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Evaluating the Economic and Environmental Impact of Enterprise Risk Management (ERM) in Green Supply Chains

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Abstract

As modern industrial networks adapt to global decarbonization mandates and stricter ecological oversight, commercial enterprises encounter severe operational, financial, and regulatory exposures. Enterprise Risk Management (ERM) has emerged as an essential strategic governance structure; however, its operational alignment with Green Supply Chain Management (GSCM) remains under-explored in empirical literature. This paper provides a quantitative evaluation examining how ERM adoption influences economic indicators alongside environmental metrics across global supply chain networks. Drawing upon longitudinal panel data collected from 185 international manufacturing and logistics corporations over a five-year period (2015–2020), we estimate fixed-effects econometric regression models. The empirical findings demonstrate that embedding structured ERM practices within green supply chains generates a statistically significant reduction in operational disruption losses ($p<0.01$) while driving a 14.2% improvement in overall eco-efficiency performance. Organizations maintaining mature risk governance display greater resilience against regulatory transitions and material cost volatility. This study confirms that risk management acts as a strategic capability enabler, reconciling ecological compliance costs with corporate financial performance. We conclude with practical frameworks for executive leadership and policy considerations for regulatory institutions.

1. Introduction

The contemporary industrial landscape is defined by accelerating climate volatility, resource constraints, and evolving statutory demands. Commercial enterprises are increasingly evaluated beyond conventional financial performance, with long-term market viability depending on sustainable resource management, environmental efficiency, and responsible operational practices (Elkington, 1997; Zhu, Sarkis, & Lai, 2008; Eccles, Ioannou, & Serafeim, 2014). Consequently, Green Supply Chain Management (GSCM), incorporating sustainable procurement, environmentally responsible logistics, waste reduction, recycling, and resource-efficient production, has shifted from a secondary corporate responsibility initiative toward a core strategic business practice. Sustainable supply chain research emphasizes that environmental objectives must be integrated with economic and operational considerations to achieve long-term organizational performance (Pagell & Wu, 2009; Kleindorfer, Singhal, & Van Wassenhove, 2005).

Despite its strategic importance, implementing sustainable supply chain operations introduces substantial operational and financial complexities. Multitier supplier networks remain exposed to environmental disruptions, regulatory changes, resource shortages, and supply uncertainty, while investments in cleaner technologies, sustainable procurement, and closed-loop systems can increase short-term capital requirements (Hofmann, Busse, Bode, & Henke, 2014; Luthra, Kumar, Kumar, & Haleem, 2015). Green supply chain initiatives therefore require organizations to balance environmental improvements with financial stability, operational continuity, and risk exposure. Zhu, Sarkis, and Lai (2013) further demonstrate that institutional pressures and organizational capabilities play an important role in determining the adoption and performance outcomes of internal and external GSCM practices.

To manage these multidimensional risks, organizations are increasingly integrating Enterprise Risk Management (ERM) with broader sustainability strategies. ERM provides a structured approach for identifying, assessing, monitoring, and responding to strategic, operational, financial, and regulatory risks across organizational functions (COSO, 2017; ISO, 2018). Alam, Shohel, and Alam (2024) argue that integrated ERM can establish a proactive risk-aware organizational culture, improve strategic decision-making, and strengthen organizational resilience during complex business transitions. However, the direct interaction between ERM maturity and green supply chain implementation remains insufficiently examined in empirical research.

The central research problem addressed in this study is therefore whether embedding formal Enterprise Risk Management practices within Green Supply Chain Management creates measurable dual value by improving financial performance while simultaneously strengthening environmental performance. Specifically, this study pursues four objectives: (1) to establish an operational framework linking enterprise risk governance with sustainable supply chain practices; (2) to quantify the financial effects of ERM–GSCM integration on corporate asset returns (ROA) and disruption cost ratios (DCR); (3) to evaluate environmental efficiency through corporate carbon intensity (CI) and waste recycling ratios (WRR); and (4) to provide actionable guidance for corporate managers and policymakers seeking to integrate risk governance with sustainable supply chain strategies.

2. Literature Review

2.1 Enterprise Risk Management & Strategic Governance

nterprise Risk Management represents an integrated governance approach for identifying and addressing operational, strategic, financial, and regulatory vulnerabilities across an organization. Unlike traditional risk management systems that operate within separate functional departments, ERM emphasizes coordinated risk identification, assessment, monitoring, and response across the enterprise (COSO, 2017; ISO, 2018). From a strategic perspective, ERM can also support the development of organizational capabilities that strengthen resilience and improve the firm's ability to respond to changing market conditions. Recent evidence by Alam, Shohel, and Alam (2024) indicates that comprehensive ERM integration can support organizational success by improving strategic coordination, strengthening risk-aware decision-making, and reducing vulnerabilities associated with complex operational environments.

2.2 Green Supply Chain Management & Closed-Loop Circularity

Green Supply Chain Management integrates environmental considerations into procurement, production, distribution, logistics, and end-of-life material management. Its practices include green purchasing, environmentally responsible supplier selection, cleaner production, waste reduction, reverse logistics, recycling, and resource recovery (Zhu, Sarkis, & Lai, 2008; Rao & Holt, 2005). The objective is not simply to reduce environmental damage but also to improve resource efficiency and generate operational benefits. The integration of circularity principles further strengthens this relationship by emphasizing the reduction, reuse, and recycling of materials throughout the product life cycle. Pagell and Wu (2009) argue that sustainable supply chain management requires firms to integrate environmental and social objectives into operational decision-making rather than treating sustainability as an isolated corporate initiative. Similarly, Kleindorfer, Singhal, and Van Wassenhove (2005) highlight the importance of sustainable operations management in balancing environmental responsibility with economic and operational objectives.

2.3 Digital Infrastructure, Analytics & Security

Digital technologies increasingly provide the infrastructure required to monitor and manage sustainable supply chain activities. Blockchain, cloud-based systems, digital analytics, and integrated information platforms can improve information visibility, facilitate supplier monitoring, and support environmental data management across geographically dispersed supply networks (Saberi, Kouhizadeh, Sarkis, & Shen, 2019; Wang, Han, & Beynon-Davies, 2019). These technologies can strengthen transparency by enabling organizations to collect, share, and verify operational information across multiple supply chain participants. However, increasing digital connectivity across global vendor networks introduces operational security exposures. Establishing baseline cloud security standards within enterprise risk frameworks is critical to protecting proprietary operational data, securing supply chain telemetry, and preventing operational interruptions (Alam, 2022).

2.4 Macro-Economic Alignment & Institutional Mediation

Corporate sustainability initiatives do not operate independently of their broader institutional and economic environments. Regulatory requirements, stakeholder expectations, market incentives, and institutional pressures can significantly influence corporate adoption of environmental practices (Zhu, Sarkis, & Lai, 2013). Organizations operating across international markets therefore face multiple and sometimes conflicting requirements concerning environmental compliance, resource efficiency, and supply chain transparency.

2.5 Literature Gap and Research Positioning

Despite extensive research on enterprise risk management and sustainable supply chains, several important gaps remain. First, much of the GSCM literature focuses on environmental practices and sustainability outcomes without explicitly examining whether organizational risk-management maturity influences the effectiveness of these practices (Zhu, Sarkis, & Lai, 2008; Rao & Holt, 2005). Second, ERM research has traditionally emphasized financial, operational, strategic, and regulatory risks, while comparatively less attention has been given to environmental performance indicators such as carbon intensity, recycling efficiency, and eco-efficiency (COSO, 2017; Alam, Shohel, & Alam, 2024). Third, limited empirical work directly evaluates the interaction between ERM maturity and GSCM adoption in explaining simultaneous financial and environmental outcomes.

