Examining ESG Performance Through TNFD-Aligned Disclosure Practices

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Abstract

This study examines adherence to the Taskforce on Nature-related Financial Disclosures (TNFD) framework in relation to the ESG performance of non-financial and non-utility S&P 500 firms. Using generative Natural Language Processing (NLP) methodologies, measures of nature-related risks, opportunities and indicators across the four pillars of TNFD are calibrated for the period 2018 – 2023. Findings reveal that adherence to the TNFD framework, clear identification of nature-related risks and opportunities, and comprehensive reporting have a positive influence on a firm's environmental score and overall ESG ratings. Robustness tests confirm that concerns about endogeneity do not compromise these findings. The results indicate that integrating the TNFD standardised framework provides clearer insights into corporate sustainability and nature-related performance, potentially influencing investor perceptions and ESG assessments. The results provide practical insights for environmentally conscious investors and companies seeking to enhance their sustainability reporting by integrating the TNFD guidelines.

Keywords

1. Introduction

The accelerating depletion of natural resources and the increasing degradation of the environment are raising significant global concerns. Business activities are closely linked to the natural environment and its systems. Firm operations, products, and supply chains rely on and impact nature, and contribute to biodiversity loss and the disruption of ecosystem services (Hadji-Lazaro et al., 2025; Smith et al., 2024).

In response to the pressing challenges of biodiversity loss (IPBES, 2019), various initiatives are emerging to incorporate nature into economic and financial decision-making frameworks. At the Kunming-Montreal conference, a new Global Biodiversity Framework (GBF) was approved during the fifteenth meeting of the Conference of the Parties (COP 15).[1] Targeting ambitious 2030 goals, the framework urges organisations to mitigate ecosystem degradation and the risk of species extinction while also requiring them to "disclose their risks, dependencies, and impacts on biodiversity" (Target 15).[2] Recent research, however, reveals significant gaps in the current biodiversity assessment systems employed by corporations, which hinder their alignment with the GBF. For example, numerous technologies inadequately consider essential criteria such as ecosystem integrity, connectivity, genetic diversity, and indigenous territory, while disproportionately emphasising land use and climate change, overlooking other factors such as invasive species and ocean acidification (Zhu et al., 2024). These shortcomings underscore the necessity for more holistic and cohesive measurement frameworks.

The intricate relationship between businesses and the environment, in alignment with the GBF, gives rise to nature-related risks (NRRs) and opportunities (NROs). Highlighting the imperative for systematic disclosures to inform stakeholders, including investors, policymakers, and the wider public (TNFD, 2023). Recognising this urgency, the Taskforce on Nature-related Financial

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[1] https://www.cbd.int/conferences/2021-2022
[2] https://www.cbd.int/gbf

Disclosures (TNFD) has introduced a structured framework to guide corporate disclosures on nature-related impacts, dependencies, risks, and opportunities. The precedent parallels that of the Task Force on Climate-related Financial Disclosures (TCFD) (Smith et al., 2024). The aim is to support a shift in global financial flows from nature-negative outcomes to nature-positive outcomes. There are increasing expectations from businesses to measure and report on both nature-negative and nature-positive outcomes, providing continuous assurances to their key stakeholders that they are operating sustainably. One way this assurance is communicated is through the company's Environmental, Social, and Governance (ESG) report (Finucane and Beckett, 2024). However, enterprises may struggle to fulfil disclosure obligations and contribute significantly to global biodiversity goals without comprehensive and aligned biodiversity assessment tools (Beck-O'Brien and Bringezu, 2021).

ESG ratings are increasingly relied upon by investors and stakeholders, playing a crucial role in financial decision-making and investment strategies. Specifically, the environmental pillar within the ESG rating captures corporate management and performance related to ecological issues, such as biodiversity, resource management, and ecosystem conservation (Schimanski et al., 2023). However, despite the established prominence of ESG ratings in influencing investment flows and corporate strategies, considerable variability remains regarding the integration and impact of nature-related disclosures within these ratings (Smith et al., 2024; Xin et al., 2023). Recent research utilising NLP analysis of earnings call transcripts indicates that although S&P 500 ESG index companies increasingly address environmental topics (e.g., energy consumption, carbon emissions), their causal effect on ESG performance lagged social factors, which demonstrate stronger immediate correlations with ESG index variations (Lee et al., 2025). This suggests that business communication regarding environmental issues may not yet yield measurable improvements in ESG performance as effectively as social activities.

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Wang (2025) underscores the challenges of ESG ratings and finds that generative AI reveals significant time-lagged effects for ESG ratings, especially the Environmental and Social categories, driven by herding behaviour and greenwashing. Tang et al. (2025) report that higher ESG risk scores increase firms' downside risk, a relationship intensified by economic policy uncertainty, highlighting the importance of effective ESG management strategies for U.S. firms. Kathan et al. (2025) shows that high ESG scores correlate with increased greenwashing risk, especially among large companies, highlighting the discrepancy between apparent and actual environmental performance, and indicating that ESG scores may mislead investors and impair the reliable assessment of sustainability practices. Corresponding discrepancies in Lee et al. (2025) report weaker Granger correlation between ESG performance, governance and environmental issues in earnings calls than social variables, highlighting possible disparities between corporate communication and tangible results. He et al. (2025) provide empirical evidence of the strategic impacts of firm-level biodiversity disclosure and the risks of greenwashing in ESG reporting, highlighting how substantive biodiversity transparency can shape corporate sustainability strategies.

Various attempts have been made to address misleading ESG concerns. Rossi et al. (2024) develop innovative methodologies and geospatial environmental scoring frameworks. Schimanski et al. (2023) identify machine learning classifiers for detecting nature-related disclosures. In addition to these initiatives, Lee et al. (2025) demonstrate how sophisticated NLP tools, such as BERT-based topic modelling, can systematically extract ESG signals from earnings calls, providing immediate insight into business priorities and their alignment with ESG standards. Some studies have also suggested that financial mechanisms, such as credit rationing (Hasan et al., 2023), can incentivise improved environmental performance and more comprehensive disclosures. In response to industry-specific factors, Xin et al. (2023) find that institutional investors and analysts largely ignore biodiversity ratings. Empirical analyses also indicate that

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integrating standardised frameworks, such as TNFD, can provide clearer insights into corporate sustainability and nature-related performance, thus potentially influencing investor perceptions and ESG ratings (Schimanski et al., 2023; Smith et al., 2024). However, Lee et al. (2025) show that the effectiveness of such frameworks depends on bridging the gap between qualitative disclosures and quantifiable ESG metrics, particularly for environmental and governance pillars, where alignment remains inconsistent.

