

Article

Measuring Environmental Exposure Beyond ESG Ratings: A Transparent Sector-Based Carbon-Exposure Measure and Firm Profitability Across Six Developed Markets

Mashaël Bakhit ¹, Fawwaz Alrwabdeh ^{2,*}, Ahmad Alomari ², Iman Babiker ¹, Amal Alharthi ¹ and Ghazal Zainy ¹

¹ Department of Accounting, College of Business Administration, Princess Nourah Bint Abdulrahman University, P.O. Box 84428, Riyadh 11671, Saudi Arabia; maabdeurhman@pnu.edu.sa (M.B.); iakhalid@pnu.edu.sa (I.B.); amalharthi@pnu.edu.sa (A.A.); ghzainy@pnu.edu.sa (G.Z.)

² Department of Accounting, School of Management, Universiti Sains Malaysia, Gelugor 11800, PG, Malaysia; ahmadalomari@student.usm.my

* Correspondence: fawazrawabdeh88@yahoo.com

Abstract

Environmental, social, and governance (ESG) ratings are now central to how firms' sustainability is assessed, yet leading providers disagree sharply, injecting measurement error and uncertainty into any rating-based decision. This study proposes and applies a transparent, fully reproducible alternative for the environmental pillar: an ordinal, sector-based carbon-exposure measure constructed solely from firms' publicly observable industry classifications, free of vendor scoring choices and reconstructable at zero cost. The measure captures structural, between-sector carbon exposure; it is not a firm-level environmental-performance score and does not use reported emissions. Using 3067 firm-year observations on 1049 listed non-financial firms that carry an observed sector classification across six developed markets (the United States, the United Kingdom, Australia, France, Italy, and Spain) over fiscal 2021–2025 (with a small number of early fiscal-2026 period-ends), we assess the measure's informativeness by estimating its association with accounting profitability in high-dimensional fixed-effects models. Descriptively, more carbon-intensive sectors are less profitable (a monotone brown tilt), but this association is not robust: once firm controls and country-by-year fixed effects are absorbed, carbon exposure is not significantly related to return on assets, return on equity, or net margin, and there is no evidence of a concave (inverted-U) pattern. The measure does recover a real operating difference, higher asset turnover among carbon-intensive sectors, but this is offset by margins and does not translate into a profitability premium. A within-firm design detects no differential effect of mandatory non-financial reporting. The contribution is a transparent, rule-based environmental measure that sidesteps rating divergence; the honestly reported null on profitability cautions that apparent effects are sensitive to sample construction and sectoral composition, and positions the measure as a complement to, rather than a substitute for, proprietary ESG ratings.

Keywords: ESG performance assessment; construction of ESG measures; ESG rating divergence; environmental exposure; carbon intensity; firm profitability; transparent measurement; legal origin

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1. Introduction

Whether a firm's environmental profile is rewarded or penalized in the capital market is among the most consequential and least settled questions in contemporary accounting and finance research. A large body of work reports that stronger environmental and sustainability performance is associated with favorable financial outcomes: lower financing constraints [1], a lower cost of equity and debt capital [2–5], higher firm value [6–8], and reduced firm risk and default probability [9–11]. Yet the evidence is far from unanimous. Other studies document weak, conditional, or even negative associations between sustainability and financial outcomes [12–14], and the two largest syntheses of the literature conclude that the aggregate relationship, while non-negative on average, is highly heterogeneous across measures, methods, and settings [15,16]. A growing consensus traces much of this heterogeneity to a deeper, prior problem: how environmental performance is measured in the first place.

This measurement problem is the point of departure for the present study, and it frames three limitations of the existing evidence. First, and most fundamentally, the overwhelming majority of prior work proxies a firm's environmental profile with commercial ESG ratings, which are proprietary, costly, and exhibit pronounced disagreement across providers; this rating divergence injects measurement error directly into firm-level estimates and undermines comparability across studies [17]. Because different agencies score the same firm differently, any inference drawn from a single vendor's rating is conditional on that vendor's undisclosed scoring choices. Second, the environmental-performance relationship is almost always modeled as monotonic, even though both theory and a small but growing empirical literature suggest the payoff to environmental positioning may be non-linear, positive over some range and negative beyond it [18,19]. Third, the most influential evidence is concentrated in a small number of settings, above all the United States; the two largest meta-analyses of the field document that North American and, to a lesser extent, European studies dominate the evidence base [15,16], leaving the institutional conditions under which environmental positioning is priced largely unexamined.

We address these limitations, beginning with measurement. We construct a transparent, fully reproducible measure of industry carbon exposure from firms' sector classifications, assigning each firm to one of three ordered carbon-intensity tiers (Low, Medium, High). The measure is deliberately an industry-based proxy: it captures structural, between-sector carbon exposure that is a deterministic function of a firm's publicly observable sector code. It is neither a firm-level environmental-performance score nor a measure of realized emissions (it uses no tonnes of CO₂, no emissions-to-sales or emissions-to-assets ratio, and no vendor rating). Because the tier is a deterministic function of an observed sector code, it is replicable at zero cost and immune to the vendor-specific scoring choices that drive ESG-rating disagreement [17]; firms that lack an observed sector classification cannot be assigned a tier and are excluded. We apply this measure to a firm-year panel of 3067 observations on 1049 listed non-financial firms drawn from the principal equity indices of six developed markets (the United States, the United Kingdom, Australia, France, Italy, and Spain) over fiscal years 2021–2025 (with a small number of early fiscal-2026 period-ends). We estimate the association between carbon exposure and accounting profitability using high-dimensional fixed-effects models that absorb every shock common to firms in a given market-year, with standard errors clustered by firm, and we test explicitly for non-linearity rather than imposing a monotonic functional form. Because the industry measure is time-invariant within firm, our identification is fundamentally cross-sectional; throughout we frame our estimates as associations rather than causal effects.

Our findings are more cautionary than the “green pays” or “brown is punished” narratives that populate the literature. At the univariate level the pattern is a monotone brown

tilt: mean return on assets (ROA) is highest for firms in low-carbon sectors and declines across the medium and high tiers. This tilt, however, is not robust. Once firm controls and country-by-year fixed effects are included, the tier is not significantly associated with ROA, and the same holds for return on equity (ROE) and net profit margin; a quadratic specification yields no evidence of a concave (inverted-U) relationship. The raw brown tilt reflects the composition of the tiers, higher-profitability knowledge and service sectors at the low end and lower-profitability extractive and utility sectors at the high end, rather than a distinct carbon-exposure premium: once we control for industry-level profitability directly, the tier adds nothing, while industry profitability itself is strongly predictive. The measure nonetheless recovers one economically meaningful operating difference: carbon-intensive sectors exhibit significantly higher asset turnover (revenue per unit of assets), a difference that is offset by margins and therefore does not surface in profitability. A within-firm design that interacts carbon exposure with the onset of mandatory non-financial reporting detects no differential profitability effect over the sample window.