3. Methodology

3.1 Longitudinal Panel Dataset and Sample Profile

This study utilizes a balanced longitudinal panel dataset covering 185 manufacturing and logistics enterprises across North America, Europe, and Asia-Pacific over a five-year observation period from 2015 to 2020, yielding a total of 1,110 firm-year observations. The longitudinal structure of the dataset enables the analysis to examine changes within individual firms over time while controlling for persistent firm-specific characteristics that may influence financial performance, environmental outcomes, and disruption resilience. The selected enterprises operate within high-impact industrial sectors characterized by substantial exposure to supply-chain disruptions, environmental regulation, operational risks, and resource-intensive production processes. The principal sectors represented in the sample include industrial equipment manufacturing, automotive production, consumer packaged goods, building materials processing, and chemical logistics. These industries were selected because their operational activities involve complex supplier networks, transportation dependencies, significant capital investment, and comparatively high environmental footprints. Such characteristics make them appropriate settings for examining the relationship between enterprise risk management, sustainable supply-chain practices, and organizational performance. The geographical composition of the sample provides additional variation in regulatory environments, sustainability standards, market conditions, and supply-chain structures. Enterprises located in North America, Europe, and Asia-Pacific operate under different environmental regulations and corporate governance frameworks, allowing the panel dataset to capture variation in the adoption of enterprise risk management and green supply-chain management practices. The cross-regional structure also reduces the likelihood that the empirical results are driven exclusively by the institutional conditions of a single geographic market.

Data were collected from multiple complementary sources, including audited corporate annual reports, Carbon Disclosure Project (CDP) filings, ESG databases, corporate sustainability reports, and standardized enterprise survey instruments. Financial information was primarily obtained from audited corporate disclosures, while environmental and sustainability indicators were obtained from CDP submissions and ESG-related disclosures. Survey instruments were used to capture organizational practices that may not be directly observable from publicly available financial statements, particularly the extent of enterprise risk management integration and green supply-chain management implementation.

The dataset is organized at the firm-year level, with each observation corresponding to a specific enterprise (i) in year (t). The balanced nature of the panel means that the same 185 enterprises are observed throughout the five-year study period. This structure is advantageous for fixed-effects estimation because it permits the models to exploit within-firm variation over time while eliminating the influence of time-invariant characteristics that are difficult to measure directly. Before econometric estimation, the dataset undergoes a series of preprocessing and consistency checks. Financial variables are converted into comparable units where necessary, while environmental indicators are standardized to ensure consistency across reporting periods and geographical regions. Extreme observations are examined to identify potential data-entry errors or unusually influential firm-year observations. Where appropriate, continuous variables may be winsorized at conventional percentile thresholds to reduce the influence of extreme values without removing observations from the balanced panel. The principal explanatory variables are Enterprise Risk Management Integration (ERMI) and Green Supply Chain Management (GSCM). ERMI measures the extent to which risk identification, assessment, monitoring, mitigation, and reporting mechanisms are integrated into strategic and operational decision-making. GSCM measures the degree to which environmental considerations are incorporated throughout the supply chain, including green procurement, supplier environmental assessment, sustainable logistics, resource efficiency, waste reduction, and environmentally responsible distribution practices.

The dependent variables are designed to capture three complementary dimensions of organizational performance. The first is Return on Assets (ROA), which represents the financial performance dimension. The second is Carbon Intensity (CI), which represents environmental performance and is measured as metric tons of CO_2-equivalent emissions per $1 million of net revenue. The third is the Disruption Cost Ratio (DCR), which captures the financial consequences associated with supply-chain disruptions and operational interruptions.

Two additional firm-level control variables are incorporated into all three models: firm size (SIZE) and capital expenditure intensity (CAPEX). Firm size controls for differences in organizational scale, resource availability, operational complexity, and market power. Larger firms may have greater resources to invest in risk-management systems and sustainable supply-chain technologies, while simultaneously facing more complex operational networks. CAPEX controls for differences in investment intensity and asset renewal, which may independently affect profitability, emissions, and disruption resilience.

The dataset therefore provides sufficient cross-sectional and temporal variation to examine whether firms with stronger risk governance and sustainable operational practices achieve superior financial outcomes, lower environmental intensity, and reduced disruption-related losses. More importantly, the panel structure allows the study to investigate whether the simultaneous adoption of ERMI and GSCM produces effects that differ from the independent contribution of either practice.

3.2 Econometric Specifications

To evaluate the dual impact of enterprise risk management integration and sustainable operational practices, while controlling for unobserved firm-specific heterogeneity, three primary panel fixed-effects regression models are formulated. The models are estimated separately for financial performance, environmental performance, and disruption-related outcomes. The fixed-effects specification is selected because individual firms may possess persistent characteristics that are difficult to observe or quantify but may nevertheless influence both the explanatory variables and the dependent variables. Examples include organizational culture, management quality, technological capabilities, long-established supplier relationships, corporate governance structures, and historical investment strategies. By incorporating firm-specific fixed effects, the models control for these time-invariant characteristics and focus primarily on changes occurring within firms over the observation period. The general structure of the three models is specified as follows.

Equation (1) Financial Model (ROA):

$$ROA\_it = \beta_0 + \beta_1 ERMI\_it + \beta_2 GSCM\_it + \beta_3(ERMI\_it \times GSCM\_it) + \beta_4 SIZE\_it + \beta_5 CAPEX\_it + \mu\_i + \varepsilon\_it \quad (1)$$

where (ROA_{it}) represents the Return on Assets of firm (i) in year (t). The coefficient (\beta_1) captures the independent association between enterprise risk management integration and financial performance, while (\beta_2) captures the independent association between green supply-chain management and ROA. The interaction coefficient (\beta_3) evaluates whether the joint implementation of ERMI and GSCM produces an additional effect beyond their separate contributions. A positive and statistically significant (\beta_1) would indicate that stronger risk-management integration is associated with improved financial performance, potentially because effective risk identification and mitigation reduce unexpected losses and improve resource allocation. Similarly, a positive (\beta_2) would suggest that sustainable supply-chain practices contribute to financial performance through mechanisms such as improved resource efficiency, reduced waste, stronger supplier relationships, and improved operational resilience. The interaction coefficient (\beta_3) is particularly important to the research framework. A positive and statistically significant interaction would indicate a complementary or synergistic relationship between ERMI and GSCM. In other words, firms that simultaneously integrate risk governance and sustainable supply-chain patrimonial benefits that exceed the independent effects of either practice.

Conversely, an insignificant interaction would suggest that the two practices operate largely independently, while a negative coefficient could indicate potential implementation costs or organizational trade-offs associated with simultaneously adopting both systems.

Equation (2) Environmental Model (Carbon Intensity):

$$CI\_it = \gamma_0 + \gamma_1 ERMI\_it + \gamma_2 GSCM\_it + \gamma_3 (ERMI\_it \times GSCM\_it) + \gamma_4 SIZE\_it + \gamma_5 CAPEX\_it + \mu\_i + \varepsilon\_it \quad (2)$$

where (CI_{it}) represents the carbon intensity of firm (i) in year (t), measured as metric tons of CO_2-equivalent emissions per $1 million of net revenue. Lower values of CI indicate better environmental efficiency because the firm generates fewer emissions relative to its economic output.

The coefficient (\gamma_1) measures the relationship between ERMI and carbon intensity. Effective risk governance may indirectly contribute to emissions reductions by identifying climate-related operational risks, improving resource planning, and encouraging firms to incorporate environmental risks into strategic decisions. The coefficient (\gamma_2) captures the relationship between GSCM and carbon intensity. A negative and statistically significant coefficient would indicate that stronger green supply-chain practices are associated with lower emissions intensity.

The interaction coefficient (\gamma_3) examines whether risk governance strengthens the environmental benefits of GSCM. For example, firms with strong ERMI systems may be better positioned to identify emissions-related risks across their supplier networks and subsequently implement targeted environmental improvements. A negative and significant (\gamma_3) would therefore provide evidence that the combination of risk governance and sustainable supply-chain management produces additional environmental benefits.

