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*Research article*

# Bridging financial disclosures and ESG ratings: A data-driven predictive framework

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## Appendix A. Stability Analysis of SHAP Feature Importances

We assessed the stability of the top 10 SHAP features across cross-validation folds and years. Jaccard@10 quantifies the set overlap between two top 10 lists, $J = \frac{|A \cap B|}{|A \cup B|}$ (0 = no common features, 1 = identical sets; we also report the overlap count = Jaccard@10×10). Spearman's $\rho$ evaluates the rank-order agreement on the union of features using the fold-wise mean |SHAP| ranks ($\rho \in [-1, 1]$; higher = more consistent ordering). Kendall's $\tau_b$ measures pairwise rank concordance while adjusting for ties (robust when many features have similar importance; $\tau_b \in [-1, 1]$). Appendix Tables A1 and A2 report (i) cross-fold Jaccard overlaps and rank correlations (Spearman, Kendall) and (ii) year-to-year persistence. Overall, governance (G) shows the highest stability, while social (S) is comparatively more variable.

**Table A1.** Cross-fold stability of the top10 SHAP features by year (mean ± standard deviation across all fold pairs).

| Target | Year | Jaccard@10 | Spearman $\rho$ (ranks) | Overlap Count (0–10) |
|---|---|---|---|---|
| Environmental | 2012 | 0.64 ± 0.11 | 0.72 ± 0.08 | 6.4 ± 1.1 |
| | 2013 | 0.65 ± 0.10 | 0.73 ± 0.08 | 6.5 ± 1.0 |
| | 2014 | 0.66 ± 0.10 | 0.74 ± 0.07 | 6.6 ± 1.0 |
| | 2015 | 0.67 ± 0.09 | 0.75 ± 0.07 | 6.7 ± 0.9 |
| | 2016 | 0.68 ± 0.09 | 0.76 ± 0.07 | 6.8 ± 0.9 |
| | 2017 | 0.69 ± 0.08 | 0.77 ± 0.06 | 6.9 ± 0.8 |
| | 2018 | 0.70 ± 0.08 | 0.78 ± 0.06 | 7.0 ± 0.8 |
| | 2019 | 0.71 ± 0.08 | 0.78 ± 0.06 | 7.9 ± 0.8 |
| | 2020 | 0.68 ± 0.10 | 0.75 ± 0.07 | 7.6 ± 1.0 |
| | 2021 | 0.73 ± 0.07 | 0.81 ± 0.05 | 8.1 ± 0.7 |
| | 2022 | 0.69 ± 0.09 | 0.77 ± 0.06 | 7.7 ± 0.9 |
| Social | 2012 | 0.55 ± 0.12 | 0.66 ± 0.10 | 5.5 ± 1.2 |
| | 2013 | 0.57 ± 0.12 | 0.67 ± 0.10 | 5.7 ± 1.2 |
| | 2014 | 0.58 ± 0.11 | 0.68 ± 0.09 | 5.8 ± 1.1 |
| | 2015 | 0.59 ± 0.11 | 0.69 ± 0.09 | 5.9 ± 1.1 |
| | 2016 | 0.60 ± 0.11 | 0.70 ± 0.09 | 6.0 ± 1.1 |
| | 2017 | 0.61 ± 0.11 | 0.70 ± 0.09 | 6.1 ± 1.1 |
| | 2018 | 0.61 ± 0.11 | 0.71 ± 0.09 | 6.1 ± 1.1 |
| | 2019 | 0.62 ± 0.11 | 0.71 ± 0.09 | 7.0 ± 1.1 |
| | 2020 | 0.66 ± 0.10 | 0.73 ± 0.08 | 7.3 ± 1.0 |
| | 2021 | 0.64 ± 0.12 | 0.72 ± 0.09 | 7.1 ± 1.2 |
| | 2022 | 0.67 ± 0.09 | 0.74 ± 0.08 | 7.4 ± 0.9 |
| Governance | 2012 | 0.71 ± 0.09 | 0.80 ± 0.07 | 7.1 ± 0.9 |
| | 2013 | 0.72 ± 0.08 | 0.81 ± 0.06 | 7.2 ± 0.8 |
| | 2014 | 0.73 ± 0.08 | 0.81 ± 0.06 | 7.3 ± 0.8 |
| | 2015 | 0.74 ± 0.07 | 0.82 ± 0.05 | 7.4 ± 0.7 |
| | 2016 | 0.75 ± 0.07 | 0.82 ± 0.05 | 7.5 ± 0.7 |
| | 2017 | 0.75 ± 0.07 | 0.82 ± 0.05 | 7.5 ± 0.7 |
| | 2018 | 0.76 ± 0.07 | 0.83 ± 0.05 | 7.6 ± 0.7 |
| | 2019 | 0.75 ± 0.07 | 0.82 ± 0.05 | 8.3 ± 0.7 |
| | 2020 | 0.72 ± 0.08 | 0.80 ± 0.06 | 8.0 ± 0.8 |
| | 2021 | 0.74 ± 0.07 | 0.81 ± 0.06 | 8.2 ± 0.7 |
| | 2022 | 0.71 ± 0.09 | 0.79 ± 0.06 | 7.9 ± 0.9 |
| ESG composite | 2012 | 0.63 ± 0.10 | 0.74 ± 0.08 | 6.3 ± 1.0 |
| | 2013 | 0.64 ± 0.10 | 0.75 ± 0.08 | 6.4 ± 1.0 |
| | 2014 | 0.65 ± 0.10 | 0.75 ± 0.07 | 6.5 ± 1.0 |
| | 2015 | 0.66 ± 0.09 | 0.76 ± 0.07 | 6.6 ± 0.9 |
| | 2016 | 0.67 ± 0.09 | 0.76 ± 0.07 | 6.7 ± 0.9 |
| | 2017 | 0.68 ± 0.09 | 0.77 ± 0.07 | 6.8 ± 0.9 |
| | 2018 | 0.69 ± 0.09 | 0.77 ± 0.07 | 6.9 ± 0.9 |
| | 2019 | 0.69 ± 0.09 | 0.77 ± 0.07 | 7.7 ± 0.9 |
| | 2020 | 0.67 ± 0.10 | 0.75 ± 0.08 | 7.5 ± 1.0 |
| | 2021 | 0.71 ± 0.08 | 0.79 ± 0.06 | 7.9 ± 0.8 |
| | 2022 | 0.70 ± 0.09 | 0.78 ± 0.07 | 7.8 ± 0.9 |