This study makes three contributions. First, and methodologically, it contributes a transparent, zero-cost measure of environmental exposure that sidesteps ESG-rating disagreement and is reproducible across markets, offering a verifiable complement to proprietary ratings for researchers and decision-makers who require an auditable environmental signal [17]. Second, it provides carefully identified evidence that carbon exposure, measured at the sector level, is not robustly associated with accounting profitability once sectoral composition and market-year heterogeneity are absorbed; this null, honestly reported, helps reconcile the positive, negative, and null findings in the literature by showing how sensitive such associations are to sample construction and to the level at which the environmental signal is defined [15,16]. Third, by documenting that the measure captures a real operating difference (asset productivity) that does not map into profitability, and by showing that any apparent tier effect is subsumed by industry-level profitability, it clarifies what an industry-based environmental proxy can and cannot reveal about firm outcomes.

The remainder of the paper proceeds as follows. Section 2 reviews the literature and develops the hypotheses. Section 3 describes the research design, sample, and measurement. Section 4 reports the results. Section 5 discusses the implications and limitations, and Section 6 concludes.

2. Literature Review and Hypothesis Development

2.1. Environmental Sensitivity and Firm Financial Outcomes

A wide body of research explores the connections among firms' environmental and sustainability standards and their financial outcomes in several ways. A number of studies provide evidence of a positive correlation between environmental performance and market valuation and operating performance [6–8,20], and indicate that sustainability-focused portfolios do not underperform conventional portfolios [14,21,22]. On the cost-of-capital margin, environmental responsibility is linked to a lower cost of equity and debt [2,4], to environmental externalities priced into the cost of capital [3], and to the disclosure of environmental, social, and governance (ESG) issues as an informational signal affecting financing costs and price informativeness [5]. Sustainability performance is related to the reduction of firm risk, idiosyncratic volatility, default risk, and credit spreads [9–11,23–25], while environmental exposure is also linked to the commodity-price and default dynamics of carbon-linked industries [26–28]. A related strand connects sustainability to financial slack and liquidity management, including financing constraints [1], corporate cash holdings [29–33], and the deployment of excess cash [34,35].

The financial payoff to environmental positioning is also shaped by uncertainty and by ownership. Economic-policy and price uncertainty affect both ESG performance and the

efficiency of corporate investment [36–38], and sustainability performance can attenuate the adverse effects of uncertainty on firm outcomes [13,39]. Ownership structure, in turn, conditions firms’ sustainable investment and ESG performance [40,41]. How investors actually price environmental activity varies across firms and settings [12,42–44], and ESG controversies are associated with weaker investment efficiency [45]. The profitability mechanics that translate these forces into accounting returns, operating efficiency, the cash-conversion cycle, and asset productivity, are themselves established determinants of firm performance [46–49].

2.2. Non-Monotonicity in the Environmental-Performance Relationship

A persistent feature of this literature is its inconsistency: positive, negative, and null associations all appear, often for similar constructs. The two largest meta-analyses conclude that the average environmental-financial performance relationship is positive but modest and highly heterogeneous [15,16]. One explanation for this heterogeneity is functional form. In an influential study, Trumpp and Guenther [18] argue that linear models are misspecified and find a non-linear relationship between corporate environmental performance and financial performance; in their data the relationship is U-shaped in environmental performance (a “too-little-of-a-good-thing” pattern in which the payoff to environmental engagement materializes only beyond a threshold). Other work reports the opposite curvature: an inverted-U in which financial performance peaks at intermediate levels of environmental engagement and falls at the extremes, a “too-much-of-a-good-thing” pattern [19]. What this literature establishes is not a single agreed direction but the more basic point that the relationship is non-linear, so that studies imposing a monotonic form, or sampling different regions of the underlying curve, will reach opposing conclusions. This reframes the empirical question from whether environmental sensitivity pays to what functional form the relationship takes, and motivates an explicit test for non-linearity rather than the imposition of a monotonic form. We note at the outset that our measure captures carbon exposure (higher for more carbon-intensive sectors), the reverse orientation of an environmental-performance score, and we are careful not to equate the two.

2.3. Instrumental Stakeholder Theory and the Shape of the Payoff

The dominant theoretical lens for why environmental positioning should carry financial consequences is stakeholder theory [50], and in particular its instrumental variant, which holds that effective management of stakeholder relationships, including the natural environment and the parties who advocate for it, is a means to superior financial performance [51]. On this logic, firms that address their environmental exposure can lower regulatory and litigation risk, secure access to capital and customers, and avoid the reputational and operational costs borne by environmental laggards. The instrumental mechanism admits two distinct shapes, however, and the theory alone does not select between them. A simple reading predicts a monotone relationship in exposure: the greater a firm’s structural carbon exposure, the greater its unmanaged environmental risk and transition cost, and the lower its profitability (a “brown discount”). A non-linear reading predicts concavity: the benefits of environmental engagement accrue at a diminishing rate while abatement, transition, and compliance costs rise steeply for the most carbon-intensive activities, so that the net payoff is greatest at intermediate exposure and erodes at the extremes, a “too-much-of-a-good-thing” pattern [19,52]. Because concavity is the more novel and less-tested prediction, and because it nests the monotone case as a limiting form, we frame the primary hypothesis around it and test for non-linearity explicitly:

H1. *The association between industry carbon exposure and firm profitability is non-monotonic (concave): profitability is highest at moderate levels of exposure and lower at both low and high levels.*

2.4. The Institutional Contingency: Legal Origin

Instrumental stakeholder theory explains why environmental exposure should matter for profitability, but not where it should matter most. The mechanism relies on disclosure, investor scrutiny, capital-market discipline, and stakeholder activism, all of which are themselves institutionally determined [21,44,53]. We therefore complement the primary lens with the legal-origin perspective of comparative institutional analysis [54], which holds that common-law and civil-law traditions differ systematically in investor protection, capital-market depth, transparency, and corporate disclosure, with common-law systems offering stronger investor protection and more market-oriented governance. The deeper, more transparent capital markets and more active institutional investors of common-law settings make them more likely to price a firm's environmental exposure, whereas the concentrated ownership and bank-centred discipline of civil-law settings make the same signal less likely to be reflected in observable market outcomes [1,14]. The instrumental stakeholder mechanism should therefore operate more powerfully where institutions reward it:

H2. *The non-monotonic association between industry carbon exposure and firm profitability is stronger in common-law markets than in civil-law markets.*

2.5. Mandatory Non-Financial Reporting: An Open Question

A natural further question is whether the introduction of mandatory non-financial (ESG) reporting alters the profitability of carbon-intensive firms. The literature on the real effects of disclosure regulation suggests the answer is theoretically ambiguous: mandatory disclosure can intensify scrutiny of high-exposure firms, but its measurable consequences depend on whether it conveys genuinely new information and on the horizon over which outcomes are measured [55]. Because theory and timing pull in opposing directions, we treat this as an exploratory research question rather than a directional hypothesis, examined within firm using the staggered onset of mandatory reporting:

RQ1. *Did the onset of mandatory non-financial reporting differentially affect the profitability of carbon-intensive firms?*

3. Materials and Methods

3.1. Sample and Data

We assemble a firm-year panel of listed large-, mid-, and small-cap companies from the principal equity indices of six developed markets: the United States (S&P 500/400/600), the United Kingdom (FTSE 350), Australia (ASX 200), France (CAC 40), Italy (FTSE MIB), and Spain (IBEX 35). Firm-level accounting and market data are obtained from published annual financial statements and daily price histories; country-level institutional and macro-environmental indicators are drawn from the World Bank Open Data archive. The raw extract contains 9559 firm-year observations on 2018 firms.