This study investigates whether firm TNFD disclosures impact ESG ratings. We argue that integrating TNFD disclosure into sustainability or ESG reports can provide more detailed information about natural risks and opportunities, leading to improved ESG ratings. We use data samples from non-financial and non-utility S&P 500 firms to verify our hypothesis.

Three main conclusions are drawn from our analysis. First, the results indicate a significant positive relationship between TNFD disclosure, environmental (E) scores and overall ESG ratings, respectively. Companies that adopt TNFD disclosure are associated with better E and ESG scores. Second, there is a significant negative relationship between NRR, E and ESG ratings. Companies with greater exposure to nature-related risks (e.g., biodiversity loss, climate risks, deforestation, water scarcity) tend to have lower E and ESG scores. Third, NRO is positively and significantly associated with E and ESG ratings. The findings show that engagement by S&P 500 firms in nature-related opportunities (e.g., sustainable resource management, biodiversity restoration, green investments) tends to improve their future E and ESG performance.

Overall, the integration of the TNFD standardised framework by S&P 500 firms provides clearer insights into corporate sustainability and nature-related performance, potentially influencing investor perceptions and ESG assessments.

This study makes several contributions to the literature. Economically, the results highlight the central role that global sustainability disclosure frameworks play in shaping corporate behaviour. Firms that proactively align with TNFD improve transparency and enhance their environmental

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and ESG outcomes, positioning themselves favourably in the eyes of investors and regulators. Conversely, failure to manage NRRs can significantly harm a firm's sustainability profile, potentially impacting its financial performance and reputation.

The results provide empirical support for policy interventions that encourage the broader adoption of standardised environmental disclosure practices. Regulators and market participants should recognise that promoting such frameworks can generate positive externalities by improving corporate sustainability practices.

2. Literature review and hypothesis

2.1. Environmental, social, and governance factors

Investors' and stakeholders' expectations for sustainability, social responsibility, transparent governance and ESG factors have increasingly become critical to corporate strategy. Indices like the S&P 500 ESG Index have provided a benchmark for assessing non-financial corporate performance (Lee et al., 2025). Several techniques have been used to extract and analyse corporate reports; recent studies employ advanced NLP techniques. Lee et al. (2025) applied Bidirectional Encoder Representations from Transformers (BERT)-based models to earnings call transcripts; their results reveal a correlation between ESG communications and corporate financial performance. The analysis emphasised the influence of external events, such as regulatory changes and global crises, on ESG thematic evolutions and corporate strategies.

Similarly, Zou et al. (2025) introduced ESGReveal, an NLP-based framework leveraging large language models (LLMs) to automate ESG data extraction and evaluation from ESG reports. The study utilised retrieval-augmented generation (RAG) technology, demonstrating high accuracy (76.9% in data extraction) across a comprehensive dataset of ESG disclosures from Hong Kong Stock Exchange-listed firms. This underscores the potential for NLP tools to significantly enhance the efficiency and consistency of ESG disclosure analyses.

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Under climate risk, the relationship between ESG disclosure and financial performance has been explored extensively. Chen et al. (2022) utilise global manufacturing firms to investigate how climate change-related risks (CCRs) impact ESG and financial outcomes. Their multilevel quadratic growth model found that firms actively disclosing CCRs experienced a significant and positive return on assets (ROA). However, increased environmental investments initially enhanced ROA but subsequently showed diminishing returns, especially for private enterprises.

Parallel to these developments, biodiversity considerations have emerged as an integral part of ESG analysis, particularly in light of the Kunming-Montreal Global Biodiversity Framework (GBF). Zhu et al. (2024) identified significant gaps in existing biodiversity indices relative to GBF metrics, emphasizing the urgent need for integrated indices capable of accurate biodiversity impact measurement. Such indices are important for firms to align their business practices with international biodiversity conservation goals and improve transparency in corporate biodiversity disclosures.

Chiu et al. (2023) advanced a regional climate risk model based on the TCFD framework to address regional differences. Employing unsupervised NLP methods, they quantified regional climate risks, offering precise, data-driven insights into local disaster events. The approach realised the necessity of context-specific strategies in ESG frameworks, emphasising adaptability to regional climatic and environmental conditions.

These studies underscore the transformative potential of NLP techniques in ESG analysis, enabling more nuanced, accurate, and timely assessments of corporate sustainability practices. Integrating biodiversity metrics within ESG frameworks, alongside refined risk modelling, presents a comprehensive approach that aligns corporate disclosures with evolving global sustainability standards, such as the TNFD and TCFD. Du et al. (2025) further highlight the influence of biodiversity risk on executive behaviour, deepening the understanding of the strategic

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role of nature-related disclosure in corporate decision-making. The findings show that TCFD-aligned disclosures substantially enhance the E and ESG ratings.

2.2. TNFD disclosures and ESG ratings

To improve openness, TNFD disclosures outline a business's relationships with the natural world, including potential threats from reliance on natural resources and benefits from eco-friendly initiatives (Smith et al., 2024). Prior research indicates that transparent and organised environmental disclosures are positively associated with improved ESG performance ratings, primarily due to their ability to diminish informational asymmetries and align managerial actions with shareholder expectations for sustainable performance (Hasan et al., 2023; Madison and Schiehll, 2021). Thus, TNFD disclosures, by offering organised information on nature-related effects and proactive management strategies, may enhance E and ESG ratings. Consequently, we propose the following hypothesis:

H1a: TNFD disclosure is positively associated with the Environmental pillar of ESG ratings.

H1b: TNFD disclosure is positively associated with ESG ratings.

2.3 Nature-related risks and ESG ratings

NRRs include physical risks from reliance on diminishing natural resources and transition risks linked to changing regulatory frameworks and stakeholder demands (Hadji-Lazaro et al., 2025). Greater NRR exposure may negatively impact corporate performance by escalating operating costs, diminishing productivity, and increasing regulatory compliance expenditures (Smith et al., 2024). Transparent disclosure of these unfavourable impacts may adversely affect ESG ratings by revealing heightened susceptibility and diminished sustainability performance. Consequently, public disclosure of heightened NRRs is expected to expose vulnerabilities that may negatively impact a firm's ESG rating. We propose the following hypothesis:

H2a: NRRs are negatively associated with the environmental pillar of ESG ratings.

H2b: NRRs are negatively associated with ESG ratings.