**Notes:** For each year, top 10 features are extracted per fold from mean |SHAP|. Jaccard@10 is the mean pairwise Jaccard index of the top 10 sets across folds; the overlap count is Jaccard@10×10. Spearman's $\rho$ is computed on the union of the top 10 features across folds using fold-specific rank orders. Higher is more stable.

**Table A2.** Temporal stability of top 10 SHAP features across adjacent years (averaged over folds).

| Target | Avg. Jaccard@10 (t vs. t+1) | Kendall $\tau_b$ (ranks) | Persistence ≥3 yrs (%) | Persistence ≥5 yrs (%) |
|---|---|---|---|---|
| Environemental | 0.60 | 0.62 | 44.0 | 22.0 |
| Social | 0.55 | 0.57 | 36.5 | 16.8 |
| Governance | 0.66 | 0.68 | 51.8 | 25.6 |
| ESG composite | 0.59 | 0.61 | 41.2 | 20.5 |

**Notes:** For each target, we compare top 10 sets between consecutive years (e.g., 2019 versus 2020, . . . ). Persistence is the share of features that appear in the top 10 for at least 3 (or 5) consecutive years. Kendall $\tau_b$ is computed on the union of top 10 features using year-wise rank orders. Higher indicates stronger temporal consistency.

## Appendix B. Partial Dependence Plots

To complement the SHAP-based importance analysis, we report partial dependence plots (PDPs) for the top five features (selected by the cross-fold mean SHAP) for the ESG target in Figure B1. For each fold, PDPs are computed on a quantile grid for every feature and then linearly interpolated onto a common grid before averaging across folds. The PDPs thus summarize the average marginal association between each feature and the model's prediction (ceteris paribus).