The observation window covers fiscal years ending in calendar 2021 through 2025, together with a small number of early fiscal-2026 period-ends (98 observations in the estimation sample) that arise from firms with non-December fiscal years whose FY2026 statements were already filed at the time of data collection (15 June 2026). We retain these observations in the main analysis for completeness and show in Section 4.4 that excluding them leaves the results unchanged; no observation relies on unreported or forecast data. The effective panel is short (a median of three firm-years per firm), a feature we return to when interpreting the within-firm tests and the generalizability of the findings.

Consistent with standard practice, we apply four screens. First, we exclude financial firms, whose capital structure and accruals are not comparable with those of non-financial firms. Second, we drop observations flagged for implausible ratios (for example, absolute ROA above one, or leverage outside the interval from 0 to 1.5), which typically reflect data-feed errors. Third, we require non-missing values for the dependent variable and the carbon-exposure measure. Fourth, because the carbon-exposure measure is a deterministic function of a firm's observed sector code (Section 3.2), we require an observed sector classification: firms for which the data provider reports no sector cannot be assigned a tier on a defensible, rule-based basis and are excluded. This fourth screen is the main change from an earlier version of the analysis; it removes roughly 1900 firm-years that lacked an observed sector and that a naive default rule would have placed in the Low tier, and it materially affects the results (Section 4). All ratio-based dependent variables and continuous controls are winsorized at the 1st and 99th percentiles within the screened sample. The resulting sample used for the descriptive statistics contains 3176 firm-year observations on 1084 firms; the baseline regression sample, after listwise deletion on the full control set, comprises 3067 firm-year observations on 1049 firms.

3.2. Measuring Industry Carbon Exposure

Firm-level ESG ratings supplied by commercial vendors are proprietary and exhibit pronounced disagreement across providers, which injects measurement error into firm-level estimates and undermines comparability [17]. We therefore adopt a transparent, fully reproducible proxy for a firm's structural environmental exposure constructed solely from its industry classification. Our primary independent variable is an ordinal carbon-intensity tier that assigns each firm to one of three categories on the basis of its sector: High (Energy, Utilities, Basic Materials), Medium (Industrials, Consumer Cyclical, Consumer Defensive, Real Estate), and Low (Technology, Health Care, Communication Services). The mapping follows the environmental-disclosure and carbon-exposure literature, which treats sector membership as a first-order determinant of a firm's direct and indirect emissions profile; the sector-by-sector rationale, together with the exact composition of each tier in our sample, is set out in Appendix B.

It is important to be precise about what this variable does and does not measure. The measure is an ordinal, sectoral-membership-based proxy for structural, between-industry carbon exposure. It is a deterministic function of a firm's observed GICS-style sector code. It is not a firm-level measure of environmental performance or management quality, and it is not built from reported emissions of any kind: it uses no tonnes of CO₂, no carbon-intensity ratio (emissions scaled by sales or assets), and no proprietary environmental score. The variable therefore answers the question "how carbon-exposed is the sector in which this firm operates?" and is silent on "how well does this firm manage its environmental footprint relative to its sector peers?" This design entails a deliberate trade-off. The benefit is transparency and reproducibility: the tier is a deterministic function of a public sector code, is free of vendor scoring choices, and can be reconstructed by any researcher at zero cost. The cost is granularity: the measure captures between-industry variation only, is time-invariant within firm over our window (no firm changes tier), cannot speak to heterogeneity in environmental management among firms in the same sector, and cannot exploit within-firm changes in exposure. We regard the three-tier ordinal scheme as adequate for our research question, which concerns the shape of the association between structural carbon exposure and profitability across the exposure distribution, because the tiers correspond to well-understood, materially distinct emissions regimes (high-emitting extractive and utility sectors; moderately exposed industrial and consumer sectors; low-emitting service and knowledge sectors), and because a coarser binary indicator discards the informative middle

category (Section 4.4). Nonetheless, the industry basis of the measure is its central limitation, which we foreground here and revisit in Section 5.4: a continuous, firm-level alternative (for example, carbon-intensity data from CDP disclosures or verified EU Emissions Trading System emissions) would refine the construct and enable within-firm identification in future work. As a robustness check, we also use a binary environmentally sensitive industry indicator (Energy, Utilities, Basic Materials = 1).

3.3. Dependent Variables and Controls

The primary measure of profitability is return on assets (ROA), net income scaled by total assets. We assess robustness using return on equity (ROE) and net profit margin, and, to identify the operating channel, asset turnover (revenue scaled by total assets). All models include firm size (natural log of total assets), leverage (total debt to total assets), revenue growth, cash holdings (cash to total assets), and capital-expenditure intensity (capex to revenue). Variable definitions and sources are reported in Appendix A.

3.4. Identification Strategy

A panel specification with firm fixed effects cannot identify the association of interest: because the carbon-intensity tier is time-invariant within firm, firm fixed effects absorb it entirely. We therefore identify the relationship from cross-firm variation within the same country and year. Our primary estimating equation is

$$ROA_{i,t} = \beta_1 \text{Medium}_i + \beta_2 \text{High}_i + \gamma' X_{i,t} + \delta_{c,t} + \varepsilon_{i,t} \quad (1)$$

where *Medium* and *High* are carbon-tier indicators (Low is the omitted base), *X* is the vector of firm controls, and $\delta_{c,t}$ is a full set of country $\times$ year fixed effects that flexibly absorbs every macro-environmental, regulatory, and business-cycle shock common to firms in a given market-year, including the staggered onset of mandatory non-financial reporting regimes.

Three features of this specification deserve comment, because reviewers reasonably ask why this equation rather than another. First, the choice of a two-way (here, country-by-year) high-dimensional fixed-effects design over a pooled regression or a random-effects model is standard in this literature and follows the guidance of Gormley and Matsa [56] on controlling for unobserved heterogeneity: additive or interacted fixed effects difference out confounders at the level at which they operate (here, the market-year), whereas random effects impose an orthogonality assumption between the regressors and the unit effect that is implausible when sector composition varies systematically across markets. Second, because the treatment is time-invariant within firm, firm fixed effects are infeasible (they would absorb the tier), so the level association must be identified cross-sectionally within market-year cells; this is a deliberate design choice dictated by the construct, not an oversight, and we are explicit that the resulting estimates are associations rather than causal effects. Third, we also report an additive specification with separate country and year fixed effects, which relaxes the full country-by-year saturation, and we cluster standard errors by firm throughout to accommodate within-firm serial correlation. Estimation is carried out by ordinary least squares within the high-dimensional fixed-effects structure, using the method of alternating projections to absorb the fixed effects (the `fixest` package in R version 4.3.3; R Foundation for Statistical Computing, Vienna, Austria), with firm-clustered standard errors; the reported coefficients are the within-cell partial associations of the tier indicators with profitability, holding the controls fixed.

