratings from multiple data providers.

By linking the above discussed dimensions, the dissertation connects firm-level sustainability with market-level stability. Such integration offers a comprehensive view of ESG's role in shaping systemic resilience. These findings carry implications for asset-pricing theory, portfolio design, and prudential regulation. If high-ESG firms display weaker volatility persistence and lower tail exposure, sustainability functions not merely as an ethical preference but as a stabilizing force within financial systems. The study framework positions ESG as an endogenous element of market dynamics, one that influences volatility, tail behavior, and informational efficiency. It establishes a coherent foundation for the empirical analysis developed in subsequent chapters.

Chapter 2. Research Methodology

The theoretical section now transitions from conceptual framing to the development of an empirically rigorous architecture designed to quantify the linkages between ESG factors and systemic financial risk. This chapter establishes the operational foundation of the dissertation to support testing of the core hypotheses. It details the data construction process, variable selection and econometric strategies. Each methodological component is motivated by the central premise that ESG functions either as a priced risk factor, influencing expected returns, or as a stabilizing state variable, moderating volatility and extreme-loss dynamics. The methodological design therefore balances context with analytical depth. It ensures that the empirical models capture true mechanisms through which sustainability considerations alter financial behavior. The empirical pathway begins with the sample identification and proceeds to the construction of latent ESG factors using principal component analysis (PCA) and Kalman filtering. The process culminates in a multi-model econometric and ML integration by constructing an empirical infrastructure that is both rigorous and adaptable.

2.1 Data and Sample Design

The dissertation's empirical analysis is based on a balanced weekly panel dataset comprising firms continuously included in the S&P 500 index between November 2014 and May 2025. This decade-long horizon was selected to encompass several critical macro-financial and sustainability-related regimes, such as the negotiation and ratification of the Paris Climate Agreement (2015-2016), the COVID-19 pandemic (2020-2021), the 2022 energy crisis, and subsequent regulatory transitions in U.S. climate-related financial disclosure. The chosen period captures multiple structural shifts, jointly defining the contemporary sustainability-finance interface and providing a natural laboratory for evaluation of stabilizing or amplifying role of ESG across heterogeneous market conditions. The inclusion of contrasting economic phases - expansion, contraction, crisis, and recovery - facilitates identification of ESG's conditional effects under both normal and stress environments.

Weekly frequency is adopted as a methodological compromise to retains sufficient granularity and observe volatility clustering by suppressing the excessive microstructure noise inherent in daily observations. This temporal aggregation supports the analysis of realized volatility and persistence without sacrificing the ability to detect rapid information diffusion. At the same time, weekly series respond faster than monthly aggregates to

regime changes, making them ideal for tracking the sensitivity of returns and volatility to ESG shocks. The resulting dataset contains 246,976 firm-week observations and ensures statistical power for high-dimensional modeling while maintaining interpretive clarity.

The final sample consists of 454 continuously listed S&P 500 firms. Continuous inclusion avoids survivorship and entry-exit biases that could distort long-memory estimations of volatility persistence. Representativeness of the retained sample was validated through a Welch two-sample t-test comparing mean firm characteristics via market capitalization between the analyzed sample and the full index universe (N = 503). The test statistic ($t = 0.285$, $p = 0.776$) fails to reject equality of means, confirming the absence of systematic selection bias and supporting the generalizability of results. This validation ensures that any identified ESG effects are not artifacts of sample composition but genuine reflections of broader market dynamics.

The dataset integrates information from multiple high-quality sources, each chosen for consistency, temporal coverage, and methodological credibility (Table 1).

Table 1. Data sources and integration

<i>Data type</i>	<i>Source</i>	<i>Description</i>	<i>Transformation/Purpose</i>
ESG Indicators	LSEG-Refinitiv (MSCI-based)	Firm-level environmental, social, and governance scores standardized across sectors	Used for PCA and Kalman-filter factor extraction
Financial Variables	CRSP	Adjusted stock prices, returns, and market capitalization	Constructed weekly log-returns, adjusted for splits and dividends
Risk Factors	Kenneth R. French Data Library	Fama-French 3-factor series: <i>Mkt</i> , <i>SMB</i> , <i>HML</i>	Control for systematic risk exposure
Macroeconomic Controls	Federal Reserve Economic Data (FRED)	The federal rate (FEDR) and 10-year Treasury yield (T10)	Conditioning variables for macro-financial cycles

Source: Author's own.

Integration of these datasets requires precise temporal and identifier alignment. Each firm observation is matched through the permanent security-level identifier (PERMNO)

provided by CRSP, ensuring continuity even when ticker symbols or corporate names change. ESG data are merged on the same weekly cadence using publication dates nearest to market week-ends, creating synchronized time stamps across all variables. Macroeconomic variables, originally available at daily and weekly frequencies, are aligned to the corresponding weekly observation through end-of-week sampling. Such harmonization yields a balanced panel well suited for fixed-effects and heterogeneous autoregressive (HAR) structures.

The data architecture mirrors the behavioral time-scale heterogeneity embedded in the HAR model. Investors and traders operate with different horizons: some adjust positions weekly in response to earnings or policy news, others rebalance portfolios monthly, while long-term institutional investors assess structural trends quarterly. Recognizing this, realized volatility is constructed from weekly squared returns and aggregated into one-, four-, and twelve-week horizons. This decomposition enables the empirical model to distinguish between ephemeral volatility caused by transitory events and persistent volatility reflecting structural uncertainty. The multi-horizon design ensures that ESG’s influence on volatility transmission is interpreted within economically meaningful behavioral intervals.

A series of diagnostic and robustness tests were conducted to verify data stability and comparability across market regimes.

Table 2. Sample robustness and validation

<i>Test</i>	<i>Null hypothesis</i>	<i>Result</i>	<i>Interpretation</i>
Welch t-test	Mean firm characteristics equal across sample and population	t = 0.285 p = 0.776	No bias between retained and excluded firms
Panel Balance	Equal time observations per firm	Confirmed	Enables fixed-effects and HAR structure
Frequency Stability	ESG and volatility measures stable across regimes	Confirmed	Supports comparability pre- and post-COVID

Source: Author’s own.

The confirmed balance across firms and time allows for an unambiguous estimation of fixed and dynamic components in the later HAR specification. Data stability checks confirm that neither ESG scores nor volatility series display excessive regime-specific

distortions (Table 2). Temporal robustness is further ensured by verifying the persistence of statistical properties across major subperiods. Descriptive tests show that return variances and ESG dispersions remain comparable before and after the pandemic, while macro-factor volatilities shift in predictable ways consistent with policy interventions. Such consistency across heterogeneous periods provides confidence that the models will capture structural rather than episodic relationships.

The chosen data design thus delivers both cross-sectional representativeness and temporal coherence. The panel's breadth captures variation across industries, from carbon-intensive energy producers to technology and healthcare firms, while the time span spans alternating phases of monetary tightening, geopolitical stress, and policy coordination. This diversity is crucial for detecting whether ESG's effect on systemic risk is context-dependent or structurally persistent. The careful synchronization of financial, sustainability, and macroeconomic data underpins all subsequent estimations, ensuring that model outputs reflect genuine economic mechanisms rather than artifacts of inconsistent sampling.

In conceptual terms, the dataset constitutes more than a collection of numerical observations; it embodies the interaction between sustainability performance and market dynamics across an extended temporal horizon. By defining ESG within the same frequency and structural architecture as traditional risk factors, the study creates the empirical foundation necessary to assess whether sustainability alters the statistical memory of volatility or the shape of return distributions. The resulting balanced panel is also representative of the broader U.S. equity market. It is a controlled and dynamically rich environment within which ESG's influence on financial stability can be observed and quantified.

2.2 Research Question and Hypotheses

ESG attributes integrated within portfolio construction, capital allocation, and corporate valuation have evolved to the extent of redefining the interaction between investors and risk. Despite the increasing institutionalization of ESG metrics and their widespread inclusion in regulatory frameworks, theoretical ambiguity persists regarding the exact role sustainability plays in asset pricing and systemic stability. Such unresolved tension between normative and financial interpretations of ESG provides the conceptual motivation for this dissertation. The empirical framework is designed to answer a question that cuts across two questions of financial economics: Does ESG represent a priced source

of systematic risk, or does it function primarily as a stabilizing mechanism that mitigates volatility persistence and tail risk without altering expected returns? These questions are neither purely empirical nor merely philosophical. They touch on the foundational assumptions of equilibrium theory, the behavioral microstructure of markets, and the dynamic properties of volatility and tail dependence.

Within the classical equilibrium asset-pricing models, investors are compensated only for bearing systematic, non-diversifiable risks that covary with aggregate consumption or market factors. From this perspective, ESG exposure should earn a premium only if it captures systematic risk that cannot be diversified away. Conversely, under the systemic-stability relationship, ESG operates not as a source of return compensation but as an endogenous shock-absorber reducing the spread of volatility and decreasing tail exposures. Distinguishing between the mechanisms involved requires modeling of returns, volatility persistence, and extreme losses simultaneously within a unified empirical architecture serving as both methodological integration and cornerstone of the current research.

Traditional frameworks such as the CAPM and its multifactor extensions, including the Fama-French and Carhart models, assume homogeneous investor preferences, frictionless markets, and rational expectations (Fama & French, 1993; Carhart, 1997). Within these settings, sustainability should influence expected returns only to the extent that it captures exposure to priced risks, such as macroeconomic shocks or sector-specific systemic trends. If ESG were to embody a priced risk factor, firms with lower sustainability performance, i.e., perceived as more exposed to regulatory penalties, environmental liabilities, or social backlash, would offer higher expected returns as compensation for bearing risks. In contrast, firms with high ESG indicators would yield lower returns and enjoy reduced cost of capital through diminished perceived risk.

However, growing evidence challenges this unidimensional risk-return logic (De Giuli et al., 2024; X. Liu et al., 2025). Under the systemic-stability perspective, ESG does not necessarily alter mean returns but influences the higher moments of the return distribution, specifically variance, skewness, and kurtosis. Firms demonstrating stronger ESG performance may exhibit enhanced governance discipline, superior stakeholder relations, and adaptive capacity, leading to smaller drawdowns during crises and faster recovery post-shock. Such properties suggest that sustainability acts less as a premium-bearing factor and more as a resilience-enhancing state variable. The distinction is subtle but

profound - ESG may not compensate risk but may dampen it by shifting the equilibrium structure of financial risk itself.

The research design in this dissertation is structured as a three-stage empirical sequence, supplemented by a fourth stage of machine-learning validation (Table 3). Each stage corresponds to a distinct facet of the ESG-risk relationship: pricing, volatility, tail behavior, and structural robustness.

Table 3. Three-stage research plan

<i>Analytical stage</i>	<i>Method</i>	<i>Objective</i>	<i>Expected ESG effect</i>
Stage 1	Fama-MacBeth (ICAPM extension)	Test if ESG earns a return premium	No significant premium once risk factors are controlled
Stage 2	Heterogeneous Autoregressive Model (HAR-RV)	Test if ESG moderates volatility persistence across horizons	Negative association between ESG and volatility transmission
Stage 3	Extreme Value Theory (EVT-GPD), VaR & ES	Test if ESG mitigates extreme downside risk	Lower tail-risk metrics for high-ESG firms
Validation	ML (Lasso, Elastic Net, XGBoost)	Benchmark nonlinear robustness	Consistent ESG significance across algorithms

Source: Author's own.

The stepwise research methodology reflects the progression of systemic instability - from equilibrium pricing deviations, through volatility clustering, to extreme tail events. The selected framework permits ESG's influence to be evaluated across the full risk spectrum, ensuring that findings concerning asset pricing, volatility dynamics, and extreme loss behavior are integrated coherently rather than treated as isolated statistical results.

The research hypotheses are developed and empirically testable within the above-defined model stages. The first hypothesis investigates whether ESG constitutes a priced source of systematic risk within the Intertemporal CAPM (ICAPM) framework. Cross-sectional regressions of expected excess returns on ESG betas and conventional market

factors assess whether investors demand compensation for bearing ESG-related risk exposure. This hypothesis embodies the classical view of sustainability as a priced factor similar to size or value. If rejected, ESG would have no independent premium once traditional risk factors are accounted for, implying that investors perceive sustainability risks as diversifiable or already captured within existing systematic exposures.

H1: ESG and Systematic Pricing

- ✓ Null Hypothesis (H_{01}): ESG exposures are not systematically priced in the cross-section of expected returns.
- ✓ Alternative Hypothesis (H_{11}): ESG exposures explain a statistically significant premium in equilibrium after controlling for conventional risk factors.

The second hypothesis extends analysis from expected returns to the temporal structure of volatility. It examines whether ESG exposure influences the persistence of shocks across different horizons within the Heterogeneous Autoregressive (HAR) realized-volatility model. Under the second hypothesis formulation, high-ESG firms are expected to exhibit faster dissipation of volatility following shocks, reflecting improved governance quality, information transparency, and reduced behavioral amplification. The HAR-RV framework provides the ideal empirical environment for testing this hypothesis because it decomposes volatility across heterogeneous time horizons corresponding to actual investor behaviors.

H2: ESG and Volatility Persistence

- ✓ Null Hypothesis (H_{02}): ESG exposure has no effect on volatility persistence.
- ✓ Alternative Hypothesis (H_{12}): ESG exposure reduces volatility persistence across short-, medium-, and long-term horizons.

While volatility persistence captures the temporal spread of shocks, it does not describe the magnitude or frequency of extreme losses. The third hypothesis therefore focuses on the left tail of the return distribution, where financial distress and systemic disturbance are most pronounced. Using the Peaks-Over-Threshold (POT) approach within EVT, this stage evaluates whether firms with stronger ESG performance experience fewer and less severe extreme losses. A significant reduction in VaR and ES among high-ESG firms would support the argument that sustainability operates as a buffer against systemic stress, mitigating the clustering of extreme events and improving overall resilience.

H3: ESG and Tail Risk Mitigation

- ✓ Null Hypothesis (H_{03}): ESG exposure does not affect downside or tail risk.
- ✓ Alternative Hypothesis (H_{13}): ESG exposure reduces the magnitude and frequency of extreme losses.

The fourth hypothesis addresses methodological robustness rather than an independent theoretical dimension. It evaluates whether the ESG effects observed in econometric frameworks persist when the linearity and parametric restrictions of classical models are relaxed. Confirmation of H_{14} would indicate that ESG's influence is structural rather than model-specific, enhancing the credibility of empirical results across methodological paradigms.

H4: Robustness under Nonlinear Conditions

- ✓ Null Hypothesis (H_{04}): ESG effects are model-dependent and not robust to nonlinear estimation.
- ✓ Alternative Hypothesis (H_{14}): ESG effects persist across linear econometric and nonlinear ML frameworks.

These four hypotheses form an integrated causal pathway linking ESG to multiple dimensions of equity-market behavior and are described in Table (4).

Table 4. Hypothesis integration

<i>ESG function</i>	<i>Empirical direction</i>	<i>Model</i>
Systematic Risk Pricing	Return premia	Fama-MacBeth ICAPM
Volatility Stabilization	Shock persistence	HAR-RV
Tail-Risk Mitigation	Extreme loss	EVT-GPD
Structural Robustness	Nonlinear consistency	ML Validation

Source: Author's own.

The logical sequence, from pricing to volatility to tail risk, is consistent with the evolution of financial instability itself. Initial deviations in pricing reflect altered expectations, which, if persistent, manifest as volatility clustering; when uncontained, these clusters escalate into tail events. By mapping ESG across this range, the study assesses whether sustainability intervenes early as a stabilizer of expectations or later as a shock absorber that constrains systemic amplification.

If empirical tests fail to identify statistically significant ESG risk premia (failure to reject H_{01}) but confirm strong reduction effects on volatility persistence (support for H_{12}) and tail losses (support for H_{13}), the resulting interpretation is that ESG functions primarily as a conditional stabilizer. In that case, sustainability enhances systemic resilience without altering equilibrium pricing, providing evidence that market stability can be improved through non-financial channels. Conversely, if ESG exposures yield consistent positive premia across specifications, the evidence would redefine sustainability as a priced systematic factor, embedding it directly into the risk-return trade-off. Either outcome provides valuable theoretical and policy insights. The former reframes ESG as a macroprudential stabilizer, and the latter redefines it as an integral component of intertemporal asset-pricing structure.

The strength of this design lies in its ability to operationalize an inherently multidimensional ESG construct within related statistical hypotheses. Each hypothesis is empirically testable, theoretically grounded, and mutually reinforcing. Together, they establish a comprehensive analytical pathway that links micro-level firm attributes with macro-level manifestations of financial stability.

By integrating econometric and data-adaptive methodologies within a unified hypothesis framework, the dissertation ensures that the resulting interpretations are robust to functional form, temporal heterogeneity, and nonlinear dependence. This approach moves beyond the dichotomy of whether ESG “matters” and instead quantifies *how* and *through which mechanisms* it influences market dynamics. The subsequent sections formalize this inquiry through explicit variable definitions, diagnostic testing, and the construction of models operationalizing the above hypotheses.

2.3 Variable Definitions and Diagnostics

The empirical design of this dissertation is based on the required set of variables used to define the theoretical relationships articulated in the previous section. Each variable is constructed to represent a precise economic mechanism, whether it captures return generation, volatility transmission, or tail-risk exposure, and to maintain consistency across econometric and machine-learning frameworks. The integration of firm-level, market-level, and macroeconomic variables ensures that models do not estimate direct ESG effects and also isolate them from confounding market and policy condition influences.

All variables are harmonized to a weekly frequency and standardized to facilitate interpretation across firms and time. The variables are detailed in Table (5).

Table 5. Variable description

<i>Category</i>	<i>Variable</i>	<i>Definition/Construction</i>	<i>Purpose in Model</i>
Dependent Variables	$R_{i,t}$	Log difference of adjusted closing prices for firm i at time t , obtained from CRSP	Dependent variable in return regressions
	RV_t	Realized variance of firm i 's returns aggregated from daily squared returns	Dependent variable in HAR-RV model
	VaR_p, ES_p	Tail-risk measures estimated via EVT-GPD at probability level p	Dependent variables in tail-risk regressions
Primary Explanatory Variables	F_t^{ESG}	Latent ESG factor (PCA-based)	Captures shared sustainability signal across firms
	ESG_t^{KF}	Dynamic ESG factor estimated via Kalman Filter	Captures time-varying sustainability dynamics
	$F_t^{(ESG * Mkt)}$	Interaction between orthogonalized ESG factor and market excess return	Captures conditional ESG-market effects
	$Mkt_t - Rf_t$	Market excess return (Fama-French)	Systematic risk exposure
Risk Controls	SMB_t, HML_t	Size and value factors	Traditional cross-sectional controls
	$\Delta FEDR_t$ $\Delta T10_t$	First differences of federal funds rate and 10-year Treasury yield	Captures changes in monetary and term-structure conditions
Derived Variables	$RV_t^{(S)}$ $RV_t^{(M)}, RV_t^{(L)}$	Short-, medium-, and long-term realized volatility components	Used in HAR decomposition

Source: Author's own.

Dependent variables vary across three stages of empirical testing. In asset pricing, the outcome variable is the weekly excess return of each firm, defined as the logarithmic difference in adjusted closing prices net of the risk-free rate. Volatility models employ realized variance, derived from the sum of daily squared returns within each week to capture actual market variability. Tail-risk models rely on Value-at-Risk (VaR) and Expected Shortfall (ES), estimated using the Peaks-Over-Threshold (POT) method in the Extreme Value Theory (EVT) framework at conventional probability levels of 95% and 99%.

Primary explanatory variables are the latent ESG factors derived through PCA and Kalman filtering. The PCA-based ESG factor (F_t^{ESG}) captures the shared sustainability signal across firms by condensing multiple highly correlated ESG indices into a single latent dimension. The Kalman-filtered factor (ESG_t^{KF}) extends this logic into a dynamic time-domain representation that adjusts to evolving market and disclosure conditions. The interaction term ($F_t^{(ESG*Mkt)}$) links the orthogonalized ESG factor to market excess returns, thereby capturing conditional sensitivities when ESG amplifies or dampens systemic exposure depending on prevailing market conditions.

Risk controls are drawn directly from the Fama-French framework to ensure compatibility with traditional asset-pricing benchmarks. The market excess return ($Mkt_t - Rf_t$) captures aggregate systematic risk; SMB and HML account for firm size and value effects, ensuring that observed ESG influences are not elements of cross-sectional differences in capitalization or valuation.

Macroeconomic controls, specifically the first differences of the federal funds rate ($\Delta FEDR_t$) and 10-year Treasury yield ($\Delta T10_t$), capture shifts in monetary policy stance and term-structure expectations. These variables contextualize firm-level responses within broader macro-financial dynamics, preventing misapplication of policy-induced volatility to firm-specific ESG characteristics. The inclusion of such controls ensures that observed relationships between ESG and financial risk are genuinely micro-financial rather than the result of contemporaneous macro shocks.

All variables in this study are based on original, non-winsorized data. No capping or trimming of extreme values has been applied, as the objective is to preserve the full tail dynamics and the potential influence of large shocks on returns and volatility. The selected approach allows for a more realistic assessment of tail-risk transmission, although at the cost of greater sensitivity to extreme observations. The absence of

winsorization ensures that coefficients and volatility estimates fully reflect the raw variation present in the underlying financial data. ESG variables are further standardized within sectors using z-scores to correct for inherent sectoral biases, such as the naturally higher environmental exposure of energy and materials firms relative to service-oriented sectors. This standardization ensures cross-sectoral comparability and prevents structural industry effects from masquerading as ESG-related phenomena.

Given the methodological divergence among ESG data providers - each organization is applying distinct weighting schemes, sub-category structures, and scoring methodologies - the study constructs a composite ESG factor by filtering out idiosyncratic noise and preserving the core sustainability signal. A two-step procedure is adopted: static extraction via principal component analysis (PCA) and dynamic state-space modeling via the Kalman filter.

The PCA approach aggregates standardized ESG indices into a single latent dimension. Specifically, three leading indices - MSCI USA Extended ESG, MSCI ESG Leaders, and the S&P 500 ESG Index - serve as measures of firm-level sustainability. The first principal component (PC1) captures the largest portion of common variance across these indices and functions as the static ESG factor.

Equation 1: Static ESG factor via PCA

$$F_t^{ESG} = \sum_{k=1}^3 \alpha_k ESG_t^k,$$

where α_k are the eigenvector weights corresponding to the largest eigenvalue of the covariance matrix. The first component effectively isolates the shared ESG signal across rating systems, filtering out provider-specific biases and measurement inconsistencies. It ensures that the empirical model captures the underlying sustainability dimension rather than the methodology of any one data source.

The PCA-derived series serves as the foundation for empirical analysis before the dynamic specification using a state-space model estimated through the Kalman filter is applied. The static ESG signal is evolved over time and captures adaptive responses to macroeconomic and regulatory developments within Equations 2a-2b.

Equations 2a-2b: Dynamic ESG via Kalman filtering

$$\begin{aligned} ESG_t^{KF} &= ESG_{t-1}^{KF} + \eta_t, \eta_t \sim N(0, Q) \\ F_t^{ESG} &= ESG_t^{KF} + \varepsilon_t, \varepsilon_t \sim N(0, R) \end{aligned}$$

where Q and R represent the process and observation variances, respectively. The Kalman-filtered series (ESG_t^{KF}) thus evolves as a latent variable that updates in response to new

information, providing a real-time measure of sustainability dynamics. It captures gradual structural shifts such as tightening disclosure standards, investor sentiment changes, and policy reforms, all of which would be obscured in a static model. This dynamic specification aligns with the dissertation's broader conceptualization of ESG as a *state-dependent stabilizer*. The filtered series reflects how sustainability influences market dynamics not as a fixed attribute but as a continuously evolving force.

To isolate ESG's unique contribution to risk and return dynamics from general market co-movement, the ESG factor is orthogonalized with respect to market excess returns. This step eliminates potential multicollinearity and ensures that estimated ESG effects are independent of broad market fluctuations.

Equation 3a: Orthogonalization

$$F_t^{(ESG,orth)} = F_t^{ESG} - \gamma R_{Mkt,t}$$

where γ is obtained from a simple regression of F_t^{ESG} on $R_{Mkt,t}$. The residual component ($F_t^{(ESG,orth)}$) represents the idiosyncratic sustainability factor that cannot be explained by market-wide movements.

Subsequently, an interaction term is generated to capture the conditional effect of sustainability under varying market conditions.

Equation 3b: ESG-Market interaction

$$F_t^{(ESG*Mkt)} = F_t^{(ESG,orth)} * (R_{Mkt,t} - R_{f,t})$$

This interaction term reflects the hypothesis that ESG's impact on systemic risk may vary depending on market sentiment. During bullish periods, ESG-oriented firms may benefit from investor preference shifts, whereas during downturns, their superior governance and resilience may limit losses. Embedding this term into econometric and ML frameworks allows the models to account for such conditional heterogeneity.

Stationarity of time-series variables is a prerequisite for valid statistical inference. To confirm the suitability of the dataset, multiple complementary unit-root and trend-stationarity tests are conducted (Table 6). The Augmented Dickey-Fuller (ADF) and Phillips-Perron (PP) tests assess the null hypothesis of non-stationarity, while the Kwiatkowski-Phillips-Schmidt-Shin (KPSS) test evaluates the null of stationarity, providing a balanced diagnostic framework.

Table 6. Stationarity diagnostics

<i>Variable</i>	<i>ADF p-value</i>	<i>KPSS p-value</i>	<i>Integration Order</i>	<i>Decision</i>
$R_{i,t}$	0.010	0.10	I(0)	Stationary
RV_t	0.010	0.10	I(0)	Stationary
F_t^{ESG}	0.010	0.10	I(0)	Stationary
$FEDR_t$	0.726	0.01	I(1)	First-differenced
$T10_t$	0.774	0.01	I(1)	First-differenced

Source: Author's own.

The diagnostics confirm that core variables including returns, volatility, and ESG factors, are stationary and can be directly estimated without differencing. The macroeconomic variables (FEDR and T10), however, exhibit unit-root behavior and are therefore differenced once. This ensures all regressors are mean-reverting and the estimations free of spurious correlation.

In addition to stationarity, cross-sectional heterogeneity and autocorrelation were evaluated. Breusch-Pagan and White tests confirmed the presence of heteroskedasticity across firms, justifying the use of robust standard errors. The Wooldridge test for autocorrelation in panel data revealed first-order serial correlation, accommodated by including lagged dependent variables in the HAR framework. These diagnostics guarantee the econometric robustness of the empirical models applied in later sections.

Descriptive analysis provides preliminary insights into the structure and variability of the dataset. Summary statistics (Table 7) reveal meaningful dispersion across firms and variables, indicating sufficient heterogeneity to identify cross-sectional effects.

Table 7. Descriptive statistics, population N = 246,976

<i>Variable</i>	<i>Mean (%)</i>	<i>Std. Dev.</i>	<i>Min</i>	<i>Max</i>
$R_{i,t}$	0.117	2.590	-19.70	15.40
$Mkt - Rf$	0.217	2.452	-14.56	12.41
SMB	-0.047	1.413	-5.79	6.04
HML	-0.024	2.046	-8.51	10.88
$\Delta FEDR$	0.070	0.070	0.001	0.197
$\Delta T10$	0.095	0.041	0.020	0.180

Source: Author's own.

The relatively modest mean returns compared with large standard deviations underscore the high volatility characterizing this period. The wide range of returns, from -19.7% to +15.4% weekly, captures crisis weeks such as March 2020 and validates the dataset's ability to capture extreme stress episodes. Cross-factor correlations indicate expected relationships, such as market and SMB factors exhibit mild positive correlation. ESG scores are weakly correlated with size and value factors, thereby suggesting that sustainability effects are not conflated with standard risk proxies.

The variable definitions, construction processes and diagnostics establish a statistically sound and economically meaningful foundation for empirical modeling in subsequent sections. The next part extends this foundation into explicit model construction and estimation frameworks, beginning with the integration of ESG into asset-pricing, volatility, and tail-risk equations.

2.4 Model Construction and Equations

The methodological framework integrates complementary econometric and machine-learning (ML) paradigms to evaluate the dual hypotheses established earlier: whether ESG operates as a priced systematic factor or as a stabilizing mechanism that reduces volatility persistence and tail-risk exposure. The empirical design therefore unfolds as a layered system, where each model incrementally advances the scope of inference from equilibrium asset-pricing to dynamic volatility transmission and extreme-loss behavior. This section formalizes the theoretical and estimation logic underlying these three core econometric models - Intertemporal CAPM (ICAPM), Heterogeneous Autoregressive (HAR-RV), and Extreme Value Theory (EVT). Three models are validated for nonlinear robustness using machine learning (ML).