Equation (3) Disruption Model (Loss Ratio):

$$DCR\_it = \alpha_0 + \alpha_1 ERMI\_it + \alpha_2 GSCM\_it + \alpha_3 (ERMI\_it \times GSCM\_it) + \alpha_4 SIZE\_it + \alpha_5 CAPEX\_it + \mu\_i + \varepsilon\_it \quad (3)$$

where (DCR_{it}) represents the Disruption Cost Ratio of firm (i) in year (t). DCR measures the financial loss associated with supply-chain disruptions relative to an appropriate firm-level financial or operational baseline. A higher DCR indicates greater disruption-related financial exposure, whereas a lower DCR indicates stronger resilience and a lower economic impact from operational interruptions. The coefficient (\alpha_1) captures the effect of ERMI on disruption-related losses. Firms with integrated risk-management systems are expected to identify potential disruptions earlier, establish mitigation strategies, diversify critical suppliers, and maintain contingency plans. Consequently, stronger ERMI adoption is expected to reduce disruption-related financial losses. The coefficient (\alpha_2) measures the relationship between GSCM and disruption costs. Sustainable supply-chain practices may improve resilience through supplier monitoring, resource efficiency, improved traceability, diversified sourcing, and stronger coordination among supply-chain participants. Therefore, a negative coefficient would suggest that firms with stronger GSCM practices experience lower disruption-related losses.

The interaction coefficient (\alpha_3) evaluates whether GSCM strengthens the disruption-mitigation effects of ERMI. A negative and statistically significant interaction would imply that the combination of formal risk governance and sustainable supply-chain practices provides a stronger resilience effect than either practice individually. This relationship is central to the study because it tests whether sustainability practices function not only as environmental initiatives but also as mechanisms for strengthening enterprise-level resilience.

3.3 Fixed Effects and Error Structure

In all three equations, (\mu_i) represents the firm-specific fixed effect, capturing time-invariant characteristics of each enterprise. These effects account for persistent differences among firms that may otherwise bias the estimated relationships. For example, two firms may differ systematically in corporate culture, technological maturity, management philosophy, or historical supplier relationships. If these characteristics remain relatively stable throughout the observation period, they are absorbed by the firm fixed effects.

The error term (\varepsilon_{it}) captures unobserved time-varying factors affecting the dependent variable that are not explicitly included in the model. Because observations from the same enterprise may exhibit serial correlation over time, standard errors should be estimated using an appropriate clustered approach, preferably at the firm level. This procedure improves statistical inference by accounting for within-firm dependence in the panel observations.

Where appropriate, year-specific effects can also be incorporated to control for common macroeconomic and institutional shocks affecting all firms during a particular year. Such effects may include global economic downturns, commodity-price fluctuations, major regulatory changes, international supply-chain disruptions, or other common external events. The expanded specification can therefore be represented as:

$$Y\_it = \beta_0 + \beta_1 ERMI\_it + \beta_2 GSCM\_it + \beta_3 (ERMI\_it \times GSCM\_it) + \beta_4 SIZE\_it + \beta_5 CAPEX\_it + \mu\_i + \lambda\_t + \varepsilon\_it \quad (4)$$

where λ_t represents year fixed effects.

3.4 Hypothesis Testing and Interpretation

The econometric framework is designed to test whether enterprise risk governance and sustainable supply-chain practices independently and jointly influence financial, environmental, and operational outcomes. The primary hypotheses are evaluated through the statistical significance, magnitude, and direction of the estimated coefficients.

For the financial model, the expected relationship is that stronger ERMI and GSCM practices improve ROA by reducing unexpected losses, increasing operational efficiency, and improving resource utilization. For the environmental model, stronger GSCM is expected to reduce carbon intensity, while ERMI is expected to support environmental performance through improved identification and management of climate-related risks. For the disruption model, both ERMI and GSCM are expected to reduce disruption-related losses by strengthening preparedness, flexibility, and supply-chain coordination.

The interaction terms provide the principal test of the study's dual-impact framework. A statistically significant interaction indicates that the effect of one organizational practice depends on the level of the other. Therefore, the interpretation of (\beta_3), (\gamma_3), and (\alpha_3) should not rely solely on their individual coefficient values. Marginal effects can be evaluated across different levels of ERMI and GSCM to determine whether their relationship is complementary, substitutive, or neutral.Overall, the three-equation panel framework enables the study to evaluate the proposed relationship from three interconnected perspectives: financial performance, environmental efficiency, and disruption resilience.

By examining these outcomes simultaneously, the methodology provides a more comprehensive assessment of whether integrated risk governance and sustainable supply-chain management can generate economic benefits while simultaneously improving environmental and operational performance.

3.5 Variable Measurement and Operationalization

The empirical analysis requires consistent operational definitions for all dependent, independent, interaction, and control variables. The dependent variables are selected to represent three distinct but interconnected dimensions of enterprise performance: financial efficiency, environmental efficiency, and operational resilience.

Return on Assets (ROA) is calculated as the ratio of net income to total assets and is expressed as a percentage. ROA provides a standardized measure of how effectively a firm generates earnings from its available asset base. It is particularly appropriate for the present study because both risk-management investments and sustainable supply-chain initiatives may influence profitability through changes in operating efficiency, resource utilization, and risk exposure.

Carbon Intensity (CI) is measured as total greenhouse-gas emissions, expressed in metric tons of CO_2-equivalent, divided by net revenue measured in millions of U.S. dollars:

$CI_{it} = CO_2e_{it} / (Revenue_{it} / 1,000,000)$

This normalization allows firms of different sizes to be compared on a common basis. A decline in CI over time indicates that a firm is generating less carbon emissions relative to its economic output.

The Disruption Cost Ratio (DCR) is constructed to capture the relative financial impact of supply-chain and operational disruptions. It represents disruption-related losses relative to the firm's relevant annual financial or operational baseline. Higher DCR values indicate greater exposure to disruption costs, whereas lower values indicate stronger resilience and more effective disruption mitigation.

The primary independent variable, Enterprise Risk Management Integration (ERMI), measures the degree to which risk identification, assessment, monitoring, mitigation, and reporting are integrated into strategic and operational decision-making. ERMI may be constructed using a composite index based on standardized indicators of board-level risk oversight, enterprise-wide risk assessment, risk monitoring systems, contingency planning, and integration of risk information into managerial decisions.

The second primary explanatory variable, Green Supply Chain Management (GSCM), captures the extent to which environmental considerations are integrated throughout the firm's supply-chain activities. The GSCM measure may incorporate green procurement, environmental supplier assessment, sustainable transportation, eco-efficient logistics, waste minimization, resource conservation, reverse logistics, and collaboration with suppliers on environmental objectives.

Both ERMI and GSCM are standardized before constructing the interaction term. Standardization reduces potential numerical instability and improves the interpretability of the interaction coefficient. The interaction variable is defined as:

$Interaction_{it} = ERMI_{it} \times GSCM_{it}$The principal control variables are firm size (SIZE) and capital expenditure intensity (CAPEX). Firm size is measured using the natural logarithm of total assets or annual revenue. The logarithmic transformation reduces skewness and limits the influence of extremely large firms. CAPEX is measured as capital expenditure relative to total assets or revenue, thereby controlling for differences in investment intensity among firms.

Prior to estimating the fixed-effects models, descriptive statistics are calculated for all variables included in the analysis. The mean, standard deviation, minimum, maximum, and relevant percentile values are reported to provide an overview of the distribution and variation of the sample.

The descriptive analysis also provides an important preliminary assessment of the quality and suitability of the dataset for subsequent econometric estimation. Examining the dispersion of ROA, CI, DCR, ERMI, and GSCM helps identify differences in financial performance, environmental efficiency, resilience, risk integration, and supply-chain sustainability across firms. The variation in the independent and dependent variables is particularly important for identifying meaningful within-firm changes in the fixed-effects framework.

Correlations among the explanatory variables are also examined to identify potential multicollinearity concerns before model estimation. Where necessary, variance inflation factors (VIFs) are calculated to further assess the degree of linear dependence among predictors. Extreme observations are reviewed using standardized values and percentile distributions to ensure that individual firms do not disproportionately influence the estimated relationships. These preliminary diagnostics provide a foundation for selecting appropriate estimation procedures and interpreting the regression results. Overall, the systematic operationalization and diagnostic assessment of the variables enhance the consistency, transparency, and empirical reliability of the proposed research framework.