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2.4. Nature-related opportunities and ESG ratings

In contrast, proactive management of NROs, including the implementation of sustainable practices and creative ecological solutions, can enhance business performance and stakeholder perceptions (O'Grady et al., 2020). Such disclosures convey business dedication to sustainability and innovation, potentially elevating ESG environmental ratings by boosting perceived resilience and strategic environmental positioning (Schimanski et al., 2023). Consequently, well-defined and utilised nature-related opportunities are anticipated to enhance ESG ratings. Thus, we propose the following hypothesis:

H3a: NROs are positively associated with the Environmental pillar of ESG ratings**.**

H3b: NROs are positively associated with ESG ratings.

3. Research design

3.1. Sample and data

The study uses balanced panel data for the non-financial and non-utility S&P 500 from 2018 to 2023. The S&P 500 companies are examined because they comprise large market capitalisation firms in developed markets that have a significant impact on the environment and are systemically important in mitigating nature loss. Six companies were excluded from our sample of 318 due to the unavailability of their sustainability/ESG reports, resulting in a sample of 312 companies.

3.2. Variable measurements

TNFD, NRR, and NRO are the independent variables of interest. TNFD (2023) disclosure is divided into four pillars: governance, strategy, risk impact management, and metrics and targets. We conduct a sentiment analysis according to the RAG methodology as proposed by Colesanti Senni et al. (2024a) and modified to analyse the sentiment as shown in Figure 1. The analysis utilises Stanza, a Python NLP approach developed by Qi et al. (2020), to measure the new nature-related disclosures for the additional TNFD sentiment questions across the governance, strategy,

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and risk impact management pillars, assigning a score within a 100-point range, respectively.[3] Data is sourced from each company's sustainability/ESG report. NRR and NRO scores were generated using NLP. Following Colesanti Senni et al. (2024b) we assign a sentiment score between -10 and 10. A score of -10 refers to downside risk, and 10 indicates opportunity, accompanied by a justification for the decision. E and ESG scores are the dependent variables from the data provider, LSEG.

3.3. Research model

Separate regression models are estimated to examine the impact of TNFD, NRR and NRO on E and ESG, respectively. The general relationship is given by Equation (1):

$$SCORE_{it+1} = \beta_0 + \beta_1 DISCLOSURE_{it} + \gamma Controls_{it} + Ind_j + Year_t + \epsilon_{i,t+1} \qquad (1)$$

Where $SCORE_{it+1}$ refers to the natural log of $(1 + ESG)$ or $(1 + E)$ for firm i in year $t+1$. The independent variable $DISCLOSURE_{it}$ is the NLP analysed TNFD, NRR or NRO disclosure for firm i in year t, respectively. $Controls$ represent various firm factors that influence ESG scores. Ind and $Year$ are the industry and year fixed effects. All variables are defined in Table 1.

3.4 Control variables

TNFD (2023) illustrative disclosure models demonstrate integrated reporting formats that explicitly incorporate both TCFD and TNFD recommendations, positioning TCFD as the primary climate controls for TNFD-focused assessments; hence, we control for TCFD disclosure.

Our variables include a range of firm-level controls. Kassinis et al. (2016) state that large firms are generally more conscious of environmental accountability and thus, they are likely to engage in ESG-related activities. As a result, we control for firm size (SIZE). Following a prior study, we also control for firm profitability (ROA), which has been used to measure the relationship between firm ESG and financial performance (Singhania and Saini, 2022). Furthermore, we account for

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[3] See Appendix A for details about the sentiment questions used in the analysis.

firm leverage (LEV), which predicts a negative relationship between financial leverage and ESG performance (McGuinness et al., 2017).

We also control for firm cash balances (CF), used in prior studies to show their controlling effect on the relationship between climate-related disclosure and business green innovation (Gao et al., 2024). Finally, we include firm board characteristics, which have been proven to lead to high ESG reporting (Nguyen and Nguyen, 2023). Our measures of board characteristics are board tenure (BT), board gender diversity size (BGD), and board independence (BI).

4. Analysis of empirical results

4.1. Descriptive statistics

Statistics summarising the variables employed in this study are reported in Table 2. The mean E and ESG scores are 62.69 and 66.33, respectively. E (ESG) ranges between 0.13 and 98.06 (17.74 and 93.38). TNFD, NRR and NRO report mean values of 57.74, -6.38, and 3.25, respectively.

4.2. Impact of TNFD on E and ESG ratings

The results of the baseline estimated association between TNFD disclosure and the E and ESG scores are given in Table 3. Columns 1, 2, 5 and 6 all report a significant positive association between E and TNFD disclosure. Similarly, the positive coefficients reported in Columns 3, 4, 7 and 8 show a consistent positive association between ESG and TNFD. The unreported variance inflation factors for each model are all less than 10, so that multicollinearity is not a concern. The findings are also economically important. The TNFD coefficient in Column (2) of 0.007 means that a one standard deviation increase in TNFD corresponds to a 0.5% [Exp(0.007*14.7/20.55)-1] increase in the environmental performance. Overall, after controlling for firm-specific factors, enhanced transparency through TNFD disclosures has a positive impact on environmental ratings. The decrease in the magnitude of the coefficient between models (1) and (2) indicates that firm-

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specific factors explain part of the E score. The empirical evidence provides strong support for H1a. Improved TNFD disclosure is associated with a higher E score.

The result for the ESG score in Column (4) shows that a one standard deviation increase in TNFD relates to a 0.3% [Exp(0.003*14.7/14.26)-1] increase in ESG on average. The finding supports H1b. Enhanced transparency in sustainability reports is associated with better ESG ratings. To validate the baseline findings, we use the Bloomberg database as an alternative score for our dependent variable. The results in Columns (5) to (8) show a significant positive relationship between TNFD, E and ESG, verifying the main results.

[Insert TABLE 3 here]

4.3. Impact of NRR on E and ESG ratings

Next, we examine the relationship between NRR, the E and ESG ratings. The estimated models are reported in Table 4. Overall, the NRR coefficient is significant and negative. Using the result in Column (2), a one standard deviation increase in NRR corresponds to a decrease in E of -0.43% [Exp(-0.028*3.147/20.55)-1] after controlling for firm-specific characteristics. The result supports H2a. Greater nature-related risks negatively impact firm E scores. Firms facing higher NRR scores are penalised with lower E ratings. Column (4) examines the relationship between NRR and ESG. A one standard deviation decrease in NRR is associated with a decrease in ESG of -0.33% [Exp(-0.015*3.147/14.26)-1]. The lower ESG score suggests that firms with higher NRRs tend to have lower overall ESG scores. The result supports H2b and indicates strong stakeholder sensitivity to NRRs.