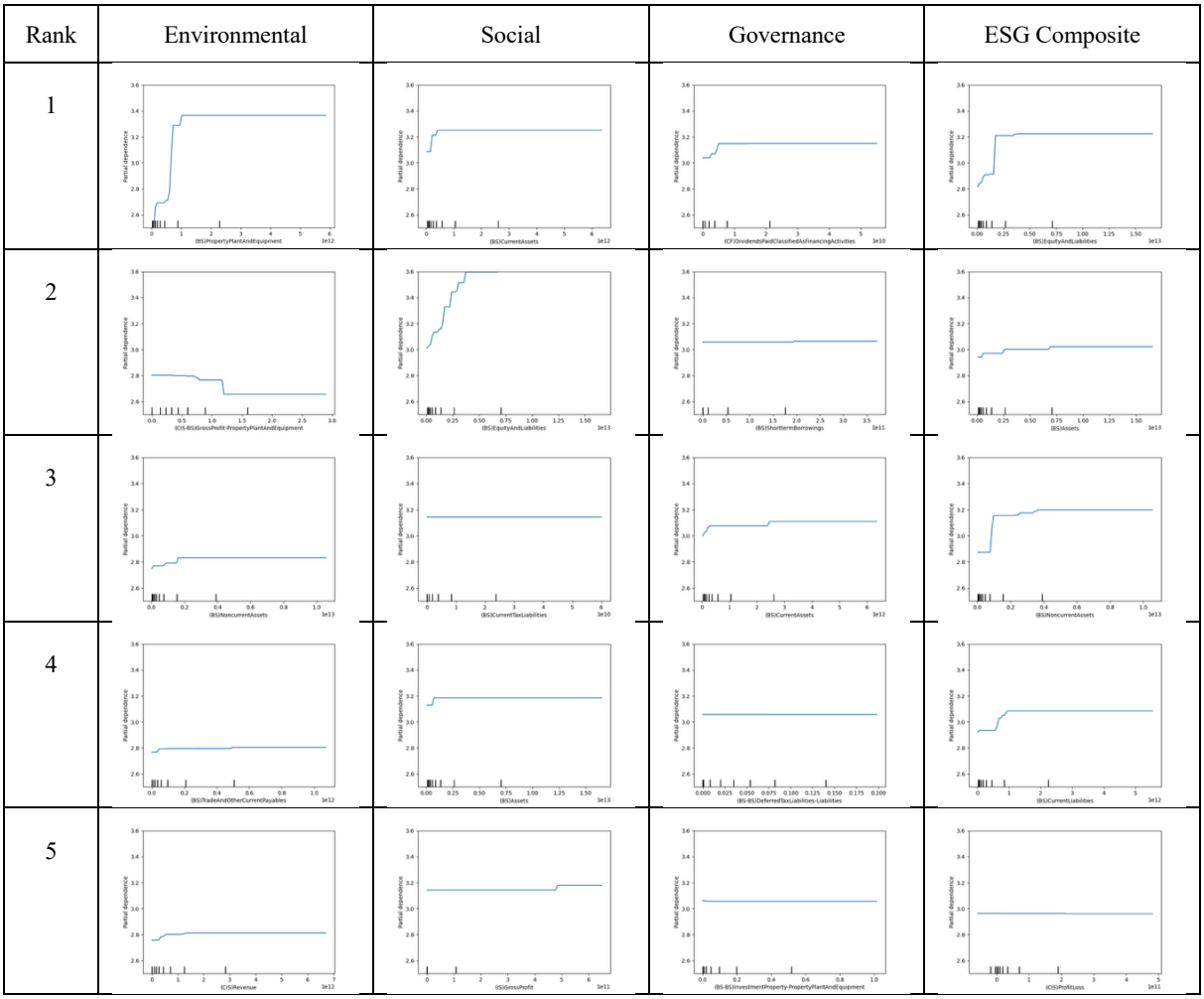


**Figure B1.** PDPs for the top five features of the ESG target. Lines show the cross-validation (CV) mean partial dependence. For each feature, the PDP is evaluated on a percentile-based grid derived from the training data to avoid extrapolation.