Because the descriptive evidence (Section 4.1) suggests a monotone rather than a concave pattern, we also estimate a quadratic specification that replaces the tier indicators with the ordinal tier (1–3) and its square; a negative, significant quadratic coefficient

would be consistent with concavity, and we compute the implied turning point as the negative of the linear coefficient divided by twice the quadratic coefficient. Given that the ordinal measure takes only three values, we treat the quadratic as corroborating the categorical evidence rather than as a free-standing test. Finally, to address the concern that the tier, being an industry construct, may simply be tracking systematic profitability differences across industries, we augment the primary model with a leave-one-out industry-mean of ROA (the mean ROA of all other firms in the focal firm’s industry), which lets us ask whether carbon exposure is associated with profitability beyond what industry membership already explains (Section 4.5). Although firm fixed effects cannot identify the level association, they can identify whether the profitability of carbon-intensive firms changed around a time-varying institutional shock; we therefore also estimate a within-firm specification interacting the carbon-intensity tier with an indicator for the post-mandatory-reporting period, with firm and year fixed effects.

4. Results

4.1. Descriptive Statistics and Univariate Evidence

Table 1 reports descriptive statistics for the estimation sample. Mean ROA is 6.1% (median 5.1%), mean leverage is 31.9%, and the average firm holds cash equal to 8.8% of assets. The carbon-intensity tier has a mean of 1.91 on the 1–3 scale. The standard deviations in Table 1 are cross-sectional: they summarize dispersion across firm-years in the pooled sample, not variation over time within a firm. For the tier, the standard deviation of 0.69 reflects the ordinal spread across the three categories; for ROA, the standard deviation of 6.65 percentage points indicates substantial cross-firm dispersion relative to a mean of 6.1 percentage points, which is typical of broad cross-market samples and motivates the firm-clustered inference used throughout.

Table 1. Descriptive statistics (estimation sample).

Variable	<i>n</i>	Mean	SD	P25	Median	P75	Min	Max
ROA	3176	0.0611	0.0665	0.0241	0.0508	0.0912	−0.1392	0.3095
ROE	3176	0.1435	0.2816	0.0594	0.1238	0.2240	−1.2184	1.2105
Net profit margin	3176	0.1088	0.1475	0.0365	0.0902	0.1585	−0.4405	0.7212
Carbon-intensity tier (1–3)	3176	1.9055	0.6914	1	2	2	1	3
Firm size (ln assets)	3176	23.0186	1.4302	22.0660	22.9881	23.9456	17.5197	27.4302
Leverage	3176	0.3190	0.1834	0.1919	0.3087	0.4296	0.0084	0.9120
Revenue growth	3176	0.0635	0.1582	−0.0102	0.0500	0.1165	−0.3668	0.7746
Cash holdings	3173	0.0880	0.0890	0.0249	0.0624	0.1188	0.0004	0.4700
Capex intensity	3070	0.0967	0.1396	0.0227	0.0423	0.0973	0.0018	0.7572

Notes: *n* = 3176 firm-year observations on 1084 non-financial firms that carry an observed sector classification, across six markets, fiscal years 2021–2025 (including a small number of early fiscal-2026 period-ends). Ratio variables are winsorized at the 1st and 99th percentiles. The carbon-intensity tier is coded 1 = Low, 2 = Medium, 3 = High.

Table 2 reports the distribution of the sample by country, year, and carbon-intensity tier, which several features of the design make it useful to display explicitly. Two points stand out. First, the sample is dominated by the United States (2357 of 3176 firm-years), and within the high-carbon tier the concentration is even stronger. Second, the civil-law markets are thinly represented once an observed sector classification is required: France contributes only three firm-years to the estimation sample (its index constituents largely lacked an observed sector code and were removed by the fourth screen), while Italy and Spain together contribute 164. This composition bears directly on how far the “six developed markets” framing can be pushed and on the interpretation of the legal-origin split in Section 4.7; we return to both points in the limitations.

Table 2. Sample distribution by country, year, and carbon-intensity tier (estimation sample).

Country	Firms	Low	Medium	High	Total
United States	805	787	1170	400	2357
United Kingdom	142	79	257	84	420
Australia	81	30	123	79	232
France	1	0	3	0	3
Italy	28	15	39	30	84
Spain	27	12	38	30	80
Total	1084	923	1630	623	3176
Panel B: firm-years by fiscal year and tier					
FY2022		3	12	6	21
FY2023		272	484	199	955
FY2024		311	540	207	1058
FY2025		303	537	204	1044
FY2026		34	57	7	98

Notes: Firm-year counts in the descriptive estimation sample ($n = 3176$). “Firms” is the count of distinct firms per country. FY2022 is sparse because the revenue-growth control requires a prior-year observation; FY2026 comprises early non-December period-ends.

The univariate pattern runs counter to the conventional inverted-U intuition and is, if anything, a monotone brown tilt. Mean ROA is 6.85% for firms in low-carbon sectors, 6.29% for the medium tier, and 4.56% for the high tier. The differences are jointly significant (one-way ANOVA $F = 23.61$, $p < 0.001$). Profitability is thus highest, not lowest, at the low-carbon end and lowest for the most carbon-intensive sectors. Figure 1 plots mean ROA by tier with 95% confidence intervals.

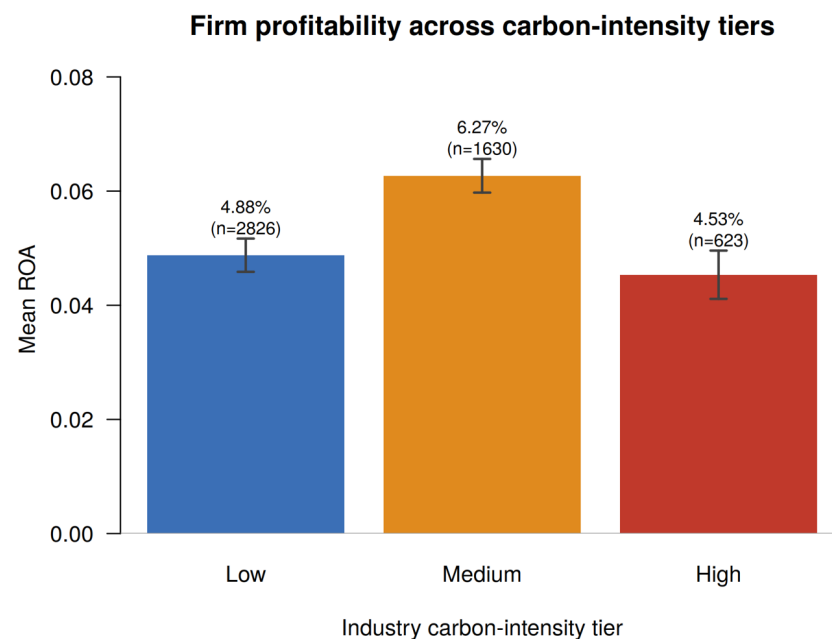


Figure 1. Mean ROA by industry carbon-intensity tier. Bars show mean ROA by carbon-intensity tier with 95% confidence intervals; n is shown above each bar. The univariate pattern is monotone decreasing (one-way ANOVA $F = 23.61$, $p < 0.001$).