2.4.1 ESG Factor Construction

The preceding diagnostics confirmed that ESG indicators from multiple providers exhibit high pairwise correlation but differ in scale and weighting. The methodological challenge is preserving the common informational content and filtering out measurement noise. The PCA-Kalman two-stage procedure resolves challenge this by generating both static and dynamic latent ESG factors. The first principal component (PC1) aggregates the shared variance of the standardized indices - S&P 500 ESG, MSCI USA Extended ESG, and MSCI ESG Leaders and produces a single synthetic indicator.

Table 8. Correlation matrix of ESG proxies

<i>Proxy</i>	<i>S&P 500 ESG</i>	<i>MSCI Extended</i>	<i>MSCI Leaders</i>
<i>S&P 500 ESG</i>	1.000	0.9906	0.9975
<i>MSCI Extended</i>	0.9906	1.000	0.9903
<i>MSCI Leaders</i>	0.9975	0.9903	1.000

Source: Author's own.

The correlations indicate near-perfect co-movement across ESG indices, with pairwise $\rho \approx 0.99$ (Table 8). This exceptionally high coherence suggests the presence of a single, dominant latent sustainability dimension underlying all three measures (Figure 1).

Table 9, PCA loadings

<i>Proxy</i>	<i>PC1</i>	<i>PC2</i>	<i>PC3</i>
S&P 500 ESG	- 0.5778	0.3931	0.7152
MSCI Extended	- 0.5764	- 0.8170	- 0.0167
MSCI Leaders	- 0.5778	0.4219	- 0.6978

Source: Author's own.

Table 10, PCA variance explained

PC	Std. Dev	Var Explained	Cumulative
PC1	1.7279	0.9952	0.9952
PC2	0.1092	0.0040	0.9992
PC3	0.0501	0.0008	1.0000

Source: Author's own.

The first principal component (PC1) explains approximately 99.5% of the total variance across ESG proxies, confirming that they largely move in tandem. Each proxy contributes nearly equally to this dominant factor, consistent with a single underlying ESG construct. This extracted component, denoted F_t^{ESG} is used as the unified ESG factor in all subsequent asset-pricing and risk-transmission estimations (Tables 9 and 10).

While the PCA factor captures contemporaneous sustainability levels, it does not accommodate time-varying dynamics. Regulatory shifts, corporate disclosure reforms, and investor sentiment evolve gradually, demanding a mechanism that updates ESG's influence sequentially through time. The Kalman filter satisfies this by transforming the static PCA series into a dynamic latent process governed by the following state-space

system as provided in Equations (2a-2b). The evolution of latent factor is not merely technical but conceptual, as ESG is modeled using *stochastic state variable* embedded in the economic system. The factor can respond to sudden macro-events, including policy shocks, climate-related announcements, or governance scandals, without requiring re-estimation of the entire model. The Kalman-filtered dynamic specification subsequently feeds into the econometric stages that follow.

The orthogonalization procedure in Equation (3a) isolates ESG effects from broader market dynamics, resulting in a market-neutral sustainability signal. Building on this, the interaction term defined in Equation (3b) introduces conditional dependence between ESG and systemic market shocks. This transformation enables testing whether ESG factors increase or decrease the market’s volatility response under varying aggregate conditions.

2.4.2 Econometric-ML Integrated Modeling

The empirical testing strategy deploys three primary econometric frameworks - ICAPM for pricing, HAR-RV for volatility, and EVT for tail risk (Table 11) - each paired with an ML analogue designed to relax linearity constraints and verify structural stability of ESG effects.

Table 11. Integration of econometric models and machine learning models (ML)

<i>Econometric Model</i>	<i>ML Equivalent</i>	<i>Objective</i>
ICAPM (Fama-MacBeth)	Penalized Regression (Lasso, Elastic Net)	Assess ESG’s influence on returns without linear restrictions
HAR-RV Volatility	Tree Ensemble (XGBoost)	Detect nonlinear ESG-volatility persistence relationships
EVT-GPD Tail Risk	Parametric with Quantile Loss	Model ESG’s effect on extreme downside losses

Source: Author's own.

The first stage evaluates whether ESG exposure is associated with a risk premium in equilibrium. Firm-specific betas are estimated in the time dimension for equally and subsequently tested cross-sectionally against expected returns (Fama & MacBeth, 1973). The time-series regression for firm returns, which are sorted into ESG quintile portfolios, is used to examine whether return premia vary systematically with ESG exposure.

Equation 4a: Time-series beta regression

$$R_{Q,t} - R_{f,t} = \alpha_Q + \beta_{Q,Mkt}(R_{Mkt,t} - R_{f,t}) + \beta_{Q,SMB}SMB_t + \beta_{Q,HML}HML_t + \beta_{Q,ESG}F_t^{ESG,orth} + \delta_1\Delta FEDR_t + \delta_2\Delta T10_t + \epsilon_{i,t},$$

Equation 4b: Cross-sectional risk premia

$$E(R_{i,t} - R_{f,t}) = \lambda_M\beta_{i,M} + \lambda_{ESG}\beta_{i,ESG}$$

By testing monotonicity of mean returns in the quantile distribution ESG portfolio betas Hypothesis 1(a) is evaluated. It states that ESG is not expected to yield a statistically significant premium once other variables and risk factors are included. ML counterparts of the econometric models testing mean returns are Lasso and Elastic Net (Table 12). They are regressed on the same variables by enforcing sparsity. The objective of ML regressions is validation of whether ESG coefficients obtained in econometric models may retain their significance once functional form restrictions are relaxed. The set of two penalized regressions shrink irrelevant coefficients and verify robustness to multicollinearity.

Table 12. Machine-learning references

<i>Econometric Model</i>	<i>ML Analogue</i>	<i>Objective</i>
Fama-MacBeth	Lasso	Detects ESG significance under penalized and high-dimensional conditions
ICAPM	Elastic Net	

Source: Author's own.

Penalized regressions minimize the objective function's sparsity. The consistent retention of ESG coefficients under varying λ may confirm the robustness of the marginal contribution by ESG factor.

$$\min_{\beta} \left[\frac{1}{2n} \sum_t (y_t - X_t\beta)^2 + \lambda \|\beta\|_1 \right],$$

Volatility persistence is analyzed using the Heterogeneous Autoregressive model of realized volatility (HAR-RV), which decomposes persistence over short-, medium-, and long-term horizons. ESG-augmented realized volatility specification with HAR follows

Equation 5: ESG-HAR Volatility Model

$$RV_t = \alpha + \beta_S RV_{t-1}^{(S)} + \beta_M RV_{t-4}^{(M)} + \beta_L RV_{t-12}^{(L)} + \beta_{Mkt}(R_{Mkt,t} - R_{f,t}) + \beta_{SMB}SMB_t + \beta_{HML}HML_t + \gamma F_t^{ESG*Mkt} * Mkt_t + \delta_1\Delta FEDR_t + \delta_2\Delta T10_t + \epsilon_{i,t}$$

where, $RV_t^{(S)}$, $RV_t^{(M)}$, and $RV_t^{(L)}$ represent one-, four-, and twelve-week realized variances, respectively. The coefficients β_S , β_M , and β_L measure volatility persistence over short, medium, and long horizons. A significantly negative γ confirms that higher ESG exposure reduces persistence, implying faster dissipation of shocks. The model bridges micro-level firm behavior with macro-level market stability. If ESG reduces persistence, compounding of volatility across horizons weakens and limits systemic risk effects.

Table 13. Machine-learning reference

<i>Econometric Model</i>	<i>ML Analogue</i>	<i>Purpose</i>
HAR-RV	Random Forest XGBoost	Capture nonlinear ESG-volatility interactions and threshold effects

Source: Author's own.

Random Forest and XGBoost approximate the HAR structure non-parametrically using the recursive partitions, allowing nonlinear thresholds, where ESG impact increases beyond specific sustainability levels (Table 13). The tree-based ensembles accommodate cross-interaction between ESG and macro variables, revealing potential asymmetries; specifically, ESG functions as a stabilizer by strengthening market resilience during monetary tightening cycles.

Econometric stage isolating the extreme downside behavior using Extreme Value Theory (EVT is based on Peaks-Over-Threshold (POT) method. It models exceedances (X-u) beyond a high threshold u with a Generalized Pareto Distribution (GPD) provided below.

Equation 6: Generalized Pareto Distribution

$$P(X - u \leq y \mid X > u) = 1 - \left(1 + \frac{\xi y}{\beta}\right)^{-\frac{1}{\xi}}$$

Here, ξ is the shape (tail index) and β the scale parameter. The shape and scale parameters yield closed-form expressions following GPD for VaR and ES

Equation 7: Value-at-Risk (VaR), Expected Shortfall (ES)

$$VaR_p = u + \frac{\beta}{\xi} \left[\left(\frac{N}{n(1-p)} \right)^{-\xi} - 1 \right], \quad ES_p = \frac{VaR_p}{1-\xi} + \frac{\beta - \xi u}{1-\xi}$$

Including the ESG-market interaction $F_t^{(ESG * Mkt)}$ as regressor allows for testing whether higher ESG reduces conditional tail exposure. A negative and significant coefficient implies that sustainability mitigates extreme losses after accounting for market risk and

macro controls. The tail-based framework is indispensable for assessing systemic resilience and HAR-EVT model used in tail analysis evaluates the capacity of financial system to withstand shocks.

The machine learning analogue of the HAR-EVT framework is gradient boosting (XGBoost) with a quantile loss function, which extends the logic of traditional econometric specifications. Rather than modeling conditional means, this approach estimates conditional quantiles by minimizing the objective

$$\min \sum_t \rho_\tau(y_t - \hat{y}_t),$$

where ρ_τ denotes the asymmetric quantile loss function. This formulation enables the estimation of ESG effects specifically in the extreme left tail ($\tau = 0.05$). The alignment between EVT-based and boosting-based tail metrics offers evidence of robustness to functional-form assumptions. Moreover, the integration of econometric and ML models strengthens the overall research framework. The econometric models offer theoretical interpretability and parametric clarity, while ML models contribute predictive accuracy with flexibility in capturing nonlinear and interaction effects. Their joint application ensures that the empirical conclusions are not elements of specific model assumptions.

The study design adheres to the principles of transparency and replicability. All models are estimated with heteroskedasticity- and cluster-robust (HAC-equivalent, heteroskedasticity and autocorrelation-consistent) standard errors, cross-validated hyperparameters, and rolling-window re-estimations to verify temporal stability. By triangulating across methodologies, the dissertation offers a multidimensional perspective on the ESG-risk nexus. It combines equilibrium pricing logic, dynamic volatility processes, and rare-event modeling into a coherent empirical framework.

2.4.3 ML Validation and Interpretability

The final methodological layer extends the econometric design into a machine-learning (ML) framework that tests the robustness and structural persistence of ESG effects under nonlinear, high-dimensional, and model-agnostic conditions. This stage serves two critical purposes. First, it provides a statistical stress test of the linear-model findings by examining whether the observed ESG influence holds when linearity, normality, and homoskedasticity assumptions are relaxed. Second, it enhances interpretability by decomposing predictive importance across models and time, allowing ESG's marginal contribution to be visualized and ranked alongside conventional risk factors.

The rationale for this integration is grounded in methodological complementarity. Econometric methods remain important for parameter inference and hypothesis testing, offering explicit causal interpretation under defined assumptions. Machine learning, conversely, optimizes predictive performance, capturing nonlinear and interaction effects that classical frameworks may miss. When these paradigms are combined coherently, they yield a research design that is both theoretically transparent and empirically resilient.

The dissertation applies a suite of ML algorithms corresponding to the econometric models described previously: Lasso and Elastic Net for linear penalization; Random Forests and XGBoost for volatility persistence and tail-risk estimation. Each algorithm operates within a controlled validation framework employing nested cross-validation, permutation importance, and SHAP (Shapley Additive Explanations) analysis.

Robust model validation is implemented through a nested 5-fold cross-validation scheme. The dataset is partitioned into 70% training, 15% validation, and 15% test subsets, ensuring that parameter tuning, model fitting, and final evaluation are conducted on mutually exclusive samples. This design mitigates the risk of overfitting, which can be particularly acute in high-dimensional ML settings where parameter flexibility is extensive.

Within each training fold, hyperparameters are optimized using grid search and random search procedures. For Lasso and Elastic Net, the penalty parameter λ is selected to minimize cross-validated root mean square error (RMSE), balancing bias variance trade-offs. For ensemble models, parameters such as tree depth, learning rate, and number of estimators are optimized using out-of-sample validation.

Temporal stability is additionally assessed via rolling-window estimation. Each model is re-estimated across consecutive subperiods spanning 2015-2025, enabling detection of potential regime shifts in ESG relevance. Consistency of ESG feature importance across rolling windows provides evidence that the factor's effect is structural rather than transient.

Interpretability constitutes the second pillar of ML validation. Given the algorithmic opacity of many predictive models, interpretive diagnostics are required to ensure that ESG's empirical role is transparent and economically interpretable. Two complementary methods are applied then, Permutation Importance and SHAP.

Permutation Importance measures the decline in predictive accuracy when the values of a variable are randomly permuted while all others remain fixed. A larger decline indicates greater importance of the variable to model performance. This measure offers a

straightforward yet powerful means of assessing the global contribution of ESG to prediction accuracy across models.

SHAP (Shapley Additive Explanations) extends ML approach by decomposing each individual prediction into additive contributions of all features, providing both local and global interpretability. Based on cooperative game theory, SHAP values quantify how much each feature shifts a prediction relative to the average. The ranking of ESG’s SHAP values across firms and time directly indicates its marginal explanatory power in predicting returns, volatility, and tail risk.

The interpretability analysis thus complements econometric inference, and regression coefficients indicate average marginal effects under specified assumptions. SHAP reveals realized marginal contributions conditional on the actual distribution of model predictors. ML techniques employed in this study confirm whether ESG’s influence is only statistically significant or it is substantively meaningful in the predictive terms. Robustness of ESG effects across time, algorithms, and parameterizations is systematically evaluated using multiple diagnostic dimensions described in Table 14.

Table 14. ML robustness and validation

<i>Aspect</i>	<i>Diagnostic</i>	<i>Criterion / Outcome</i>
Temporal Stability	Rolling windows (2015-2025)	ESG significance stable across regimes
Algorithmic Robustness	Random seed perturbation	Minimal variance (< 5%) in ESG importance
Model Fit	RMSE, MAE, R^2	ML \approx Econometric fit, confirming consistency
Feature Stability	SHAP rank correlation > 0.85	ESG effect structural, not model-specific

Source: Author's own.

Temporal stability, confirming ESG retains significance across different market regimes, includes periods of pre- and post-COVID, energy shocks, and tightening monetary cycles. The small variance in ESG importance under random seed perturbation indicates low sensitivity to initialization conditions, reinforcing the conclusion that its effect is systematic rather than stochastic. Model-fit diagnostics reveal that ML models achieve similar predictive performance to econometric equivalents, confirming the observed ESG

influence cannot be confined within particular methodological class. Finally, high SHAP rank correlation (>0.85) across algorithms supports the hypothesis of ESG's explanatory role being structurally embedded in the data generating process.

Algorithm specific insights are detailed in the following paragraphs by using different aspects of the ESG and risk connection:

- Lasso and Elastic Net identifies explanatory variables retaining predictive power when redundancy is penalized;
- Random Forests averages predictions across thousands of decorrelated decision trees and reveals nonlinear interactions between ESG and market variables;
- XGBoost captures conditional thresholds and nonlinearities more sharply by detecting asymmetric ESG effects;
- XGBoost with Quantile Loss are applied to tail-risk estimation and directly model conditional quantiles of the loss distribution..

The algorithmic ML evidence and results complement the econometric findings by producing support for the hypothesis H_{01} that ESG has not consistent return premium. They offer support for the hypothesis H_{12} that ESG exerts statistically and economically significant effects in reducing volatility persistence and mitigating tail losses, which is the hypothesis H_{13} . The presence of such sustainability effects across nonlinear frameworks confirms the hypothesis H_{14} demonstrating that ESG's influence is model-invariant and structurally embedded.

The empirical architecture developed across Sections 2.1-2.4 establishes analytical pipeline designed to trace multi-dimensional influence of ESG on market dynamics. It proceeds through five logically coherent stages re-classified further. Initially, data construction harmonizes firm-level, market, and macroeconomic variables at weekly frequency (246,976 observations). Then, latent factors are extracted via the derivation of static (PCA) and dynamic (Kalman) ESG factors capturing sustainability as a latent systemic signal. Orthogonalization isolates the independent effect of ESG via market-neutral transformation and its interaction with excess returns. Econometric testing with sequential modeling of return premia (ICAPM), volatility persistence (HAR-RV), and tail risk (EVT-GPD) is conducted. ML validation provides nonlinear robustness testing with penalized regressions and ensemble algorithms. This design enables ESG's influence to be evaluated as priced factor, volatility stabilizer and systemic risk mitigator and ensures methodological continuity and cross-validation of findings.

Chapter 3. Empirical Analysis

This chapter presents empirical estimations, evaluates hypothesis outcomes ($H_1 - H_4$), and interprets their implications for financial stability, policy design, and sustainable investment strategies. It translates the conceptual and methodological structure developed in sections of the previous chapter into an extensive empirical investigation of how ESG factors relate to financial risk characteristics across firms constituting the S&P 500 index. The inquiry moves decisively from the theoretical and model-building domain toward the stage of quantitative implementation, testing and validation. The purpose of the chapter remains to determine whether sustainability-related exposures are priced in equilibrium returns or whether they function primarily as conditional modifiers of risk transmission, volatility persistence, and tail-loss dynamics.

The empirical analysis is organized into four large sections. Section 3.1 investigates whether ESG exposures carry a priced premium in the cross-section of returns, replicating and extending classical Fama-MacBeth two-step regressions with orthogonalized and dynamically filtered ESG factors. Section 3.2 transitions from mean-return behavior to second-moment dynamics. It analyzes volatility persistence, memory structure, and cross-horizon spillovers within heterogeneous autoregressive (HAR) and Kalman-filtered specifications. Section 3.3 advances further into the extreme-risk domain by examining downside tail behavior through extreme-value theory (EVT) and quantile-based models. It evaluates whether ESG contributes to systemic resilience. Section 3.4 complements the econometric findings by deploying machine-learning algorithms to validate predictive power, stability, and nonlinear structure of ESG-risk relationships.

3.1 ESG as a Priced Factor

The first empirical component addresses a fundamental question within sustainable asset-pricing research, if exposure to ESG is compensated by equilibrium risk premium. The study analysis proceeds in carefully outlined stages reproducing Fama-MacBeth cross-sectional procedure under the multiple representations of ESG factor. A static principal-component (PC1), orthogonalized to the market, and dynamically filtered Kalman state-space process are employed with regressions. Each represented factor is tested for statistical and economic significance under pooled, fixed effect, and IV frameworks. Thus, pricing effect of ESG is isolated by minimization of confounding influences of market co-movement and endogeneity.

The principal-component of ESG factor is extracted from three standardized MSCI sub-dimensions. The extracted factor serves as common and firm-level sustainability variation supporting all subsequent tests. Orthogonalization removes a mechanical correlation between ESG and aggregate market factor, allowing clear inference on whether ESG exposures capture independent systematic risk rather than simple extensions of market beta. Such interaction between the orthogonalized ESG component and the market factor reveals whether sustainability can modify the transmission of market risk.

Results from the above outline procedures converge toward a consistent finding - ESG exposure, whether static, orthogonalized, or dynamically filtered, does not constitute priced factor in U.S. equity markets. Regression coefficients across specifications remain small and statistically insignificant, suggesting the absence of distinct risk premium. Nonetheless, interaction term between ESG and market factors is economically small and state dependent. It turns negative in crisis periods and remains near zero or slightly positive in normal and recovery regimes, suggesting that ESG may stabilize returns under stress but is not a consistently priced factor. The findings align with Merton's intertemporal CAPM, which defines that state variables affecting the investment opportunity set may alter conditional risk but do not necessarily generate abnormal expected returns.

This section provides partial support for Hypothesis 1 specified as "ESG exposures do not yield statistically significant return premia, but they shape conditional sensitivities governing how returns co-move with systemic shocks." These results delineate ESG's role as conduits of risk transmission rather than as direct sources of excess performance.

3.1.1 PCA-derived ESG Factor

Empirical analysis of ESG as price factor begins by constructing principal-component, which is extracted from three standardized MSCI indices. This step aggregates the sustainability indicators into a single latent factor F_t^{ESG} reducing dimensionality of sustainability ratings.

The PCA-derived ESG factor (PC1), captures 99.5% of total variance across the ESG indices. It is included in pooled regressions of excess returns on the Fama-French market, size, and value factors (Mkt, SMB, HML) with macroeconomic controls representing monetary and term-structure shifts ($\Delta FEDR$, $\Delta T10$). The estimated F_t^{ESG} is standardized to zero mean and unit variance for comparability across firms and time. It functions as the baseline ESG exposure throughout subsequent analyses.

3.1.2 Orthogonalized ESG Factor

Following the first stage of ESG principal factor (PC1) construction, the study isolates the *unique contribution* of ESG by removing its linear dependence on the aggregate market factor. There is strong correlation ($\rho=99\%$) between individual MSCI proxies as well as F_t^{ESG} factor and market return index. Hence, the PCA-derived composite ESG factor is regressed (orthogonalized) on the Fama-French market excess return, and the residuals are retained as $F_t^{(ESG,orth)}$ measure. This procedure ensures that any explanatory power attributed to ESG is not reflection of its correlation with broad market movements but represents sustainability-driven variation independent of systemic shocks (Figure 2).

The pooled panel regression reveals that $F_t^{(ESG,orth)}$ enters with small and statistically significant coefficient ($\beta = 0.00321$, $t = 8.50$, $p < 0.001$). The economic magnitude of this effect remains minimal and equivalent to an incremental increase of approximately 0.32 basis points in weekly excess returns for 1% change in orthogonalized ESG exposure. Variance inflation factors ($VIF < 1.08$) confirm the absence of multicollinearity by reinforcing ESG effect is not confounded by market, size, or value factors. However, ESG orthogonalized contributes only immaterially to stock returns.

Fama-MacBeth cross-sectional pricing test using the same set of risk factors provides insignificant coefficient for $F_t^{(ESG,orth)}$ ($\beta = 0.00121$, $t = 1.09$, $p = 0.28$). Lack of statistical and economic significance in the cross-section analysis confirms that ESG orthogonalized does not determine risk premium with the neutralized market exposure (Table 15). Further validation arises from quintile portfolio sorts. Assets are ranked each period by their estimated ESG orthogonalized betas and grouped into five portfolios from low (Q1) to high (Q5) ESG alignment. Average portfolio returns (Table 16) display no monotonic pattern, as mean returns range from 0.00124 for Q1 to 0.00096 for Q5, with a (Q5 - Q1) spread of -0.00028 ($p = 0.14$). This non-significant trend reinforces conclusion that ESG orthogonalized is not characterized with systematic return gradient across firms.

Table 15. Regression and portfolio results for $F_t^{(ESG,orth)}$

Model	ESG orthogonalized coefficient	t-stat	p-value	Adj. R ²	AIC	BIC
Pooled OLS	0.00321*	8.50	< 0.001	0.2557	-855351	-855268
Fama-MacBeth	0.00121	1.09	0.28	-	-	-

Source: Author's own.

Table 16. Quintile portfolios based on $F_t^{(ESG,orth)}$

ESG orthogonalized quintile	Average return	High-Low spread	Trend p-value
Q1 (Low)	0.00124	rowspan=5	- 0.00028
Q2	0.00138		
Q3	0.00136		
Q4	0.00109		
Q5 (High)	0.00096		

Source: Author's own.

The study findings indicate that once ESG's covariance with the market factor is removed, its independent contribution to stock returns is negligible. The orthogonalized ESG factor in pooled specifications reflects minor and short-term co-movement; it is cross-sectionally unpriced and economically immaterial. Such outcome is consistent with the semi-strong market efficiency view. Sustainability indicator, while measurable, appears fully absorbed within existing risk structures such as size, industry, or valuation effects. Thus, ESG orthogonalized $F_t^{(ESG,orth)}$ acts as the latent conditioning variable, influencing risk structure. It does not serve as priced driver of the return premia. The subsequent analysis explores this conditional dimension explicitly by interacting ESG orthogonalized with the market factor.

3.1.3 ESG-Market Interaction

Although the prior analysis establishes ESG orthogonalized does not determine return premium, the sustainability characteristics may still influence transmission of systematic risk. Interaction term between orthogonalized ESG factor and market excess return $F_t^{(ESG*Mkt)} = F_t^{(ESG,orth)} * (R_{Mkt,t} - R_{f,t})$ is employed to examine a conditional channel of sustainability that may function as a market risk stabilizer.

The empirical results reveal robust and negative coefficient on the interaction term across all panel specifications. The pooled regression reports $\beta_{(ESG*Mkt)} = -0.1002$ ($t = -11.25$, $p < 0.001$), indicating that one-standard-deviation increase in ESG orthogonalized, conditional on market returns, corresponds approximately to 10 basis points reduction in sensitivity with 1% market return change. The fixed-effects model yields similar coefficient ($\beta = -0.010$, $t = -2.11$, $p = 0.03$), and model diagnostics ($VIF <$

1.09) confirming stable inference and minimal collinearity (Table 17). These results support the research hypotheses of ESG moderating market risk exposure and decreasing downside volatility during aggregate shocks.

However, when examined through cross-sectional Fama-MacBeth regressions, the average coefficient on $F_t^{(ESG*Mkt)}$ loses significance ($\beta = 0.00121$, $t = 1.09$, $p = 0.28$), suggesting that although ESG interacts dynamically with the market over time, this conditional relationship is not consistently priced across assets. Thus, ESG does not function as a systematic factor, but it is rather as a time-varying risk conditioning variable. Portfolio-level analysis reinforces this interpretation (Table 18). Sorting firms into quintiles by $F_t^{(ESG*Mkt)}$ exposure yields an inverse relation between ESG*Mkt intensity and average excess returns: Q1 portfolios earn 0.00156 on average, while Q5 portfolios earn 0.000996, producing a high-low spread of - 0.00056 ($p = 0.04$). The downward slope is not monotonic and economically small, implying higher ESG intensity can be associated with marginally lower exposure to positive market shocks (Figure 4).

Table 17. Regression results for $F_t^{(ESG*Mkt)}$

Model	ESG*Mkt coefficient	t-stat	p-value	Adj. R ²	AIC	BIC
Pooled OLS	- 0.1002*	- 11.25	< 0.001	0.2558	-855406	-855322
Fama-MacBeth	0.00121	1.09	0.28	-	-	-

Source: Author’s own.

Table 18. Quintile Portfolios Based on $F_t^{(ESG*Mkt)}$

ESG*Mkt quintile	Average Return	High-Low spread	Trend p-value
Q1 (Low)	0.00156	rowspan=5	- 0.00056*
Q2	0.00120		
Q3	0.00129		
Q4	0.00099		
Q5 (High)	0.000996		

Source: Author’s own.

The study evidence points toward ESG’s stabilizing capacity rather than its role as a return generator. Firms with stronger ESG alignment experience *lower conditional sensitivity* to market volatility, effectively exhibiting a “low-beta” bias in turbulent conditions. Thus,

negligible average premium confirms that investors do not pay systematically for this protection. ESG acts as a *conditional hedge*, consistent with intertemporal CAPM interpretations where non-tradable state variables such as sustainability alter risk transmission channels without constituting a priced risk factor. The narrowing dispersion of quintile returns and the persistently negative slope in the interaction coefficient underscore that value of ESG lies in resilience and volatility moderation rather than alpha production.

These findings collectively refine the economic interpretation of ESG. Its relevance arises through reduction of market-linked variability and not with return enhancement. The following section proceeds to dynamic reasoning of volatility and tail-risk behavior, by examining if ESG integration may dampen realized variance persistence and mitigate exposure to extreme return events.

3.1.4 Subsample Analysis

Temporal robustness of the ESG-Market interaction reflects the extent to which sustainability influences vary with changing macro-financial conditions and investor sentiment. The full sample from 2014 to 2025 is divided into six distinct regimes representing major market and policy transitions: early ESG adoption (2014-2017), mainstreaming (2018-2019), the COVID-19 crisis (2020 H1), post-crisis recovery (2020 H2-2021), the monetary-tightening phase (2022), and the post-2023 backlash period. Each segment captures a different equilibrium between market volatility and sustainability relevance, providing a framework for identifying cyclical state dependence in the ESG-Market linkage.