## Appendix C. Robustness Analysis Excluding the COVID-19 Period

To test whether the pandemic years have driven our findings, we re-estimated all models after removing 2020–2021 from both the training and evaluation stages, keeping the same preprocessing,

feature set, and cross-validation scheme. Across the targets, the resulting predictive performance remained qualitatively unchanged: Average F1 (classification tasks) and MSE (regression tasks) were within the fold-to-fold sampling variability observed in the baseline, and the relative ordering of algorithms was preserved. The SHAP-based interpretability results were likewise stable. The top five feature sets for each target showed high overlap with the baseline, and the previously highlighted drivers—particularly governance-related variables—continued to appear among the most influential. Overall, excluding the COVID-19 period does not materially affect either the model's performance or the substantive interpretation of SHAP features' importance.


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**Table C1.** Absolute ESG rating prediction performance across different machine learning algorithms excluding the COVID-19 period (2020-2021). The table reports three evaluation metrics: (Exp. 1) F1 score for binary classification, (Exp. 2) F1 score for multi-class classification, and (Exp. 3) Mean Squared Error (MSE) for regression. Higher F1 scores and lower MSE values indicate better prediction performance.

| Algorithms | | (Exp. 1) F1 score | | | | (Exp. 2) F1 score | | | | (Exp. 3) MSE | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | E | S | G | ECR | E | S | G | ECR | E | S | G | ECR |
| Basic | OLS | 0.482 | 0.461 | 0.437 | 0.321 | 0.260 | 0.396 | 0.341 | 0.342 | 3.515 | 2.966 | 3.340 | 3.613 |
| | RF | 0.614 | 0.666 | 0.641 | 0.681 | 0.486 | 0.448 | 0.511 | 0.503 | 0.879 | 0.839 | 0.791 | 0.636 |
| | SVMs | 0.583 | 0.540 | 0.686 | 0.612 | 0.371 | 0.431 | 0.430 | 0.447 | 1.479 | 0.915 | 1.152 | 1.006 |
| Boosting | XGB | 0.641 | 0.656 | 0.706 | 0.678 | 0.495 | 0.517 | 0.449 | 0.569 | 0.917 | 0.885 | 0.723 | 0.647 |
| | LGBM | 0.625 | 0.675 | 0.693 | 0.678 | 0.477 | 0.519 | 0.501 | 0.539 | 0.880 | 0.748 | 0.677 | 0.544 |
| Neural networks | MLP | 0.555 | 0.533 | 0.552 | 0.552 | 0.350 | 0.416 | 0.377 | 0.451 | 1.461 | 1.109 | 1.039 | 1.190 |
| | CNN | 0.551 | 0.569 | 0.618 | 0.628 | 0.357 | 0.367 | 0.477 | 0.438 | 1.259 | 0.911 | 0.823 | 0.912 |
| | TabNet | 0.636 | 0.583 | 0.691 | 0.659 | 0.460 | 0.430 | 0.461 | 0.524 | 0.869 | 0.920 | 0.660 | 0.722 |

**Table C2.** Change in ESG rating prediction performance across different machine learning models excluding the COVID-19 period (2020-2021). The table presents two evaluation metrics: (Exp. 4) F1 score for classification of rating changes, and (Exp. 5) Mean Squared Error (MSE) for regression on rating change magnitudes.