4.2. Primary Multivariate Results

Table 3 reports the primary regressions and tells a consistent story: the raw brown tilt is explained by firm characteristics and market-year heterogeneity, and does not survive as a distinct tier effect. In the pooled specification without controls (column 1), High-exposure firms earn ROA 2.29 percentage points lower than Low-exposure firms ($\beta = -0.0229$,

$p < 0.001$), and Medium firms are statistically indistinguishable from Low ($\beta = -0.0055$, $p = 0.24$), consistent with the univariate brown tilt. Once firm controls enter (column 2), the High discount disappears ($\beta = -0.0005$, $p = 0.93$), indicating that the raw difference is absorbed by size, leverage, cash, and capital intensity. In the fully saturated model with country $\times$ year fixed effects and firm-clustered standard errors (column 3), neither tier coefficient is significant: Medium is $+0.0063$ ($t = 1.36$, $p = 0.17$) and High is $+0.0042$ ($t = 0.77$, $p = 0.44$). A specification with additive country and year fixed effects (column 4) is essentially identical. Control coefficients carry sensible signs: cash holdings and revenue growth are positively associated with ROA, and capital intensity negatively. The within- R^2 of the saturated model is 11.7%.

The economic reading is that, in this sample and after absorbing market-year shocks, accounting profitability does not differ significantly across carbon-exposure tiers. For calibration, the point estimates (below 0.7 percentage points) are small relative to the 6.1-percentage-point sample mean ROA and to the modest average effect sizes reported in the two large meta-analyses of the environmental-financial performance literature [15,16]; they are also statistically indistinguishable from zero. We interpret this as an absence of a robust carbon-exposure premium or discount at the sector level, not as evidence of a precisely estimated null.

Table 3. Industry carbon exposure and firm profitability (DV = ROA).

Variable	M1	M2	M3	M4
Constant	0.0685 *** (0.0041)	0.0905 ** (0.0391)		
Carbon tier = Medium	−0.0055 (0.0047)	0.0036 (0.0047)	0.0063 (0.0047)	0.0064 (0.0047)
Carbon tier = High	−0.0229 *** (0.0050)	−0.0005 (0.0054)	0.0042 (0.0054)	0.0040 (0.0054)
Firm size (ln assets)		−0.0017 (0.0017)	−0.0030 * (0.0017)	−0.0030 * (0.0017)
Leverage		−0.0111 (0.0131)	−0.0149 (0.0131)	−0.0156 (0.0131)
Revenue growth		0.0325 *** (0.0113)	0.0344 *** (0.0115)	0.0339 *** (0.0113)
Cash holdings		0.1717 *** (0.0264)	0.1699 *** (0.0263)	0.1694 *** (0.0264)
Capex intensity		−0.0462 *** (0.0124)	−0.0429 *** (0.0124)	−0.0429 *** (0.0123)
Country $\times$ Year FE	No	No	Yes	No
Country FE	No	No	No	Yes
Year FE	No	No	No	Yes
Std. errors	Firm-clustered	Firm-clustered	Firm-clustered	Firm-clustered
Observations	3176	3067	3067	3067
R-squared	0.0147	0.0990	0.1166	0.1141

Notes: Cell entries are coefficients with firm-clustered standard errors in parentheses. The base category is the Low carbon-intensity tier. Models 1–2 are pooled; Model 3 adds country-by-year fixed effects; Model 4 uses additive country and year fixed effects. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$.

4.3. Testing for Concavity: Quadratic Specification

Table 4 reports the quadratic model that H1 predicts. The linear term in the ordinal tier is positive but insignificant ($\beta = 0.0191$, $p = 0.20$) and the quadratic term is negative but insignificant ($\beta = -0.0043$, $p = 0.24$). Neither term is distinguishable from zero, so the data provide no support for the concave (inverted-U) relationship of H1; the mechanical turning point (2.24) is reported for completeness but is not meaningful given the insignificant quadratic term. The reported R^2 (11.7%) is a within, or partial, R^2 : because the country-by-year fixed effects absorb all market-year variation before the regressors enter, the statistic measures the share of the residual variation in ROA explained by the tier and controls, and modest values are the norm in cross-sectional profitability regressions rather than a sign of misspecification. Taken with Table 3, the evidence points to no robust association of carbon exposure with profitability, monotone or concave, once market-year heterogeneity and firm characteristics are absorbed.

Table 4. Quadratic specification (test of concavity; DV = ROA).

Variable	Model
Carbon tier (linear)	0.0191 (0.0149)
Carbon tier squared	−0.0043 (0.0036)
Firm size (ln assets)	−0.0030 * (0.0017)
Leverage	−0.0149 (0.0131)
Revenue growth	0.0344 *** (0.0115)
Cash holdings	0.1699 *** (0.0263)
Capex intensity	−0.0429 *** (0.0124)
Country × Year FE	Yes
Implied turning point (not significant)	2.24
Observations	3067
R-squared	0.1166

Notes: The carbon-intensity tier is entered linearly (coded 1–3) and as a square term. Neither term is statistically significant, so there is no evidence of concavity; the implied turning point is shown only for completeness. Firm-clustered standard errors. *** $p < 0.01$, * $p < 0.10$.

4.4. Robustness and the Operating Channel

Table 5 summarizes robustness checks and the operating-channel analysis. (i) Using ROE, the tier coefficients are insignificant (Medium $\beta = 0.0251$, $p = 0.18$; High $\beta = -0.0070$, $p = 0.73$). (ii) For net profit margin, the coefficients are essentially zero (Medium $\beta = 0.0002$, $p = 0.99$). (iii) Replacing the ordinal tier with the binary environmentally sensitive indicator yields a coefficient indistinguishable from zero ($\beta = 0.0001$, $p = 0.99$). (iv) Excluding U.S. firms, the coefficients turn negative but remain insignificant (Medium $\beta = -0.0155$, $p = 0.15$; High $\beta = -0.0144$, $p = 0.16$), consistent with a brown tilt outside the United States that the small non-U.S. sample cannot pin down. (v) Dropping the 98 early fiscal-2026 observations leaves the estimates essentially unchanged (Medium $\beta = 0.0059$, High $\beta = 0.0041$; $n = 2971$), confirming that the results do not depend on the sparse final period. (vi) The one place the measure registers a strong, significant difference is asset turnover: Medium- and High-exposure firms have markedly higher revenue per unit of assets (Medium $\beta = 0.2396$, High $\beta = 0.1983$, both $p < 0.001$). Figure 2 displays the primary ROA coefficients with confidence intervals, both of which comfortably include zero.

Table 5. Robustness and operating channel: alternative dependent variables, binary exposure, excluding the United States, excluding fiscal 2026, and asset turnover.