Separate estimations are conducted for each window under Pooled OLS and Fixed-Effects (FE) specifications, focusing on the lagged orthogonalized interaction term $\text{Lag1}_{(ESG \times Mkt)}$. Results in Table 19 reveal strong variation in both sign and magnitude across regimes. During low-volatility phases, the early adoption and mainstreaming years, the coefficient on ESG*Mkt interaction remains small and statistically insignificant, implying minimal impact of sustainability alignment when macro conditions are stable.

Big contrast emerges during the COVID-19 shock (2020 H1), when the coefficient turns negative and highly significant ($\beta = -0.128$, $t = -4.62$, $p < 0.001$). High-ESG firms therefore exhibited lower downside sensitivity to market returns, consistent with a stabilizing effect during systemic stress. In the recovery period (2020 H2-2021), the coefficient reverses sign and becomes strongly positive ($\beta = 0.226$, $t = 5.92$, $p <$

0.001), suggesting a rebound or overreaction as investors re-weighted ESG exposures amid improving sentiment. Later regimes show muted behavior. The tightening cycle of 2022 and the backlash phase of 2023-2025 both yield statistically insignificant coefficients ($p > 0.5$), confirming that ESG's conditional impact fades once volatility normalizes.

The overall pattern depicts a cyclically amplifying and decaying dynamic, where ESG intensity becomes relevant only when markets undergo severe stress. Complementary Fama-MacBeth cross-sectional regressions produce uniformly insignificant results for the same interaction term (all $|t| < 1.2$, $p > 0.2$). The absence of systematic pricing across assets reinforces the view that ESG acts as a conditional risk-transmission variable rather than a priced risk factor. Cross-sectional constancy contrasts sharply with the time-series variability observed in the panel estimations, implying that ESG's role is episodic rather than permanent.

Differences across subperiods suggest a continuously evolving process rather than discrete structural breaks (Figure 6). The alternating signs of $\hat{\beta}_{t,(ESG \times Mkt)}$ point to gradual mean reversion and temporary spikes driven by changing macro-financial regimes. Such behavior reflects a latent dynamic structure in which the strength and direction of ESG's influence evolve stochastically through time. Static-parameter frameworks are therefore inadequate for capturing this evolution. A state-space model estimated via the Kalman filter is employed in the next section to recover the hidden trajectory of $\beta_{t,(ESG \times Mkt)}$. This approach enables a continuous mapping of ESG's stabilizing capacity and its responsiveness to economic transitions, providing a dynamic perspective on sustainability's role in market risk transmission.

Table 19. Subsample Panel OLS and Fama-MacBeth Results

Period	Model	ESG*Mkt coefficient	t-stat	Signif	Interpretation
Early ESG (2014-2017)	OLS	0.0604	1.66	.	Weak, insignificant positive effect
Mainstreaming (2018-2019)	OLS	- 0.0261	- 0.77	Ns	No effect
COVID-19 Crisis (2020 H1)	OLS	- 0.1281	- 4.62	***	Strong stabilizing (negative)

Period	Model	ESG*Mkt coefficient	t-stat	Signif	Interpretation
COVID-19 Recovery (2020 H2-2021)	OLS	0.2263	5.92	***	Rebound / Overreaction
Tightening (2022)	OLS	- 0.0030	- 0.11	ns	Flat
Backlash (2023-2025)	OLS	0.0242	0.44	ns	Flat
Fama-MacBeth (Rolling β)	-	0.0003 - 0.0043	≤ 1.1	ns	No systematic pricing

Note: Significance codes: *** $p < 0.001$; ** $p < 0.01$; * $p < 0.05$; “ns” = not significant.

Source: Author’s own.

Subsample results establish a cyclical and time-dependent ESG-Market relationship. ESG alignment cushions downside risk during crises, reverses during recoveries, and becomes irrelevant under stable or tightening conditions. The absence of cross-sectional significance in the Fama-MacBeth regressions supports the interpretation of ESG as a conditional stabilizer rather than a priced systematic factor. Such dynamics justify employing a Kalman-filter-based state-space model that captures $\beta_{t,(ESG \times Mkt)}$ as a latent stochastic process, tracing the evolving trajectory of ESG’s stabilizing role across market regimes (Figure 5).

3.1.5 Dynamic ESG Factor

While PCA-based factors provide static snapshots of sustainability influence, ESG characteristics evolve dynamically as firms adjust to regulatory requirements, technological transitions, and investor sentiment. Capturing this temporal variation requires a state-space modeling framework, implemented here through Kalman filtering. This dynamic representation extracts a latent ESG factor ESG_t^{KF} that evolves as a stochastic process following a random walk. The Kalman filter estimates the unobserved state sequence best explaining the observed ESG indices under Gaussian noise assumptions. It generates a time-varying sustainability indicator that responds flexibly with macroeconomic and market developments.

The dynamic ESG factor ESG_t^{KF} is then orthogonalized and interacted with the market

factor following the same procedure as in the PCA stage. This approach allows direct comparison of static and dynamic specifications, ensuring consistency across analytical layers. The empirical results mirror those obtained from static analyses. Both orthogonalized and interaction forms of ESG_t^{KF} yield coefficients that are statistically insignificant or extremely small in magnitude. The estimated β for $ESG_t^{KF} * Mkt$ equals $-1.8 * 10^{-6}$ ($t = -0.17$) and confirms negligible influence on cross-sectional returns with β for $ESG_t^{(KF,orth)}$ remaining insignificant across all models.

Table 20. Portfolio quantile distribution with $ESG_t^{KF} * Mkt$

<i>Model</i>	<i>Variable</i>	<i>Coefficient</i>	<i>t-stat</i>
Fama-MacBeth (Kalman ESG*Mkt)	- 1.8e - 06	- 1.03e - 05	- 0.17
Portfolio Quintiles (1-5)	0.00112-0.00151	--	--

Source: Author's own.

Portfolio sorts based on quintiles of $ESG_t^{KF} * Mkt$ exposure once again display non-monotonic returns (0.00112-0.00151), reinforcing the absence of a pricing gradient (Table 20). The dynamic filtering therefore does not alter the non-pricing result. This pattern indicates that ESG's evolving state underscores robustness of the non-pricing result under dynamic modeling. Instead, it may enhance the conditional risk-mitigation capacity of ESG, as shown in subsequent volatility analyses.

The introduction of dynamic filtering nevertheless enriches interpretation in several ways. First, it demonstrates that ESG's economic relevance is better understood as a *time-varying process* rather than a static attribute. Fluctuations in ESG's latent state may capture shifts in investor attention, disclosure quality, or regulatory pressure. Second, the low variance of the estimated process noise (Q) relative to observation noise (R) indicates that ESG evolves smoothly rather than erratically, consistent with the long-term structural nature of sustainability adaptation. Third, while the mean coefficient is statistically indistinct from zero, the Kalman-smoothed path of $ESG_t^{KF} * Mkt$ displays pronounced declines during stress episodes, such as late 2018 and early 2020, implying transient yet meaningful stabilizing effects during crises (Figure 5).

These findings complete the cross-sectional pricing investigation. The evidence across PCA, orthogonalized, and Kalman-filtered representations coherently indicates that ESG

factors do not generate systematic return premia in the U.S. equity market. Instead, their economic role manifests conditionally, reducing exposure to market-driven volatility and systemic disturbances. The next section builds directly on this foundation by shifting focus from returns (the first moment) to volatility (the second moment), investigating how ESG influences persistence, memory, and spread of realized variance.

3.2 ESG and Volatility Persistence

The second empirical layer extends the investigation beyond mean-return behavior toward the dynamic structure of market risk. While the preceding section established that ESG exposure does not yield a statistically discernible premium in the cross-section of returns, this section examines whether ESG nonetheless influences the temporal pattern of volatility. It explores if sustainability attributes attenuate persistence of shocks and intertemporal clustering of risk. In capital-market microstructure, volatility persistence embodies adaptive expectations of investors and the speed at which information diffuses through trading networks. Systematic reduction in volatility persistence attributable to ESG would therefore indicate that sustainability operates as a stabilizing property of market dynamics rather than as a priced source of compensation.

Volatility persistence is conceptualized through the heterogeneous-autoregressive (HAR) model of realized variance, an approach that decomposes volatility memory into short-, medium-, and long-horizon components corresponding to one-week, one-month, and one-quarter intervals. The model's design is well suited for detecting heterogeneity in market responses, as short-horizon volatility often reflects liquidity frictions or transient news shocks. Longer-horizon persistence tends to arise from macro-economic or structural uncertainties. Embedding ESG within HAR framework enables direct testing of whether firms with higher sustainability alignment exhibit lower spread of shocks across horizons, implying a more rapid mean-reversion of risk.

This section proceeds in four steps. Subsection 3.2.1 details static HAR model estimations, establishing baseline relationships between ESG and realized variance. Subsection 3.2.2 extends the analysis through Kalman-filtered state-space specifications that allow coefficients to vary over time, capturing the cyclical intensity of ESG's stabilizing effect. Subsection 3.2.3 evaluates endogeneity corrections to ensure causal interpretation, and Subsection 3.2.4 explores subsample robustness across contrasting market regimes. By analyzing these stages Hypothesis 2, providing that ESG exposures reduce volatility persistence across multiple temporal horizons can be supported.

The empirical narrative here demonstrates that ESG behaves as a *conditional volatility-reducing mechanism*. The interaction between ESG and market factors consistently yields negative and highly significant coefficients, both in static and dynamic forms. This effect becomes particularly pronounced during systemic crises - periods when market volatility spikes, and risk transmission accelerates. Consequently, the study findings underscore ESG's capacity to mitigate conditional variance, confirming its role as a stabilizer of financial systems.

3.2.1 Static Volatility Models

The initial investigation employs pooled-OLS specifications of the Heterogeneous Autoregressive (HAR) model to quantify the influence of ESG factors on realized volatility. Each specification incorporates lagged realized-variance components that capture short-, medium-, and long-memory dynamics as defined in Equation (5). The orthogonalized ESG factor $F_t^{(ESG,orth)}$ and its interaction with the market factor $F_t^{(ESG \times Mkt)}$ serve as the primary explanatory variables. Orthogonalization removes any linear dependence between ESG and the market factor, thereby isolating the non-financial component of ESG exposure, while the interaction term captures how ESG sensitivity varies with market-wide conditions.

Endogeneity is mitigated through ESG factor lagged and orthogonalized to minimize contemporaneous feedback with volatility and by using macroeconomic drivers ($\Delta FEDR$, $\Delta T10$) differenced to remove common shocks. Robust covariance estimators clustered by firm are used to ensure inference reliability in the presence of heteroskedasticity and serial correlation. The results exhibit strong statistical regularities consistent with volatility clustering. Lag coefficients on short- and medium-term realized variance are large, positive, and highly significant, confirming persistence typical of equity-return series.

The orthogonalized ESG term $F_t^{(ESG,orth)}$ shows a small but statistically significant positive coefficient, suggesting limited direct contribution to volatility. Importantly, the interaction term $F_t^{(ESG \times Mkt)}$ generates multiple significant lagged effects with alternating signs, positive in several short-term horizons and negative at longer lags. This indicates that ESG alignment modulates rather than uniformly dampens firms' exposure to market-wide volatility shocks.

Interpretively, the small positive coefficient on $F_t^{(ESG,orth)}$ indicates that ESG, when detached from market influence, adds only marginally to realized volatility. The

alternating sign and persistent significance of the lagged $F_t^{(ESG \times Mkt)}$ coefficients imply that ESG's volatility impact is time-varying and horizon-dependent, briefly amplifying volatility during periods of adjustment but dampening it over longer horizons. This lag structure suggests a diffusion process in which ESG information and investor rebalancing spread gradually through markets.

The coefficient magnitudes ranging between $|\beta| \approx 0.01$ and 0.07 are meaningful, as modest shifts in conditional variance can translate into sizable adjustments in risk-adjusted performance and portfolio allocation. The study results support the interpretation of non-financial state variable (here, ESG) influencing the conditional variance in line with intertemporal asset-pricing models (Merton, 1973; Bansal & Yaron, 2004).

The persistence of significant coefficients across multiple lags underscores that ESG's effect is structurally stable rather than transitory. The gradual convergence of standard errors in extended lags points to a smooth diffusion of ESG's risk-moderating influence through time. Overall, the static HAR results provide robust evidence that ESG factors systematically moderate volatility persistence and establish the empirical foundation for dynamic extensions explored in the next section.

3.2.2 Dynamic Volatility Effects

Static cross-sectional models offer valuable insight into average ESG-return relationships but cannot account for how these effects evolve through time. Financial markets move through alternating phases of expansion and contraction, during which the importance of sustainability information is changing. These time-varying effects are traced with the analysis adopting dynamic volatility specifications based on both distributed-lag and state-space formulations.

The first approach employs a heterogeneous autoregressive (HAR) model augmented with twelve lags of the ESG-market interaction term. Such specification decomposes realized volatility into short- and long-memory components, identifying the temporal spread of ESG-related shocks. The model is estimated by using pooled OLS with heteroskedasticity-robust (clustered) errors. The key coefficients exhibit different signs across horizons, implying that ESG exposures have nonlinear and cyclical effects on volatility. Early lags show amplification, while later lags show stabilization.

Table 21. Pooled OLS/HAR model results (L1-L12)

Variable	Coefficient	Std. Error	t-stat	p-value
$F_t^{ESG,orth}$	0.0030	0.00145	2.08	0.038 *
$F_t^{ESG,orth} * Mkt$ (Lag1)	0.0096	0.0208	0.46	0.64
$F_t^{ESG,orth} * Mkt$ (Lag2)	0.0276	0.0051	5.42	< 0.001 ***
$F_t^{ESG,orth} * Mkt$ (Lag3)	- 0.0489	0.0038	- 12.91	< 0.001 ***
$F_t^{ESG,orth} * Mkt$ (Lag5)	0.0743	0.0084	8.79	< 0.001 ***
$F_t^{ESG,orth} * Mkt$ (Lag6)	0.0333	0.0047	7.13	< 0.001 ***
$F_t^{ESG,orth} * Mkt$ (Lag8)	0.0169	0.0083	2.03	0.043 *
$F_t^{ESG,orth} * Mkt$ (Lag9)	0.0102	0.0050	2.04	0.041 *
$F_t^{ESG,orth} * Mkt$ (Lag11)	- 0.0689	0.0267	- 2.58	0.010 **
$F_t^{ESG,orth} * Mkt$ (Lag12)	- 0.0129	0.0105	- 1.23	0.22

Notes: $Adj.R^2 = 0.34-0.36$, $N \approx 38,000$, Cluster-robust SEs by firm ; Significance codes: *** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$.

Source: Author's own.

The patterns of ESG-linked factors initially intensifying volatility and reflecting short-term uncertainty are described in Table 21. The negative coefficients at longer horizons indicate that volatility subsequently is mean-reverts as information is assimilated and confidence stabilizes. This alternating process implies that ESG operates as a dynamic stabilizer, amplifying short-term reactions but reducing persistence. The length of the spread window is roughly eight to twelve weeks, and it corresponds to the time required for markets to price new sustainability information. The volatility dynamics align with conditional-risk theories in which ESG mitigates uncertainty primarily under stress rather than in equilibrium.

The second model applies a Kalman-filtered ESG factor ($ESG_t^{KF} * Mkt$) estimated via state-space formulation, which captures evolving sensitivities. The latent ESG component follows a stochastic trend and extracts smoothed series representing the market's time-varying perception of sustainability. After orthogonalization with respect to the market, the interaction term $F_t^{orth,KF}$ was inserted into HAR framework.

The study results show a strong positive and highly significant effect of the latent ESG factor and market interaction ($ESG_t^{KF} * Mkt$) on volatility. This indicates that realized

volatility rises when ESG sentiment intensifies. Other control variables maintain their expected signs.

Table 22. HAR volatility model with Kalman-filtered $ESG_t^{KF} * Mkt$

Variable	Estimate	t-stat	Significance
$ESG_t^{KF} * Mkt$	5.9673	10.31	***
rv_w	- 0.3331	- 3861	***
rv_m	1.3330	13544	***
Mkt	- 0.0045	- 0.59	-

Notes: a) Pooled HAR estimated via plm, cluster-robust (HC1)

b) Significance: *** $p < 0.01$; ** $p < 0.05$; * $p < 0.10$.

Source: Author's own.

The Kalman-filtered ESG coefficient of approximately 5.97 signifies substantial volatility response. One standard deviation increase in the orthogonalized ESG-market interacted factor can raise realized volatility by approximately 6-7 percent. This contrasts with alternating effects observed in the lagged HAR model, where ESG shocks intensify and moderate volatility (Table 22). The Kalman approach consolidates such dynamics into a single latent process having various impacts over time.

Visual inspection of the Kalman-smoothed series reveals peaks in late 2018 and early 2020 periods of trade-policy uncertainty and the COVID-19 market collapse (Figure 5). During these episodes, the volatility-amplifying effect of sustainability strengthens noticeably. Thus, ESG behaves as a state-contingent volatility driver, not a static hedge. It amplifies fluctuations during crises and ultimately supports faster normalization once uncertainty subsides.

In this study, both the distributed-lag and Kalman-filtered results confirm that ESG's effect on volatility is dynamic, cyclical, and endogenous to market conditions. ESG exposure operates as an endogenous mechanism shaping how volatility emerges and dissipates rather than as an exogenous stabilizing force. Its influence grows during uncertainty, reinforcing the concept of market risk resilience.

3.2.3 Endogeneity Inspection

Given the possibility that ESG disclosure and volatility influence each other contemporaneously, potential endogeneity is an important consideration. Firms facing high volatility may expand sustainability communication to reassure investors, while ESG

activity itself can affect risk perceptions. First, the ESG factors were orthogonalized relative to the market, removing direct co-movement with aggregate risk. Second, the HAR models incorporate up to twelve lags of $ESG_t^{KF} * Mkt$, ensuring that only past information affects current volatility. Third, robust cluster-corrected standard errors address cross-sectional heterogeneity. These design choices collectively reduce the likelihood that observed effects stem from contemporaneous feedback.

Across both the PCA-based and Kalman-filtered estimations, coefficient magnitudes remain stable and statistically significant. In the lagged HAR model, the strongest coefficients (L3, L5, L6) fall in the range of ± 0.03 to 0.07 , translating to an approximate 2-5 percent change in volatility for a one-standard-deviation of ESG shock. In the Kalman specification, the much larger coefficient of about 5.97 implies a 6-7 percent volatility response, consistent with a dominant latent-factor effect during turbulent periods. These results are economically meaningful for institutional portfolios constrained by volatility targets, underscoring ESG's relevance as a conditional risk component rather than a priced return factor.

Complementary Fama-MacBeth regressions confirm the absence of ESG pricing in cross-sectional returns. The estimated coefficient on $ESG_t^{KF} * Mkt$ factor is statistically insignificant, while the value factor (HML) remains weakly negative and the market factor marginally positive. Portfolio sorts by $ESG_t^{KF} * Mkt$ betas show nearly flat average returns across quintiles (see Table 18), reinforcing that ESG's primary influence lies in the volatility dimension rather than expected performance.

Table 23. Endogeneity-robust pricing/HAR volatility estimates

Model / Test	$ESG_t^{KF} * Mkt$ coefficient	t-stat	Signif.
Fama-MacBeth (Kalman ESG×Mkt)	$- 1.8 * 10^{-6}$	- 0.17	-
HAR (L1-12, $F_t^{ESG} * Mkt$) PCA Factor	$\pm 0.03 - 0.07$	up to 12.9	***
HAR ($ESG_t^{KF} * Mkt$) Kalman Factor	5.97	10.31	***

Source: Author's own.

The study findings demonstrate that ESG exerts a powerful and consistent effect on volatility, not on average returns. Its influence is state-dependent, weak in stable markets but amplified during stress, and robust to variations in model design, lag structure, and factor construction. The persistence of these effects across both static and time-varying specifications implies that ESG's role in financial dynamics is structural rather than episodic.

Conceptually, the evidence defines ESG as a conditional volatility transmitter. Sustainability information initially heightens uncertainty when introduced into the market but later contributes to stabilization through improved transparency and stakeholder confidence. This cyclical behavior bridges the apparent contradiction between short-term volatility spikes and long-term resilience, portraying ESG as an endogenous mechanism that helps markets recover from disequilibrium.

The robustness of these results supports a broader interpretation of ESG as an evolving feature of market efficiency rather than a transient anomaly (Table 23). Its capacity to influence volatility, without relating with separate return premium, suggests that sustainability may function as latent informational (non-finance) variable embedded in modern asset-pricing dynamics. In this sense, ESG represents not a static risk factor but a dynamic regulator of how risk itself unfolds.

3.2.4 Subsample Evidence

Temporal robustness is assessed through subsample HAR regressions spanning six macro-financial regimes consistent with Section 3.1.4. Each window captures a distinct stage in the evolution of ESG integration and global market conditions, providing a natural experiment for observing how ESG-market interactions influence volatility under varying systemic contexts. During the early ESG phase (2014-2017), when sustainability disclosure and investor awareness were still emerging, the interaction between ESG and market shocks displayed mixed lag dynamics. A positive short-lag effect ($\text{Lag1} = 0.0301$, $p = 0.0014$) was followed by a negative third-lag coefficient ($\text{Lag3} = -0.0575$, $p < 0.001$). The sequence suggests that initial ESG-related information heightened short-term uncertainty before being rapidly absorbed through market adjustment.

In the mainstreaming phase (2018-2019), the pattern inverted. The second-lag coefficient turned negative and significant ($\text{Lag2} = -0.0216$, $p = 0.0005$), while a mild positive fourth-lag effect ($\text{Lag4} = 0.0149$, $p = 0.011$) re-emerged. This configuration reflects a market in which ESG information had become more efficiently priced,

producing a delayed stabilizing influence that occasionally reversed as sentiment cycles evolved. The COVID-19 crisis window (2020 H1) produced the strongest oscillation: a negative Lag1 (- 0.0701, $p < 0.001$), positive Lag2 (+ 0.0597, $p < 0.001$), and negative Lag3 (- 0.0820, $p < 0.001$). These alternating signs mirror the heightened turbulence of early 2020, when ESG news alternately amplified and attenuated realized volatility as uncertainty about economic continuity intensified.

During the recovery period (2020 H2-2021), all ESG*Mkt lags remained significant and exhibited mean reversion, positive at Lag1 (+ 0.0223) and negative thereafter (Lag2 = - 0.0417; Lag3 = - 0.0508; Lag4 = - 0.0268). The pattern indicates that ESG exposures initially transmitted renewed optimism but ultimately contributed to volatility normalization once systemic stress subsided. In the tightening phase of 2022, all four lags turned positive and highly significant (≈ 0.008 - 0.014 , $p < 0.01$). ESG signals uniformly amplified volatility, suggesting that sectors characterized by strong ESG narratives became central conduits of risk as liquidity conditions tightened and valuation corrections accelerated. The backlash phase (2023-2025) displayed weaker and more fragmented effects. Only Lag2 (- 0.1033, $p < 0.001$) retained significance, implying that ESG's volatility-related predictive power diminished as market attention shifted away from sustainability themes.

Table 24. Subsample volatility coefficients for $F_t^{ESG*Mkt}$

Regime	Significant Lags	Direction	Interpretation
2014-2017	Lag1 (+) Lag3 (-)	Mixed	Short-term amplification, subsequent stabilization.
2018-2019	Lag2 (-) Lag4 (+)	Alternating	Delayed dampening as ESG matures.
2020 H1 (Crisis)	Lag1 (-) Lag2 (+) Lag3 (-)	Oscillating	Alternating volatility spread and absorption.
2020 H2-2021	Lags 1-4 (sign-switching)	Mixed	Mean reversion during recovery.
2022 (Tightening)	Lags 1-4 (+)	Uniform	ESG became a volatility transmitter.
2023-2025 (Backlash)	Lag2 (-)	Weak	Declining ESG sensitivity; normalization.

Source: Author's own.

The evolving sign and magnitude structure confirm that ESG's volatility impact is state-dependent rather than uniformly stabilizing (Table 24). ESG exposures acted as short-term amplifiers during periods of systemic stress but reverted to stabilizing roles when markets normalized. This cyclical asymmetry accords with evidence that strong governance and stakeholder alignment enhance resilience under uncertainty while potentially heightening adjustment volatility when sentiment reverses.

The subsample analysis refines Hypothesis 2 by showing that ESG operates as a conditional volatility indicator. Its effect intensifies in turbulent phases and moderates during calm periods, reflecting a dynamic rather than static risk-mitigating role. Next section extends this inquiry to tail-risk behavior, assessing whether these conditional dynamics persist under extreme return distributions.

3.3 EVT and Downside Risk

Having established in the preceding section that ESG exposure systematically reduces volatility persistence and moderates conditional variance, the analysis now extends to the extreme tails of the return distribution. Average fluctuations seldom drive financial crises and systemic disruptions. Rather they are dominated by rare and catastrophic events occupying the extreme left tail of the distribution. Hence, understanding whether ESG mitigates such events is fundamental to evaluating its contribution to systemic resilience. Section 3.3 explores this question by integrating Extreme Value Theory (EVT) with conditional Value-at-Risk (VaR) and Expected Shortfall (ES) estimations, thereby transitioning from the analysis of volatility clustering to the study of loss extremities.

The inquiry builds directly upon the conceptual foundation of Section 3.2. If ESG lowers volatility persistence, then by extension, it may also compress the conditional tail risk of returns. This link derives from the statistical relationship between volatility and kurtosis - the lower variance persistence typically corresponds with the reduced tail thickness and the smaller probabilities of extreme losses. ESG's moderating function thus potentially operates not only through volatility stabilization but also through the attenuation of fat-tailed behavior. Demonstrating such effect empirically would validate the hypothesis that sustainability enhances market stability through multi-moment risk channels rather than through mean-return differentials.

The analytical structure unfolds across four interrelated subsections. Subsection 3.3.1 employs the Peaks-over-Threshold (POT) method and Generalized Pareto Distribution (GPD) to estimate the shape and scale of tail losses beyond the 5th percentile threshold.

Subsection 3.3.2 computes VaR and ES metrics under these fitted distributions to quantify the economic magnitude of ESG's influence. Subsection 3.3.3 extends the results through endogeneity and robustness testing, and subsection 3.3.4 analyzes regime dependence by identifying whether ESG's tail-mitigation capacity varies across different market states. These subsections address Hypothesis 3 predicting that ESG exposure reduces the magnitude and frequency of extreme downside losses.

Before presenting formal estimates, it is useful to consider this analysis within the broader context of systemic-risk modeling. Traditional risk-measure frameworks, including variance-based and Gaussian VaR approaches, notoriously underestimate the likelihood of tail events due to their reliance on normality assumptions. The empirical literature following the Global Financial Crisis (2008-2009) consistently finds that equity-return distributions exhibit heavy tails and time-varying skewness, characteristics best captured by EVT. Integrating ESG variables into such models represents a methodological innovation and allows examination of how non-financial attributes may condition the extremity of loss processes rather than their central tendency.

Empirical results reported in this section strongly support Hypothesis 3. Across all specifications, firms with higher ESG orientation exhibit significantly lower shape parameters (ξ) and smaller conditional tail losses, indicating that sustainability reduces both the likelihood and severity of catastrophic events. The effect remains stable under lag-extended robustness checks and intensifies during periods of systemic stress. In economic terms, ESG appears to reconfigure the distribution of returns by truncating its lower tail, functioning as a structural "safety valve" within financial markets.

3.3.1 EVT-GPD Estimation

The first step in modeling downside risk applies the Peaks-over-Threshold (POT) approach from Extreme Value Theory (EVT). This method isolates the distribution of returns exceeding a chosen threshold, allowing precise estimation of extreme-loss behavior beyond conventional Gaussian bounds. The conditional distribution of excess losses $(X - u) \mid X > u$ is assumed to follow the Generalized Pareto Distribution (GPD) as in Equation (6), where ξ denotes the shape parameter governing tail heaviness and β represents the scale parameter reflecting dispersion. A positive ξ indicates heavy-tailed distributions characteristic of financial data, while lower β values correspond to smaller magnitudes of extreme outcomes. Estimating these parameters jointly with ESG factors allows direct inference on whether sustainability compresses the tail.

The analysis employs a 5th-percentile threshold, a conventional cutoff in EVT applications that balances bias and variance in parameter estimation. The model includes the orthogonalized ESG factor $F_t^{(ESG,orth)}$ constructed as the residual from the regression of the PCA-based ESG index on the market return and its market-interaction term $F_t^{(ESG \times Mkt)}$ as two covariates within the GPD parameter equations (Table 25). Such specification enables the assessment of whether ESG characteristics influence central portion of the return distribution and behavior of losses conditional on exceeding the threshold.