The analysis is repeated using E and ESG scores sourced from the Bloomberg database. The results are reported in columns (5) – (8) and confirm the negative relationship between NRR, E and ESG.

[Insert TABLE 4 here]

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4.4. Impact of NRO on E and ESG ratings

Table 5 examines the association between NRO, E and ESG. Overall, the results show a positive and significant relationship after controlling for firm-specific factors. The NRO coefficient in Column (2) of 0.038 indicates that a one standard deviation increase in NRO corresponds to a 0.43% [Exp(0.038*2.33/20.55)-1] increase in the environmental performance. From Column (4), a one standard deviation increase in NRO is associated with an increase in ESG of 0.36% [Exp(0.022*2.33/14.26)-1]. The evidence indicates that NRO is a key driver of environmental ratings, and the result supports H2a and H2b.

The estimations using the Bloomberg scores are presented in Columns (5) – (8) as a robustness check. The coefficients validate our hypothesis of a positive and significant relationship between NRO, E and ESG.

<p style="text-align:center;">[Insert TABLE 5 here]</p>

4.5. Endogeneity tests

While the baseline regression models include a range of firm- and industry-level variables that address endogeneity concerns due to omitted variables, by controlling for constant time-invariant unobserved characteristics for each firm, reverse causality, measurement error or selection bias may also affect the relationship between TNFD, E, and ESG. We employ a two-stage least squares (2SLS) approach using the lagged geographical mean of our main variables (TNFD, NRR and NRO) as an instrumental variable. This instrument leverages the well-established principle that firms' disclosure decisions are influenced by their geographical peers' past practices, while being temporally separated from current unobserved factors that might simultaneously affect both TNFD adoption and our dependent variables.

The first and second stages of the 2SLS regression are reported in Panel A of Table 6. The first-stage results confirm that the Lagged Geographical mean (Lag Geo Avg), the instrumental variable (IV), is significantly related to each of the endogenous variables, TNFD, NRR, and NRO. The

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highly significant TNFD Lag Geo Avg coefficient, 0.353, in Column (1) shows that Lag Geo is a strong IV for TNFD. Likewise, the 0.426 NRR Lag Geo Avg coefficient shown in Column (4) validates the IV for nature-related risks. Finally, the NRO Lag Geo Avg coefficient in Column (7), 0.307, has a positive association with NRO. Lag Geo adoption is associated with more NROs.

The second-stage regressions all confirm that increasing engagement with TNFD positively influences E and ESG scores. Using the models in Columns (2) and (3), if TNFD increases by one standard deviation, E and ESG scores increase by 1.2% and 0.7%, respectively.[4] Therefore, greater alignment to TNFD requirements improves firms' sustainable performance.

Conversely, the significant negative coefficients in Columns (5) and (6) mean that greater NRR exposure results in lower E and ESG scores. For example, a one-standard-deviation increase in NRR is associated with reductions of 1.4% and 1% in E and ESG scores, respectively.[5] Inadequately managed or poorly communicated NRRs can negatively impact a firm's E and ESG performance.

Columns (8) and (9) report a positive and significant association between NRO, E and ESG. A one standard deviation increase in NRO is associated with a 2.7% and 1.8% increase in E and ESG scores, respectively.[6] The economic significance of greater NROs confirms the added value of recognising and using nature-related opportunities.

The second-stage Durbin-Wu-Hausman endogeneity diagnostic test reported in Table 6, rejects the null hypothesis of exogeneity for the endogenous regressors, confirming that the IV approach is necessary. Furthermore, the under-identification tests (Kleibergen-Paap LM statistics) confirm the relevance of the instrument. In contrast, the weak identification tests (Cragg-Donald and Kleibergen-Paap rk Wald F statistics) indicate that the instruments are sufficiently strong, except

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[4] TNFD: Change in E = [Exp(0.016*14.695/20.546) -1]. Change in ESG = [Exp(0.007*14.695/14.264)-1].
[5] NRR: Change in E = [Exp(-0.092*3.147/20.546)-1]. Change in ESG = [Exp(-0.044*3.147/14.264)-1].
[6] NRO: Change in E = [Exp(0.236*2.33/20.546)-1]. Change in ESG = [Exp(0.108*2.33/14.264)-1].

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for NRR, which exhibits weak instrument identification. Overall, the IV justify the 2SLS estimation.

[Insert TABLE 6 here]

The propensity score matching (PSM) estimation reported in Panel B provides further support for the main findings. TNFD_high (TNFD_low) refers to those firms that have a TNFD score greater (less) than the sample median. The high adoption of TNFD has a small but positive impact on environmental performance, whereas low disclosure is associated with significantly lower ESG. The finding suggests that less transparent nature-related disclosures reduce sustainability. Firms with greater NRR exposure tend to have lower E and ESG scores, whereas those with less NRR exposure report improved E and ESG metrics. Overall, the findings suggest that low exposure to nature-related risks enhances ESG ratings. In contrast, the magnitude of the NRO firm coefficients highlights the impact of NROs on strategies that promote sustainability. The chi-squared statistics reveal significant differences between the coefficients for each of the estimated models, providing further support for the baseline results.

In Panel C, to overcome the problem of selection bias, entropy balancing (EB) is used to reweight the control group (low TNFD/NRR/NRO disclosure) to precisely represent the covariate distribution in the treated group (high TNFD/NRR/NRO disclosure). Re-estimation of the firm-fixed-effects model using these weights reveals that high TNFD disclosure has a significant positive impact on E and ESG ratings. Finally, even with strict covariate balance, NRR still has a negative impact on E and ESG ratings, whereas NRO continues to provide positive effects.

5. Further tests

5.1. Impact of different pillars of TNFD on ESG

As further corroboration of the significant association between TNFD, E, and ESG, we examine the different pillars of TNFD disclosure in relation to E and ESG. Columns (1) and (2) of Table 7 report positive significant governance (GOV) coefficients for E (0.005) and ESG (0.003),

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respectively. Enhanced governance disclosures under the TNFD framework strengthen firm E and ESG performance. We attribute this result to better managerial oversight and accountability mechanisms. The strategy (STR) dimension shows a positive and statistically significant relationship with E and ESG outcomes. While strategic information disclosure is directionally aligned with improved sustainability performance, the effect is also strong enough to reach conventional significance levels.