Variable	ROE	Net Margin	Binary IV	Excl. USA	Excl. FY2026	Asset Turnover
Carbon tier = Medium	0.0251 (0.0189)	0.0002 (0.0088)		−0.0155 (0.0107)	0.0059 (0.0046)	0.2396 *** (0.0354)
Carbon tier = High	−0.0070 (0.0203)	−0.0073 (0.0116)		−0.0144 (0.0103)	0.0041 (0.0054)	0.1983 *** (0.0416)
Env-sensitive (0/1)			0.0001 (0.0042)			
Firm size (ln assets)	0.0064 (0.0064)	0.0036 (0.0030)	−0.0031 * (0.0017)	−0.0077 *** (0.0029)	−0.0031 * (0.0017)	−0.0320 *** (0.0121)
Leverage	−0.0876 (0.0817)	−0.0228 (0.0240)	−0.0121 (0.0129)	−0.0005 (0.0229)	−0.0140 (0.0133)	−0.1505 * (0.0884)
Revenue growth	0.0747 * (0.0383)	0.1156 *** (0.0266)	0.0337 *** (0.0114)	0.0238 * (0.0135)	0.0328 *** (0.0107)	−0.1932 *** (0.0675)
Cash holdings	0.1684 (0.1251)	0.0991 ** (0.0452)	0.1658 *** (0.0261)	0.1644 *** (0.0483)	0.1731 *** (0.0255)	0.3597 ** (0.1729)
Capex intensity	−0.0429 (0.0492)	0.1415 *** (0.0398)	−0.0433 *** (0.0124)	−0.0338 ** (0.0168)	−0.0432 *** (0.0125)	−1.5440 *** (0.1064)
Country × Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Observations	3067	3067	3067	801	2971	3067
R-squared	0.0162	0.0531	0.1151	0.1684	0.1163	0.2265

Notes: DV by column: (1) ROE; (2) net profit margin; (3) ROA with a binary environmentally sensitive indicator replacing the ordinal tier; (4) ROA excluding U.S. firms; (5) ROA excluding the 98 early fiscal-2026 observations; (6) asset turnover (revenue/total assets), the DuPont operating channel. All models include country-by-year fixed effects and firm-clustered standard errors. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$.

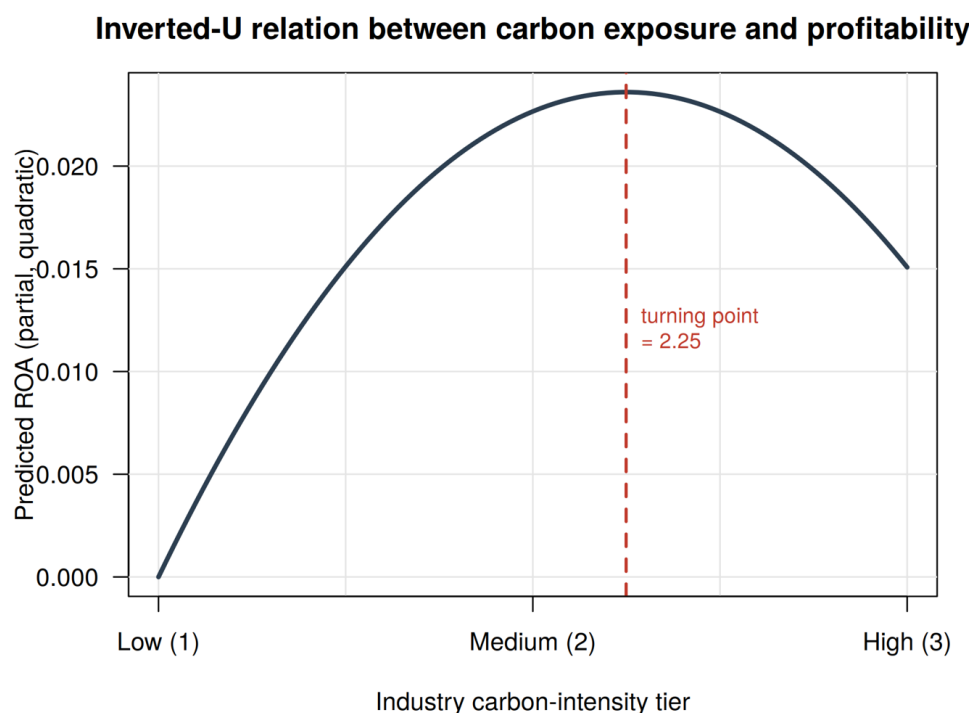


Figure 2. Carbon-tier coefficients (primary model). Point estimates and 95% confidence intervals for the Medium-versus-Low and High-versus-Low carbon-tier coefficients from the country-by-year fixed-effects model (Table 3, Model 3), with firm-clustered standard errors. Both intervals include zero.

4.5. Is the Tier Just Tracking Industry Profitability?

Because the carbon-exposure tier is an industry construct, a natural concern, raised in review, is that it may simply be picking up systematic profitability differences across industries rather than a distinct environmental signal. Table 6 addresses this directly by augmenting the primary model with a leave-one-out industry-mean of ROA (the mean ROA of all other firms in the focal firm's industry, excluding the firm itself). Two results follow. First, on the sample for which this control is defined, the tier coefficients are already insignificant before the control is added (Medium $\beta = 0.0069$, $p = 0.14$; High $\beta = 0.0050$, $p = 0.35$), and they remain insignificant at conventional levels after it is added (Medium $\beta = 0.0072$, $p = 0.12$; High $\beta = 0.0095$, $p = 0.07$). Second, industry-mean profitability is itself strongly and positively associated with firm ROA ($\beta = 0.3417$, $p < 0.001$), confirming that industry membership is the operative source of the between-tier differences visible in the raw data. Carbon exposure adds little to the explanation of profitability beyond what industry membership already supplies. We stress the limit of this exercise, following the reviewer's caution: because our measure is tied to industry, we cannot rule out that any residual between-tier variation reflects sector-specific macroeconomic sensitivities during the 2021–2025 period (energy-price, supply-chain, and interest-rate shocks that fell unevenly on sectors) rather than pure environmental positioning, and coefficient-stability bounds for unobservable selection [57] are uninformative here precisely because the baseline association is not distinguishable from zero.

4.6. The Operating Channel: Asset Turnover

The asset-turnover result in Table 5 is worth drawing out, because it shows the measure is not empty even where profitability is a wash. Decomposing ROA in the spirit of the DuPont identity ($\text{ROA} \approx \text{net margin} \times \text{asset turnover}$), carbon exposure is strongly positively associated with asset turnover (Medium $\beta = 0.240$, High $\beta = 0.198$, $p < 0.001$)

but not with net margin (Section 4.4). The two components move in opposite directions: carbon-intensive sectors generate more revenue per unit of assets, but earn no higher, and if anything slightly lower, margins, so the two effects offset and ROA does not differ. The transparent tier therefore recovers a genuine, systematic difference in operating structure (asset productivity) across carbon-exposure regimes, even though this difference does not translate into a profitability premium. This clarifies that the measure carries real information about firms' operating models, distinct from any claim about their profitability.

Table 6. Does carbon exposure predict profitability beyond industry? Leave-one-out industry-mean control (DV = ROA).

Variable	Baseline (Same Sample)	+ Industry-Mean ROA
Carbon tier = Medium	0.0069 (0.0046)	0.0072 (0.0045)
Carbon tier = High	0.0050 (0.0053)	0.0095 * (0.0052)
Industry-mean ROA (leave-one-out)		0.3417 *** (0.0675)
Firm controls	Yes	Yes
Country $\times$ Year FE	Yes	Yes
Observations	3045	3045
R-squared	0.1174	0.1374

Notes: The leave-one-out industry-mean of ROA is the mean ROA of all other firms in the focal firm's industry, excluding the focal firm; it is defined for firms in non-singleton industries ($n = 3045$). Firm controls are firm size, leverage, revenue growth, cash holdings, and capex intensity. Firm-clustered standard errors. *** $p < 0.01$, * $p < 0.10$.