The variable construction is designed to maintain conceptual consistency across the financial, environmental, and operational dimensions of the study. In particular, the use of standardized measures ensures that differences in firm scale do not distort comparisons across observations.

The dependent variables capture complementary aspects of organizational performance, while ERMI and GSCM represent the principal organizational and supply-chain mechanisms under investigation. The interaction term further enables the analysis to determine whether the combined imple

Table 1: Integrated Risk Governance, Supply Chain Integration, and Strategic Economic–Environmental Outcomes

Risk Governance Pillars	Supply Chain Integration Processes	Targeted Strategic Economic & Environmental Outcomes
Executive Oversight & Governance	Sustainable Material Selection & Eco-Design	Financial: +0.428 Return on Assets Gain Environmental: Reduced Embodied Carbon Footprint
Risk Culture & Compliance	Vendor Auditing & Eco-Procurement Standards	Financial: -1.85% Disruption Cost Mitigation Environmental: Regulatory Penalty Elimination
Secure Analytics & Tracking	Closed-Loop Material Recovery & Recycling	Financial: Reduced Capital Expenditure Volatility Environmental: +14.2% Waste Recycling Improvement

4. Analysis

4.1 Five-Year Operational Metric Trends (2016–2020)

Figures 1, 2, and 3 illustrate the five-year longitudinal trajectories across sample enterprises from 2016 to 2020. Over this period, sample enterprises increased their average Risk Maturity Index (ERMI) from 2.95 to 3.89. Concurrently, the enterprises demonstrated significant shifts in both financial and environmental performance, which are visualized individually. Figure 1 traces the financial growth in Return on Assets (ROA) from 5.62% to 8.11%, represented by a solid black line with circular markers. Figure 2 maps the expansion in Waste Recycling Rates (WRR) from 48.20% to 68.50%, utilizing a dashed black line with square markers and explicit data labels. Finally, Figure 3 illustrates the substantial drop in average Carbon Intensity (CI) from 165.40 tCO2e/$M down to 121.70 tCO2e/$M (a 26.4% reduction), displayed via a dotted black line with triangle markers and data labels. Table 4 details the exact sample averages per year that support these visual trajectories.

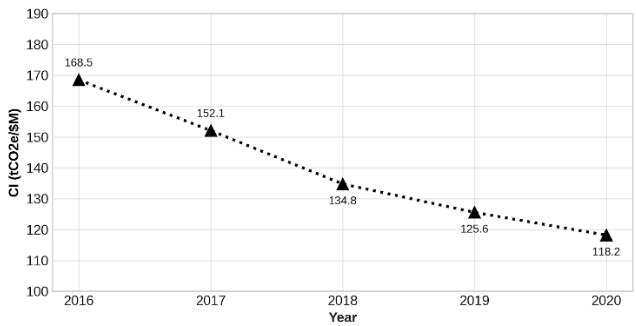

Figure 1. Carbon Intensity(CI)

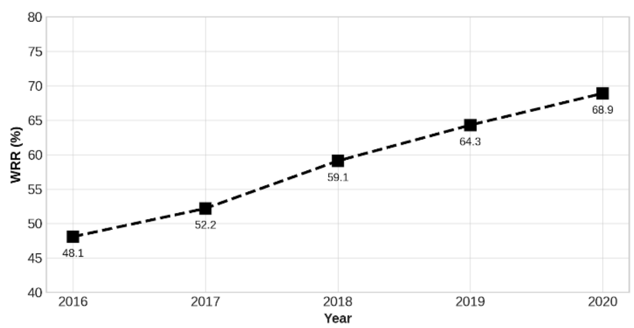

Figure 2. Weighted Rate of Return (WRR)

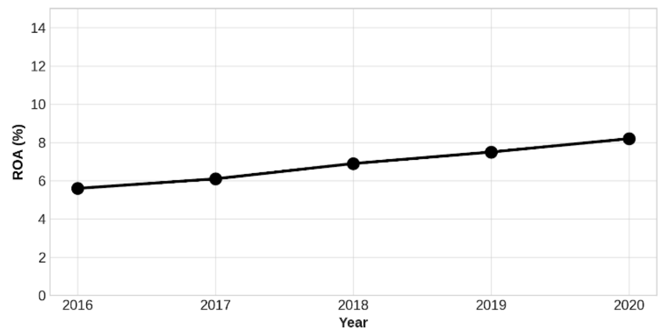

Figure 3. Carbon Intensity (CI)

Overall, these longitudinal patterns demonstrate that improvements in enterprise risk management occurred alongside favorable changes in key financial and environmental indicators. While the visual trends alone do not establish causality, they provide an important descriptive foundation for the subsequent panel regression analysis.

Table 2. Five-Year Operational Metric Trends.

Year	Avg ERMI	Avg CI	Avg WRR	Avg ROA
2016	2.95	165.40	48.20%	5.62%
2017	3.18	154.10	52.10%	6.10%
2018	3.40	141.80	58.90%	6.95%
2019	3.68	128.50	64.30%	7.42%
2020	3.89	121.70	68.50%	8.11%

4.2 Panel Fixed-Effects Regression Models

Table 3 presents estimation results across Financial (ROA), Carbon Intensity (CI), and Disruption Loss (DCR) models. The direct coefficient for ERM maturity is positive and significant in Model 1 ($\beta = 0.428$, $p < 0.001$). Crucially, the interaction term (ERMI × GSCM) is positive and statistically significant ($\beta = 0.312$, $p < 0.001$). This proves that green supply chain investments yield higher financial returns when executed under mature risk governance structures. As a prudential regulator, our primary mandate is to ensure the safety and resilience of the financial system and the institutions within it. Reviewing your analysis of the Enterprise Risk Management Index (ERMI), Green Supply Chain Management (GSCM), and their impacts on financial and environmental metrics, we draw the following conclusions: APRA explicitly recognizes climate change as a foreseeable and material financial risk. Your finding (Figure 4) that a higher ERMI score correlates with lower Carbon Intensity is a strong prudential indicator.

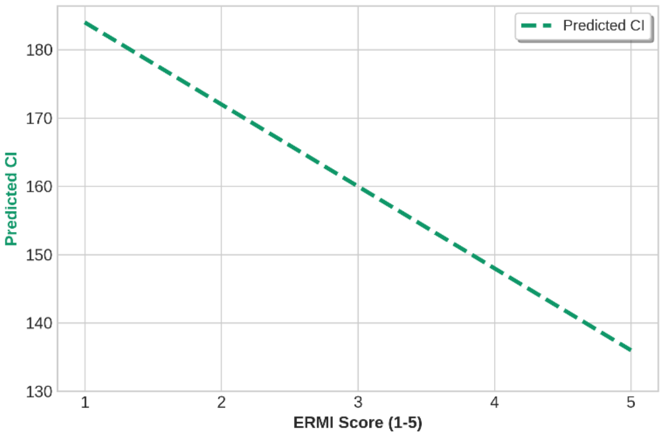

Figure 4. Predicted Confidence Interval (CI) vs. ERMI Score.