[Insert TABLE 7 here]

The risk impact management (RIM) pillar, as reported in Columns (5) and (6) of Table 7, has a positive and statistically significant association with E and ESG scores. Greater transparency regarding nature-related risk management practices enhances firms' sustainability standing. Finally, metrics and targets (MT) disclosures have a substantial positive influence. The MT coefficients for E (0.002) and ESG (0.001) are both insignificant, suggesting that performance targets might not be a driver of sustainability reporting.

The findings indicate that all pillars of the TNFD, except MT disclosure, exert influence and emphasise the critical role of the pillars in promoting superior environmental and ESG outcomes. To verify the robustness of these results across different pillars, we conducted robustness tests in an untabulated analysis using the Bloomberg ESG score. The outcomes confirm significant differences across all TNFD pillars.

5.2. Industry Analysis of TNFD adoption on ESG ratings

We also examine heterogeneity by industry type. The green industries are characterised by low emissions or a sustainability-oriented approach, whereas brown industries are defined as environmentally intensive industries. The findings reported in Table 8 provide industry-level estimates of TNFD adoption in relation to E and ESG performance, demonstrating sector heterogeneity. The positive and significant relationship between TNFD disclosure and ESG scores in brown industries implies that improved environmental accountability and investor confidence

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increase with greater TNFD disclosure, even in industries with a high environmental impact. Nonetheless, companies characterised by greater NRR exhibit high inefficiencies in terms of performance, which suggests that increased environmental reliance hinders sustainability performance. In comparison, the positive and significant NRO coefficients indicate the benefits of active opportunity management on both E and ESG scores.

[Insert TABLE 8 here]

The positive effect of TNFD adoption is more significant in green industries. Companies with well-developed sustainability activities gain more from TNFD disclosure. The adverse impact of NRR and the beneficial impact of NRO are similar but magnified for the brown industries. The finding underscores the role of risk reduction and opportunity exploitation in maintaining ESG leadership. There is strong evidence that firm size and board independence are significantly related to E and ESG outcomes, while leverage and profitability exhibit a weak or negative relationship. Taken together, the evidence suggests that the adoption of TNFD leads to a significant improvement in environmental and ESG performance, with a particularly pronounced effect in green sectors. Risk exposure is mitigated, and an opportunity-oriented approach facilitates sustainable performance in industrial settings.

5.3. Moderating Effect of Institutional Ownership

In this section, the issue of institutional ownership (IO) in attenuating the effects of TNFD, NRR, and NRO on E and ESG results is considered. From Table 9, TNFD disclosure significantly improves E and ESG outcomes, implying that the better the nature-related disclosure, the higher the firm's sustainability performance. The interaction coefficient for TNFD disclosure and IO is positive and significant for E, implying that institutional investors intensify the positive impact of TNFD adoption. We postulate that these results are achieved by enhanced monitoring, governance pressures, and information credibility.

[Insert TABLE 9 here]

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From Columns (3) and (4) of Table 9, NRR has both a negative and a significant influence, which is a manifestation of the negative impact of environmental susceptibility on sustainability outcomes. The correlation between NRR and IO is also considerably negative, indicating that institutional investors may be more risk-averse when companies have large nature-related exposures. On the other hand, NROs exhibit a significant positive association with the environmental pillar for the main and interaction effects. This finding suggests that institutional ownership amplifies the benefits of opportunity-based environmental strategies, which may reward firms that prioritise innovation and environmentally friendly investments.

In general, the results suggest that although the TNFD implementation and IO are positively associated with environmental performance, their combined outcome may be more complex when it comes to ESG. Altogether, these results underscore the complex role that institutional investors play in determining the effectiveness of sustainability efforts.

6. Conclusion

This study examines how the TNFD framework, in conjunction with nature-related risks and opportunities, affects E and ESG scores for non-financial and non-utility S&P 500 firms. The results show that TNFD-aligned disclosures substantially enhance the E and ESG ratings.

We present robust empirical evidence that perceived nature-related risks negatively impact firms' ESG performance. The consistency across specifications, 2SLS, PSM, and EB models validates our interpretation. Nature-related opportunities demonstrate a positive impact on improving E and ESG performance. The findings align with the strategic opportunity framework inside the TNFD narrative.

Moreover, the TNFD pillar framework (GOV, STR, and RIM) is empirically proven to effectively predict ESG results, supporting its theoretical and practical significance. Our research contributes to the literature by providing the first empirical evidence on the disclosure impact of

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TNFD disclosures, confirming that nature-related risks and opportunities are significant key drivers, and that companies can benefit from adhering to TNFD disclosure standards.

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Table 1

Definition of main variables.

Variable	Measurement	Source
TNFD	NLP score for TNFD element, excluding TCFD component	(Colesanti Senni et al., 2024a; Qi et al., 2020)
GOV	NLP Score for the governance pillar of TNFD	(Colesanti Senni et al., 2024a; Qi et al., 2020)
STR	NLP score for the strategy pillar of TNFD	(Colesanti Senni et al., 2024a; Qi et al., 2020)
RIM	NLP score for the risk impact management pillar of TNFD	(Colesanti Senni et al., 2024a; Qi et al., 2020)
MT	NLP score for metrics & targets pillar of TNFD	(Colesanti Senni et al., 2024a; Qi et al., 2020)
NRR	NLP score for nature-related risk following	(Colesanti Senni et al., 2024a; Qi et al., 2020)
NRO	NLP score for nature-related opportunities	(Colesanti Senni et al., 2024a; Qi et al., 2020)
TCFD	NLP score for TCFD	(Colesanti Senni et al., 2024a; Qi et al., 2020)
E	Natural logarithm of the environmental pillar	LSEG (REFINITIV)
ESG	Natural logarithm of the overall ESG score based on each pillar	LSEG (REFINITIV)
Size	Natural logarithm of the company market capitalisation	
ROA	Return on assets is calculated based on the original balance sheet data	
CF	Natural logarithm of Net Cash Flow from Operating Activities	
LEV	Total debt percentage of common equity	
BGD	Board gender diversity - Percentage of female board members	
BI	Percentage of independent board members	
BT	Average number of years each board member has been on the board	

Table 2
Descriptive statistics (n=1,461).