4.7. Heterogeneity by Legal Origin

Table 7 splits the sample by legal origin to test H2. In common-law markets (United States, United Kingdom, Australia) the tier coefficients are positive but insignificant (Medium $\beta = 0.0074$, $p = 0.12$; High $\beta = 0.0047$, $p = 0.40$; $n = 2900$). In civil-law markets (France, Italy, Spain) they are negative and insignificant ($n = 167$). H2 is therefore not supported: we find no significant carbon-exposure association in either institutional setting, and no evidence that the association is stronger in common-law markets. This contrast should in any case be read with great caution, because the civil-law subsample is very small and, as Table 2 shows, France contributes almost nothing to it once an observed sector classification is required.

Table 7. Heterogeneity by legal origin (DV = ROA).

Variable	Common Law	Civil Law
Carbon tier = Medium	0.0074 (0.0048)	−0.0122 (0.0148)
Carbon tier = High	0.0047 (0.0056)	−0.0008 (0.0151)
Firm size (ln assets)	−0.0024 (0.0018)	−0.0120 ** (0.0053)
Leverage	−0.0143 (0.0136)	−0.0918 * (0.0485)
Revenue growth	0.0349 *** (0.0118)	0.0393 (0.0263)
Cash holdings	0.1731 *** (0.0268)	0.1567 * (0.0939)
Capex intensity	−0.0492 *** (0.0131)	0.0327 (0.0240)
Country $\times$ Year FE	Yes	Yes
Observations	2900	167
R-squared	0.1132	0.3001

Notes: Common-law markets are the United States, the United Kingdom, and Australia; civil-law markets are France, Italy, and Spain. All models include country-by-year fixed effects and firm-clustered standard errors. The civil-law subsample is very small ($n = 167$) and its estimates should be interpreted with great caution. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$.

4.8. Did Mandatory ESG Reporting Change the Payoff? A Within-Firm Test

Table 8 reports the within-firm design. After the onset of mandatory non-financial reporting, the change in profitability for High-, Medium-, and Low-exposure firms is

statistically indistinguishable from zero (all interaction terms insignificant). We find no evidence that the introduction of mandatory ESG disclosure differentially affected the profitability of carbon-intensive firms over our sample window. Section 5.2 discusses the interpretation of this null.

Table 8. Within-firm design: carbon exposure and mandatory non-financial reporting (DV = ROA).

Variable	Model
Low $\times$ Post-ESG	0.0097 (0.0249)
Medium $\times$ Post-ESG	0.0063 (0.0078)
High $\times$ Post-ESG	−0.0136 (0.0183)
Firm size (ln assets)	−0.0008 (0.0132)
Leverage	−0.1777 *** (0.0361)
Revenue growth	0.0162 (0.0099)
Cash holdings	0.1384 *** (0.0409)
Capex intensity	−0.0287 (0.0295)
Firm FE	Yes
Year FE	Yes
Observations	3067
R-squared	0.8004

Notes: The model interacts the carbon-intensity tier with an indicator for the post-mandatory-reporting period, with firm and year fixed effects (which absorb the time-invariant main effect of the tier). Firm-clustered standard errors. None of the interaction terms is statistically significant. *** $p < 0.01$.

4.9. Summary

The evidence does not support a “green pays” or “brown is punished” narrative, nor the concave pattern that H1 predicted. Descriptively, profitability declines with carbon exposure (a monotone brown tilt), but this reflects the composition of the tiers: once firm controls and country-by-year fixed effects are absorbed, carbon exposure is not significantly associated with ROA, ROE, or net margin, and there is no concavity. Controlling directly for industry-mean profitability leaves the tier insignificant while industry profitability is strongly predictive, indicating that industry membership, not carbon exposure per se, drives the raw differences. The measure does capture a real operating difference, higher asset turnover among carbon-intensive sectors, that is offset by margins. No differential effect of mandatory ESG reporting is detectable within firm over the short sample window.

5. Discussion

5.1. Summary and Interpretation of Findings

This study asked whether environmental sensitivity, measured through a transparent, sector-based proxy for structural carbon exposure, is associated with accounting profitability across six developed markets. The short answer is that it is not, at least not robustly. At the univariate level, profitability declines with carbon exposure, from a mean ROA of 6.85% in low-carbon sectors to 4.56% in the most carbon-intensive. This descriptive brown tilt is consistent with the simplest reading of instrumental stakeholder theory, under which greater unmanaged environmental exposure carries greater risk and cost [50,51]. It is not, however, robust to firm controls or to market-year fixed effects, and it is subsumed by industry-level profitability. The concave (inverted-U) relationship that H1 predicted, motivated by a “too-much-of-a-good-thing” logic [19,52], receives no support: the quadratic term is insignificant, and profitability does not peak at intermediate exposure. H2, which predicted a stronger association in common-law markets, is likewise unsupported, though the civil-law subsample is too small to sustain a sharp institutional contrast. This pattern of results is consistent with the meta-analytic conclusion that the environmental-financial performance relationship is modest and highly heterogeneous [15,16], and it illustrates con-

cretely how sensitive such relationships are to how the environmental signal is constructed and to the controls employed.

5.2. Interpreting the Null

A null on profitability admits several readings that are worth separating. First, the level at which the signal is defined matters: our measure captures between-industry exposure, and once industry-level profitability is controlled for directly (Table 6), the tier carries essentially no independent information. The raw brown tilt is a statement about which sectors happen to be profitable in 2021–2025, not about a carbon-exposure premium net of industry. Second, the consequences of environmental positioning may fall on outcomes other than contemporaneous accounting returns: a large literature locates the first-order effect of environmental profile and disclosure in the cost of capital and in the informativeness of prices rather than in operating profitability [2,3,5]. Third, for the mandatory-reporting question specifically, the post-mandate horizon in our panel is short, and the real effects of disclosure regulation may operate over longer horizons and through channels other than current returns [55]; mandatory disclosure may also have conveyed little new information for large listed firms in developed markets, where sophisticated investors could already infer a firm's environmental exposure from its sector. Distinguishing among these readings, especially by examining cost-of-capital and valuation outcomes over longer horizons, is a natural next step. What our design does establish is that the transparent sector-based measure, applied rigorously to firms with an observed sector code, does not recover a profitability effect, and that an apparent effect can be manufactured by looser sample construction, a cautionary point in its own right.