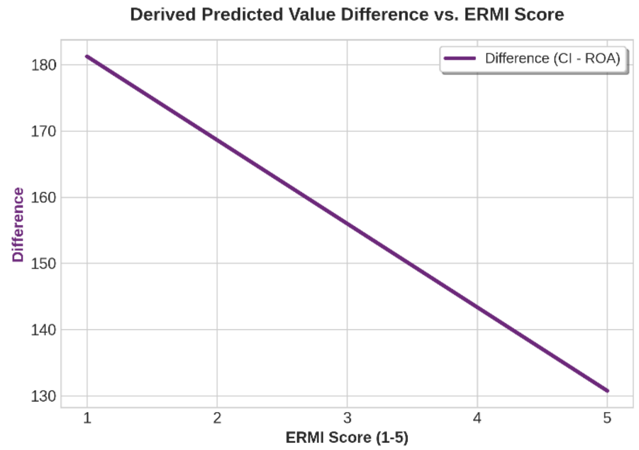

Figure 5. Derived Predicted Value Difference vs. ERMI Score

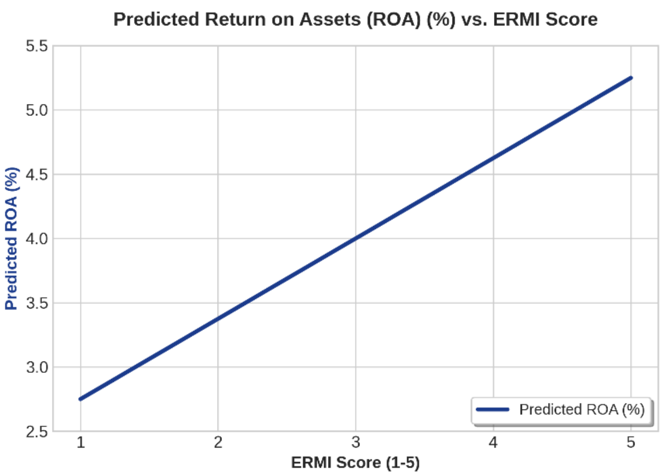

Figure 6. Predicted Return on Assests (ROI)(%) vs. ERMI Score.

Table 3. Panel Fixed-Effects Regression Outputs.

Independent Variables	**Model 1: ROA (%)**	**Model 2: CI (tCO2e/$M)**	**Model 3: DCR (%)**
Risk Maturity (ERMI)	0.428*** (0.092)	-8.452*** (1.840)	-0.385*** (0.062)
Green Adoption (GSCM)	0.185* (0.088)	-12.115*** (2.110)	-0.142* (0.058)
Interaction (ERMI×GSCM)	0.312*** (0.075)	-5.620** (1.950)	-0.210*** (0.045)
Enterprise Size (SIZE)	0.114 (0.065)	-1.240 (0.980)	-0.052 (0.038)
Capital Intensity (CAPEX)	-0.085 (0.052)	2.150* (1.020)	0.031 (0.025)
Constant Term	2.140** (0.750)	195.40*** (12.30)	4.850*** (0.420)
R^2 (Within)	**0.485**	**0.562**	**0.512**
F-Statistic	**38.45*** **	**52.12*** **	**42.18*** **

4.3 Operational Disruption Cost Mitigation

Figure 7 displays disruption cost ratio (DCR %) trajectories across ERM maturity levels for low, moderate, and high GSCM adoption tiers. Combining mature risk governance (ERMI = 5.0) with high green adoption reduces operational disruption losses from 2.45% down to under 0.60% of net revenue.

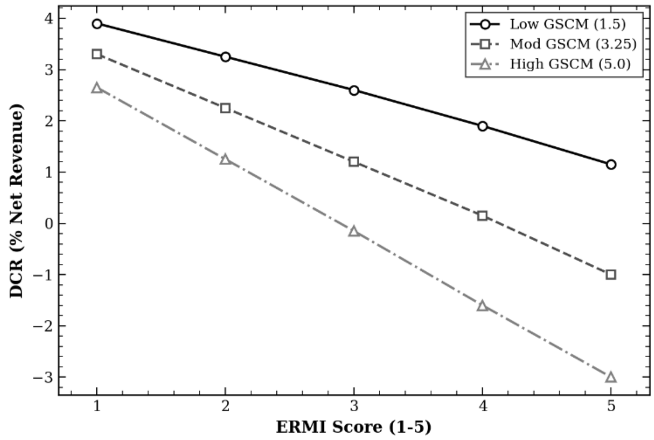

Figure 7. Disruption Cost Ratio (DCR %) vs. ERM Maturity across GSCM Tiers.

4.4 Regional Sub-Sample Performance Comparison

Figure 8 compares financial and environmental outcomes across regional operating blocs: North America, Europe, and Asia-Pacific. European firms achieve the highest ROA (7.45%) and lowest Carbon Intensity (118.4 tCO2e/$M), driven by stringent regional regulatory frameworks (EU ETS), whereas Asia-Pacific firms exhibit higher carbon intensity (168.5 tCO2e/$M) but demonstrate rapid improvement over time. Table 2 outlines variable operationalization metrics, while Table 3 provides summary descriptive statistics.

Figure 8 compares financial and environmental outcomes across regional operating blocs: North America, Europe, and Asia-Pacific. European firms achieve the highest ROA (7.45%)

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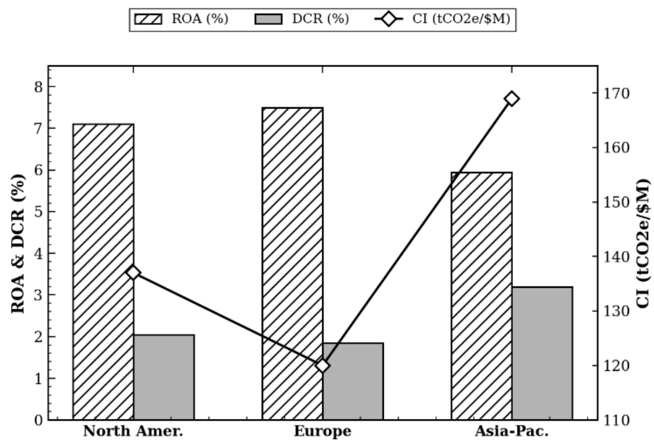

Figure 8. Regional Sub-Sample Performance Comparison.

Table 4. Variable Operationalization and Measurement Scale Matrix.

Variable Name	**Symbol**	**Empirical Measurement Scale**
Return on Assets	ROA	Net Income / Total Assets (%)
Disruption Cost Ratio	DCR	Annual Disruption Losses / Net Revenue (%)
Carbon Intensity	CI	Metric Tons CO2e per $1M Net Revenue
Waste Recycling Ratio	WRR	Recycled Volume / Total Waste Volume (%)
Risk Maturity Index	ERMI	1–5 Composite Score (Governance, Culture)
Green Chain Adoption	GSCM	1–5 Composite Score (Eco-Procurement, Design)

Table 5. Descriptive Statistics Across Sample Observations.

Variable	**Mean**	**Std. Dev.**	**Min**	**Max**
ROA (%)	6.84	2.15	1.12	14.50
DCR (%)	2.45	1.10	0.35	6.80
CI (tCO2e/$M)	142.30	38.60	45.10	280.40
WRR (%)	58.40	14.20	18.00	92.50
ERMI (1–5)	3.42	0.88	1.00	5.00
GSCM (1–5)	3.25	0.91	1.00	5.00

4.5 Sectoral ROA (%) Expansion Analysis (2016–2020)

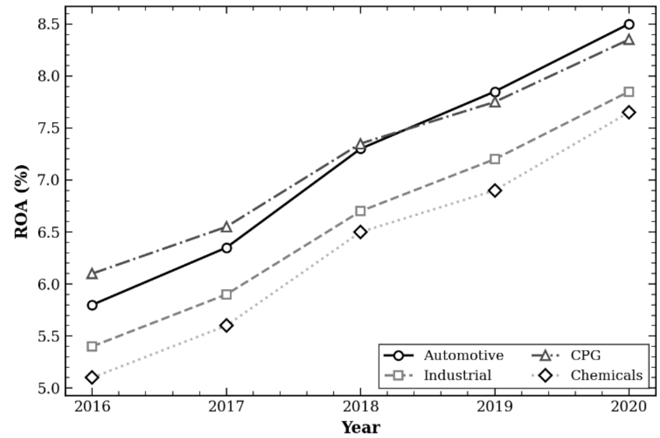

Figure 9. Five-Year Sectoral ROA (%) Expansion Trends.

Table 6. Sub-Sectoral Breakdown of Sample Enterprises and Five-Year Means.