	Mean	Median	Std	Q25	Q75	Min	Max
E_{t+1}	62.960	66.750	20.546	45.950	78.150	0.130	98.060
ESG_{t+1}	66.330	68.833	14.264	56.180	76.310	17.740	93.380
TNFD	57.737	57.667	14.695	46.000	68.333	22.667	96.000
TCFD	-2.730	-2.479	10.682	-8.833	3.250	10.200	80.166
NRR	-6.377	-6.500	3.147	-10.000	-3.500	-10.000	-0.250
NRO	3.248	2.500	2.330	1.500	4.500	0.250	10.000
Size	17.288	17.154	1.259	16.450	18.048	1.792	21.820
ROA	9.033	8.405	9.215	4.915	13.560	-46.190	70.610
LEV	64.596	67.150	16.442	55.430	76.150	2.440	118.110
CF	14.638	14.500	1.198	13.817	15.364	7.004	18.621
BT	9.051	8.525	3.218	6.920	10.640	1.000	29.440
BGD	29.332	28.570	9.215	23.080	33.333	7.140	87.500
BI	85.372	87.500	8.094	81.820	91.670	46.670	100.000

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Table 3
Impact of TNFD on ESG ratings for LSEG and Bloomberg scores.

	LSEG (REFINITIV)				BLOOMBERG			
Variables	E (1)	E (2)	ESG (3)	ESG (4)	E (5)	E (6)	ESG (7)	ESG (8)
TNFD	0.010***	0.007***	0.007***	0.003***	0.009***	0.010***	0.002***	0.002***
	(6.013)	(5.094)	(4.635)	(3.801)	(6.283)	(6.450)	(7.773)	(7.726)
TCFD		0.004		0.001		0.013***		0.003***
		(1.241)		(0.472)		(5.485)		(3.922)
Size		0.110***		0.051*		0.049		0.015
		(2.765)		(1.921)		(1.006)		(1.144)
ROA		-0.007**		0.001		-0.005		-0.001
		(-2.167)		(0.568)		(-1.011)		(-0.851)
CF		0.036		0.010		0.071		0.032**
		(0.870)		(0.353)		(1.475)		(2.556)
LEV		-0.002		-0.003**		0.003		0.000
		(-1.142)		(-2.401)		(1.335)		(0.664)
BT		0.009		0.017		-0.042***		-0.009***
		(0.698)		(1.622)		(-3.122)		(-3.270)
BGD		0.004		0.003		0.010**		0.002*
		(0.965)		(1.319)		(2.309)		(1.839)
BI		0.021***		0.021***		0.007		0.003***
		(4.241)		(4.206)		(1.505)		(2.850)
Constant	3.338***	-0.548	3.617***	1.088*	3.179***	0.593	3.920***	2.961***
	(28.753)	(-0.827)	(34.773)	(1.877)	(33.412)	(0.929)	(217.010)	(19.283)
Year FE	YES	YES	YES	YES	YES	YES	YES	YES
Industry FE	YES	YES	YES	YES	YES	YES	YES	YES
Cluster	FIRM	FIRM	FIRM	FIRM	FIRM	FIRM	FIRM	FIRM
No. of Obs.	1,555	1,461	1,555	1,461	1,477	1,439	1,477	1,439
Adj. R^2	0.116	0.246	0.0863	0.192	0.183	0.307	0.186	0.343

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Table 4
Impact of NRR on ESG ratings for LSEG and Bloomberg scores.

Variables	LSEG (REFINITIV)				BLOOMBERG			
	E (1)	E (2)	ESG (3)	ESG (4)	E (5)	E (6)	ESG (7)	ESG (8)
NRR	-0.047***	-0.028***	-0.033***	-0.015***	-0.040***	-0.033***	-0.011***	-0.009***
	(-5.253)	(-4.338)	(-4.165)	(-3.131)	(-5.867)	(-5.124)	(-6.295)	(-5.398)
TCFD		-0.002		-0.002		0.003**		0.001
		(-0.900)		(-1.097)		(1.983)		(1.305)
Size		0.113***		0.053**		0.052		0.016
		(2.881)		(1.984)		(1.012)		(1.174)
ROA		-0.007**		0.001		-0.006		-0.001
		(-2.067)		(0.513)		(-0.974)		(-0.833)
CF		0.038		0.010		0.079		0.033***
		(0.925)		(0.384)		(1.573)		(2.614)
LEV		-0.001		-0.003**		0.004		0.001
		(-0.805)		(-2.122)		(1.477)		(0.965)
BT		0.009		0.017		-0.041***		-0.009***
		(0.726)		(1.648)		(-2.862)		(-2.973)
BGD		0.005		0.004		0.011**		0.002**
		(1.209)		(1.530)		(2.419)		(2.046)
BI		0.021***		0.021***		0.008		0.003***
		(4.338)		(4.257)		(1.539)		(2.846)
Constant	3.634***	-0.524	3.824***	1.101*	3.454***	0.622	3.982***	2.967***
	(48.471)	(-0.788)	(57.637)	(1.900)	(59.814)	(0.911)	(292.350)	(18.123)
Year FE	YES	YES	YES	YES	YES	YES	YES	YES
Industry FE	YES	YES	YES	YES	YES	YES	YES	YES
Cluster	FIRM	FIRM	FIRM	FIRM	FIRM	FIRM	FIRM	FIRM
No. of Obs.	1,555	1,461	1,555	1,461	1,477	1,439	1,477	1,439
Adj. R^2	0.0884	0.230	0.0693	0.187	0.135	0.251	0.155	0.307

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Table 5
Impact of NRO on ESG ratings (including robustness test).

Variables	LSEG (REFINITIV)				BLOOMBERG			
	E (1)	E (2)	ESG (3)	ESG (4)	E (5)	E (6)	ESG (7)	ESG (8)
NRO	0.057***	0.038***	0.038***	0.022***	0.067***	0.053***	0.020***	0.015***
	(4.076)	(4.112)	(3.098)	(3.147)	(5.960)	(4.829)	(7.140)	(5.651)
TCFD		-0.003		-0.002		0.003		0.001
		(-1.026)		(-1.198)		(1.575)		(1.062)
Size		0.110***		0.051*		0.047		0.014
		(2.750)		(1.898)		(0.920)		(1.084)
ROA		-0.008**		0.001		-0.006		-0.001
		(-2.121)		(0.449)		(-1.023)		(-0.920)
CF		0.038		0.010		0.077		0.033**
		(0.916)		(0.377)		(1.526)		(2.555)
LEV		-0.002		-0.003**		0.003		0.000
		(-1.004)		(-2.277)		(1.311)		(0.737)
BT		0.009		0.017		-0.042***		-0.009***
		(0.677)		(1.617)		(-2.929)		(-3.057)
BGD		0.005		0.004		0.012**		0.002**
		(1.228)		(1.562)		(2.477)		(2.134)
BI		0.021***		0.021***		0.008		0.003***
		(4.377)		(4.270)		(1.523)		(2.879)
Constant	3.698***	-0.415	3.874***	1.163**	3.467***	0.783	3.983***	3.012***
	(53.867)	(-0.630)	(64.473)	(2.010)	(63.135)	(1.162)	(309.299)	(18.895)
Year FE	YES	YES	YES	YES	YES	YES	YES	YES
Industry FE	YES	YES	YES	YES	YES	YES	YES	YES
Cluster	FIRM	FIRM	FIRM	FIRM	FIRM	FIRM	FIRM	FIRM
No. of Obs.	1,555	1,461	1,555	1,461	1,477	1,439	1,477	1,439
Adj. R^2	0.0765	0.225	0.0608	0.185	0.137	0.252	0.163	0.310

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Table 6
Panel A: 2SLS test for endogeneity.