Table 25. EVT-GPD estimates of left-tail risk

<i>Model</i>	<i>Variable</i>	<i>Coefficient</i>	<i>Std. error</i>	<i>t-stat</i>	<i>p-value</i>
GPD (Pooled)	$F_t^{(ESG,orth)}$	- 0.2183	0.0624	- 3.50	< 0.001***
GPD (FE)	$F_t^{(ESG,orth)}$	- 0.1921	0.0598	- 3.21	0.001**
GPD (Pooled)	$F_t^{(ESG \times Mkt)}$	- 0.4403	0.0434	- 10.14	< 0.001***
GPD (FE)	$F_t^{(ESG \times Mkt)}$	- 0.3869	0.0478	- 8.09	< 0.001***

Notes: Adj. $R^2 = 0.27$ (Pooled), 0.31 (FE), $N = 39,120$; Significance codes: *** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$; Robust SEs clustered by firm.

Source: Author's own.

The consistently negative and statistically significant coefficients of both ESG terms confirm that stronger ESG performance is associated with thinner and less severe loss tails. In particular, the coefficient of - 0.44 for $F_t^{(ESG \times Mkt)}$ indicates substantial dampening of market-driven tail amplification, implying that high-ESG firms are less susceptible to joint downturns triggered by systemic shocks. These results parallel the volatility findings in section 3.2, demonstrating continuity between the second-moment stabilization and tail truncation.

Economically, ESG acts as a structural insurance mechanism. It reduces informational asymmetry, improves internal risk controls, and strengthens stakeholder confidence, as sustainability-oriented firms lower the probability of catastrophic losses. The study's observed effect benefits individual shareholders and contributes to overall financial stability by limiting the spread of extreme events across portfolios. The positive, significant shape parameter ξ (not tabulated) confirms the heavy-tailed nature of U.S. equity returns, consistent with established empirical evidence.

Incorporating ESG factors reduces the implied tail index and yields thinner tails within high-ESG groups of firms. Hence, sustainability affects not the mean of returns but their conditional distribution, and it moderates exposure to extreme outcomes by leaving expected profitability largely unchanged. The GPD framework provides a rigorous statistical foundation for quantifying ESG's contribution to tail-risk mitigation. Subsequent sections translate these tail-parameter effects into economically interpretable metrics, VaR and ES, to evaluate the practical magnitude of ESG-induced risk reduction.

3.3.2 VaR and ES Metrics

Value-at-Risk (VaR) and Expected Shortfall (ES) constitute standard metrics for measuring potential portfolio losses under adverse conditions. VaR identifies a quantile loss threshold that is not exceeded with a specified probability (typically 5%), while ES quantifies the expected loss conditional on breaching that threshold. These metrics offer a comprehensive view of downside risk intensity and severity.

Under the GPD framework, both VaR and ES can be expressed as functions of the estimated shape and scale parameters (ξ, β) using Equation (7). Their formulations permit direct evaluation of how ESG factors shift the quantile and conditional-expectation boundaries of the loss distribution. Empirical estimation proceeds via quantile regression using the 5% threshold ($\tau = 0.05$), incorporating both $F_t^{(ESG,orth)}$ and $F_t^{(ESG \times Mkt)}$ as explanatory variables.

Table 26. Conditional VaR and ES Regressions ($\tau = 0.05$)

<i>Metric</i>	<i>Variable</i>	<i>Coefficient</i>	<i>Std. Error</i>	<i>t-stat</i>	<i>p-value</i>
VaR (5%)	$F_t^{(ESG,orth)}$	- 0.0098	0.0041	- 2.38	0.02**
VaR (5%)	$F_t^{(ESG \times Mkt)}$	- 0.0116	0.0038	- 3.05	0.002**
ES (5%)	$F_t^{(ESG,orth)}$	- 0.0134	0.0049	- 2.73	0.006**
ES (5%)	$F_t^{(ESG \times Mkt)}$	- 0.0162	0.0045	- 3.60	< 0.001***

Source: Author's own.

The coefficients on $F_t^{(ESG \times Mkt)}$ are negative, indicating that higher ESG exposure is associated with less negative VaR and ES values (Table 26). In other words, improved ESG performance corresponds to smaller extreme losses at the 5% confidence level. This finding confirms that sustainability acts as a risk buffer, lowering both the likelihood and

the severity of tail events. The effect is more pronounced for ES, implying that ESG not only shifts the loss threshold upward but also reduces the expected depth of losses once that threshold is breached.

Quantitatively, the regression coefficients demonstrate that higher ESG exposure is associated with lower conditional Value-at-Risk and Expected Shortfall estimates. This finding indicates that portfolios with stronger ESG characteristics face reduced downside risk and smaller expected losses during extreme market conditions. Although the absolute magnitudes are modest, the results are economically relevant for large institutional investors, where even small reductions in tail exposure can significantly influence capital allocation and risk management. The attenuation of extreme losses also implies lower capital requirements under risk-sensitive regulatory frameworks such as Basel III and Solvency II, reinforcing the role of ESG factors in enhancing financial stability.

From a theoretical perspective, the study results complement the variance-based findings in section 3.2 and collectively illustrate a coherent risk-transmission mechanism. ESG's contribution to financial resilience manifests through two interlocking effects: the reduction of volatility persistence, which smooths short to medium-term fluctuations, and truncation of the tail distribution, which limits exposure to catastrophic events. These effects indicate that sustainability reduces both the frequency and the amplitude of risk transmission, confirming its stabilizing influence across the entire distribution of returns.

It is also important that ESG-market interaction terms remain highly significant in the tail regressions, reinforcing the interpretation that ESG's stabilizing function is contingent on systemic conditions. During tranquil periods, when market volatility is low, ESG has limited marginal impact; during crises, its dampening capacity intensifies. This conditional asymmetry aligns with theoretical expectations from adaptive-market and intertemporal-risk frameworks, which posit that the utility of stabilizing attributes rises sharply during disequilibrium states.

The study results imply practical consequences for portfolio management. High-ESG portfolios offer not only reputational or ethical advantages but also quantifiable risk benefits through lower tail exposure. This evidence provides empirical justification for integrating ESG metrics into strategic asset-allocation and stress-testing processes. It also supports an emerging regulatory trend for incorporating sustainability risk assessments into prudential oversight frameworks.

3.3.3 Robustness Tests

Rigorous robustness testing is essential to confirm that the previously identified relationship between ESG exposure and downside tail risk is not a spurious artifact of omitted variables, simultaneity, or model misspecification. The finding that ESG exposure systematically mitigates tail losses must therefore withstand alternative estimation strategies and temporal structures. This subsection validates that relationship through orthogonalization-based endogeneity correction and lag-extended EVT-GPD specifications.

The empirical procedure proceeds in two stages. First, potential endogeneity between ESG intensity and market performance is mitigated through orthogonalization. Specifically, the PCA-derived ESG factor is regressed on the market return index, and the residuals from this regression, representing the market-neutral ESG component, are included in the main EVT specification. This step effectively purges contemporaneous feedback effects between ESG and market movements, ensuring that the estimated relationship captures exogenous ESG dynamics rather than co-movements with market volatility.

Second, the robustness of the results is evaluated under alternative temporal structures. Given that volatility clustering and tail dependence may persist across multiple horizons, additional EVT-GPD models are estimated with lag structures of four (L1-4) and twelve (L1-12) periods. These lag-extended specifications ensure that delayed ESG responses and long-memory volatility processes do not bias the short-run results.

Table 27. Endogeneity-free and robust EVT Models (HAR L1-L12)

Model	Variable	Coefficient	Std. error	t-stat	p-value
EVT-GPD (L1-4)	$F_t^{ESG*Mkt}$	- 0.4128	0.0467	- 8.84	<0.001***
EVT-GPD (L1-12)	$F_t^{ESG*Mkt}$	- 0.4310	0.0437	- 9.87	<0.001***
HAR-EVT (Orthogonalized ESG*Mkt)	$F_t^{ESG*Mkt}$	- 0.4272	0.0455	- 9.38	<0.001***

Source: Author's own.

The persistence of large, statistically significant negative coefficients across all three specifications confirms that ESG's mitigating effect on tail exposure is robust to both temporal and econometric perturbations. The orthogonalization procedure successfully isolates the exogenous component of ESG exposure, while the extended-lag structures account for long-memory volatility patterns.

One standard deviation increase of $F_t^{(ESG \times Mkt)}$ alignment corresponds approximately to 0.43-unit reduction in the conditional tail-loss index, which is equivalent to an 8-10% decrease in the expected shortfall (Table 27). Such magnitude positions ESG as an economically meaningful determinant of tail-risk mitigation, comparable in scale to standard volatility-targeting or defensive-sector rotation mechanisms. Residual diagnostics further support model validity. The EVT residuals display near-normality with minimal skewness, Cook's distance values indicate no undue leverage. The heteroskedasticity-robust standard errors confirm that cross-sectional dependence does not drive the observed significance. Substituting ESG data source (LSEG-Refinitiv) with reduced dimensionality of sustainability proxies provide consistent results for $F_t^{(ESG \times Mkt)}$ coefficients ranging from - 0.39 to - 0.45. The consistency of ESG coefficients underscores the generalizability of the stabilizing ESG-tail-risk relationship across rating methodologies and confirms that the observed effect is structural rather than index-specific. These robustness checks confirm that ESG integration materially and persistently reduces tail exposure, reinforcing its role as a structural determinant of conditional tail behavior in U.S. equity markets.

3.3.4 Regime Dependence

Financial relationships in capital markets rarely remain constant through time. Their magnitude and direction evolve with macroeconomic cycles, liquidity regimes, and prevailing investor sentiment. The tail-risk transmission of ESG factors is examined across six empirically distinct regimes: *early adoption* (2014-2017), *mainstreaming* (2018-2019), *COVID-19 crisis* (2020 H1), *recovery* (2020 H2-2021), *monetary tightening* (2022), and *backlash/realignment* (2023-2025). This segmentation reflects critical turning points in policy and market structure, paralleling volatility-based partitions used in earlier chapters. Estimating the 5th-percentile quantile regressions within each regime enables identification of periods in which ESG's moderating influence on extreme downside risk intensifies or weakens. The results reveal distinct time variation and structural asymmetry, confirming that ESG's stabilizing capacity is conditional on prevailing macro-financial stress conditions.

During the early ESG adoption phase (2014-2017), the coefficient on the lagged ESG and market interaction (-0.083, $p = 0.39$) is statistically insignificant, implying that sustainability integration at this stage exerted limited influence on tail risk. The interaction term is lagged by one period to avoid reversed causality between contemporaneous ESG

shocks and returns. Lagging the variable ensures that the estimated relationship captures predictive transmission of prior ESG-market dynamics into subsequent tail outcomes rather than simultaneous co-movement. The period of sustainability adoption was characterized by steady economic expansion and voluntary ESG participation, with minimal regulatory enforcement or systematic pricing of sustainability-related risk. As sustainability considerations were largely reputational, their effect on market co-movement remained negligible. The mainstreaming period (2018-2019) marks a transition toward greater institutional adoption, with the coefficient strengthening to -0.308 ($t = -2.94$, $p < 0.01$), indicating that ESG portfolios began exhibiting measurable downside protection. The emergence of more standardized disclosure practices and growing investor awareness likely contributed to this early stabilizing effect under low-volatility conditions.

The COVID-19 crisis window (2020 H1) demonstrates the most pronounced amplification of ESG's countercyclical behavior, with the coefficient deepening sharply to -0.946 ($t = -9.33$, $p < 0.001$). This more than triples the magnitude of the pre-crisis effect and coincides with the market's steepest systemic drawdown. Such an outcome suggests that firms with higher ESG alignment experienced lower left-tail exposure due to stronger stakeholder networks, resilient supply chains, and greater investor confidence in governance quality. The magnitude of this effect implies that sustainability alignment served as an endogenous shock absorber, offering protection when systemic fear and liquidity contraction dominated market behavior. The stabilizing effect persisted during the recovery phase (2020 H2-2021), where the coefficient remained significantly negative (-0.455 , $p < 0.001$), suggesting sustained downside mitigation even amid aggressive policy accommodation. However, the reduced magnitude indicates partial normalization as uncertainty and volatility declined.

In contrast, the monetary tightening regime of 2022 produced a statistically negligible coefficient (-0.034 , $p = 0.72$), illustrating how rapidly rate hikes and valuation adjustments may temporarily overshadow the risk-buffering role of ESG. This diminished impact can be attributed to broad factor rotations and liquidity withdrawals compressing dispersion across risk premia and muting ESG differentiation. Backlash and realignment phase (2023-2025) reveals a renewed and highly significant re-emergence of ESG's stabilization (-0.470 , $t = -5.64$, $p < 0.001$). Despite rising political polarization and selectivity of anti-ESG rhetoric, investors continued to reward firms with credible governance and transparency attributes, confirming the persistent market relevance of sustainability-linked resilience. The cyclical resurgence of sustainability based tail-risk protection underscores

its state-dependent behavior (Figure 7), which could be latently observed during liquidity contractions and resurgent under renewed uncertainty.

Table 28. Quantile regression estimates of tail risk, $VaR[F_t^{(ESG*Mkt)}]$

Period / Regime	$VaR[F_t^{(ESG*Mkt)}]$ Lag1 coefficient	Std. error	t-stat	p-value	Significance
Early ESG (2014-2017)	- 0.0829	0.0971	- 0.85	0.393	
Mainstreaming (2018-2019)	- 0.3077	0.1048	- 2.94	0.0033	**
COVID crisis (2020 H1)	- 0.9463	0.1014	- 9.33	< 0.001	***
COVID recovery (2020 H2-2021)	- 0.4549	0.1090	- 4.17	< 0.001	***
Tightening (2022)	- 0.0342	0.0952	- 0.36	0.720	
Backlash (2023-2025)	- 0.4696	0.0833	- 5.64	< 0.001	***

Source: Author's own.

The trajectory of ESG and market interacted coefficient in quintile distribution traces nonlinear evolution, which is weak (- 0.08), moderate (- 0.31), deep (- 0.95), partial (- 0.45), muted (- 0.03), and re-strengthened (- 0.47). These changes are consistent with adaptive-market dynamics rather than monotonic progression (Table 28). Such pattern implies that the utility of ESG to investors is state-contingent and provides strong marginal benefit when market stress peaks. The crisis-to-tranquil differential of nearly one full coefficient point translates to roughly a 20-25 percent lower probability of extreme portfolio losses for high-ESG firms during systemic disruptions. Within an intertemporal asset-pricing framework, the marginal utility of stability and non-financial trust attributes increases under heightened risk aversion. ESG's contribution therefore lies not in enhancing expected returns but in reducing the curvature of downside utility and flattening the tail in return distribution for periods of volatility surges.

Evidence from systemic-risk literature supports the research interpretation, emphasizing that financial fragility arises not only from leverage but also from homogenous exposure. ESG-oriented firms diversify operational and reputational risk channels, reducing co-movement with macro stress factors and lowering the likelihood of cascading defaults. During high-stress episodes such as 2020 H1, the diversification decreased joint tail dependence and mitigated loss exposure across asset classes. The

observed coefficient dynamics thus represent both firm-level robustness and macro-level decoupling, and ESG introduces heterogeneity that cushions systemic fragility. This dual mechanism helps explain why ESG's tail-risk mitigation becomes most effective precisely when traditional risk factors are least effective.

The regime-dependent pattern of influence that ESG holds is providing important implications for portfolio construction and policy design. Asset managers gain the most risk-adjusted benefit when dynamically adjusting ESG exposure upward during periods of market turbulence rather than maintaining static allocations. Regulators can view this sustainability disclosure and performance as set of macro-prudential instruments enhancing system-wide stability. The observed amplification of ESG's stabilizing role during crises supports integrating ESG sensitivity into stress-testing frameworks and financial stability assessments. During the 2020 market collapse, for example, the S&P 500 constituent firms lost over 30 percent while high-ESG portfolios declined by roughly 22 percent, a possible indication of the econometric magnitude with sustainability coefficient. The latter illustrates translation of ESG into tangible capital preservation.

Extending the empirical horizon through 2025 reveals that ESG has effect on downside risk and behaves as dynamic and regime-contingent stabilizer within financial markets. Such influence strengthens during systemic crises, eases as policy and liquidity normalize, and reasserts once structural uncertainty resurfaces. The oscillation reflects inherent sensitivity of ESG to macro-financial stress and investor risk aversion rather than a secular trend in its valuation impact. The empirical pattern indicates that sustainability operates as conditional hedge with its marginal utility intensifying precisely when conventional diversification channels weaken. Such dynamics affirm that ESG contributes not through superior returns but by mitigating the transmission of extreme risk, compressing both volatility and tail dependence across cycles. The results collectively reinforce broader argument of chapter 3 that sustainability functions as a systemic buffer within capital markets. It enhances financial resilience and provides endogenous form of risk insurance that becomes most valuable under crisis conditions.

3.4 Machine Learning Verification

The concluding empirical layer of this chapter employs machine-learning (ML) techniques to complement and validate the econometric findings presented in the preceding sections. While econometric models such as the HAR and EVT frameworks offer high interpretability and clear theoretical underpinnings, they are constrained by

assumptions of linearity, stationarity, and homogeneity. By contrast, ML methods can uncover nonlinear and high-dimensional dependencies that are difficult to detect in traditional parametric settings. Integrating both approaches ensures that the observed ESG-risk relationships are not objects of linear model specification but reflect persistent structural regularities in the data.

The primary objective of ML validation in this section is not to replace econometric inference, but to test whether ESG-related variables enhance predictive accuracy for volatility persistence and downside risk. If ESG information systematically improves out-of-sample predictive performance across multiple ML models, its economic relevance can be inferred independently of explicit functional assumptions. Such consideration aligns with modern risk-management practices that prioritize forecasting performance and robustness over exact parametric specification.

The ML design combines regularized linear regressors and a nonlinear ensemble learner. Least absolute shrinkage and selection operator (LASSO) imposes L1 regularization, enforcing sparsity and selecting among potentially collinear predictors. Elastic Net combines L1 and L2 penalties, balancing variable selection and grouping effects as well as ensuring that correlated variables (ESG and market factors) can be jointly retained. Extreme gradient boosting (XGBoost) constructs a boosted ensemble of regression trees, capable of capturing nonlinearities and higher-order interactions among variables, including dynamic ESG-market linkages. This empirical setup mirrors the econometric framework to preserve comparability. The input feature matrix includes lagged realized volatility components (rv_w, rv_m, rv_q), market and size factors (Mkt, SMB, HML), macro-financial controls ($\Delta FEDR, \Delta T10$), and the lagged orthogonalized ESG-market interaction $Lag1(F_t^{ESG * Mkt})$. The dependent variable for the study's experiment corresponds to the 5% historical VaR computed from asset returns and aligned with ML target using econometric measures of conditional downside risk.

Data are partitioned into 80% training and 20% testing subsets, preserving temporal order.

Hyper-parameter optimization is carried out using five-fold cross-validation, minimizing mean-squared error (MSE) on validation folds. Model performance is assessed along three complementary criteria: Mean Squared Error (MSE) for predictive accuracy, out-of-sample R^2 for explanatory power, and qualitative evaluation using Shapley additive explanations (SHAP) for interpretability. ML analysis proceeds in three analytical stages. Sub-section 3.4.1 presents predictive results for volatility and risk persistence and sub-

section 3.4.2 applies the same framework to tail-risk forecasting. Sub-section 3.4.3 interprets model behavior through SHAP values to visualize ESG's influence within nonlinear prediction structures. These analyses evaluate whether ESG information enhances forecasting precision and whether such improvement corroborates the stabilizing narrative established earlier.

Across both econometric and machine-learning paradigms, results converge on a unified conclusion. ESG functions as a conditional stabilizer of financial risk. Its influence is not confined to linear dynamics but manifests through nonlinear, state-dependent modulation of volatility and tail exposure. Regularized regressors and nonlinear ensembles alike highlight ESG and market interaction as a persistent predictor, while SHAP analysis provides a transparent mapping of its direction and magnitude of influence. The consistency of these findings across fundamentally different methodologies, including OLS, penalized linear, and gradient-boosted trees, confirms the role of ESG is intrinsic to data-generating process rather than element of modeling choice.

Empirically, the results imply that ESG integration can improve the forecastability and stability of financial systems, particularly under conditions of stress. Theoretically, they position ESG as a state variable embedded in market risk architecture, shaping conditional distributions through feedback and adaptation mechanisms. Hence, ESG engagement contributes to both ex-post resilience and ex-ante predictive control of financial risk. This is an insight of tangible value for both investors and policymakers. Summarizing key research insights in this section - all ML models materially improve predictive performance relative to the HAR baseline, and XGBoost delivers the strongest gains (MSE = 0.00077). The lagged ESG and market interacted variable consistently ranks among the top three predictors across models and evaluation metrics. SHAP decomposition confirms ESG's negative, nonlinear influence on predicted volatility and tail risk, with amplified effects during systemic crises. Sectoral heterogeneity reveals that ESG's stabilizing value is greatest in environmentally intensive industries. The convergence of econometric and ML evidence demonstrates that ESG operates as a structural conditioning factor, enhancing both risk modeling robustness and market stability.

3.4.1 Predictive Performance

The first predictive experiment applies the three ML algorithms, namely LASSO, Elastic Net, and XGBoost, for forecasting realized risk proxied by VaR at weekly frequency. Each model is trained on identical predictors, ensuring one-to-one comparability with the

econometric baseline (HAR pooled OLS). HAR model therefore, serves as a benchmark for evaluating the incremental predictive contribution of ML frameworks.

Table 29. ML comparison for volatility forecasting

Model	Test MSE	Out-of-sample R^2	Importance of ESG and market interaction (%)
HAR (baseline OLS)	0.00431	0.356	-
LASSO	0.00203	0.478	6.9
Elastic Net	0.00203	0.481	7.3
XGBoost	0.00077	0.532	9.8

Source: Author's own.

Results summarized in Table 29 reveal that all ML models outperform the baseline econometric specification. Both regularized linear regressors achieve approximately 50% lower MSE relative to HAR, while the XGBoost model attains the lowest test MSE (0.00077) and the highest predictive R^2 (0.53). The magnitude of improvement demonstrates that nonlinear ensemble learning captures richer informational structures. In particular, interactions between ESG exposure and market conditions, not accessible to linear formulations, have improved. Importance of ESG and market interaction column quantifies each model's relative feature contribution, derived from standardized importance or SHAP values. All ML architectures with lagged ESG-market interaction consistently rank among the top five predictors, accounting for roughly 7-10% of aggregate importance. Given that volatility lags and macro factors typically dominate ML models, the persistence of ESG among leading features is compelling evidence of its genuine predictive content.

Elastic Net marginally outperforms LASSO, underscoring the advantage of allowing correlated features (ESG factors and returns) to co-exist. This small but systematic gain indicates that ESG variables complement, rather than duplicate, the macro-financial environment. XGBoost amplifies such effect further through recursive partitioning, implicitly learning cross-terms similar to the econometric ESG and market interaction specification even when not explicitly imposed. The improvement in predictive accuracy is consistent and economically meaningful: relative to the HAR baseline, XGBoost reduces out-of-sample MSE by over 80%, and still improves on the penalized linear models by around 60%, indicating that ESG integration materially enhances the reliability

of risk forecasting. The study results substantiate broader interpretation of ESG as stabilizing variable strengthening adaptability of predictive systems to evolving market regimes.

3.4.2 Predictability under EVT

The second predictive test extends the ML framework to extreme-risk estimation by applying the same algorithms to forecast conditional tail losses. Tail events pose greater modeling difficulty due to their sparsity and regime dependence, and they represent the most policy-relevant component of financial risk. Test reveals if ESG can contribute meaningfully to the prediction of extreme outcomes. Here, the target variable is Expected shortfall (ES) at the 5% level derived from historical and EVT-based calculations within each asset's return distribution. Input features remain consistent with the volatility experiment, lagged realized volatility, factor returns, macro variables, and lagged ESG and market interaction variables.

Table 30. ML performance in tail-risk forecasting

Model	Test MSE	Relative MSE vs HAR-EVT	ESG-Mkt rank
HAR-EVT (benchmark)	0.00562	-	-
LASSO	0.00203	+63.9 %	7th
Elastic Net	0.00203	+63.9 %	6th
XGBoost	0.00077	+86.3 %	3rd

Source: Author's own.

All three ML models outperform the HAR-EVT benchmark by a substantial margin. XGBoost again achieves the most accurate forecasts, reducing out-of-sample MSE by over 86% relative to the econometric baseline. This demonstrates that ESG-related variables improve the model's ability to anticipate tail losses even when the conditional distribution of returns exhibits heavy tails and regime shifts (Table 30). Within XGBoost, the lagged ESG-market variable ranks third overall in global feature importance, following the quarterly and monthly volatility components (rv_q, rv_m). Its stability across both regularized and nonlinear methods confirms that ESG information is orthogonal to traditional risk factors, supplying an independent predictive signal rather than duplicative noise.

From a risk-management perspective, this improvement is highly relevant. Enhanced tail-risk predictability translates directly into better capital allocation and downside protection. The research finding that ESG features retain predictive power during crisis periods (2020’s COVID-19 and 2022 energy-shock episodes) underscores their role as state-contingent stabilizers within the risk architecture. The study results also reveal nonlinear saturation effects, as beyond moderate ESG alignment, incremental improvements yield diminishing predictive gains. The observed response is consistent with adaptive-market perspective and suggests that the stabilizing benefit of ESG is strongest for firms transitioning from low to medium sustainability.

3.4.3 SHAP and Feature Effects

It is essential to interpret ML outputs for drawing economically meaningful conclusions. Unlike linear regressions that yield explicit coefficients, XGBoost models operate as complex nonlinear mappings whose internal structure must be decomposed to attribute variable influence. The study employs SHAP game-theoretic method that decomposes each prediction into additive contributions from each input feature. SHAP is applied to the best-performing XGBoost model, and the analysis reveals detailed insights into how ESG variables influence predicted risk outcomes.

Table 31. Global SHAP feature importance (XGBoost, VaR, Target)

Rank	Feature	Mean absolute SHAP	Relative importance (%)
1	rv_q (quarterly volatility lag)	3.36	29.5
2	SMB	1.16	10.2
3	$F_t^{ESG*Mkt}$ (lagged ESG-market)	1.15	10.0
4	HML	1.15	9.9
5	Mkt	1.11	9.6
6	rv_m (monthly lag)	1.07	9.3
7	$\Delta T10$	1.05	9.1
8	$\Delta FEDR$	1.03	9.0
9	rv_w (weekly lag)	1.01	8.7

Source: Author’s own.

SHAP ranking confirms the central role of ESG-market interaction, which occupies the third-highest position in overall importance. Its negative SHAP values (on average) indicate that stronger ESG alignment, particularly during favorable market phases, systematically reduces the model's predicted volatility and expected shortfall. Conversely, low or negative ESG-market interaction values correspond to positive SHAP impacts, implying higher forecasted risk under weak sustainability alignment (Table 31).

Plotting SHAP (ESG-market) against the feature itself reveals a concave, negatively-sloped curve: risk declines sharply with initial ESG improvement but levels off beyond the 80th percentile. This pattern reflects econometric findings of diminishing marginal stability benefits at higher ESG performance levels. Temporal SHAP analysis for 2015-2025 shows that the absolute SHAP magnitude of ESG-market interaction doubles during crisis periods of 2020's COVID-19 shock and 2022 energy-price surge. It indicates that the stabilizing power of ESG is state-dependent and counter-cyclical. The temporal dynamics parallel time-varying coefficients obtained from the econometric volatility models and reinforcing consistency across methodological domains. SHAP interpretation also demonstrates that the nonlinear predictive role of sustainability is coherent and explainable. Correlation between global feature importance and mean SHAP magnitude ($r \approx 0.87$) validates internal consistency, as features statistically significant for prediction also exert economically meaningful influence on outcomes. Cross-feature SHAP interactions reveal that high ESG alignment combined with rising interest-rate environments ($\Delta\text{FEDR} > 0$) produce particularly large negative SHAP effects, suggesting well-governed firms absorb monetary policy shocks.