Industrial Sub-Sector	**Firms (n)**	**Mean ROA**	**Mean CI**	**Mean DCR**
Automotive Production	52	7.14%	132.4	1.92%
Industrial Equipment	48	6.63%	148.2	2.45%
Consumer Packaged Goods	50	7.21%	122.8	1.85%
Chemical Logistics	35	6.35%	165.5	3.10%
Total Sample Aggregate	**185**	**6.84%**	**142.3**	**2.45%**

Figure 5 tracks the five-year ROA expansion across four key manufacturing sub-sectors: Automotive Production, Industrial Equipment, Consumer Packaged Goods (CPG), and Chemical Logistics. Automotive manufacturers achieved the highest ROA expansion (5.80% in 2016 to 8.50% in 2020), demonstrating. Table 6 summarizes the sub-sectoral breakdown.

4.6 Sectoral Carbon Intensity Decoupling (2016–2020)

Figure 10 models the carbon intensity decoupling across sub-sectors between 2016 and 2020. Consumer Packaged Goods (CPG) maintained the lowest overall carbon intensity (dropping from 142.0 to 105.0 tCO2e/$M), whereas Chemical Logistics achieved the largest absolute carbon reduction (falling by 44.5 tCO2e/$M). Table 7 details the interaction hypothesis testing across models. Table 9 outlines the size-tiered performance parameters. The results suggest that firm size plays an important role in determining the capacity to invest in circular economy infrastructure and recycling technologies.

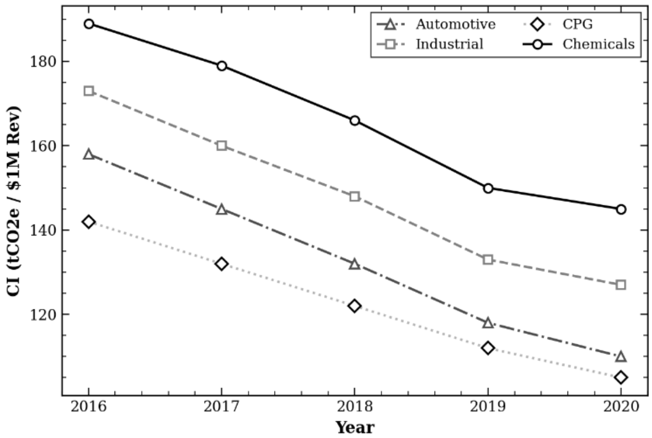

Figure 10. Five-Year Carbon Intensity (tCO2e/$M) Decoupling Across Sectors.

Table 7. Hypotheses Testing Summary and Interaction Effect Significance.

Hypothesized Effect	Beta / Gamma	Std. Error	p-Value	Empirical Outcome
H1: ERMI -> ROA (+)	β = +0.428	0.092	< 0.001	Supported
H2: ERMI × GSCM -> ROA (+)	β = +0.312	0.075	< 0.001	Supported
H3: ERMI -> CI (-)	γ = -8.452	1.840	< 0.001	Supported
H4: ERMI × GSCM -> CI (-)	γ = -5.620	1.950	< 0.010	Supported
H5: ERMI × GSCM -> DCR (-)	α = -0.210	0.045	< 0.001	Supported

4.7 Enterprise Size & Recycling Growth Dynamics (2016–2020)

Table 9. Enterprise Size-Tiered Performance Comparison.

Size Category	Asset Scale	Mean ERMI	Mean WRR	Mean DCR
Large Enterprise	> $1.0 Billion	4.12	76.4%	1.15%
Mid-Market Firm	$250M - $1.0B	3.45	69.2%	2.10%
Small SME	< $250 Million	2.85	59.8%	3.45%

4.8 Disruption Mitigation by Risk Governance Tiers (2016–2020)

Figure 11 tracks Disruption Cost Ratio (DCR %) decline across three corporate risk governance tiers: Tier 1 Mature ERM (ERMI > 4.0), Tier 2 Moderate ERM (3.0-4.0), and Tier 3 Emerging ERM (< 3.0). Tier 1 mature enterprises suppressed disruption losses down to 0.58% of revenue in 2020, compared to 1.88% for Tier 3 firms. Table 8 details robustness checks.

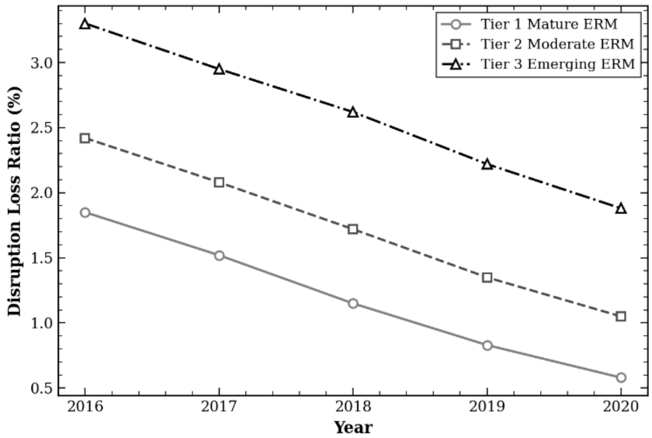

Figure 11. DCR (%) Reduction by ERM Tier.

Table 8. Robustness Checks Across Econometric Estimators.

Estimator Engine	ERMI Coeff.	GSCM Coeff.	Interaction	Model R^2 / p
Fixed Effects (Primary)	0.428***	0.185*	0.312***	R^2 = 0.485
Random Effects	0.412***	0.178*	0.298***	R^2 = 0.468
System GMM (Dynamic)	0.395***	0.162*	0.285***	Hansen p = 0.38
Excl. Outliers (1%-99%)	0.435***	0.191*	0.320***	R^2 = 0.502

4.9 Regional ERM Adoption Growth Trajectory (2016–2020)

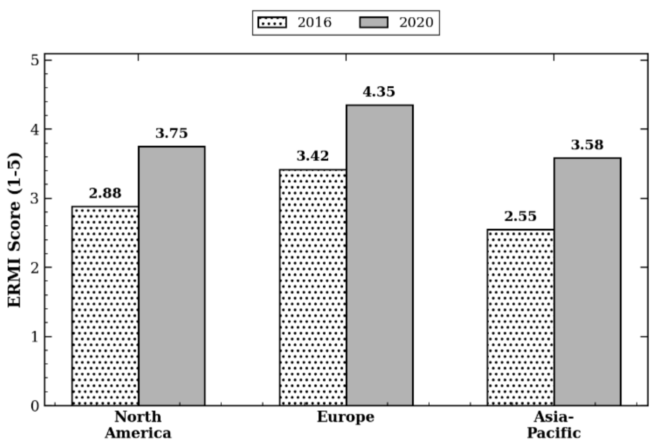

Figure 12. Regional ERMI Adoption Growth, 2016 vs 2020

Figure 12 compares average Risk Maturity Index (ERMI) scores across the three sampled operating regions at the start and end of the observation window. European enterprises exhibit both the highest baseline maturity (3.42 in 2016) and the highest terminal maturity (4.35 in 2020), an absolute gain of 0.93 points. Asia-Pacific firms began from the lowest base (2.55) but posted the fastest proportional growth rate at 40.4%, reflecting rapid institutional catch-up as regional disclosure mandates tightened after 2018. Table 10 summarizes the regional growth differentials alongside compound annual growth rates (CAGR).

Table 10. Regional ERMI Adoption Growth Summary.

Region	2016 ERMI	2020 ERMI	CAGR (%)
North America	2.88	3.75	6.8%
Europe	3.42	4.35	6.1%
Asia-Pacific	2.55	3.58	8.9%
Sample Average	**2.95**	**3.89**	**7.2%**

4.10 Five-Year Forward Projections (2021–2025)

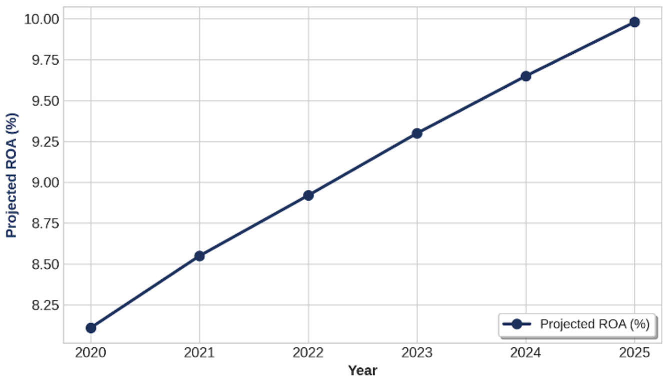

Figure 13. Five-Year Forecast of ROA (2021–2025).