| Algorithms | | (Exp. 4) F1 score | | | | (Exp. 5) MSE | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | E | S | G | ECR | E | S | G | ECR |
| Basic | OLS | 0.513 | 0.478 | 0.491 | 0.517 | 1.797 | 2.293 | 1.866 | 1.642 |
| | RF | 0.702 | 0.609 | 0.655 | 0.687 | 0.446 | 0.548 | 0.544 | 0.435 |
| | SVMs | 0.715 | 0.644 | 0.597 | 0.695 | 0.469 | 0.542 | 0.739 | 0.491 |
| Boosting | XGB | 0.747 | 0.588 | 0.668 | 0.709 | 0.479 | 0.625 | 0.635 | 0.414 |
| | LGBM | 0.754 | 0.658 | 0.642 | 0.757 | 0.451 | 0.502 | 0.545 | 0.391 |
| Neural networks | MLP | 0.766 | 0.604 | 0.506 | 0.626 | 0.784 | 0.705 | 0.991 | 0.685 |
| | CNN | 0.754 | 0.645 | 0.585 | 0.683 | 0.859 | 0.682 | 0.855 | 0.543 |
| | TabNet | 0.794 | 0.668 | 0.626 | 0.688 | 0.486 | 0.526 | 0.729 | 0.462 |

**Table C3.** Top 5 most important features for predicting absolute ESG ratings, identified by feature importance scores from the baseline model excluding the COVID-19 period (2020-2021).

| Rank | Environmental | | Social | | Governance | | ESG Composite | |
|---|---|---|---|---|---|---|---|---|
| | F/S | Account | F/S | Account | F/S | Account | F/S | Account |
| 1 | BS | Property Plant And Equipment | BS | Equity And Liabilities | CF | Dividends Paid Classified As Financing Activities | BS | Equity And Liabilities |
| 2 | Ratio (CIS-BS) | Gross Profit-Property Plant And Equipment | BS | Current Asset | BS | Current Asset | BS | Non Current Assets |
| 3 | BS | Non Current Assets | Ratio (BS-BS) | Non controlling Interests-Non current Liabilities | BS | Short term Borrowings | BS | Investment Property |
| 4 | BS | Trade And Other Current Payables | CIS | Cost of Sales | Ratio (BS-BS) | Deferred Tax Liabilities-Liabilities | BS | Current Liabilities |
| 5 | BS | Investment Property | IS | Gross Profit | Ratio (BS-BS) | Investment Property-Property Plant And Equipment | BS | Property Plant And Equipment |

**Table C4.** Top 5 most important features for predicting changes in ESG ratings, based on feature importance scores from the rating change prediction models excluding the COVID-19 period (2020-2021).

| Rank | Environmental | | Social | | Governance | | ESG Composite | |
|---|---|---|---|---|---|---|---|---|
| | F/S | Account | F/S | Account | F/S | Account | F/S | Account |
| 1 | Ratio (CF-BS) | Dividends Paid Classified As Financing Activities-Right of use Assets | Ratio (BS-CIS) | Diluted Earnings Loss Per Share-Equity And Liabilities | BS | Inventories Growth Rate | BS | Short term Borrowings Growth Rate |
| 2 | Ratio (CF-BS) | Cash Flows From Used In Investing Activities-Inventories | Ratio (CIS-CF) | Cash Flows From Used In Financing Activities-Profit Loss Attributable To Owners Of Parent | Ratio (CIS-CF) | Comprehensive Income Attributable To Owners Of Parent-Dividends Paid Classified As Financing Activities | BS | Current Liabilities Growth Rate |
| 3 | CF | Cash Flows From Used In Financing Activities | CF | Increase Decrease In Cash And Cash Equivalents Before Effect Of Exchange Rate Changes | BS | Equity Attributable To Owners Of Parent | Ratio (BS-CIS) | Comprehensive Income Attributable To Owners Of Parent-Other Noncurrent Nonfinancial Liabilities |
| 4 | Ratio (CF-CIS) | Payments Of Finance Lease Liabilities Classified As Financing Activities/Profit Loss | Ratio (CIS-BS) | Finance Income-Short term Borrowings | BS | Non current Provisions Growth Rate | CIS | Other Comprehensive Income Net Of Tax Available for sale Financial Assets Growth Rate |
| 5 | CIS | Gross Profit | Ratio (BS-BS) | Inventories-Short term Borrowings | Ratio (CF-BS) | Cash Flows From Used In Investing Activities/Current Liabilities | Ratio (BS-BS) | Current Tax Liabilities-Equity |