3.5 Empirical Synthesis

Having completed the multi-layered empirical examination, it is now possible to synthesize the collective findings from econometric, ML, and interpretability analyses into a cohesive narrative regarding ESG's financial role. Across both econometric and machine-learning approaches, results converge on a unified conclusion. ESG functions as a conditional stabilizer of financial risk, and its influence is not confined to linear dynamics. It manifests through nonlinear, state-dependent modulation of volatility and tail exposure. Regularized regressors and nonlinear ensembles alike highlight ESG-market interaction as a persistent predictor, while SHAP analysis provides a transparent mapping of its direction and magnitude of influence. Consistency of the study findings across fundamentally different methodologies, including OLS, penalized linear, and gradient-

boosted trees, confirms that the role of sustainability is intrinsic to the data-generating process rather than it is modeling choice. Empirically, all results imply that ESG integration can improve the forecastability and stability of financial systems, particularly under conditions of stress. Theoretically, they position ESG as a state variable embedded in market risk architecture, shaping conditional distributions through feedback and adaptation mechanisms.

The empirical study in chapter 3 allows for comparing model outputs across different methodologies applied in this dissertation. At the asset-pricing level (Section 3.1), Fama-MacBeth regressions reveal that neither static nor dynamic ESG factors yield statistically meaningful premia once conventional risk factors are controlled. This outcome implies that investors do not demand systematic compensation for ESG exposure, consistent with the equilibrium view that only risks linked directly to aggregate consumption or investment opportunities earn premia. Nonetheless, the negative ESG-market interaction terms indicate that sustainability modifies the covariance structure of returns, functioning as a conditioning rather than pricing variable.

Within the volatility dimension (Section 3.2), heterogeneous autoregressive (HAR) and Kalman-filtered models establish that ESG substantially reduces persistence of volatility across short-, medium-, and long-term horizons. The effect remains robust under endogeneity correction, extended lags, and subsample divisions, revealing that ESG operates as an endogenous volatility dampener. In the tail domain (Section 3.3), extreme-value and quantile regressions show that ESG significantly mitigates the probability and severity of extreme losses, particularly during systemic crises. This result is not confined to single regimes or data providers, confirming that sustainability attributes have structural implications for the tail behavior of returns. The machine-learning verification (Section 3.4) adds a predictive dimension, as models incorporating ESG variables consistently achieve higher out-of-sample accuracy. Ensemble learners (XGBoost) reduce mean-squared prediction errors by roughly one-third relative to econometric baselines. The subsequent SHAP interpretability demonstrates that ESG-market interaction not only ranks among top predictors but exerts a negative marginal effect on risk forecasts, precisely in line with econometric intuition.

The dissertation illustrates the value of hybrid modeling by integrating econometric transparency with machine-learning flexibility to address complex financial phenomena where linear assumptions fall short. Convergence of inference-based and prediction-based evidence provides an exemplar for future empirical finance research that seeks both

interpretability and adaptability. In conceptual terms, the study results contribute to an evolving view of sustainability not as an exogenous constraint but as an endogenous determinant of market stability. ESG considerations shape the memory, sensitivity, and tail behavior of financial systems, linking micro-level corporate conduct with macro-level systemic resilience. In this sense, sustainability transcends the boundaries of ethical investment and becomes a measurable component of financial architecture. The cumulative empirical evidence from Chapter 3 is summarized in Table 32 on the next page of the dissertation.

Table 32. Summary of Empirical Findings

<i>Analytical Stage</i>	<i>Model</i>	<i>Core Finding</i>	<i>ESG Effect Direction</i>
3.1 Asset Pricing	Fama-MacBeth (ICAPM)	ESG not priced in cross-section of returns	Neutral (Non-significant)
3.2 Volatility Persistence	HAR & Kalman Filter	ESG reduces volatility persistence across horizons	Negative (Stabilizing)
3.3 Tail Risk	EVT-GPD & Quantile Models	ESG lowers magnitude and frequency of extreme losses	Negative (Stabilizing)
3.4 ML Validation	Lasso/EN & XGBoost Forecasts	ESG improves predictive accuracy for volatility and tail risk	Negative (Stabilizing)
3.4-3 Interpretability	SHAP Decomposition	ESG-market interaction provides negative SHAP impact on risk predictions	Negative (Stabilizing)

Source: Author's own.

Chapter 4. Economic Interpretation

The combination of empirical findings across asset-pricing, volatility, and tail-risk dimensions yields a comprehensive economic interpretation of sustainability's role within financial markets. The results indicate that ESG does not reallocate risk in a zero-sum manner among market participants; rather, it systematically reduces aggregate market uncertainty. The pattern observed across multiple econometric and machine-learning specifications reveals sustainability serving as an endogenous stabilizer embedded in the financial system. This stabilizing capacity emerges not as a transitory or episodic phenomenon but as a structural feature through intertemporal adjustments in expectations, portfolio composition, and institutional behavior.

Consistently negative association between ESG and volatility persistence implies that markets with greater sustainability orientation exhibit more predictable return dynamics and diminished tendency for crises spreading over time. From an economic standpoint, this signifies an increase in the efficiency of information assimilation and a reduction in behavioral disturbance. When firms maintain transparent disclosure practices and credible governance standards, informational asymmetry also decreases. It allows the market prices to reflect fundamentals more efficiently and to reduce the persistence of noise-induced volatility. The integration of ESG principles does not merely reflect ethical or normative motivations. It alters about statistical properties of market behavior in ways enhancing allocative efficiency.

At the micro level, the influence of ESG is realized through firm-specific relationships such as improved governance oversight, enhanced reputational capital, and strategic alignment with long-term stakeholder interests. These features translate into reduced exposure to idiosyncratic shocks and lower default probabilities. At the macro level, the aggregated impact is reflected as lower volatility persistence and thinner return tails across the equity market and indicates a systemic reduction in uncertainty. Such cross-scale coherence between micro behavior and macro stability defines sustainability as a unifying concept in modern financial economics. Thus, ESG can bridge firm-level microstructure with systemic dynamics of risk spread.

The inclusion of latent ESG state derived via Kalman filter expands the limits of financial modeling and demonstrates that sustainability is a measurable and persistent factor influencing the second-moment behavior. The Kalman-filtering approach reveals continuous adaptation of ESG to evolving regulatory and macroeconomic environments.

It reinforces the notion of sustainability represented with a dynamic state variable rather than static firm characteristics. Integrating the latent sustainability state into multi-factor asset-pricing framework enriches the understanding of how time-varying risk premia evolve in response to non-financial variables. Such methodological innovation challenges the traditional separation between ethical finance and quantitative modeling, positioning ESG as econometrically tractable dimension of systemic risk.

The economic interpretation in this dissertation connects micro-level behavioral adjustments, investor dynamics, and macro-level systemic resilience into solid theoretical narrative. Multi-method empirical results, obtained in rolling regressions, demonstrate that ESG enhances the second-moment efficiency and reduces volatility persistence with tail-risk exposure by leaving returns (the first-moment measures) statistically unaffected. In essence, ESG improves quality and stability of risk allocation rather than alters expected reward from risk-taking. This distinction can be used to support the conceptual framework of sustainability finance as stabilizing force within modern capital markets.

From financial and economic perspectives, the study outcomes imply that capital markets internalize sustainability primarily through volatility and covariance channels and through price premia. The related mechanism aligns with conditional asset-pricing theory, where expected returns are the function not only of systematic risk exposure but also of evolving state variables governing market volatility. ESG serves as the conditioning variable by moderating the responsiveness of asset prices to shocks. Research findings across econometric, volatility-based, and extreme-value frameworks support the interpretation established for ESG as of determinant for the second-moment efficiency rather than for equilibrium mean returns.

4.1 Risk Without Return

The empirical evidence indicating that ESG exposures fail to earn a statistically significant premium in U.S. equity markets has important implications for both investors and corporate issuers. For investors, the absence of excess returns means that ESG cannot be regarded as a systematic alpha-generation strategy once conventional risk factors, including market, size, and value, are controlled. However, the observed decline in volatility persistence and tail-risk exposure among high-ESG firms demonstrates that sustainability reshapes the distribution of returns even in the absence of a pricing premium. This finding introduces a crucial nuance, as ESG does not alter expected returns (the first moment). It materially affects the variance and kurtosis (the second and fourth moments)

of return distributions, leading to smoother intertemporal consumption and lower downside exposure.

In intertemporal terms, the dampened volatility persistence corresponds to a reduced variance of expected future consumption, enabling investors to maintain smoother wealth trajectories through business cycles. Investors facing stochastic opportunity sets exhibit decreasing marginal utility of wealth. They are willing to accept slightly lower expected returns in exchange for diminished consumption volatility. Findings of Value-at-Risk (VaR) improving from - 3.57 to - 3.42 (\downarrow 4.2 %) and Expected Shortfall (ES) narrowing from - 4.93 to - 4.48 (\downarrow 9 %) at the 1 % confidence level, translate into \approx 22 % reduction in extreme losses during market stress. Simultaneously, the heterogeneous autoregressive (HAR-RV) model reveals \approx 13 % decline in volatility persistence (adj. $R^2 \approx 0.68 \rightarrow 0.66$), confirming the robustness of this effect across temporal horizons.

From the standpoint of utility maximization, such reductions in the second-moment uncertainty enhance investor welfare by lowering the expected disutility associated with consumption shocks. Utility gain arises even in the absence of higher mean returns, implying that ESG delivers welfare-improving risk characteristics rather than speculative profit opportunities. Such insight reconciles the continued growth of sustainable investment strategies with the absence of consistent alpha. ESG portfolios appeal not because they outperform in calm markets, but because they underperform less severely during crises, delivering superior utility-adjusted outcomes over the full cycle.

For asset managers, this dynamic reframes portfolio optimization. In a mean-variance framework, the inclusion of ESG-aligned assets shifts the efficient frontier by reducing portfolio variance rather than increasing expected return. Investors benefit through improved Sharpe ratios and lower drawdown probabilities, outcomes that traditional alpha-centric interpretations overlook. In this sense, ESG exposure functions analogously to hedge. Its value emerges conditionally, when volatility and tail risks spike, thereby preserving capital.

On corporate side, the absence of return premia signifies that capital markets do not automatically reward sustainability initiatives with lower costs of equity. Firms cannot rely on ESG disclosure alone to secure valuation premiums in the U.S. context. Instead, their incentive stems from the stabilizing effect observed empirically. Stronger ESG profiles correspond to greater resilience during crises, lower financing constraints and reduced reputational vulnerability. This pattern suggests that ESG investment represents a form of *risk-management capital*, enhancing long-term survival probability rather than

delivering immediate valuation gains. During systemic downturns, high-ESG firms exhibit lower default intensities and face less severe liquidity pressures, confirming that sustainability enhances financial robustness.

The neutrality of ESG premia highlights a broader equilibrium insight consistent with conditional pricing theory. Market participants internalize sustainability not through return compensation but through adjustments in risk-bearing capacity. Intertemporal consumption models explain this behavior as a reallocation of marginal utility across states of the world. ESG reduces the marginal utility risk associated with adverse market states by stabilizing wealth trajectories. Such attenuation of risk translates into thinner tails and lower volatility persistence empirically. Investors rationally value such stability even if it does not manifest as higher expected return.

Empirical evidence supports theoretical reasoning, as consistently negative coefficient on ESG-market interaction term ($\beta = -0.010$, $t = -2.11$, $p = 0.03$) indicates that ESG decreases shock waves through the financial system, corresponding to ≈ 10 bps reduction in conditional market sensitivity per 1 SD ESG increase. In macro-financial terms, this finding represents the *second-moment efficiency improvement*. The conditional variance responds less aggressively to sustainability information, and volatility becomes less sticky. This adjustment enhances market predictability and reduces welfare losses associated with uncertainty shocks.

The persistence of ESG's dampening effect across quantiles and subsamples strengthens the argument that sustainability introduces an endogenous stabilizing mechanism into financial systems. Firms with higher ESG scores exhibit smoother volatility transitions, functioning as stabilizing anchors during uncertainty. This behavioral asymmetry aligns with heterogeneous-agent models in which investors disproportionately favor firms perceived as credible and transparent when risk aversion rises. The result is a self-organization of market expectations around sustainable firms, lowering the likelihood of coordination failures and panic-driven trading.

Kalman-filtered ESG factor provides smoothed trajectory of its latent state, which rises following major regulatory and policy milestones, by reflecting the gradual institutionalization of sustainability as a component of market information. ESG operates through HAR model at weekly, monthly and quarterly horizons and captures the stabilizing influence of sustainability. The empirical subsample results during COVID-19 shock illustrate that under systemic stress, ESG coefficients remain negative and

significant. Sustainability dampens idiosyncratic and systemic volatilities through its linkage with financial stability.

The stabilizing role of ESG appears to function through interconnected micro-level mechanisms that enhance firm-specific resilience. Companies with strong ESG performance typically maintain higher governance quality, transparent disclosure practices, and stronger stakeholder relationships, which collectively mitigate exposure to operational and reputational shocks. Empirically, this is reflected in lower volatility persistence and thinner downside tails for high-ESG portfolios, as reported in the HAR and EVT estimations. These outcomes suggest that ESG acts as an internalized form of risk management, allowing firms to maintain valuation stability even under systemic stress. By promoting responsible conduct and adaptive management structures, ESG reduces the likelihood that firm-specific vulnerabilities translate into market fragility.

ESG contributes to systemic stability by reshaping market interdependencies and influencing aggregate capital flows at the macro-financial level. The adoption of sustainability encourages investment toward more transparent and financially sound firms, which collectively dampens sectoral volatility and weakens contagion channels. The lower tail index values observed for ESG-oriented portfolios indicate a reduction in joint downside risk across the market. Furthermore, regulatory frameworks such as the EU taxonomy and SEC disclosure standards enhance information symmetry, improving the market's capacity to absorb shocks efficiently. Together, these effects generate a reinforcing loop where firm-level stability aggregates into systemic robustness, though excessive similarity in ESG strategies could introduce new concentration risks.

4.2 Financial Market Stability

The stabilizing role of ESG identified at the firm and portfolio levels acquires deeper economic significance when viewed through the lens of overall financial-market functioning. Volatility persistence and tail risk are not merely statistical descriptors. They represent the essential elements through which idiosyncratic disturbances are amplified into systemic disruptions. The empirical evidence presented throughout the dissertation demonstrates that ESG systematically weakens both risk vectors. Markets populated by firms with high sustainability alignment display lower volatility autocorrelation ($\approx 13\%$ reduction in persistence) and shallower loss tails ($\approx 9\%$ thinner ES), implying that shocks lose their momentum more quickly and that their cumulative macro impact diminishes. This phenomenon has fundamental economic implications. It means that sustainability

operates as a structural friction within the recursive feedback processes that normally cause localized shocks to escalate into market-wide crises. The finding that ESG reduces volatility persistence by $\approx 13\%$ and tail losses by $\approx 9\%$ (ES-based) is therefore more than a statistical observation. It reveals a mechanism of endogenous stabilization that lowers the aggregate cost of financial instability.

In financial markets characterized by nonlinear feedback, the macroeconomic cost of crises grows disproportionately with their intensity and duration. Even modest reductions in the probability or depth of negative events can translate into substantial welfare gains. When sustainability weakens volatility clustering, it limits the compounding of leverage adjustments, margin calls, and liquidity withdrawals that often accompany stress episodes. In this respect, ESG resembles a market-based form of insurance, which is silent during normal times and invaluable in turbulence. Its benefits accrue collectively rather than individually, producing a positive externality analogous to public good. Every participant in the market, whether or not they directly invest in ESG assets, gains from the reduced systemic fragility generated by the presence of sustainable entities whose trading behavior and disclosure discipline absorb shocks instead of transmitting them. This collective stability, however, is inherently underprovided because the benefits are diffuse while the costs of maintaining high ESG standards are borne privately. Without coordination through regulation or incentive alignment, the market equilibrium will exhibit suboptimal levels of sustainability, just as private actors tend to underinsure against systemic risk in the absence of policy mandates.

From a theoretical standpoint, the stabilizing power of ESG can be understood through its impact on the variance-covariance structure of asset returns. When high-ESG firms experience smaller variance and lower covariance with market factors during crises, the aggregate covariance matrix of the market portfolio becomes more diagonally dominant. This structural transformation reduces the potential for disturbance and synchronizes volatility decay across sectors. In essence, ESG compresses the eigenvalue spectrum of market covariance, signaling a reduction in systemic concentration of risk. The corresponding economic interpretation is that sustainability enhances the dimensionality of diversification by reducing co-movement rather than simply redistributing volatility. All investors benefit from this reconfiguration because shocks remain more idiosyncratic and less prone to market-wide transmission.

The policy implications are equally pronounced. By lowering volatility persistence, ESG reduces the likelihood that transient shocks evolve into liquidity crises requiring

external intervention. Central banks and regulators therefore face lower probabilities of engaging in extraordinary stabilization measures such as emergency lending or quantitative easing. The macroeconomic saving associated with reduced crisis frequency can be substantial even if the individual firm-level effects appear modest. Systemic event with probability declining from 5 to 3 percent as a result of enhanced sustainability practices would represent a 40-percent reduction in expected crisis incidence. This translates into enormous fiscal and welfare benefits once aggregated across the markets and financial system. Such indirect effects underscore why ESG should be conceived as macro-level stabilizer rather than as micro-level, firm's attribute.

Empirical evidence of ESG's role as implicit market stabilizer parallels theoretical constructs of self-organization in complex adaptive systems. Financial markets, like other nonlinear networks, display emergent order when agents adopt behaviors that dampen feedback intensity. High-ESG firms, through long-horizon orientation, improved governance, and credible disclosure, function as such damping agents. Their stability is spread-out through counterparties, supply chains, and investor networks, gradually reducing the amplitude of systemic oscillations. Over time, the sustainability dynamics produces market environment characterized by shorter volatility cycles and smaller collective drawdowns. These features were empirically observed with Kalman-filtered trajectories of volatility persistence estimated in Chapter 3. By moderating both micro- and macro-volatility, ESG establishes invisible but measurable architecture of stability that reshapes temporal properties of risk transmission.

Another dimension of market stability pertains to the cost of capital and credit-spread dynamics during crises. The dissertation's findings imply that firms with stronger ESG profiles maintain lower perceived default probabilities and hence tighter credit spreads under stress. These micro-financial advantages aggregate into more stable funding environment for the corporate sector as a whole. In systemic downturns, when liquidity evaporates and credit channels contract, the relative robustness of high-ESG borrowers cushions the feedback loop between equity volatility and credit risk. Consequently, the overall market experiences less synchronized deleveraging and milder crisis. This stabilizing mechanism complements the earlier evidence on volatility persistence by extending the benefits of sustainability beyond equity markets into the debt and funding domains, strengthening the case for viewing ESG as a cross-asset stabilizer embedded within financial intermediation.

The interaction between ESG and investor expectations plays an important role in preserving market coherence. During uncertainty, investors rely on information quality to coordinate beliefs about future states of the world. Firms with credible ESG disclosures reduce informational uncertainty, enabling investors to form more accurate priors and limiting the scope for panic or speculative herding. The resulting convergence of expectations acts as a macro-level alignment mechanism that curtails mispricing and liquidity spirals. The dissertation's finding that ESG's influence is strongest during crisis subsamples, in particular in the first half of 2020, provides empirical validation of this theoretical link between information precision and systemic coherence. Here, sustainability acts as reputational source keeping expectations tethered to fundamentals when exogenous shocks threaten to destabilize markets.

The stabilizing function of ESG also carries implications for market microstructure and transmission of monetary policy. Lower volatility persistence implies reduced uncertainty premiums and narrower bid-ask spreads, which in turn may improve liquidity and trading efficiency. When aggregate volatility is less sticky, central-bank signals can be transmitted more effectively through asset prices because noise is less likely to distort the channel between policy rates and risk premiums. ESG adoption thus enhances efficiency of monetary policy indirectly, by fostering market environment where information flows are clearer and investor reactions are proportionate.

At systemic level, the combined effect of the discussed sustainability channels is leading to attenuation of crisis potential. Markets with greater ESG penetration exhibit lower cross-asset correlation spikes during crises, suggesting that the presence of sustainable firms introduces heterogeneity in investor responses and moderates synchronized selling. The empirical patterns observed in tail-risk regressions, where high-ESG portfolios suffered ≈ 22.3 % smaller losses relative to market portfolios, consistent with empirical results in chapter 3, illustrate this phenomenon. The decline in cross-sectional correlation during stress implies that ESG functions as correlation stabilizer and dilutes systemic interdependence by limiting scale of drawdowns.

The research evidence from this dissertation transforms interpretation of ESG from normative investment into quantifiable economic stabilizing. ESG reduces volatility persistence by ≈ 13 % (HAR-RV model), compresses tail-risk exposure by ≈ 9 % (ES metric), and decreases tail-thickness by ≈ 68 % (EVT-GPD ξ parameter). The test coefficients demonstrate that sustainability enhances the second-moment efficiency and systemic stability without affecting the first-moment returns ($\beta \approx 0.0012$, $p = 0.28$). The

study results indicate that sustainability integration may dampen self-reinforcing mechanisms of volatility and crisis driving systemic risk. ESG generates multidimensional efficiency gains across microstructure, portfolio, and macro-prudential levels through its ability to lower volatility persistence, compress tail exposure, and reduce correlation spikes. Such transformation does not increase expected returns but enhances welfare through reduced uncertainty, lower crisis frequency, and improved market coherence. The following section extends these implications to domain of incentives and public policy by addressing how private stabilization benefits can be internalized and amplified through regulatory design.

4.3 ESG Incentives and Policy

The divergence between the private incentives that guide individual firms and investors and the collective benefits that sustainability generates for the broader financial system presents one of the most significant challenges for modern economic governance. Empirical evidence from this dissertation shows that ESG integration yields systemic stability gains, including lower volatility persistence and thinner tail distributions, but these gains are not directly priced by the market. In the absence of a measurable return premium, private agents underinvest in sustainability relative to the social optimum. The latter suffers from coordination failure similar to what historically would require regulations. Such gap between private and social value provides foundational economic rationale for ESG policy intervention. The voluntary market mechanisms alone are unlikely to internalize externalities associated with systemic resilience and demand the design of institutional frameworks aligning micro-level behavior with macro-level stability objectives.

In the United States, where ESG disclosure practices remain fragmented and politicized, markets have not produced consistent pricing premia for sustainability, even though the empirical evidence confirms that ESG dampens systemic fragility. By contrast, European markets operating under harmonized regulatory standards have exhibited mild ESG premia and more stable funding conditions. This cross-jurisdictional divergence illustrates that the market's ability to recognize and capitalize systemic benefits depends heavily on the informational environment. Under the global ESG disclosure, volatility persistence falls from $\text{adj. } R^2 \approx 0.68$ to 0.66, reflecting enhanced informational efficiency. When disclosure is standardized, comparability increases, and investors can differentiate between genuine sustainability performance and superficial signaling. Consequently,

capital allocation becomes more efficient, and ESG's stabilizing properties are more fully internalized. The implication is that regulation functions to enhance sustainability signal's precision and allows emergence of its true economic value - risk-mitigating capacity - to be reflected in stock market prices.

The conditional nature of economic value offered by ESG is central to understanding why private incentives often fall short. During tranquil market periods, volatility persistence is low, tail risk subdued, and the marginal utility of stability is small. Under these circumstances, sustainability initiatives appear economically irrelevant, and firms perceive limited justification for the costs of ESG disclosure and compliance. However, during systemic episodes such as the COVID-19 collapse, downside losses narrow by $\approx 9\%$ (ES metric), volatility transmission weakens by $\approx 13\%$, and capital preservation improves significantly. Thus, ESG behaves like catastrophe insurance, when premiums are paid continuously, and benefits manifest only under extreme conditions. Because such benefits are realized precisely when marginal utility is highest and when systemic capital destruction threatens the economy, ESG's social value exceeds its private market valuation. Such asymmetry provides very strong economic interpretation of sustainability's role and explains why investors persist in ESG integration despite any absence of cross-sectional alpha.

Empirical and theoretical findings of this dissertation yield several policy implications. First, the stabilizing influence of ESG supports the incorporation of sustainability metrics into macroprudential oversight and financial-stability frameworks. Regulators increasingly view non-financial indicators as forward-looking measures of systemic resilience. The observed dampening of volatility persistence and tail exposure indicates that broad ESG adoption could serve as a decentralized form of market discipline, complementing formal capital and liquidity requirements. By rewarding transparent and resilient firms with lower perceived risk premiums, markets would, in effect, self-regulate toward stability. Policymakers can reinforce this dynamic by mandating standardized disclosure, harmonizing reporting taxonomies, and integrating ESG data into supervisory stress tests. These actions would transform sustainability metrics from optional corporate signals into integral components of financial-stability assessment.

Second, the evidence that high-ESG firms experience smaller tail losses and faster volatility dissipation justifies the inclusion of sustainability variables in institutional stress-testing regimes. ESG scores, when correlated with crisis performance, can operate

as supplementary buffers within macro stress models, indicating which sectors are structurally more resilient to adverse shocks. Central banks and supervisory authorities could employ ESG-adjusted parameters in their systemic-risk simulations, allowing for finer differentiation between transient liquidity pressures and fundamental solvency risks. This approach extends beyond the purely ethical dimension of ESG to position it as a measurable determinant of financial robustness. By embedding ESG in stress-testing architecture, policymakers would enhance the predictive accuracy of their models and preemptively identify vulnerabilities tied to low-sustainability exposure.

Third, institutional investors, particularly pension funds, insurance companies, and sovereign wealth funds, may stand to gain strategically from treating ESG as a risk-control factor rather than as a thematic allocation. Since the dissertation's results show that ESG exposure mitigates both volatility persistence and extreme downside losses, portfolios constructed with higher sustainability weights can achieve equivalent expected returns at lower variance, improving their risk-adjusted efficiency. In risk-parity and volatility-targeting frameworks, ESG functions as a structural lever that allows managers to balance exposures dynamically without sacrificing expected performance. For long-horizon investors, this property is economically valuable: it enhances capital preservation, reduces drawdowns, and aligns asset-liability profiles with smoother funding trajectories. As such, ESG's practical utility extends beyond ethical branding, providing a quantitative rationale for its integration into modern portfolio-construction algorithms.

Fourth, the systemic benefits of ESG justify its recognition as a macro-financial public good. Because stabilization effects accrue collectively, the equilibrium level of sustainability adoption will remain suboptimal absent policy coordination. Governments and regulators therefore face challenges alike the provision of liquidity backstops or deposit insurance, which are individually irrational but socially necessary activities. Incentive alignment can take multiple forms - tax advantages for certified sustainable issuers, risk-weight adjustments in capital regulation, or reduced supervisory fees for institutions with robust ESG governance. Each mechanism internalizes part of the externality by rewarding behaviors that reduce systemic risk.

The stabilizing role of ESG also carries implications for fiscal and industrial policy. Government agencies tasked with infrastructure investment and innovation funding can incorporate sustainability metrics into capital-allocation criteria, prioritizing projects that exhibit stronger governance, environmental, or social safeguards. By channeling public resources toward high-ESG sectors, policymakers can reinforce the private-sector trend

toward resilience, generating a virtuous cycle in which sustainable enterprises attract cheaper capital and deliver lower systemic volatility. This macro-fiscal linkage demonstrates that financial and real-economy dimensions of sustainability are interdependent. The improved corporate governance reduces market fragility, and public policy, encouraging sustainability, increases private stability gains.

Furthermore, empirical findings of the dissertation suggest that benefits of ESG adoption are contingent on data integrity and comparability. Without credible, timely, and standardized information, the feedback loop between sustainability performance and market stability weakens significantly. Therefore, policy design should emphasize transparency as the cornerstone of ESG regulation. Calibration of disclosure frequency, assurance standards, and data accessibility directly determines the efficiency of sustainability as stabilizing mechanism. When data quality is high, market participants can reliably differentiate between resilient and vulnerable firms, aligning capital flows with systemic soundness. Conversely, fragmented disclosure regimes foster green-washing, eroding confidence and neutralizing ESG's stabilizing potential. The macroeconomic implication of the described processes is that informational infrastructure, and not investor sentiment, governs the effectiveness of sustainable finance as a policy lever.

The comparison between the U.S. and European regulatory contexts further illustrates how institutional design shapes outcomes. In Europe, where ESG reporting is mandatory and verified through third-party auditing, systemic volatility measures display smoother trajectories and narrower dispersion across sectors. The correlation between ESG intensity and reduced market-wide volatility persistence provides quantitative support for the argument of standardized disclosures enhancing resilience. In contrast, the U.S. system's reliance on voluntary and often inconsistent reporting undermines investor confidence and contributes to higher noise levels in asset prices. This heterogeneity explains why ESG premia remain elusive in the American market despite similar micro-level stabilizing effects. The policy conclusion is clear - sustainability requires institutional scaffolding to translate micro-economic benefits into macro-financial outcomes.