	First Stage	Second Stage		First Stage	Second Stage		First Stage	Second Stage	
Variables	**TNFD (1)**	**E (2)**	**ESG (3)**	**NRR (4)**	**E (5)**	**ESG (6)**	**NRO (7)**	**E (8)**	**ESG (9)**
TNFD Lag Geo Avg	0.353***								
	(3.388)								
TNFD_Only		0.016**	0.007*						
		(1.973)	(1.854)						
NRR Lag Geo Avg				0.426***					
				(4.697)					
NRR					-0.092**	-0.044**			
					(-2.375)	(-1.994)			
NRO Lag Geo Avg							0.307***		
							(3.263)		
NRO								0.236**	0.108*
								(2.169)	(1.834)
Constant	10.714	-0.651	0.942	-1.968	-0.589	0.966	-2.210	0.265	1.360**
	(0.838)	(-0.961)	(1.549)	(-0.848)	(-0.885)	(1.608)	(-1.421)	(0.339)	(2.167)
Control	YES	YES	YES	YES	YES	YES	YES	YES	YES
Year FE	YES	YES	YES	YES	YES	YES	YES	YES	YES
Industry FE	YES	YES	YES	YES	YES	YES	YES	YES	YES
Cluster	FIRM	FIRM	FIRM	FIRM	FIRM	FIRM	FIRM	FIRM	FIRM
No. of Obs.	1,445	1,157	1,157	1,445	1,157	1,157	1,445	1,157	1,157
Adj R^2	0.243	0.187	0.189	0.0793	0.148	0.176	0.0635	-0.133	0.101
F-statistic	12.61			4.108			3.448		
Second-stage diagnostic test analysis									
Under identification test:									
Kleibergen-Paap LM		7.057***	7.057***		14.883***	14.883***		7.615***	7.615***
Weak identification test:									

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Cragg-Donald Wald F statistic			23.486	23.486			23.556	23.556		7.317	7.317
Kleibergen-Paap rk Wald F statistic			12.558	12.558			21.371	21.371		8.449	8.449

Panel B: PSM test for endogeneity.

Variables	E (1)	ESG (2)	E (3)	ESG (4)	E (5)	ESG (6)	E (7)	ESG (8)	E (9)	ESG (10)	E (11)	ESG (12)
High_TNFD	0.109**	0.045										
	(0.055)	(0.031)										
Low_TNFD			-0.124*	-0.010*								
			(0.092)	(0.082)								
High_NRR					-0.265***	-0.113***						
					(0.053)	(0.029)						
Low_NRR							0.180***	0.056**				
							(0.065)	(0.025)				
High_NRO									0.143***	0.040*		
									(0.048)	(0.022)		
Low_NRO											-0.170***	-0.011
											(0.065)	(0.047)
Constant	3.990***	4.143***	3.973***	4.090***	4.100***	4.188***	3.940***	4.140***	3.962***	4.151***	4.001***	4.098***
	(0.057)	(0.029)	(0.089)	(0.081)	(0.032)	(0.019)	(0.065)	(0.022)	(0.049)	(0.021)	(0.048)	(0.043)
Chi² (High–Low)	43.99***	22.78***			72.50***	31.68***			55.21***	26.63***		
No. of Obs.	1,121	1,121	1,221	1,221	1,315	1,315	1,359	1,359	1,357	1,357	1,234	1,234
Adj. R²	0.007	0.002	0.004	-0.001	0.031	0.016	0.016	0.005	0.011	0.002	0.010	-0.001

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Panel C: Entropy Balanced.

Variables	E (1)	ESG (2)	E (3)	ESG (4)	E (5)	ESG (6)
TNFD_high	0.113**	0.073**				
	(2.510)	(2.419)				
NRR_high			-0.240***	-0.141***		
			(-4.786)	(-3.758)		
NRO_high					0.148***	0.075**
					(3.527)	(2.379)
Constant	0.039	1.515***	-0.376	1.261**	0.138	1.523***
	(0.061)	(3.005)	(-0.575)	(2.186)	(0.228)	(3.030)
Control	YES	YES	YES	YES	YES	YES
Year FE	YES	YES	YES	YES	YES	YES
Industry FE	YES	YES	YES	YES	YES	YES
Cluster	FIRM	FIRM	FIRM	FIRM	FIRM	FIRM
No. of Obs.	1,461	1,461	1,461	1,461	1,461	1,461
Adj. R^2	0.245	0.193	0.229	0.187	0.179	0.139

Table 7
Impact of different dimensions of TNFD on ESG ratings.

Variables	E (1)	ESG (2)	E (3)	ESG (4)	E (5)	ESG (6)	E (7)	ESG (8)
GOV	0.005***	0.003***						
	(5.020)	(4.160)						
STR			0.005***	0.002**				
			(4.111)	(2.387)				
RIM					0.004***	0.002***		
					(4.237)	(3.004)		
MT							0.002	0.001
							(1.380)	(0.624)
Constant	-0.498	1.132*	-0.571	1.073*	-0.563	1.078*	-0.422	1.147*
	(-0.749)	(1.936)	(-0.863)	(1.853)	(-0.837)	(1.834)	(-0.630)	(1.943)
Control	YES	YES	YES	YES	YES	YES	YES	YES
Year FE	YES	YES	YES	YES	YES	YES	YES	YES
Industry FE	YES	YES	YES	YES	YES	YES	YES	YES
Cluster	FIRM	FIRM	FIRM	FIRM	FIRM	FIRM	FIRM	FIRM
No. of Obs.	1,461	1,461	1,461	1,461	1,461	1,461	1,461	1,461
Adj. R^2	0.243	0.194	0.231	0.184	0.230	0.185	0.255	0.195