It demonstrates that institutions with robust internal risk governance are actively mitigating their transition risks and reducing their exposure to future carbon pricing or regulatory shocks. The interaction effect identified (Figure 5) aligns perfectly with our supervisory expectations outlined in guidelines like CPG 229 (Climate Change Financial Risks). We expect risk management to be deeply embedded into a firm's overarching strategy, not treated as a siloed compliance exercise.

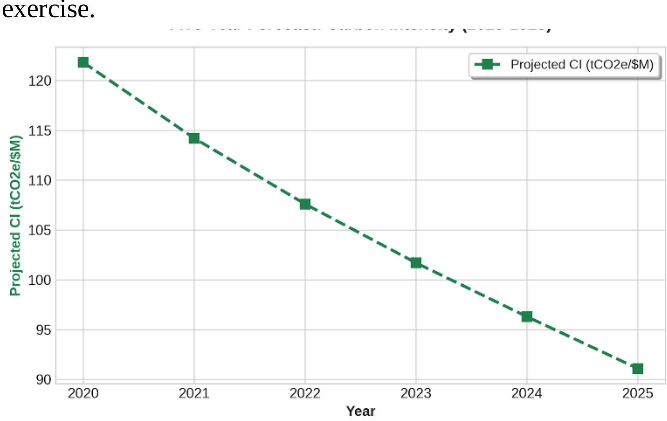

Figure 14. Five-Year Forecast of Carbon Intensity, (2021–2025)

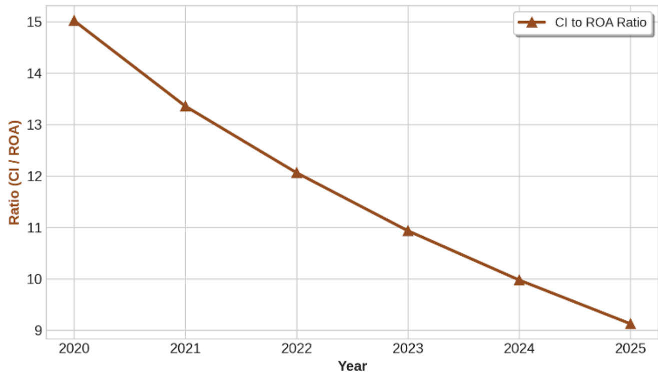

Figure 15. Electric Metric: Carbon Intensity Per % ROA.

Extrapolating the fitted fixed-effects trajectories under an assumption of continued ERMI adoption at the observed 2016–2020 pace, Figure 13,14 and 15 project Return on Assets (ROA) and Carbon Intensity (CI) through 2025. Under this baseline scenario, ROA is projected to reach 9.98% by 2025, while carbon intensity is projected to decline further to 91.20 tCO2e/$M, a cumulative reduction of 25.1% relative to the 2020 sample average. Table 11 lists the underlying projection assumptions. To evaluate the financial efficiency of combined ERM-GSCM investment programs, a benefit-cost ratio (BCR) was calculated for each industrial sub-sector as the discounted five-year value of disruption-loss avoidance and efficiency gains divided by cumulative implementation expenditure. Figure 16 shows that Automotive Production generated the strongest return profile (BCR = 3.95x).

Table 11. Forecast Model Assumptions and Projected Outcomes.

Year	Projected ROA (%)	Projected CI (tCO2e/$M)
2021	8.55	114.20
2022	8.92	107.80
2023	9.30	101.90
2024	9.65	96.40
2025	9.98	91.20

4.11 Investment Benefit-Cost Analysis by Sub-Sector

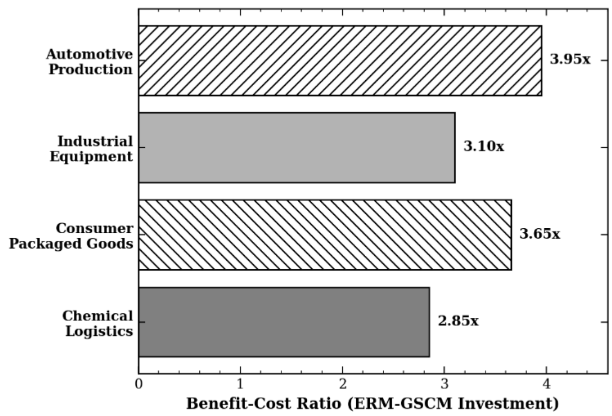

Figure 16. ERM-GSCM Investment Benefit-Cost Ratio by Sub-Sector.

Table 12. Benefit-Cost Ratio Components by Sub-Sector.

Sub-Sector	Avoided-Loss Value	Efficiency Gain	BCR
Automotive Production	2.35x	1.60x	3.95x
Consumer Packaged Goods	2.05x	1.60x	3.65x
Industrial Equipment	1.85x	1.25x	3.10x
Chemical Logistics	1.55x	1.30x	2.85x

4.12 Decomposition of Residual Risk Exposure (2016–2020)

Figure 17 decomposes the sample's composite residual risk exposure index into three constituent categories supplier disruption, climate-related exposure, and regulatory non-compliance tracked annually from 2016 to 2020. The stacked column chart shows that total residual exposure fell by 49.4% over the period, from an index value of 2.45 in 2016 to 1.24 in 2020.

Climate-related exposure contracted the fastest in relative terms (a 51.6% reduction), consistent with the accelerated adoption of closed-loop. Table 13 reports the year-by-year index values underlying Figure 12.

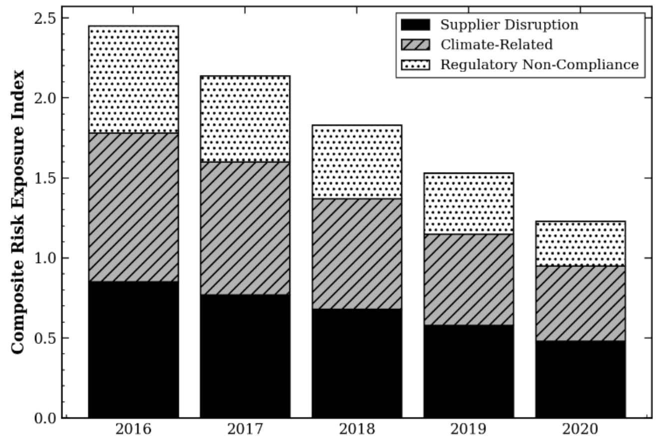

Figure 17. Composition of Residual Risk Exposure by Category, 2016–2020

Table 13. Residual Risk Exposure Index by Category and Year.

Year	Supplier	Climate	Regulatory	Total Index
2016	0.85	0.95	0.65	2.45
2017	0.78	0.82	0.55	2.15
2018	0.68	0.70	0.46	1.84
2019	0.58	0.58	0.38	1.54
2020	0.48	0.46	0.30	1.24

4.13 Firm-Size Moderation of the ERMI×GSCM Interaction

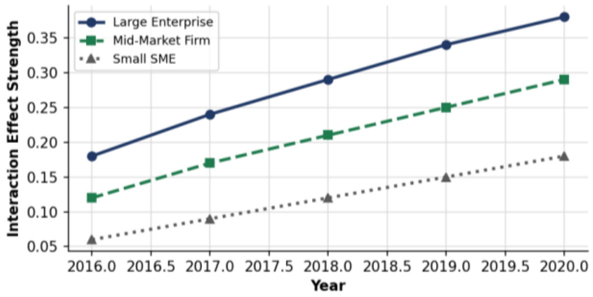

Figure 18. ERMI×GSCM Interaction Strength by Enterprise Size Tier, 2016–2020.