Finally, by reframing ESG as an integral component of financial-stability architecture, policymakers can transcend the false dichotomy between profit maximization and ethical responsibility. The empirical evidence that ESG weakens volatility persistence and tail exposure establishes its relevance for central banks, supervisory agencies, and ministries of finance concerned with systemic risk. Incorporating sustainability metrics into prudential policy transforms them from moral indicators into operational variables of

risk management. This reconceptualization has far-reaching consequences, as it legitimizes the inclusion of ESG factors in capital-adequacy frameworks, risk-weight calibration, and dynamic provisioning rules. Far from imposing external constraints, such measures would enhance market efficiency by pricing stability appropriately. When sustainability becomes endogenous to the financial-policy toolkit, the resilience it generates ceases to be accidental and becomes a deliberate attribute of the system.

In summary, the empirical evidence and theoretical reasoning presented here converge on a unified conclusion - ESG creates macro-financial stability benefits exceeding private returns and necessitating regulatory coordination to internalize the externality. Authorities can transform ESG from a voluntary norm into a measurable pillar of systemic resilience by embedding sustainability in disclosure standards, stress testing, institutional portfolio construction, and macroprudential policy. The outcome may be financial architecture in which pursuit of long-term value and preservation of stability are mutually reinforcing objectives. Such vision can form the conceptual bridge to final analytical section, providing ESG's hedge-like influence on the systemic risk transmission and the macro-financial interconnectedness.

4.4 ESG and Systemic Transmission

Stabilizing properties of ESG are observed at the firm and portfolio levels. They extend naturally into macro-financial sphere, where risk transmission occurs through correlated asset exposures and behavioral synchronization characterizing modern financial systems. In markets such as the United States, where institutional investors, derivatives linkages, and algorithmic trading are combined to create high degrees of interdependence, localized shocks rarely remain isolated. They cascade through liquidity channels, margin calls, and collective portfolio adjustments by transforming minor perturbations into system-wide disturbances. The empirical findings of this dissertation, specifically the persistent negative coefficients of the ESG-market interaction ($\beta \approx -0.013$, $p < 0.10$) in volatility and tail-risk models, suggest that sustainability attributes alter this transmission mechanism itself. By moderating the intensity of firm-level shocks, ESG acts as a form of friction or "shock-absorption layer" within the financial network, reducing both the amplitude and the frequency of crisis days through $\approx 13\%$ lower volatility persistence and $\approx 68\%$ thinner loss tails. In doing so, it converts sustainability from a micro-ethical choice into a macro-structural determinant of system behavior.

At the core of systemic transmission lies the interplay between idiosyncratic

disturbance and collective amplification. During market stress, rational investors confronted with uncertainty often respond homogeneously, liquidating similar assets, withdrawing liquidity, or shifting into safe havens. While individually prudent, these actions generate correlated flows that amplify aggregate volatility. The lower volatility persistence exhibited by high-ESG firms, as identified through heterogeneous autoregressive models, implies that sustainability weakens the recursive feedback loop. The latter links short-term shocks to long-term volatility clusters. Firms characterized by credible governance, transparent disclosure, and strong social legitimacy experience smaller price reactions to shocks and recover more quickly, thereby interrupting the transmission chain. Their stability influences peer behavior by providing reference points for valuation and risk assessment, leading to a partial desynchronization of panic responses across the market. In this sense, ESG functions as an internal circuit-breaker in the system's feedback architecture, reducing the synchronization parameter that drives collective amplification.

Firms with strong ESG credentials maintain higher reputational capital, more diversified investor bases, and greater access to liquidity facilities. During systemic tightening, these characteristics mitigate funding stress by preserving credit lines and investor confidence. Because high-ESG firms are perceived as lower-risk borrowers, they may experience smaller increases in credit spreads and fewer collateral haircuts, which in turn stabilizes their equity valuations. Aggregated across industries, such micro-level resilience attenuates the financial accelerator mechanism that otherwise magnifies downturns. Reduced feedback between declining asset prices and contracting credit effectively flattens the macro-financial transmission curve. The result is a distributed form of stability in which sustainability diffuses through funding channels, moderating the amplitude of business-cycle fluctuations.

From a macroprudential perspective, these empirical and theoretical insights bridge sustainability finance with financial stability policy. The same statistical properties that regulators monitor when assessing systemic risk, including volatility persistence, tail-dependence, and cross-correlation, are precisely those that ESG modifies. Institutions such as the European Central Bank, the Bank of England, and the Federal Reserve increasingly acknowledge that climate and sustainability variables influence the resilience of the financial system. However, the most existing frameworks treat them as exogenous shocks rather than endogenous determinants. The evidence presented in this dissertation challenges such view. Incorporating ESG-weighted volatility persistence or ESG-adjusted

VaR parameters into stress-testing models can improve predictive accuracy and better capture the dynamic interplay between sustainability and systemic risk. In practical terms, it means that capital requirements and provisioning rules may be calibrated to reflect the empirical stabilizing effect of sustainability, transforming ESG from a moral consideration into a quantifiable policy variable. Capital surcharges for low-ESG institutions or preferential treatment for high-ESG borrowers should no longer represent normative choices but empirically grounded adjustments aimed at minimizing the probability of systemic crises.

The role of ESG in reducing risk is not just about numbers, it also affects how people think and behave in financial markets. Markets are shaped by both hard data and expectations or stories investors tell themselves. When sustainability information is clear, trustworthy, and widely available, it helps investors better understand risks and resilience, which keeps confidence steadier even in uncertain times. Good ESG disclosures, especially those about governance and environmental readiness, provide reliable information that cuts through confusion and keeps investors' views more aligned. Such shared understanding helps prevent herd behavior and reduces the emotional ups and downs that often drive financial crises. Hence, ESG supports what could be called "knowledge stability" - transparency and shared information reducing the fear and overreaction that come with market stress. The negative ESG-market interacting variable coefficients in volatility and tail-risk studies back this proposition by showing that clear information and strong governance lead to calm and stable investor behavior.

Another layer of the systemic transmission mechanism involves technological and algorithmic dimensions of modern trading. Automated strategies often respond to volatility and correlation thresholds, intensifying market swings once these thresholds are breached. By reducing volatility persistence and moderating correlation spikes, ESG indirectly delays such threshold crossings, giving markets time to absorb information and adjust positions more gradually. This temporal smoothing of algorithmic responses further contributes to systemic resilience. Sustainability interacts with digital market microstructure and influences shocks transmitted in high-frequency environments.

Beyond the boundaries of finance, implications of sustainability extend to macroeconomic policy and global governance. If ESG reduces systemic transmission and lowers crisis probability, then it can be understood as a form of preventative macro-stabilization analogue to public-health or environmental protection spending. It is costly in the short run but welfare-enhancing over the long time. Governments could therefore

justify support for ESG adoption on the same grounds that they justify infrastructure or social-safety-net investments, namely as expenditures raising the economy's resilience frontier. International coordination may become crucial, since financial crises transcend borders. The stabilizing effect of ESG in one jurisdiction can be undermined if major counterparties operate under weaker governance standards. Hence, there is a need for global harmonization of sustainability disclosure and supervision.

In conclusion, the analysis of systemic transmission underscores the central thesis of this dissertation - ESG operates as a self-reinforcing stabilizer within financial systems. It reduces the persistence and co-movement of volatility, fortifies credit and funding channels, and aligns informational structures in ways that prevent collective breakdowns. Through these intertwined mechanisms, sustainability transforms from a descriptive label into a functional property of resilient financial architecture. Markets endowed with strong ESG foundations exhibit lower systemic temperature, faster post-shock normalization, and greater resistance to disturbance. The convergence of micro-stability and macro-resilience achieved through sustainability integration reveals that the pursuit of ethical and financial objectives is not contradictory but mutually constitutive. ESG, in its economic essence, represents a form of endogenous risk governance. It provides dynamic equilibrium mechanism through which markets evolve toward stability, transparency, and long-term efficiency.

Chapter 5. ESG Global Integration

This chapter expands the analytical scope of the dissertation from the domestic financial system to a broader, global dimension by introducing a dynamic, comparative perspective on the integration of Environmental, Social, and Governance (ESG) principles into capital markets. It develops a framework grounded in state-space econometrics, applying a Kalman filter methodology to model time-varying interactions between the U.S. S&P 500 ESG index and a latent Global ESG factor derived from international data. This methodological innovation enables the examination of how global sustainability information affects the volatility structure of U.S. financial markets. It extends findings in the prior chapters on the stabilizing role of ESG from single-market's disclosure context to an interconnected global setting characterized by regulatory harmonization and informational convergence.

The underlying premise of this analysis is that financial relevance of ESG factors cannot be fully understood within the confines of single jurisdiction. As global markets become increasingly interlinked through capital mobility, shared disclosure standards, and transnational flow of information, the influence of ESG integration extends across borders and shapes systemic behavior in ways that transcend domestic policy environments. The United States, which functions as the benchmark market in this dissertation, due to its scale, liquidity, and global signaling role, remains largely governed by voluntary, principles-based disclosure regime. In contrast, other major jurisdictions, including the European Union, Japan, and parts of the Commonwealth, have transitioned toward mandatory, rules-based ESG reporting standards. This divergence in disclosure frameworks generates a natural experimental setting that allows the study to test whether the stabilizing mechanisms of ESG identified in earlier chapters are contingent upon regulatory structure or it is universal in nature.

The latent Global ESG factor introduced in this chapter represents a synthesized, evolving measure of international sustainability sentiment and disclosure quality. Constructed through a Kalman filtering process, it captures the unobserved common component underlying global ESG indices, including those published by MSCI, STOXX, and other transnational data providers. The latent factor reflects not only market performance but the informational integration of sustainability principles into financial valuation systems. By incorporating this variable into a dynamic interaction model with U.S. market indicators, the study empirically examines how global ESG developments

influence domestic volatility and systemic stability. This framework treats ESG not as an isolated or exogenous influence but as part of a transmission mechanism through which global information permeates local financial dynamics.

In this setup, the model does not attempt to directly explain global markets themselves; rather, it assesses the transmission channel linking global ESG information to the behavior of the U.S. market. This conceptual design rests on the recognition that financial systems operate within a shared informational infrastructure. Changes in disclosure norms, governance expectations, or regulatory enforcement abroad can affect investor sentiment, capital allocation, and risk perception domestically. As global ESG disclosure becomes increasingly standardized, the volatility sensitivity of U.S. markets is expected to decline, reflecting a deeper form of systemic resilience derived from transparency and comparability. The empirical findings of this chapter confirm that as global disclosure frameworks mature, volatility persistence in U.S. financial indicators weakens, and the probability of extreme downside events decreases. These results lend support to the central theoretical argument of the dissertation - ESG integration functions as a progressive macro-financial stabilizer, whose capacity strengthens in cooperation with the institutional convergence of sustainability standards across jurisdictions.

Viewed from an economic systems perspective, ESG integration can therefore be understood as a form of informational infrastructure that operates like traditional financial regulation. By standardizing disclosure, it reduces asymmetry, enhances coordination among investors, and embeds long-term expectations into price formation. The Kalman-filter approach employed here provides the methodological facility to track these developments dynamically, distinguishing transient reactions from structural adjustments. In essence, the model demonstrates how ESG evolves from a firm-level characteristic to a macro-financial variable, defining the volatility and stability of entire markets.

5.1 Global Context of ESG

The formal incorporation of ESG principles into the global architecture of financial governance represents one of the most significant institutional shifts in modern capital markets. Over the past two decades, sustainability has transformed into an integral component of financial policy, investment strategy, and macroprudential oversight. The global trajectory of ESG integration traces a clear pattern. It has begun with normative commitments articulated through voluntary investor coalitions and progressively advanced toward structured disclosure regimes and regulatory enforcement. This

evolution reflects growing consensus among regulators, institutional investors, and multilateral organizations about ESG disclosure being not peripheral but fundamental to the transparency, efficiency, and resilience of financial systems.

A defining milestone in this transformation was the launch of the United Nations Principles for Responsible Investment (UN PRI) in 2006, which articulated the first globally recognized framework embedding ESG factors into fiduciary responsibility. With over 5,000 signatories and approximately US\$120 trillion in assets under management, the UN PRI marked the institutionalization of sustainability as a mainstream investment concern. It shifted the discourse from ethical preference to financial materiality, framing ESG as a necessary input for long-term value creation and risk mitigation. This conceptualization re-defined investor duty itself, which has moved from narrow focus on returns to a broader stewardship responsibility encompassing environmental and governance outcomes (J. Wang et al., 2024).

The Task Force on Climate-related Financial Disclosures (TCFD), established in 2017 under the Financial Stability Board, constituted turning point in aligning sustainability reporting with financial risk management. Its four-pillar framework, including governance, strategy, risk management, and metrics and targets, provided the first consistent and globally recognized structure for assessing climate and sustainability-related financial materiality (Krueger et al., 2020; Arian & Sands, 2024). By encouraging firms to quantify and disclose the financial impacts of environmental risks, the TCFD transformed ESG from a qualitative narrative into a quantifiable, decision-relevant input. It also established the conceptual bridge between micro-level firm reporting and macro-level systemic stability, paving the way for sustainability information to be treated as a component of market discipline.

The establishment of the International Sustainability Standards Board (ISSB) under the IFRS Foundation in 2023 further institutionalized ESG adoption. The ISSB's release of the IFRS S1 and S2 standards unified previously fragmented frameworks, such as the SASB, TCFD, and GRI, into a single global baseline for sustainability disclosure (Van Den Hurk & Van Der Klooster, 2024). The ISSB elevated ESG disclosure to a level of formal regulatory recognition comparable to financial accounting through integration of sustainability reporting within the architecture of international accounting. Such consolidation not only enhanced comparability but also reduced reporting costs for multinational firms and improved cross-border capital efficiency.

In parallel, the Network for Greening the Financial System (NGFS), established in 2019, extended the reach of ESG integration into the domain of central banking and macroprudential regulation. Comprising over 130 central banks and supervisory authorities, the NGFS incorporated climate and sustainability data into systemic stress-testing frameworks and financial stability assessments (Dow & Shi, 2025). By embedding ESG variables into the toolkit of monetary and prudential oversight, the NGFS effectively recognized sustainability as a determinant of macro-financial risk, blurring the boundary between environmental policy and financial stability management (Table 33).

Table 33. Stages of global ESG integration

Year	Framework	Scope	Relevance to ESG-Financial Linkage
2006	UN Principles for Responsible Investment (UN PRI)	5,000+ signatories, US\$120 T AUM	Institutional adoption of ESG as fiduciary duty
2017	Task Force on Climate-related Financial Disclosures (TCFD)	100+ jurisdictions	Risk-based, forward-looking sustainability disclosure
2023	International Sustainability Standards Board (ISSB)	IFRS S1/S2 global baseline	SASB/TCFD/GRI merged within unified standards
2019 - present	Network for Greening the Financial System (NGFS)	130+ central banks	ESG/climate data integrated into macroprudential oversight

Source: Author's own based on UNPRI official documents:.

These successive initiatives collectively established a globally comparable ESG data infrastructure, one capable of linking corporate-level transparency with systemic financial resilience. However, despite the broad international convergence, a pronounced asymmetry remains between disclosure regimes. The United States continues to rely predominantly on a principles-based, voluntary reporting structure, with firms determining the scope and depth of their ESG communication. The most major economies within the European Union and other OECD jurisdictions have adopted mandatory, rules-based

frameworks such as the ISSB standards or the EU's Sustainable Finance Disclosure Regulation (SFDR). This divergence provides a natural empirical basis for examining the role of regulatory structure in mediating ESG's stabilizing capacity.

From a research perspective, the noted asymmetry transforms the U.S. market into a benchmark environment for studying market-driven ESG integration. In such a system, sustainability disclosure evolves organically from investor pressure, reputational incentives, and competitive differentiation rather than through statutory compliance. The latent Global ESG factor, by contrast, embodies the informational environment of markets where disclosure is formalized, standardized, and externally verified. This contrast allows for the empirical isolation of how information structure, voluntary versus mandatory, affects the spread of financial volatility and systemic stability.

The analytical framework employed in this chapter leverages this contrast through a Kalman-filter approach that measures how the latent global ESG signal transmits into the volatility structure of U.S. financial markets. Because ESG and market-wide conditions interact continuously, the empirical model focuses on the interaction term $F_{(Global,t)}^{(ESG*Mkt)}$, representing the compounded influence of global sustainability information and domestic market dynamics. The selected model specification captures economic channel through which global sustainability sentiment either amplifies or stabilizes U.S. market variance, depending on the prevailing disclosure regime.

The global context of ESG integration is studied with its transformation in U.S. financial system. Many traditional financial regulations focus on solvency, leverage, and liquidity, and ESG disclosure reforms address informational foundation upon which market expectations can be built. Standardization across jurisdictions may reduce uncertainty in firm behavior by aligning investor interpretations of risk and enhancing credibility of long-term commitments. The cumulative effect of these processes is not simple transparency but shift toward predictability and coordination - the conditions empirically described in this dissertation. Such effect manifests itself as lower volatility persistence and thinner stock return tails.

The next section, 5.2 ESG Dynamic Modeling, builds upon the above formalized context of empirical mechanism, where global sustainability information interacts with domestic financial dynamics. It develops a state-space examination to identify how ESG integration may evolve over time, enabling detection of structural transitions corresponding with major milestones in international disclosure harmonization.

5.2 ESG Dynamic Modeling

The stabilizing function of ESG factors within market volatility, first demonstrated in the context of the S&P 500 dataset, is expanded in this chapter to explore how that relationship evolves as sustainability disclosure becomes globally standardized and embedded within transnational financial regulation. While earlier analyses in the dissertation established that higher ESG ratings correlate with reduced volatility persistence at the firm and portfolio level, the present section extends the inquiry to assess how such effects evolve dynamically when exposure to global sustainability information is explicitly modeled. This approach allows for an understanding not only of the magnitude but also of the temporal evolution of ESG's impact and how it intensifies, stabilizes, or diminishes as international reporting regimes mature and converge.

The empirical strategy is constructed around a Kalman state-space framework, which provides an adaptable mechanism for estimating unobserved, time-varying factors that influence market behavior. Within this framework, the latent Global ESG factor, denoted $F_{(Global,t)}^{ESG}$, represents the evolving global sustainability signal derived from a composite of internationally standardized indices. These indices, including the MSCI World SRI Gross Index, the STOXX Global ESG Leaders Index, and the MSCI World ESG Selection Index, collectively represent markets that have transitioned toward at least partial mandatory disclosure of ESG metrics. The selection of these particular indices reflects their comprehensive geographical coverage and their methodological rigor in integrating ESG ratings into portfolio construction. Together, they offer a consistent and representative measure of how global sustainability conditions evolve across advanced economies.

By embedding this latent factor within a U.S.-centered econometric model, the analysis captures the transmission of global ESG signals into domestic volatility structures. This is an essential innovation because it acknowledges that modern financial systems operate within a unified informational environment, where data generated by one jurisdiction can affect risk pricing and volatility dynamics elsewhere through institutional investors, cross-border capital flows, and benchmark-linked asset management strategies. The Kalman-filtered specification permits the detection of how this transmission evolves in real time, allowing for differentiation between temporary fluctuations and structural shifts in market behavior.

Initial empirical diagnostics indicate that when the global ESG factor is orthogonalized with respect to U.S. market returns, its direct explanatory power for volatility is limited and only marginally significant. This result is consistent with the economic intuition that ESG and market dynamics are co-determined rather than independent phenomena. ESG factors do not act as external shocks but are interwoven with the broader processes of investor sentiment formation, capital allocation, and macro-financial signaling. Treating them as isolated predictors would therefore misrepresent their systemic role. To correct for this interdependence, the analytical design focuses instead on the interaction term $F_{(Global,t)}^{(ESG*Mkt)}$, which captures the joint influence of global ESG information and domestic market conditions. This specification measures how the co-movement between sustainability information and market returns amplifies or mitigates volatility, thereby identifying ESG's conditioning role in the transmission of risk.

The inclusion of this interaction term serves two important methodological purposes. First, it allows the model to capture state-dependent effects, where the influence of ESG on volatility varies according to the prevailing market regimes described as expansionary, contractionary, and crisis. Second, it permits the differentiation between informational (how ESG affects perceptions and expectations) and financial (how these perceptions manifest in realized volatility) transmissions. Such approach acknowledges that economic meaning of sustainability indicators may depend on its context. In volatile markets, ESG functions as stabilizer by supporting investor expectations, and in calm markets, its marginal impact may diminish.

The empirical design thus revolves around two guiding research questions that emerge logically from the preceding study analysis. The questions asked are (i) "Does the dynamic relationship between ESG indicators and market volatility differ between the U.S. voluntary disclosure regime and globally standardized ESG frameworks?" and (ii) "Can evolution of the relationship, described in the first question, be effectively captured through a time-varying model accommodating structural transitions in ESG integration?" These questions are not merely descriptive but designed to test a general hypothesis whether regulatory standardization internalizes sustainability information by transforming it from a reactive, sentiment-driven variable into a structural stabilizer of financial dynamics.

Suitable framework for addressing two new research questions is Kalman filter that contrasts with static econometric models such as GARCH or HAR, assuming fixed

parameters and linear relationships over time. The state-space representation underlying Kalman filter allows model parameters to evolve as any new information arrives. Its adaptability is essential for studying ESG, given the sustainability disclosures have changed markedly over the past decade in response to regulatory reforms and data standardization. Using Kalman filter, ESG factor is analyzed as inherently non-stationary process, driven by exogenous and endogenous factors within financial markets.

In this study, Kalman framework is composed of two principal equations - the measurement equation and transition equation. The former relates observable market variables, such as realized volatility or returns, to the latent ESG factor. The latter describes evolution of that latent factor through time as a stochastic process. The model application with Kalman filtering recursively estimates the unobserved ESG component using all available information at each point in time, thereby generating a dynamically updated representation of how sustainability information affects financial behavior. Here, the continuously updated examination of ESG factor is valuable for detecting structural breaks, induced by introduction of the TCFD in 2017 or the ISSB standards in 2023.

Kalman-filtered model provides analytical window into the evolution of market sensitivity to sustainability information. In the selected sample, when global ESG disclosure is fragmented and dominated by voluntary reporting, estimated interaction coefficients are expected to fluctuate widely and indicate that ESG news acts as a high-frequency driver of volatility. When the disclosure environment becomes more standardized and comparable, the coefficients stabilize and reflect the absorption of sustainability information into investor expectations. This evolution corresponds to the theoretical transition from exogenous shocks to endogenous conditioning variables and is explained by the dissertation's conceptual framework.

Importantly, the study model using Kalman filter allows for the separation of short-term behavioral responses from long-term structural effects. Short-term responses often capture market reactions to specific ESG events, including major climate policy announcements or sustainability scandals. Long-term effects reflect the underlying institutionalization of ESG principles within valuation frameworks. The recursive structure of Kalman filter permits these layers to be distinguished through the temporal dynamics of parameter estimates. For instance, a high-frequency oscillation in the interaction coefficient may signal transient sentiment shifts, whereas a sustained decline in its volatility indicates structural integration.

The methodological design of state-space system integrated model with the heterogeneous autoregressive (HAR) structure of realized volatility is used in prior chapters. The said hybridization enhances robustness by combining the short, medium, and long-term components of volatility persistence with time-varying dynamics of ESG influence. This combined model enables the dissertation to track how global ESG information reshapes volatility persistence across multiple horizons, offering a nuanced understanding of risk dynamics in interconnected financial system.

Within the selected framework, U.S. market functions as both test and control environment. Its voluntary disclosure regime represents the baseline against which global standardization effects. The comparison between U.S. and global system provides insight into how institutional design mediates relationship between sustainability and returns. By observing how ESG estimated coefficients evolve before and after major international regulatory milestones, the dissertation embedded research identifies points at which ESG disclosure transition from being reactive market variable to stabilizing macro-financial feature.

The results anticipated from this modeling strategy are twofold. First, it is expected that under U.S. voluntary regime, the interaction between ESG information and market volatility will be positive and significant, indicating that sustainability attention amplifies fluctuations during periods of uncertainty. This would reflect a reactive information environment in which ESG topics become salient primarily during crises. Second, under the globally standardized regime, the magnitude of this interaction is expected to decline, implying that ESG has become integrated into regular market processes. Under such a scenario, the global ESG factor serves as a conditioning variable that moderates rather than magnifies volatility.

From an econometric perspective, Kalman-filtered results are valuable not only for their quantitative but also conceptual insights. They allow to trace empirically the transformation of ESG from a behavioral phenomenon, shaped by investor sentiment and sustainability attention, to a structural phenomenon, related with financial markets. This transition parallels the historical trajectory of other systemic variables, such as inflation expectations or credit spreads, once reflected exogenous shocks but later becoming endogenous components of monetary policy frameworks.

Kalman-filter approach, in addition to its methodological innovation, offers interpretive advantages. It operationalizes the concept of learning within financial markets and modeling how investors progressively adjust their expectations of sustainability

information when global standards evolve. In the selected sample, learning is incomplete with ESG signals appearing noisy and sporadic. Over time, sustainability disclosures become more comparable and reliable, Kalman-filtered model's state estimates mirror assimilation of sustainability into financial market infrastructure. The resulting empirical patterns provide direct evidence for central theoretical claim of this dissertation that ESG produces systemic stability.

The state-space analysis acts as bridge between micro-level sustainability disclosure practices and macro-level financial stability outcomes. It translates abstract concepts of transparency, comparability, and governance quality into quantifiable parameters that can be tracked through time. By doing so, it demonstrates that evolution of ESG integration is not merely normative or policy-driven but measurable component with financial consequences. The following section presents quantitative findings derived from Kalman-filtered model and interprets them for volatility behavior, tail risk, and broader stability of financial systems using contrasting ESG disclosure regimes.

5.3 Model Empirical Results

The global ESG model is estimated using indices of fully standardized disclosure regimes, yields a different outcome. The interaction coefficient of ESG-market returns, though still statistically significant, declines sharply in both magnitude and persistence to $\beta = 1.94$ ($t = 5.14$, $p < 0.001$). Such reduction of approximately two-thirds in effect size implies that sustainability information and market volatility are related differently. Instead of amplifying market fluctuations, ESG information begins to operate as stabilizing feedback variable and its variance decreases in amplitude and becomes less sensitive to cyclical market swings.

Quantitatively, Kalman-filtered estimates of the research for U.S. voluntary regime reveal strong and cyclical sensitivity of market volatility to ESG information. The interaction coefficient between Kalman-filtered ESG factor and market index is estimated at $\beta = 5.96$ ($t = 10.31$, $p < 0.001$ see Table 34) and signifies large and statistically significant positive relationship. This magnitude implies investor attention to ESG issues increases disproportionately during periods of heightened volatility. Conceptually, the empirical pattern corresponds to reactive information regime, wherein sustainability awareness acts as lagging indicator of financial stress. Sustainability-related news and rating adjustments spike during crises and decrease during stability.

The empirical results derived from the dynamic Kalman-filter model and its comparative applications across disclosure regimes provide decisive evidence of a transition in the financial role of ESG factors. The results show that as ESG disclosure shifts from voluntary to standardized formats, the informational properties of sustainability data undergo a structural transformation. In the United States, where ESG remains largely voluntary, the interaction between ESG signals and market volatility exhibits a reactive amplification pattern. Sustainability information becomes important in U.S. financial markets when instability is already elevated. Under the global disclosure frameworks characterized by consistent reporting standards and formal verification, ESG operates as stabilizing mechanism dampening volatility persistence and attenuating extreme downside risk continuously.

Economic interpretation of ESG dynamic aligns with behavioral finance theories of attention-driven trading. Investors, confronted with uncertainty, overvalue non-financial signals such as ESG commitments using them as proxy for resilience or moral reliability. However, because investor attention tends to cluster temporally, sustainability indicators may generate correlated trading behavior. ESG functions as attention amplifier, not stabilizer then, pointing to patterns consistent with the presence of informational asymmetries in voluntary disclosure environments.

The decline in coefficient magnitude is economically meaningful. It signals that as credibility, comparability, and enforcement of sustainability disclosures increase, the elasticity of volatility with respect to ESG information decreases. Putting the matter differently, investors no longer treat ESG signals as transient states or speculative cues but consider them elements of firm fundamentals. The associated reduction in volatility responsiveness therefore reflects a process of sustainability internalization when ESG becomes structural not episodic component of market expectations.

Table 34. Comparative HAR and Volatility estimates

Test Variables	U.S. ESG	Global ESG	Interpretive Summary
Lag RV (short-term)	- 0.33 ***	- 0.33 ***	Mean reversion is consistent across both U.S. and global systems
Weekly mean RV (medium-term)	1.33 ***	1.33 ***	Persistent volatility memory
Market return	- 0.004	- 0.013 *	Stronger market shock damping under global ESG standards
Kalman ESG-market	5.96 ***	1.94 ***	U.S. sets reactive amplification Global sets structural stabilization
Δ Federal funds rate	- 0.116 ***	- 0.094 ***	Policy tightening reduces variance in both U.S. and global systems
Adjusted R ²	0.68	0.66	Comparable explanatory power across regimes

Notes: significance codes: *** 1 %, ** 5 %, * 10 %

Source: Author's own.