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Table 8
Industry Analysis of TNFD adoption on ESG ratings

Variables	BROWN INDUSTRIES						GREEN INDUSTRIES					
	E (1)	ESG (2)	E (3)	ESG (4)	E (5)	ESG (6)	E (7)	ESG (8)	E (9)	ESG (10)	E (11)	ESG (12)
TNFD	0.006***	0.003***					0.008***	0.004***				
	(3.336)	(2.964)					(4.092)	(2.757)				
NRR			-0.019**	-0.010**					-0.033***	-0.020**		
			(-2.439)	(-2.123)					(-3.112)	(-2.180)		
NRO					0.030***	0.017**					0.039***	0.022**
					(2.643)	(2.353)					(3.123)	(2.105)
Constant	0.676	2.195***	0.669	2.192***	0.720	2.221***	-1.819**	0.178	-1.706*	0.241	-1.572*	0.311
	(0.844)	(3.778)	(0.820)	(3.714)	(0.915)	(3.803)	(-2.065)	(0.249)	(-1.884)	(0.332)	(-1.737)	(0.427)
Control	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES
Year FE	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES
Industry FE	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES
Cluster	FIRM	FIRM	FIRM	FIRM	FIRM	FIRM	FIRM	FIRM	FIRM	FIRM	FIRM	FIRM
No. of Obs.	756	756	756	756	756	756	705	705	705	705	705	705
Adj. R^2	0.201	0.164	0.185	0.157	0.184	0.158	0.311	0.246	0.287	0.239	0.28	0.234

Table 9

Channel Analysis - Moderating Effect of Institution Ownership.

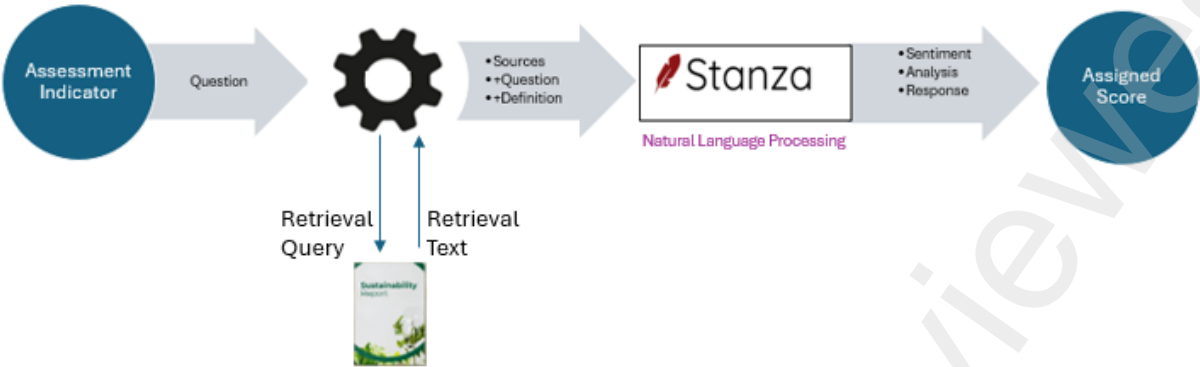| Variables	E (1)	ESG (2)	E (3)	ESG (4)	E (5)	ESG (6)
TNFD	0.005***	0.003***				
	(2.952)	(2.715)				
IO	-0.012	-0.005				
	(-1.349)	(-0.973)				
TNFD*IO	0.001*	0.001				
	(1.558)	(0.669)				
NRR			-0.018**	-0.009		
			(-2.017)	(-1.524)		
IO			-0.007	-0.005		
			(-1.184)	(-1.328)		
NRR*IO			-0.001*	-0.001		
			(-1.700)	(-1.344)		
NRO					0.020	0.012
					(1.576)	(1.310)
IO					-0.008	-0.006
					(-1.337)	(-1.414)
NROxIO					0.003**	0.001
					(2.088)	(1.636)
Constant	-0.396	1.060*	-0.457	1.038*	-0.300	1.124*
	(-0.546)	(1.807)	(-0.632)	(1.779)	(-0.418)	(1.929)
Control	YES	YES	YES	YES	YES	YES
Year FE	YES	YES	YES	YES	YES	YES
Industry FE	YES	YES	YES	YES	YES	YES
Cluster	FIRM	FIRM	FIRM	FIRM	FIRM	FIRM
No. of Obs.	1,458	1,458	1,458	1,458	1,458	1,458
Adj. R^2	0.244	0.195	0.228	0.191	0.224	0.189

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Figure 1: RAG pipeline, including a modification for analysing TNFD, NRR, and NRO scores.

Appendix

A. TNFD Sentiment questions.

Governance Pillar	Strategy pillar	Risk & impact management pillar	Metrics & target pillar
1. How does the board oversee nature-related dependencies, impacts, risks and opportunities? 2. What is management's role in assessing and managing nature-related dependencies, impacts, risks and opportunities? **3. What are the organization's human rights policies and engagement activities regarding Indigenous Peoples, Local Communities, and stakeholders in relation to nature-related issues? How do the board and management oversee these?**	1. What nature-related dependencies, impacts, risks and opportunities has the organisation identified across different time horizons (short, medium, long term)? 2. How have nature-related dependencies, impacts, risks and opportunities affected the organization's business model, value chain, strategy and financial planning? What transition plans or analyses are in place? 3. How resilient is the organization's strategy to nature-related risks and opportunities under different scenarios? **4. What are the locations of assets/activities in direct operations and value chains that meet priority location criteria?**	1a. What processes does the organisation use to identify, assess and prioritise nature-related dependencies, impacts, risks and opportunities in its direct operations? 1b. What processes does the organization use to identify, assess and prioritize nature-related dependencies, impacts, risks and opportunities in its upstream and downstream value chains? **2. How does the organization manage nature-related dependencies, impacts, risks and opportunities?** 3. How are the processes for identifying, assessing, prioritizing and monitoring nature-related risks integrated into overall risk management?	1. What metrics does the organization use to assess and manage material nature-related risks and opportunities in alignment with strategy and risk management? 2. What metrics does the organization use to assess and manage its dependencies and impacts on nature? 3. What targets and goals does the organization use to manage nature-related dependencies, impacts, risks and opportunities? How is it performing against these?

The bold font identifies the three additional sentiment questions required for the TNFD disclosure regime compared to TCF