5.3. Implications

Three implications follow. First, for the assessment of ESG and environmental performance, the results carry a constructive message about measurement rather than about profitability: a transparent, rule-based environmental measure, free of the divergence that afflicts commercial ratings [17], can be constructed and applied at zero cost and can recover economically meaningful structure in firm outcomes, here in asset productivity, even where it recovers no profitability effect. Such a measure merits a place alongside proprietary scores as an auditable benchmark, precisely because its construction is fully visible and its limits are explicit. Second, the null on profitability, set against significant differences in asset turnover, cautions against reading a single accounting ratio as the verdict on “does it pay to be green.” The operating models of carbon-intensive and low-carbon sectors differ in ways (asset productivity, margins) that offset in ROA; researchers using alternative methods, from system-GMM and propensity-matching to quantile and threshold regressions, have likewise reported that the sign and shape of environmental-financial relationships depend heavily on specification and on the region of the distribution examined [12,13,18,19], and our fixed-effects estimates add a carefully identified null to that body of evidence. Third, for practice and policy, the findings imply that carbon-exposure effects on operating profitability are neither uniform across firms nor evident in the short run, and that disclosure mandates, at least over our window, leave no detectable imprint on the operating profitability of carbon-intensive firms.

5.4. Limitations and Future Research

Several limitations qualify the results, and one deserves to be stated first because it shapes everything else. The measure captures industry-level environmental exposure, not firm-level environmental performance; its transparency and reproducibility come at the cost of not distinguishing among firms in the same industry, and, as Table 6 shows, its association with profitability is not separable from industry membership. A continuous,

firm-level measure, for example carbon-intensity data from CDP disclosures or verified EU Emissions Trading System emissions, would refine the construct, distinguish environmental leaders from laggards within a sector, and enable within-firm identification. Second, the result is sensitive to sample construction: requiring an observed sector classification, which the measure's own logic demands, materially changes the estimates relative to a looser rule that defaults unclassified firms into the low-carbon tier. We regard the stricter sample as the correct one, but the sensitivity is itself a caution about the fragility of environmental-financial associations. Third, the sample, though drawn from six markets, is heavily weighted toward the United States, and the civil-law markets are thinly represented once the sector screen is applied (France contributes only three firm-years); the "six developed markets" framing therefore describes the sampling frame more accurately than the effective identifying variation, and the legal-origin contrast in particular should be read as suggestive at best. Fourth, several large developed markets, among them Germany, Canada, Japan, and the Netherlands, are not in the sample; they were outside the set of indices assembled for this study, and their inclusion, especially of additional civil-law and non-Anglophone common-law jurisdictions, would provide a stronger test of the institutional contingency and is a natural extension. Fifth, the panel is short and recent (fiscal years 2021–2025), which limits the power of the within-firm design and precludes long-horizon analysis. Finally, accounting profitability is only one outcome of interest; applying the transparent measure to the cost of capital, firm risk, and market-based measures would test whether the null documented here is specific to operating returns or general across outcomes.

6. Conclusions

Using a transparent, sector-based measure of carbon exposure built entirely from public industry classifications, this study finds that carbon exposure is not robustly associated with the accounting profitability of listed firms in six developed markets. A descriptive brown tilt, more carbon-intensive sectors are less profitable, does not survive firm controls or market-year fixed effects and is subsumed by industry-level profitability; there is no concave relationship and no institutional contrast strong enough to sustain. The measure is not empty: it recovers a real difference in operating structure, higher asset turnover among carbon-intensive sectors, that is offset by margins and so leaves profitability unchanged. The contribution is therefore less a finding about the profitability of "green" firms than a demonstration that a fully reproducible, zero-cost environmental measure can sidestep the divergence afflicting commercial ESG ratings while making its own limits transparent, and that, applied rigorously, it delivers an honest null on profitability. Recognizing how sensitive environmental-financial associations are to sample construction and to the level at which the signal is defined is, we hope, a useful corrective for a literature that has too often reported a single sign with more confidence than the measurement warrants.

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Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A. Variable Definitions

Table A1 reports the definitions and construction of all variables used in the analysis.

Table A1. Variable definitions.

Variable	Definition
ROA	Net income scaled by total assets
ROE	Net income scaled by total shareholders' equity
Net profit margin	Net income scaled by revenue
Asset turnover	Revenue scaled by total assets
Carbon-intensity tier	Ordinal sector-based measure: 1 = Low (Technology, Health Care, Communication Services), 2 = Medium (Industrials, Consumer Cyclical, Consumer Defensive, Real Estate), 3 = High (Energy, Utilities, Basic Materials). Assigned only for firms with an observed sector classification.
Env-sensitive (0/1)	Binary indicator equal to 1 for firms in Energy, Utilities, and Basic Materials, and 0 otherwise
Firm size	Natural logarithm of total assets
Leverage	Total debt scaled by total assets
Revenue growth	Year-over-year growth rate of revenue
Cash holdings	Cash and cash equivalents scaled by total assets
Capex intensity	Capital expenditure scaled by revenue
Industry-mean ROA (leave-one-out)	Mean ROA of all other firms in the focal firm's industry, excluding the focal firm

Notes: All ratio variables are winsorized at the 1st and 99th percentiles. Industry classifications follow firms' GICS-style sector and industry codes as reported by the data provider.

Appendix B. Sector-to-Tier Assignment: Rationale and Sample Composition

Because the carbon-intensity tier is the study's central construct, this appendix sets out the rationale for each sector's assignment and reports the exact composition of each tier in the estimation sample. The mapping is not bespoke to this study: it follows the standard practice in the environmental-disclosure and carbon-exposure literature of treating GICS-style sector membership as a first-order determinant of a firm's direct (Scope 1) and indirect (Scope 2) emissions profile, and it aligns with the widely documented ranking of sectoral carbon intensity in which extractive, power-generation, and heavy-materials activities sit at the top and knowledge- and service-based activities at the bottom [18,26,28]. We do not assign tiers from reported emissions; the tier is a transparent, ordinal summary of the sector-level exposure that this literature establishes.

The High tier comprises Energy (oil, gas, and coal extraction and refining), Utilities (electricity and gas generation and distribution), and Basic Materials (mining, metals, and

chemicals). These are the sectors whose core physical processes, combustion, extraction, and energy-intensive transformation, place them consistently among the highest direct emitters, and whose transition and regulatory exposure is greatest. The Medium tier comprises Industrials (manufacturing, capital goods, transport), Consumer Cyclical and Consumer Defensive (goods production and retail with substantial supply-chain and logistics footprints), and Real Estate (buildings, whose operational energy use is material but whose direct process emissions are lower than the High tier). The Low tier comprises Technology, Health Care, and Communication Services, knowledge- and service-based sectors whose direct emissions are dominated by purchased electricity and are structurally low relative to the other tiers. Financial firms are excluded from the analysis altogether. Table A2 lists the tier of each sector and the number of firm-year observations it contributes to the estimation sample, so that the mapping is fully auditable.

Table A2. Sector-to-tier mapping and sample composition (estimation sample).

Tier	GICS-Style Sectors	Firm-Years
Low (1)	Technology; Health Care; Communication Services	923
Medium (2)	Industrials; Consumer Cyclical; Consumer Defensive; Real Estate	1630
High (3)	Energy; Utilities; Basic Materials	623
Total		3176

Notes: Firm-year counts in the descriptive estimation sample ($n = 3176$). Sectors follow the data provider's GICS-style classification. Firms without an observed sector classification are not assigned a tier and are excluded. A continuous, firm-level carbon-intensity measure would refine this ordinal scheme (Section 5.4).

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