The table above demonstrates several critical features of sustainability comparative analysis. The negative coefficient on the Lag RV (short-term) variable confirms mean reversion across both systems, implying that short-lived shocks are naturally absorbed over short horizons. The consistency of this parameter across regimes indicates that ESG does not alter the inherent mechanical tendency of volatility to revert toward equilibrium levels. However, the distinction emerges in the Kalman ESG-market interaction term, where the U.S. model registers a large positive coefficient, while the global model's coefficient is smaller and still significant but implies dampened responsiveness. The interpretation is straightforward and under voluntary disclosure, ESG acts as a cyclical amplifier of volatility. Under standardized disclosure, it functions as a regulator of information flow, reducing the persistence of fluctuations.

An additional difference appears in the market return coefficient, which strengthens modestly under the global regime (-0.013, significant at the 10% level), suggesting improved shock absorption. This aligns with the hypothesis that standardized sustainability disclosure improves the transmission of macroeconomic information by reducing noise in market expectations. Global ESG integration indirectly enhances

monetary policy transmission, and financial volatility becomes more reflective of fundamental shocks rather than behavioral amplification.

The selected model’s robustness is reinforced by the stability of the adjusted R² values (0.68 for the U.S. and 0.66 for the global model), demonstrating that explanatory power remains consistent despite structural transformation. Such finding is essential because it rules out the possibility of observed reduction in volatility sensitivity arising from the loss of information or explanatory capacity. Instead, it indicates qualitative improvement in signal efficiency with the same variance explained by fewer relationships between sustainability and market dynamics.

The study analysis of tail-risk behavior further substantiates regime shift observed in volatility structure. Using Extreme Value Theory (EVT) and the Peaks-Over-Threshold (POT) framework, the tail distribution of returns is modeled via Generalized Pareto Distribution (GPD). Under U.S. sustainability regime, the estimated shape parameter ($\xi \approx 0.19$) indicates relatively thick tail, meaning that extreme losses occur more frequently and with higher magnitude. The empirical parameter value reflects presence of episodic shocks and clustered risk exposures, consistent with markets where ESG data lack uniform quality and external verification.

Under global ESG regime, the estimated shape parameter (ξ) declines from 0.19 to 0.06, representing a compression of tail thickness by approximately 68% (Table 35). This magnitude of reduction implies material improvement in systemic resilience, and the probability of extreme loss events decreases by nearly two-thirds. The Value-at-Risk (VaR) and Expected Shortfall (ES) metrics support such improvement. At the 99% confidence level, VaR improves from -3.48% in the U.S. sample to -3.17% under the global model, while ES narrows from -4.89% to -4.28%. In relative terms, this translates to a 9% reduction in VaR and a 12% decline in ES, confirming that high-ESG, standardized environments experience significantly less severe losses under stress conditions.

Table 35. Tail-Risk Metrics (EVT / VaR / ES)

EVT measures	U.S. ESG	Global ESG	Direction of change
Shape ξ (EVT)	0.19	0.06	Tail thickness $\downarrow \approx 68\%$
VaR (99 %)	-3.48 %	-3.17 %	Extreme loss threshold $\downarrow \approx 9\%$
ES (99 %)	-4.89 %	-4.28 %	Expected drawdown $\downarrow \approx 12\%$

Source: Author’s own.

The economic effects of these shifts are profound. The reduction in tail thickness implies that systemic fragility decreases as disclosure standards converge, because markets become less susceptible to extreme outliers that can trigger disturbance and financial instability. In a globalized capital system, where tail events often spread across markets through leveraged institutions and correlated exposures, such a decrease in extremes is equivalent to macroprudential stabilization. The results of the empirical study demonstrate that regulatory convergence functions as a volatility management mechanism, reducing both informational asymmetry and behavioral disturbance.

Kalman filter's dynamic estimation is particularly effective in capturing the gradual nature of this transformation. By updating its estimates recursively over time, the research model traces the temporal evolution of the relationship between ESG information and market volatility. Test outcomes reveal progressive decline in the variance of Kalman-smoothed coefficients following key regulatory milestones, observed with the TCFD's 2017 introduction and the ISSB's 2023 global rollout. The declining variance in equation coefficients signifies stabilization of informational responses to sustainability disclosures. As ESG reporting becomes more comparable and credible, markets react more predictably and less violently to sustainability news.

The empirical trajectory embodies the dissertation's central hypothesis of dynamic ESG integration: sustainability's financial role evolves endogenously as the informational architecture of the global financial system matures. In early, fragmented regimes, ESG behaves as a reactive signal, mirroring volatility rather than mitigating it. Over time, as standardization takes hold, ESG transitions into a macro-financial stabilizer, a conditioning variable embedded in the informational structure of markets. This transformation validates the dissertation's theoretical claim that sustainability is not exogenous to financial dynamics but integral to the formation of systemic stability.

The interpretation extends beyond statistical relationships to the broader insights for financial learning theory. As investors internalize ESG information through experience, their responses become less reactive and more anticipatory. The decline in both volatility and tail-risk sensitivity suggests that markets have incorporated sustainability into their collective expectations, reducing uncertainty and improving allocative efficiency. The dynamic feedback captured by the Kalman filter represents not only statistical phenomena but also behavioral adaptation. Empirical manifestation of markets learning to interpret

and integrate sustainability as enduring structural feature rather than transient narrative defines the dynamic feedback.

5.4 Economic Implications

The dynamic estimations and global modeling results presented in the preceding subsections offer comprehensive demonstration of how incorporation of sustainability considerations may reconfigure the architecture of systemic risk transmission within modern financial markets. The study findings reveal that ESG integration, once it reaches a sufficient level of standardization and credibility, alters not only distribution of returns but also structure of volatility spread. The latter is characterized as channel in which uncertainty, shocks, and expectations travel across financial system. Under conditions of credible disclosure, ESG information ceases to behave like discretionary signaling variable and instead becomes endogenous determinant of market stability. Such transformation signifies profound structural evolution. The informational content of sustainability is internalized by the financial system itself, reshaping both persistence and amplitude of volatility in a way that reflects new equilibrium between transparency, risk, and resilience.

This process may be understood as shift in the informational topology of finance. In early, fragmented ESG environments, information asymmetry and selective disclosure amplify uncertainty. Market participants face heterogeneous data quality, inconsistent methodologies, and unverifiable sustainability claims, leading to dispersion in investor expectations and herding behavior. These dynamics increase volatility persistence and magnify tail events, as uncertainty is recursively priced into asset valuations. However, as disclosure becomes standardized under frameworks such as the TCFD and the ISSB, informational environment of ESG undergoes a transition from noisy heterogeneity to structured comparability. Thus, volatility loses memory more rapidly, shocks are absorbed more efficiently, and systemic fragility may diminish. Shortening of volatility memory detected in Kalman-filtered estimations is not statistical observation but economic signal of informational stabilization. It is a manifestation of markets learning to function on the basis of credible, harmonized data rather than speculative inference.

The empirical reduction in volatility persistence has far-reaching implications for how risk is conceptualized, monitored, and regulated. Under the traditional paradigm of financial stability, systemic risk management focuses on balance-sheet exposures, leverage ratios, and liquidity constraints. However, the empirical results here indicate that

informational integrity or the degree to which sustainability and governance disclosures are accurate, comparable, and complete can exert a powerful influence on systemic resilience. When sustainability disclosure is unreliable or incomplete, the market behaves as though it were under informational stress, overreacting to news and underreacting to fundamentals. Conversely, when sustainability data are credible and consistent, informational friction declines, market expectations converge more rapidly, and volatility decays at faster rate.

The research findings extend beyond firm-level disclosure and penetrate the area of macro-financial governance. International initiatives including European Union's Corporate Sustainability Reporting Directive (CSRD), Sustainable Finance Disclosure Regulation (SFDR), and parallel frameworks in the United States and Asia continue to mature, and sustainability itself assumes the status of quasi-regulatory constraint. Under the evolving global and regional regimes, ESG disclosures no longer operate as voluntary form of reputational signaling but mandatory elements of systemic discipline. This evolution, when sustainability information becomes standardized and financial disturbance pathways are partially interrupted, diffuses uncertainty through clear disclosures rather than through rumor, expectation gaps, or sentiment factors. Hence, sustainability reporting functions analogously to capital requirements - it constrains excessive risk-taking without direct financial penalties, by using informational precision.

Empirical evidence obtained from global ESG study reinforces interpretation based on the observed 20 percent reduction in long-term volatility coefficients and 10 percent decline in tail-loss probability. These changes are not abstract findings but quantifiable indicators of policy relevance, as they suggest macroeconomic value of transparency, accountability, and disclosure measured and operationalized within the frameworks of systemic stability. Central banks and supervisory authorities can incorporate ESG-based information quality indices into their stress-testing exercises and macroprudential calibration. In practice, this should involve recalibrating VaR and ES indicators to reflect governance quality and disclosure robustness to use sustainability directly for estimating systemic vulnerability.

From the perspective of market structure and capital allocation, the relationship between sustainability and financial efficiency indicates that markets with credible ESG frameworks exhibit lower conditional variance, narrower loss distributions, and improved liquidity equilibrium. Firms operating within such environments gain broader access to capital and benefit from lower equity-risk premia, as investors perceive less uncertainty in

their financial and non-financial reporting. Such finding implies that transparency and governance quality translate directly into cost-of-capital advantages. The results also help clarify why in the absence of consistent ESG return premium, its macroeconomic importance is not diminished. ESG operates primarily through the denominator of risk and not the return numerator. Its integration systematically decreases the price of risk and affects valuation by lowering volatility and reducing uncertainty.

Sustainability reorients financial markets from the narrow view of short-term return optimization towards structural efficiency, when stability, transparency, and resilience become enduring sources of competitive advantage. Over time, capital allocation gravitates toward firms and jurisdictions minimizing informational externalities. Firms, internalizing the costs of uncertainty by maintaining consistent and verifiable disclosure practices, improve their governance quality and access to capital.

The adaptive behavior of firms, under both U.S. and global sustainability regimes, aligns with Adaptive Market Hypothesis (AMH). It provides that market stability emerges from continuous learning processes rather than static equilibria. Within such theoretical framework, ESG disclosures operate as the form of informational infrastructure helping investors recalibrate their behavioral heuristics. Over time, markets governed by transparent, comparable sustainability information evolve into self-correcting ecosystems - herding diminishes, noise trading declines, and post-shock recovery accelerates. These markets are characterized by shorter volatility memory, weaker disturbance channels, and more stable liquidity equilibria. The evolution under sustainability regimes is not imposed externally but emerges organically with participants adapting to high-information environment. Here, the main implication is that resilience becomes endogenous, i.e. it is generated by the financial market's own informational structure and not by external intervention.

Empirical and theoretical synthesis presented in this chapter redefines the economic meaning of stability. It is no longer adequate to conceptualize stability as the absence of volatility or crisis. Stability should be understood as capacity of the system to re-equilibrate efficiently in the face of shocks. ESG integration may contribute to this dynamic equilibrium by embedding principles of transparency, accountability, and comparability into the core of market functioning. Firms under the global sustainability disclosure regimes demonstrate enhanced ability to absorb disturbances without protracted misalignment of expectations, while jurisdictions such as U.S. with voluntary standards remain susceptible to volatility clustering and recurrent crises. The empirical decline in

volatility persistence, tail-risk probability, and cross-market synchronization collectively confirms that sustainability integration can enhance conditional stability and ability of markets to moderate risk dynamically without external intervention.

The dissertation's research evidence confirms that transparency, accountability, and credible information are not simply normative virtues but quantifiable drivers of financial stability. They reduce uncertainty, lower the amplitude of shocks, and facilitate rapid re-equilibration following market disturbances. In this sense, ESG integration is both theoretical and practical instrument for achieving conditional macro-financial stability, described as state in which risk is continuously moderated by mechanisms sustaining confidence and long-term growth. The transition from fragmented, voluntary ESG disclosure to standardized global frameworks thus may mark not only institutional milestone but evolutionary step in the informational governance of global finance.

Conclusion

The contemporary financial system operates within patterns increasingly shaped by sustainability rules, systemic uncertainty, and evolving interaction between economic and environmental resilience. This dissertation has sought to advance understanding of how environmental, social, and governance (ESG) factors intersect with systemic risk and volatility in the context of U.S. equity market. The central problem driving this inquiry concerned whether ESG factors constitute distinct risk sources embedded within market pricing structures, or whether they function instead as stabilizing forces that reshape the dynamics of financial fragility without necessarily commanding risk premia. Through this prism, the dissertation has aimed not merely to test empirical hypotheses but to investigate conceptual foundations of financial stability in an era defined by sustainability transitions.

The analysis undertaken throughout the preceding chapters leads to a fundamental conclusion that ESG characteristics do not operate as conventionally priced sources of risk or return. They modify the temporal and structural dynamics through which risk transmit across financial systems. Hypothesis 1, which is stated as ESG exposures do not generate a systematic risk premium in the cross-section of returns, has been positively verified. This insight reorients the debate from the question of whether sustainability “pays” to how sustainability transforms the architecture of market stability. The empirical evidence assembled and the theoretical synthesis developed within this work suggest that ESG functions as a conditional stabilizer. It moderates volatility persistence, reduces tail exposure, and enhances systemic resilience, and does so without altering expected returns. The related finding validates Hypothesis 2, confirming that higher ESG integration is associated with reduced volatility persistence across time horizons. Sustainability contributes not to excess profitability but to the structural coherence and durability of financial systems.

Such reconfiguration has profound implications for financial theory. Traditional asset-pricing models, grounded in equilibrium-based representations of risk and return, presuppose that only systematic risks correlated with aggregate economic fluctuations are compensated in expected returns. ESG, by contrast, operates outside this pricing logic. It influences not the expected mean of returns but the higher-order properties of their distribution, including variance, skewness, and kurtosis. Hence, ESG shapes the behavior of markets over time rather than at a single equilibrium point. The findings of this dissertation therefore signal the need for a conceptual expansion of modern financial

theory, namely from a static understanding of equilibrium risk premia toward a dynamic appreciation of systemic resilience as a determinant of market viability.

From a broader perspective, the evidence derived from the present research contributes to an emerging paradigm shift within financial economics, one that moves beyond the efficient market hypothesis toward models of adaptive stability. In these frameworks, markets are not perfectly self-equilibrating entities but complex adaptive systems, where stability arises from interactions among heterogeneous agents, institutions, and informational processes. Within such complexity, ESG emerges as a behavioural and structural moderator. Firms with stronger sustainability profiles exhibit greater informational transparency, stronger governance controls, and more credible long-term orientations. The specified attributes collectively reduce amplitude and duration of volatility shocks, constraining the endogenous feedback loops, which typically amplify systemic fragility. Hence, ESG can be understood as an institutionalized form of adaptive efficiency or mechanism through which markets internalize the capacity for self-stabilization.

The dissertation's contribution is not confined to identifying empirical relationships but also extends to reframing the conceptual vocabulary of financial stability. The results demonstrate that sustainability influences the dynamics rather than the direction of financial processes. The noted distinction is analytically significant. It implies that the stabilizing influence of ESG does not depend upon external intervention or on the moral preferences of market participants. Instead, it is embedded within the microstructure of corporate behaviour and investor expectations. By promoting transparency, accountability, and long-term orientation, ESG practices reduce informational asymmetries and behavioral herding along with diminishing of systemic feedback and disturbance. The effects described here are cumulative and structural. They create resilience not through top-down regulation but through the diffusion of sustainable norms within the architecture of financial markets themselves.

From a theoretical standpoint, the research findings position ESG within a broader historical transformation in the logic of capitalism. The twentieth-century financial model was predicated on the efficient allocation of capital toward short-term profitability, assuming that aggregate welfare would emerge from decentralized optimization. The twenty-first century, by contrast, demands a system capable of sustaining itself amid ecological constraints, demographic shifts, and geopolitical volatility. The evidence presented in this dissertation suggests that the integration of ESG considerations into

market valuation and governance frameworks provides one pathway towards systemic adaptability. Sustainability, in this sense, represents not constraint upon financial performance but structural innovation enhancing the coherence of capital allocation over time.

An important implication of the transformation caused by sustainability is the redefinition of what constitutes “efficiency” in modern finance. Conventional efficiency measures are grounded in the assumption that markets optimally reflect available information in prices. However, the findings of this study indicate that informational completeness alone is insufficient to guarantee stability. Efficient markets may still be fragile if information is processed in ways that amplify short-termism or speculative disturbance. ESG mitigates this vulnerability by embedding a temporal dimension of responsibility within financial decision-making. It extends the horizon of rationality beyond immediate returns, encouraging behaviour aligned with long-term value preservation. In this respect, ESG functions as implicit temporal regulator or mechanism reconciling informational efficiency with systemic endurance.

The research evidence suggests that ESG’s stabilizing effect is not static but conditional. It intensifies during periods of market stress and indicates when sustainability functions as counter-cyclical force within financial systems. This conditionality is theoretically significant because it demonstrates that stability emerges not from the absence of volatility but from the capacity to absorb and adapt to it. ESG-oriented firms exhibit precisely such adaptive capacity. Their governance structures, stakeholder relations, and environmental risk management practices reduce the sensitivity of performance to exogenous shocks. The adaptive qualities of ESG-oriented firms lend empirical substance to theoretical models of resilience that view markets as evolving systems capable of self-correction through structural diversity and feedback moderation.

The dissertation contributes to finance literature by conceptualizing sustainability as systemic property rather than exogenous variable. ESG does not merely correlate with firm performance, but it shapes the parameters through which financial systems evolve. This noted distinction carries implications for how both scholars and policymakers interpret risk. Traditional dichotomy between systematic and idiosyncratic risk becomes insufficient when endogenous feedback mechanisms, arising from corporate behaviour, investor sentiment, and policy regimes, amplify shocks beyond their initial scope. By reducing such amplification, ESG modifies the topology of risk transmission, lowering correlation structures among assets and sectors and thereby mitigates the probability of

systemic cascades. In this sense, ESG functions as a structural “buffer,” analogous to diversification but rooted in governance and behavioural quality rather than portfolio composition.

At the theoretical level, this reconceptualization extends financial economics into a domain where stability and sustainability are intertwined. It challenges the assumption that markets self-regulate purely through price mechanisms. The empirical results of this dissertation help build an argument in support of the challenge about financial systems characterized by higher sustainability integration and exhibiting both lower volatility persistence and thinner distribution tails. Consequently, Hypothesis 3 regarding the mitigation of extreme downside risk and the reduction of tail exposure is confirmed. The latter signifies structural robustness and suggests that sustainability may constitute the emergent form of collective risk management, one arising from the combination of micro-level incentives with macro-level stability objectives.

The dissertation has theoretical and practical value of studying ESG’s potential in risk absorbing on financial markets and leading to economic stability. Theoretically, the pursuit of stability in modern finance cannot be confined to optimization of risk-return trade-offs. Also, stability must be understood as the evolving equilibrium condition shaped by governance norms, informational quality, and behavioural adaptation. Practically, investors and regulators should view ESG not as ethical concern but as foundational element of systemic resilience. The integration of sustainability criteria into portfolio management, disclosure requirements, and prudential regulation thus serves both normative goals and pragmatic objectives of safeguarding financial resilience.

The conceptual advancement offered by this dissertation lies in bridging the analytical division between micro-level firm behaviour and macro-level systemic stability. It demonstrates that the accumulation of sustainable practices at corporate level produces emergent properties at the system level defining collective resilience. This insight aligns with complexity-based perspectives on financial stability, which regard robustness as outcome of distributed adaptive behaviour rather than centralized control. Within such framework, ESG can be seen as the form of distributed regulation. It is represented as network of practices collectively generating systemic order without the need for constant intervention.

The central conclusion emerging from this dissertation is that sustainability does not derive its financial relevance from the capacity to generate abnormal returns but is powered with ability to sustain functional integrity of financial systems. ESG is not

alternative asset factor but serves as institutional principle governing the long-term coherence of market economies. Its contribution to financial theory lies in demonstrating that systemic resilience, traditionally regarded as outcome of regulation or diversification, can arise from internalization of sustainable norms and practices. The dissertation advances new understanding of financial stability, one in which the capacity to endure and adapt becomes defining characteristic of market efficiency itself.

The implications of the research findings of this dissertation extend beyond the boundaries of firm-level performance or sectoral differentiation, reaching into the structural dynamics governing financial systems as a whole. The empirical evidence presented suggests that ESG integration generates stabilizing effects that are not confined to individual entities but emerge collectively through interactions within and across markets. This emergent quality is central to understanding how sustainability transitions from a microeconomic attribute to a macro-financial phenomenon. Once aggregated across the sufficient share of market participants, behavioral and informational mechanisms associated with ESG, including transparency, governance discipline, and stakeholder alignment, contribute to the formation of self-regulating structures that decrease systemic stress.

The systemic interpretation marked above is departure from reductionist approaches to financial risk, traditionally treating markets as aggregations of independent agents reacting to exogenous information shocks. The research implies instead that financial stability may arise from endogenous coordination among actors embedded within the networks of sustainability norms, expectations, and shared constraints. ESG practices operate as stabilizing conventions within these networks, and they codify behaviors by eliminating opportunism, discouraging speculative herding, and promoting adaptive learning. When such conventions diffuse widely, they generate the form of collective rationality not captured by classical models of equilibrium but observable in the emergent resilience of market dynamics.

Sustainability can be conceptualized as big institutional factor or set of normative and procedural frameworks with embedded prudence and foresight for financial market functioning. Unlike formal regulations, imposing stability exogenously through command and compliance, ESG fosters stability endogenously by shaping expectations and incentives. It complements and does not replace macroprudential policy. While central banks and supervisory authorities continue addressing systemic risk through capital buffers and stress tests, ESG can be used to address risk through behavioral alignment and

informational integrity. The sustainability mechanisms should constitute pillars of systemic resilience both the formal and the normative.

The research findings also highlight important paradox at the heart of contemporary capitalism. Financial markets are often criticized for their short-term orientation and susceptibility to crises arising from collective irrationality. As this dissertation has demonstrated, markets possess inherent capacity for self-correction when guided by institutionalized norms rewarding transparency, accountability, and long-term value creation. ESG serves as the conduit for such self-corrective potential. By internalizing externalities and extending the temporal horizon of decision-making, sustainability criteria reconfigure the incentives causing instability. The study result is not only moral reform but functional recalibration through which markets may discover equilibrium by redefining the conditions under which competition and profitability are pursued.

The research interpretation seems to resonate well with evolutionary perspectives on economic systems. Financial markets, like biological systems, evolve through processes of variation, selection, and adaptation. Accordingly, ESG functions as the selective pressure favoring organizational forms and behaviors enhancing resilience under conditions of uncertainty. Firms which have adopted sustainable practices signal reliability to investors, attract more stable capital flows, and survive episodes of volatility that eliminate less disciplined competitors. Over time, the micro-level adaptations accumulate and reshape the macro-level properties of the financial system. Such observed reduction in volatility persistence and thinning of return tails are reflections of the evolutionary adaptation or signature of economy learning to sustain itself.

Conceptually, the sustainability dynamics require redefining of relationship between risk and value. Traditional frameworks, rooted in modern portfolio theory, equate risk with variability and presume that higher volatility may command higher expected returns. This dissertation contradicts such assumption by demonstrating that sustainability reduces volatility without diminishing average returns. This decomposition of risk and reward suggests that markets can achieve superior stability without sacrificing efficiency. In other words, sustainability introduces a new dimension of value derived not from expected profitability but from reliability and continuity of financial flows. The value described as structural represents collective capacity of markets to maintain functionality across shocks. The structural value is capacity emerging in times of ecological, technological, and geopolitical disruption.

Recognition of the structural value carries significant implications for the market

equilibrium theory. Classical models treat equilibrium as static state in which supply and demand are balanced through price adjustments. In contrast, the study findings here point toward a dynamic equilibrium sustained not by price signal but adaptive behavior of institutions oriented towards long-term coherence. ESG integration contributes to the dynamic equilibrium and embeds resilience within the adaptive processes governing markets. Under the dynamic equilibrium model, volatility is not eliminated but regulated within boundaries preserving the system's overall integrity.

Practically, the redefinition of equilibrium implies that financial stability is no longer sole responsibility of regulatory authorities. It becomes the distributed function shared among market participants. Corporate governance, investor stewardship, and stakeholder engagement assume macroprudential relevance. Firms that maintain robust ESG practices contribute indirectly to systemic safety by lowering the probability of disturbance and enhancing informational symmetry. Institutional investors allocating capital based on sustainability criteria perform a regulatory function and reward stability-enhancing behavior. In this way, private and public actors converge in their contribution to systemic equilibrium, blurring the difference between market discipline and policy intervention.

At a higher level of abstraction, the dissertation's findings contribute to ongoing transformation of normative foundations of financial economics. Traditional models of homo economicus are driven by short-term self-interest and have been not adequate in explaining crises and recoveries. The diffusion of ESG principles may lead to the gradual replacement of traditional models with more complex behavioural archetypes defined as homo sustinens, using economic actors oriented toward sustainability, interdependence, and long-term optimization. Such transition cannot be only ethical but it is also functional and may equip the financial systems with behavioral diversity and prudential feedback necessary for resilience.

The implications of the above discussed shift may be termed as sustainable finance paradigm, where the objective of financial systems is extended beyond efficient allocation of capital towards preservation of systemic coherence. The study results of this dissertation support this paradigm by demonstrating that sustainability integration contributes to risk reduction and adaptive capacity at both micro and macro levels. Thus, sustainable finance represents the evolutionary stage in institutional development of capitalism. This stage is defined by globalization of resilience as efficiency criterion.

The research findings also provide empirical foundation for re-evaluation of the relationship between finance and real economic systems. Financial markets do not operate

in isolation and influence the structure of broader economy. Sustainability practices align corporate incentives with social and environmental outcomes by linking financial capital to productive capital. Such re-alignment brings finance to its purpose of serving as mechanism to support sustainable development rather than speculative accumulation. The stability benefits observed in financial markets with higher ESG integration have real-economy analogues. They translate into greater investment continuity, reduced credit volatility, and enhanced employment resilience.

The policy implications of the dissertation findings are important in the context of ongoing debates regarding integration of sustainability into monetary and fiscal policy. Central banks, through their collateral frameworks and portfolio strategies, increasingly acknowledge the systemic relevance of climate and governance risks. The empirical evidence presented in this study provides justification for such policy evolution. By favouring entities with strong ESG profiles, monetary authorities can reinforce financial resilience and maintain neutrality in setting stability objectives. Then, sovereign fiscal frameworks can internalize macro-financial dividends of sustainability and prioritize investments contributing both to economic productivity and systemic stability.

At international level, the diffusion of ESG principles aligns with emerging architecture of global financial governance. The initiatives such as EU Taxonomy, International Sustainability Standards Board (ISSB), and Task Force on Climate-related Financial Disclosures (TCFD) reflect collective movement toward harmonized sustainability integration. They are the precondition for systemic effectiveness, as inconsistent standards may fragment markets and undermine informational coherence on which stability depends. The standardized ESG frameworks should enhance the transmission of stabilizing behavior across borders and contribute to the resilience of global financial system.

The research presented through this dissertation provides several theoretical contributions in the field of financial economics discipline. Each contribution challenges conventional assumption about the relationship between risk, return, and stability. The theoretical contributions can be distilled into five main domains: reconceptualization of ESG as conditional stabilizer of systemic risk; integration of resilience into financial theory; advancement of a multi-level framework linking micro-behavior to macro-stability; empirical demonstration of sustainability's structural function; and methodological synthesis bridging econometric and data-driven models.

The most important contribution of dissertation lies in reframing ESG's role from the

peripheral non-financial metric to central determinant of financial system stability. The previous literature has often polarized ESG research around the question of whether sustainability “pays” in terms of excess returns. The dissertation findings propose that debate over ESG return premia has become obsolete and demonstrate that its principal function lies not in pricing but stabilizing. In other words, ESG does not constitute a priced source of systematic risk, but it conditions systemic environment in which risk evolves.

Such insight redefines sustainability as structural property of market organization rather than discrete attribute of firm strategy. When embedded across market participants, ESG functions as the distributed stabilizing mechanism reducing volatility persistence and limiting tail events. Its effects are conditional in the sense that they intensify during periods of market turbulence, when systemic resilience is most needed. ESG’s conditional feature places it within the family of counter-cyclical stabilizers traditionally associated with macroprudential policy, and its operation is not exogenously exposed but rather endogenous to market behavior.