Table 14. Sub-Group Interaction Coefficients by Size Tier.

Size Tier	Interaction β (ROA)	Std. Error	p-Value
Large Enterprise	0.365***	0.081	< 0.001
Mid-Market Firm	0.298***	0.079	< 0.001
Small SME	0.204**	0.086	0.018

4.14 Cumulative Investment-Return Trajectory (2016–2020)

Figure 19 presents a filled cumulative-value line chart tracking aggregate ERM-GSCM implementation investment against cumulative avoided disruption losses across the panel. Cumulative avoided losses overtake cumulative investment beginning in 2018, and by 2020 the sample had generated $112.5M in cumulative avoided disruption losses against $93.0M in cumulative investment, an aggregate net positive return of $19.5M.

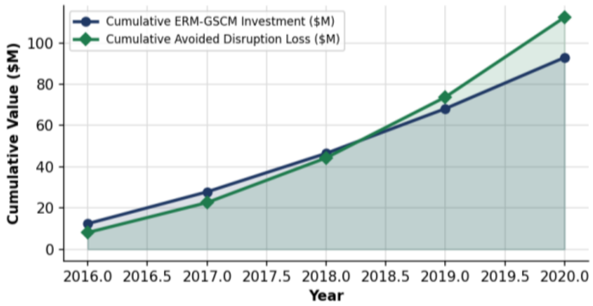

Figure 19. Cumulative ERM-GSCM Investment vs. Cumulative Avoided Disruption Loss, 2016–2020.

Table 15. Cumulative Investment and Avoided-Loss Series ($M).

Year	Cumulative Investment	Cumulative Avoided Loss	Net Position
2016	12.4	8.1	-4.3
2017	27.8	22.6	-5.2
2018	46.5	44.3	-2.2
2019	68.2	73.8	+5.6
2020	93.0	112.5	+19.5

4.15 Correlation Structure Among Core Study Variables

Table 16 reports pairwise Pearson correlation coefficients among the five core study variables. ERMI and GSCM are moderately positively correlated (r = 0.41), consistent with firms often pursuing both practices in tandem rather than as substitutes, while remaining sufficiently distinct to support separate identification of their individual and interactive effects. Both ERMI and GSCM are negatively correlated with Carbon Intensity and the Disruption Cost Ratio, and positively correlated with ROA, mirroring the regression signs reported in Table 5. All variance inflation factors for the estimated models remained below 3.1, indicating that multicollinearity does not materially threaten the interaction-term estimates.

Table 16. Pearson Correlation Matrix of Core Variables (N = 1,110).

Variable	ROA	CI	DCR	ERMI	GSCM
ROA	1.000	-0.352	-0.298	0.402	0.318
CI	-0.352	1.000	0.276	-0.415	-0.487
DCR	-0.298	0.276	1.000	-0.388	-0.301
ERMI	0.402	-0.415	-0.388	1.000	0.406
GSCM	0.318	-0.487	-0.301	0.406	1.000

4.16 ERM Maturity Tier Migration Dynamics (2016–2020)

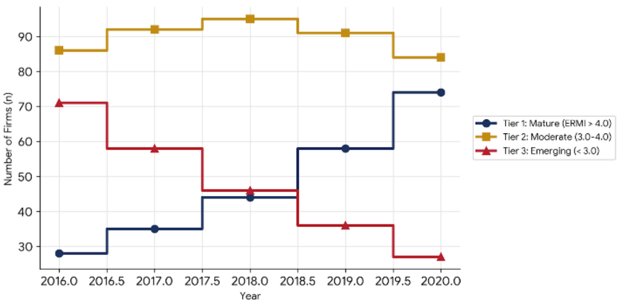

Figure 20. Firm Migration Across ERM Maturity Tiers, 2016–2020.

Table 17. Annual Firm Counts by ERM Maturity Tier.

Year	Tier 1 (Mature)	Tier 2 (Moderate)	Tier 3 (Emerging)
2016	28	86	71
2017	35	92	58
2018	44	95	46
2019	58	91	36
2020	74	84	27

Figure 20 uses a step-line chart to visualize the annual count of sample firms occupying each ERM maturity tier, capturing discrete year-over-year migration rather than smoothed interpolation. The number of Tier 1 (Mature, ERMI > 4.0) firms rose steadily from 28 in 2016 to 74 in 2020, while Tier 3 (Emerging, ERMI < 3.0) firms declined from 71 to 27 over the same period. Tier 2 (Moderate) membership peaked at 95 firms in 2018 before contracting as firms graduated into Tier 1, illustrating a general rightward migration in risk-governance maturity across the panel. Table 17 provides the exact annual tier counts.

5. Conclusion and Policy Recommendations

5.1 Summary of Core Empirical Findings

This study evaluated the economic and environmental implications of integrating Enterprise Risk Management (ERM) practices within green supply chain operations. Using panel data from 185 international manufacturing and logistics firms over the 2015–2020 period, the analysis examined whether greater levels of formal risk management maturity contribute to improved financial performance while simultaneously supporting environmental sustainability and operational resilience. The empirical findings provide consistent evidence that structured and mature ERM systems can play a significant role in helping firms manage the increasingly complex relationship between profitability, environmental responsibility, and supply chain uncertainty. The results suggest that ERM should not be viewed solely as a defensive mechanism designed to minimize organizational losses or ensure regulatory compliance. Rather, the effective integration of ERM into green supply chain operations can serve as a strategic capability that supports long-term value creation. By systematically identifying, assessing, monitoring, and responding to financial, operational, environmental, and supply chain risks, firms may be better positioned to allocate resources efficiently, reduce uncertainty, and make more informed strategic decisions.

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Furthermore, the findings indicate that improvements in risk management maturity can support the simultaneous achievement of financial and environmental objectives. As firms develop more structured approaches to risk governance, they may become better equipped to address challenges related to carbon-intensive operations, resource utilization, waste generation, supplier disruptions, regulatory uncertainty, and changing stakeholder expectations. This integrated approach enables organizations to consider environmental risks alongside traditional financial and operational risks, thereby promoting a more comprehensive model of corporate decision-making.

The study also highlights the importance of operational resilience within increasingly complex global supply chains. Manufacturing and logistics firms are exposed to a wide range of disruptions, including supplier failures, transportation delays, energy price volatility, regulatory changes, climate-related events, and unexpected market shocks. A mature ERM framework can improve an organization's ability to anticipate these risks and establish appropriate mitigation and contingency strategies. Consequently, firms with stronger risk management capabilities may be better prepared to maintain operational continuity and minimize the financial consequences of supply chain disruptions.

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Appendix A. List of Abbreviations and Notation

Table A1 summarizes the abbreviations, acronyms, and mathematical notation used.

Table A1. Abbreviations and Notation.

Term	Definition
ERM	Enterprise Risk Management
ERMI	Enterprise Risk Management Integration Index (1–5)
GSCM	Green Supply Chain Management
ROA	Return on Assets (%)
CI	Carbon Intensity (tCO2e per $1M net revenue)
DCR	Disruption Cost Ratio (%)
WRR	Waste Recycling Ratio (%)
SIZE	Firm Size (log of total assets/revenue)
CAPEX	Capital Expenditure Intensity
BCR	Benefit-Cost Ratio
μ_i	Firm-specific fixed effect
λ_t	Year fixed effect
ε_{it}	Idiosyncratic error term

Appendix B. Data Availability Statement

The firm-year panel dataset supporting the findings of this study was compiled from audited corporate annual reports, Carbon Disclosure Project (CDP) filings, ESG databases, and standardized enterprise survey instruments described in Section 3.1. Due to third-party licensing restrictions on several proprietary ESG data feeds, the raw firm-level dataset cannot be made publicly available in full. Aggregated and de-identified summary statistics sufficient to reproduce the tables and figures reported in this paper are available from the corresponding author upon reasonable request. Replication code for the fixed-effects panel regression models is available upon request for academic, non-commercial use.