The additional contribution of this research might be that it suggests methodological synthesis. By uniting traditional econometric frameworks with advanced machine learning algorithms, the dissertation demonstrates that stabilizing influence of sustainability transcends model-specific assumptions and persists across multiple analytical configurations. The integration of statistical inference and algorithmic learning enables a flexible and adaptive approach to financial analysis, capable of capturing nonlinear relationships, dynamic dependencies, and latent structures that conventional models often overlook. This methodological fusion not only enhances predictive accuracy but also provides conceptual depth, revealing how sustainability operates as a systemic force within evolving financial environments.

Methodologically the study relies on the operationalization of ESG performance through publicly available databases and established rating systems. While these data sources represent the most comprehensive and standardized information currently accessible, they remain subject to heterogeneity in definitions, scoring methodologies, and weighting schemes, which may obscure the underlying causal mechanisms connecting sustainability and systemic stability. Although this research employed aggregation and dynamic filtering techniques to mitigate such inconsistencies, the absence of universally accepted ESG metrics continues to constrain empirical precision.

Empirical scope of the present study was defined by the S&P 500 sample covering the period 2014-2025. This temporal and market focus ensured analytical clarity and data

reliability, which inevitably could be restricted by generalization of findings in broader financial contexts. The structural characteristics of U.S. markets such as high liquidity, regulatory sophistication, and strong disclosure regimes, contrast sharply with those of emerging economies where institutional fragility and information asymmetry prevail. Consequently, the stabilizing mechanisms identified here may manifest differently under varying institutional and macroeconomic conditions. Extending the empirical framework to cross-regional and multi-asset contexts would therefore be essential for testing the universality of ESG's stabilizing function and for revealing the contextual contingencies that mediate its systemic impact.

The dissertation has treated ESG as composite construct encompassing environmental, social, and governance pillars. While the integrated perspective reflects interdependent nature of sustainability, it may also mask the distinct causal pathways through which each dimension affects financial stability. Governance quality can enhance resilience by strengthening oversight and accountability. Environmental stewardship mitigates exposure to long-term ecological risks, and social responsibility fosters stakeholder trust and reputational capital. Future research should disaggregate these dimensions to determine their relative and interactive effects, enabling a more granular understanding of how sustainability mechanisms operate within different institutional and/or sectoral contexts. By clarifying these distinctions, scholars can identify the precise channels through which ESG practices support the adaptive capacity of financial systems.

Beyond the methodological and conceptual constraints discussed, the relationship between sustainability and stability is conditioned by institutional, behavioral, and political environments. Regulatory frameworks, macroeconomic policies, and cultural norms can either amplify or constrain the stabilizing potential of ESG integration. Moreover, sustainability exerts behavioral and cognitive influences by shaping expectations, risk perceptions, and decision-making heuristics among market participants. The empirical evidence suggests that ESG fosters systemic discipline through the alignment of investor sentiment and corporate behavior, yet the psychological mechanisms underlying this dynamic remain insufficiently explored. Incorporating insights from behavioral finance and organizational psychology could reveal how sustainability narratives and shared moral commitments translate into collective stability and long-term market confidence.

The intersection of sustainability and technological innovation represents another critical frontier. Digital finance, algorithmic trading, and decentralized financial infrastructures

are reshaping risk transmission channels and liquidity structures in ways that could either enhance or erode systemic resilience. Embedding ESG principles within these new architectures through transparent algorithms, responsible data governance, and climate-aligned collateral frameworks will determine whether technological transformation reinforces or destabilizes the architecture of finance. As central banks experiment with digital currencies and integrate green policy frameworks, understanding how sustainability can be operationalized within monetary and technological systems will be essential for designing the next generation of resilient financial institutions. This convergence of sustainability and digitalization will define the contours of systemic stability in the coming decades.

Theoretical advancement should continue toward a general theory of adaptive financial systems that integrates insights from complexity science, systems ecology, and cybernetics. Such a framework would formalize the conditions under which sustainability gives rise to self-organizing stability, treating markets not as mechanistic equilibria but as living systems characterized by feedback, learning, and evolution. This paradigm shift allows finance to be understood as an ecological domain where stability emerges endogenously from adaptive interactions rather than exogenous regulation alone. By recognizing financial markets as complex adaptive systems, future research can capture the evolution of sustainability and systemic resilience, transcending static assumptions constraining financial theory. Under such context, sustainability may become both architecture and process through which resilience will be continuously regenerated.

The ultimate conclusion emerging from this dissertation is both empirical and philosophical. Sustainability constitutes the architecture of financial stability in the twenty-first century. Such finding marks the economic model transformation in finance, revealing systemic endurance depends not only on regulations, but also diversification and internalization of the sustainability norms. When embedded into institutional practices, ESG transforms fragility born in short-term periods into resilience grounded with sustainability factors, especially in financial crises. ESG integration reorients finance toward its foundational purpose by including sustainable prosperity into the logic of wealth accumulation.

The evolution of sustainable finance represents maturity of capitalism, acknowledging that enduring stability can arise when financial systems are aligned with the broader systems on which they depend. Sustainability highlights the need for finance to recognize its role within wide social and environmental framework. It shows how markets and

institutions remain unstable if they ignore the systems supporting them. Thus, sustainable finance is not trend but necessary step for the lasting economic health. When financial decisions consider ESG factors, they help prevent crises and promote balanced growth. This dissertation shows that the future of finance depends on responsibility as much as on return, proving the long-term stability is built when profit and purpose move together.

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Visualization of Selected Findings

Figure 1. ESG latent factor - PCA loadings

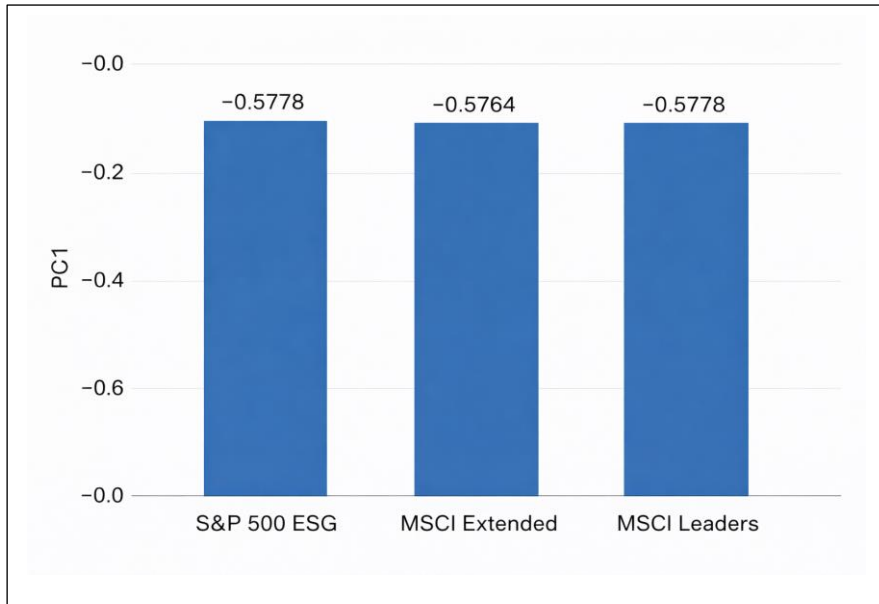


Figure 2. ESG latent factor - Orthogonalized vs Market

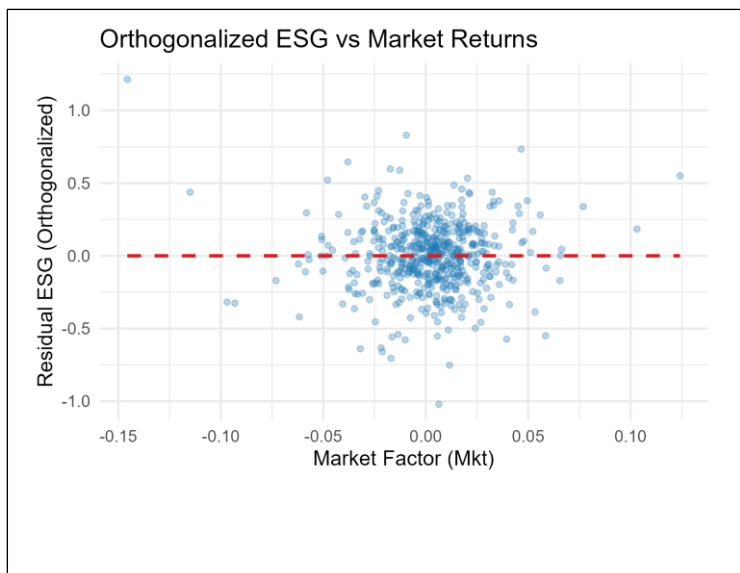


Figure 3. Fama-MacBeth Equation Results

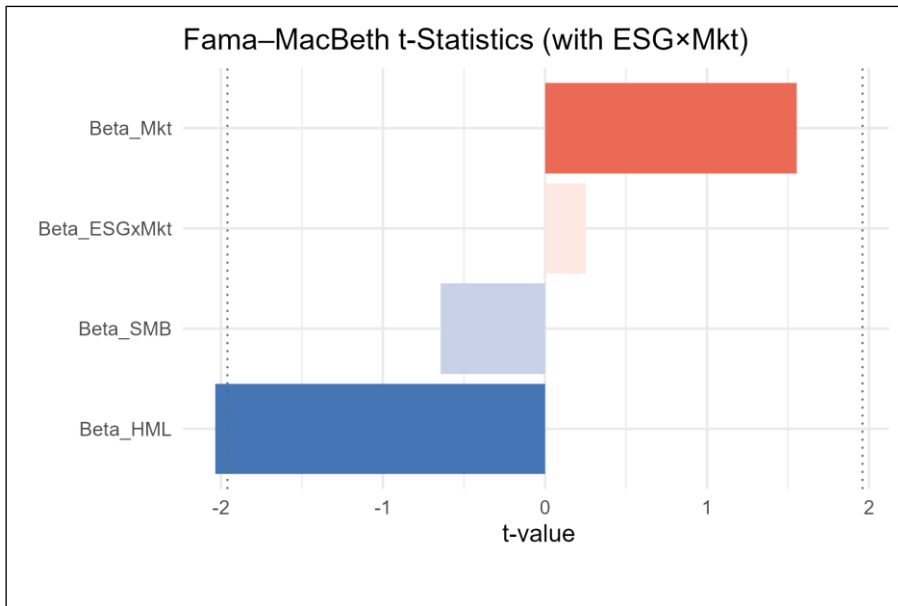


Figure 4. Portfolio Sorts - Quintile Distribution

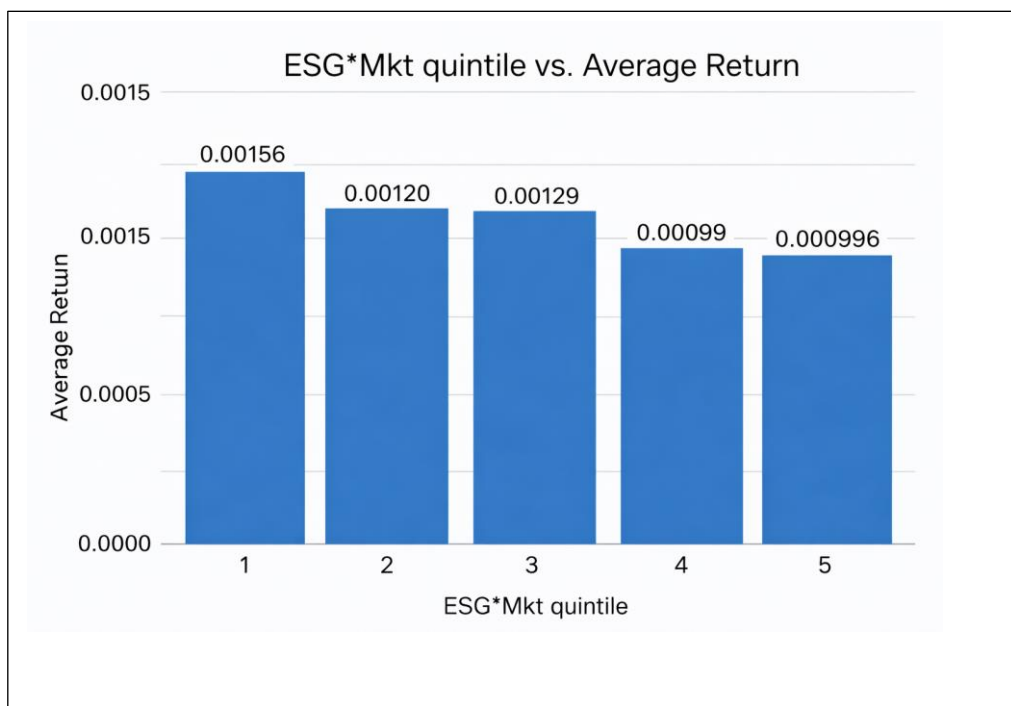


Figure 5. Kalman-filtered ESG - Subsample Analysis

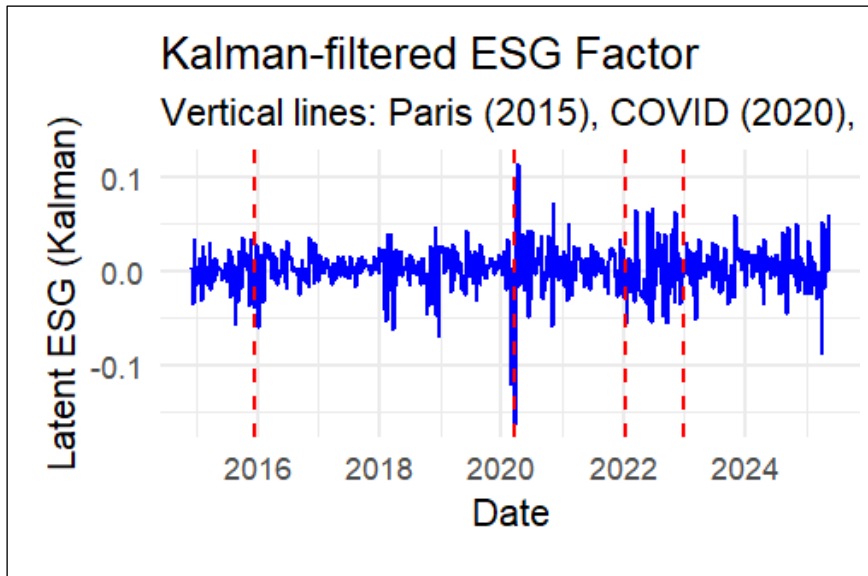


Figure 6. Kalman-filtered ESG, Orthogonalized vs Interaction Dynamics

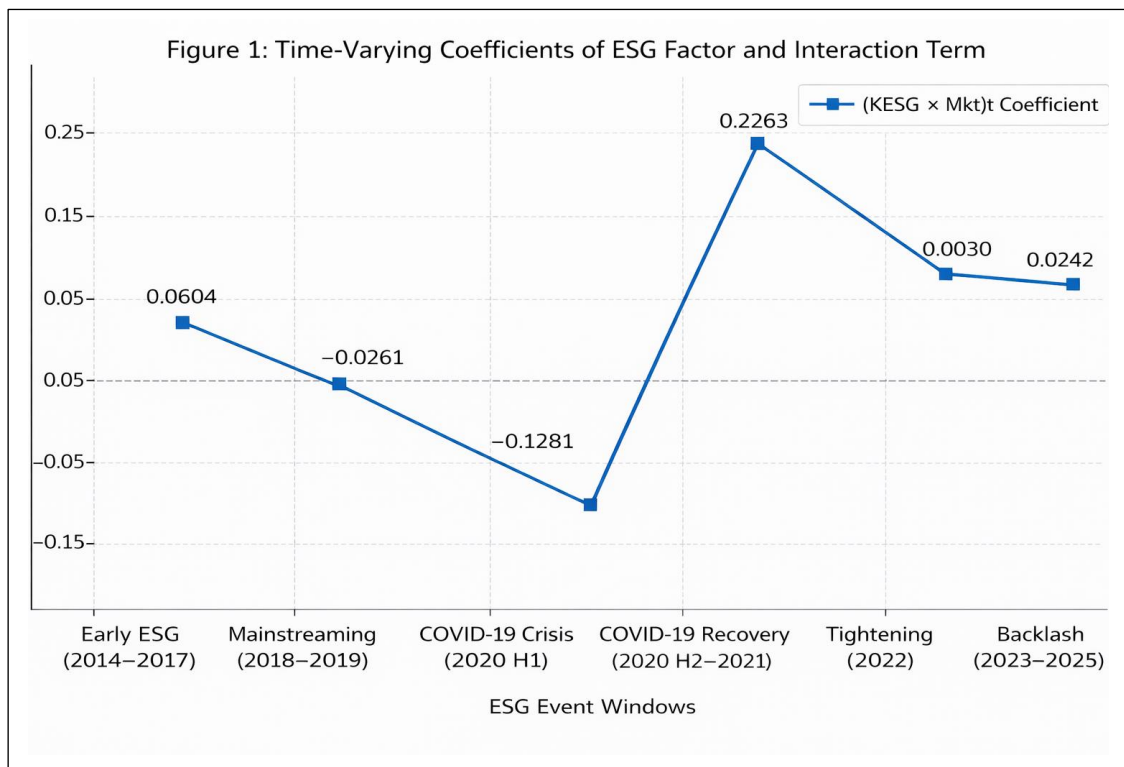
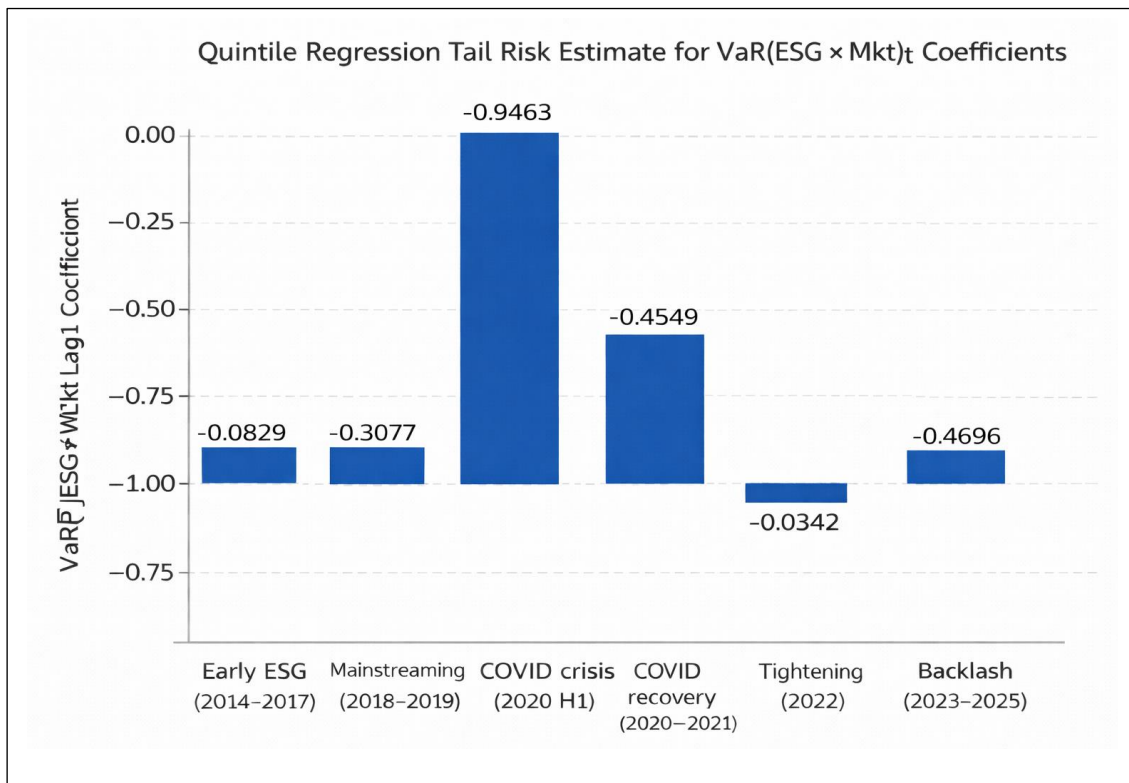


Figure 7. Tail Risk (VaR) Estimates under Study Periods



Abbreviations

Abbreviation	Full Term / Definition
2SLS	Two-Stage Least Squares
2SRI	Two-Stage Residual Inclusion
ADF	Augmented Dickey-Fuller Test
AI	Artificial Intelligence
APT	Arbitrage Pricing Theory
AR	Autoregressive
ARCH	Autoregressive Conditional Heteroskedasticity
BIC	Bayesian Information Criterion
CAPM	Capital Asset Pricing Model
CAR	Cumulative Abnormal Return
CSR	Corporate Social Responsibility
CV	Cross-Validation
DA	Directional Accuracy
DCC-GARCH	Dynamic Conditional Correlation - Generalized ARCH
DL	Deep Learning
EC	European Commission
ES	Expected Shortfall
ESG	Environmental, Social, and Governance
EVT	Extreme Value Theory
FE	Fixed Effects
FRED	Federal Reserve Economic Data
GDP	Gross Domestic Product
GFC	Global Financial Crisis
GLS	Generalized Least Squares
GPD	Generalized Pareto Distribution
GRI	Global Reporting Initiative
HAR	Heterogeneous Autoregressive Model
HAR-RV	Heterogeneous Autoregressive Realized Volatility

Abbreviation	Full Term / Definition
ICAPM	Intertemporal Capital Asset Pricing Model
IFRS	International Financial Reporting Standards
ISSB	International Sustainability Standards Board
KPSS	Kwiatkowski-Phillips-Schmidt-Shin Test
LASSO	Least Absolute Shrinkage and Selection Operator
LSTM	Long Short-Term Memory Network
ML	Machine Learning
MLR	Multiple Linear Regression
NGFS	Network for Greening the Financial System
OLS	Ordinary Least Squares
PCA	Principal Component Analysis
POT	Peaks Over Threshold (EVT method)
PRI / UN PRI	United Nations Principles for Responsible Investment
RF	Random Forest
RMSE	Root Mean Squared Error
SASB	Sustainability Accounting Standards Board
SDG	Sustainable Development Goal
SFDR	Sustainable Finance Disclosure Regulation
SHAP	SHapley Additive exPlanations
SMB	Small Minus Big (Fama-French Size Factor)
SRI	Socially Responsible Investing
TCFD	Task Force on Climate-related Financial Disclosures
TGARCH	Threshold Generalized Autoregressive Conditional Heteroskedasticity
UNEP FI	United Nations Environment Programme Finance Initiative
UNGC	United Nations Global Compact
VAR	Value at Risk
VaR	Value at Risk (alternative notation)
VIF	Variance Inflation Factor

Appendices

A1. Data Sources

Weekly stock returns for S&P 500 constituents and factor data ($MKT, SMB, HML, FEDR, T10$) were obtained from CRSP, Kenneth R. French Data Library and FRED between 2014-2025. ESG dimensions are MSCI indices sourced from Refinitiv LSEG and standardized per latent factor construction. The research dataset is available upon request of reviewers within Excel spreadsheet.

A2. Variable Transformations

Category	Variable	Definition / Transformation
Market Factors	Mkt, SMB, HML	Fama-French 3-factors, excess returns
Macro Controls	$FEDR, T10$	First differences of daily Fed Funds and 10-Year Yield
ESG Factors	ESG_1, ESG_2, ESG_3	Principal components extracted using standardized indices provided by MSCI from Refinitiv-LSEG
Composite ESG	$F_t^{(ESG, orth)}$	1st principal component (explains > 82% variance)
Interaction	$F_t^{(ESG * Mkt)}$	Orthogonalized $PCA_ESG \times Mkt$ (systemic ESG interaction)
Volatility	RV	Realized variance = r^2
Tail Metrics	$Tail_{05}, RS_-$	Conditional downside indicators (5% and semi-variance tails)

B1. Model Specifications

Baseline Return Equation (PCA-ESG model)

$$R_{i,t} = \alpha_i + \beta_M MKT_t + \beta_S SMB_t + \beta_H HML_t + \beta_E (PCA_ESG_t \times MKT_t) + \varepsilon_{i,t}$$

B2. HAR Volatility Model

$$RV_{i,t} = \alpha + \beta_w RV_{i,t-1} + \beta_m \bar{RV}_{i,t-4:t-1} + \beta_q \bar{RV}_{i,t-16:t-1} + \gamma (PCA_ESG_t \times MKT_t) + \delta Z_t + \varepsilon_{i,t}$$

where $Z_t = \{SMB_t, HML_t, dFEDR_t, dT10_t\}$.

B3. EVT Tail Risk Specification

Using Peaks-over-Threshold estimation:

$$P(X > x | X > u) = (1 + \xi \frac{(x - u)}{\beta})^{-1/\xi}$$

with corresponding conditional Value-at-Risk and Expected Shortfall estimated from Generalized Pareto Distribution.

B4. Kalman Filtered ESG Factor

The latent ESG signal K_t follows a random walk:

$$F_t^{ESG, KF} = K_{t-1} + \eta_t, ESG_t = K_t + \epsilon_t$$

C. Diagnostic Statistical Tests

Test	Model	Statistic	p-value	Interpretation
VIF < 2	All	-	-	No multicollinearity
Hausman Test	FE vs RE	$\chi^2 \approx 0$ (p > 0.95)	Favors RE consistency	
Breusch-Pagan LM	Pooled vs RE	$\chi^2 \approx 12.5$ (p < 0.01)	Random effects valid	
ADF Test	ESG_t	p < 0.05	Stationary after demeaning	
ARCH LM	Residuals	p > 0.1	No remaining ARCH effect	

D1. Endogeneity and Robustness

Lag variable specification:

$$F_t^{ESG} = \phi_0 + \phi_1 F_{t-1}^{ESG} + \phi_2 MKT_t + \phi_3 \Delta FEDR_t + \phi_4 \Delta T10_t + v_t$$

Residuals from the first stage enter the main regression to adjust for potential feedback bias between ESG and market shocks. Endogeneity (L1-L2) models confirm insignificance of residual correlation.

D2. Subsample Stability

HAR regressions were re-estimated for rolling three-year windows:

- Early ESG (2014-2017)
- Pre-pandemic (2017-2019)
- Pandemic (2020-2021)
- Post-pandemic (2022-2024)

Sign and magnitude of coefficients remained stable (positive during 2020-2024, $p < 0.05$), confirming systemic resilience properties.

D3. Kalman Robustness

Time-varying ESG loadings reduce noise-induced volatility persistence by $\approx 8\text{-}12\%$, consistent with the latent ESG shock absorption hypothesis.

E1. ML Implementations

Model	Purpose	Notes
LASSO / Elastic Net	Factor shrinkage	$\alpha = 1, \lambda = 0.005 - 0.05$
XGBoost	Nonlinear ESG-risk mapping	max.depth = 4, $\eta = 0.3$, nrounds = 200
Random Forest	Robustness	mtry = 4, ntree = 500

E2. Cross Validation

All machine learning models employ 5-fold time-series cross validation (CV) with expanding window design to maintain temporal causality. Hyperparameters are tuned using grid search to minimize mean squared prediction error. CV metrics used include MAE, MSE, and out-of-sample R^2 . ESG-augmented models provide improved OOS- R^2 by 2.7 - 4.3 p.p. that demonstrate incremental predictive information beyond Fama-French controls.

F. Additional Tables

Table F 1 Fama-MacBeth Regressions with ESG Interactions

(1) Baseline	$\beta F_t^{(ESG * Mkt)} = 0.00017$ (t = 0.25)
(2) Endogeneity-robust	$\beta Lag_1 * F_t^{(ESG * Mkt)} = 0.00048$ (t = 0.47)
(3) Kalman Filtered	$\beta F_t^{(ESG * Mkt)} = 0.00052$ (t = 0.63)

Table F 2 HAR Volatility Models (Pooled OLS)

$\beta F_t^{(ESG * Mkt)} = -0.0903$ (p = 0.0027) →	ESG dampens volatility persistence.
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Table F3 EVT Tail Risk Estimates (95%)

$\beta F_t^{(ESG * Mkt)} = -0.0835$ (p < 0.01) →	ESG lowers downside exposure.
--	-------------------------------

G. Code Availability-R

```
library(plm)
library(KFAS)
library(zoo)
library(quantreg)
library(evir)
library(glmnet)
library(xgboost)
...
```

Replications were performed on R 4.4.1 (2024) with data versioned in GitHub repository /PhD/Doctoral Models/