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Determinants of capital adequacy in global banking: key environmental, social, and governance indicators across countries

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Abstract

This research investigates which specific Environmental, Social, and Governance (ESG) indicators most strongly influence banking stability, as measured by the Bank Capital to Asset Ratio, across 80 countries over four years. The research addresses a key question in the ESG-finance literature: which individual ESG metrics are most relevant for reinforcing capital adequacy in the banking sector? Drawing from a dataset of 37 ESG indicators, we apply a best subset selection procedure and Least Absolute Shrinkage and Selection Operator (LASSO) techniques to identify the most significant predictors within each ESG category. To confirm the findings and ensure robustness, we employ a meta-learning framework that integrates ensemble machine learning models, including Gradient Boosting Machines and eXtreme Gradient Boosting (XGBoost), as well as Generalized Linear Models. Results reveal that the most influential environmental indicator is the value added by agriculture, forestry, and fishing as a share of GDP; for the social dimension, the under-five mortality rate per 1,000 live births is most predictive; and in the governance domain, the number of published scientific and technical journal articles emerges as the leading factor. These results show evidence that targeted ESG metrics are instrumental in influencing banking resilience. The study gives actionable understandings for regulators and financial institutions aiming to align ESG integration with capital adequacy objectives and broader sustainability strategies.

Keywords ESG indicators · Capital adequacy · Panel data · Meta-learning

Extended author information available on the last page of the article

1 Introduction

The integration of Environmental, Social, and Governance (ESG) factors into banking practices has become increasingly important for promoting financial resilience in the face of growing global uncertainty. Once centered on economic performance, banks are now expected to incorporate ESG dimensions as core components of risk management and strategic decision-making. Rather than serving merely as a compliance obligation, ESG integration is emerging as a strategic tool for enhancing stability and long-term competitiveness. This research investigates the influence of specific ESG indicators on banking sector resilience, with a key emphasis on their effect on the Bank Capital to Asset Ratio, a well-established measure of capitalization strength, using a global dataset of 80 countries spanning the 2013–2016 period.

Against this backdrop, our central research question is: “Which ESG indicators most critically impact the Bank Capital to Asset Ratio, a key measure of financial stability, across countries?” By identifying the ESG factors that exhibit the strongest associations with capital adequacy, this research seeks to move beyond aggregated ESG scores and provide a more granular understanding of how individual components of sustainability performance affect banking resilience. This question is highly important in an international context where ESG integration is increasingly expected to play a strategic role in strengthening financial systems and guiding investment priorities.

Although several studies suggest a stabilizing role for ESG, the evidence on which components of ESG drive these outcomes remains mixed. For example, Chiaramonte et al. (2022) show that banks with higher ESG scores exhibit reduced financial fragility during crises, particularly when ESG disclosures are sustained over time. Similarly, Citterio & King (2023) demonstrate that ESG indicators significantly improve the ability to detect bank distress, reducing misclassification errors even under alternative prediction models. However, others highlight complex trade-offs. Gutiérrez-Ponce and Wibowo (2024), for instance, find that the effect of ESG on banks' financial performance is heterogeneous across regions and ESG pillars, with some negative short-term impacts on profitability. Yuen et al. (2022) further identify a U-shaped relationship between ESG and profitability, suggesting that the short-term costs of ESG adoption may be offset by long-term benefits.

ESG integration can also generate tangible financial advantages. Agnese & Giacomini (2023) show that banks with stronger ESG practices, particularly in governance and transparency, face lower costs when issuing debt in primary markets. In parallel, Alves & Meneses (2024) find that ESG scores carry additional, non-redundant information on borrower risk that traditional credit models fail to capture. On the other side of the banking relationship, Cheng & Hasan (2023) document that banks not only adjust lending terms based on firms' ESG behavior but also learn from responsible borrowers and enhance their own ESG scores over time.

Nonetheless, effective ESG implementation remains constrained by concerns over data quality and comparability. Busch et al. (2016) emphasize that the full potential of ESG integration hinges on enhancements in data trustworthiness and a shift toward long-term sustainability paradigms. Inconsistent or unreliable ESG metrics limit the ability of financial institutions to incorporate these dimensions into forward-looking

risk assessments. Despite these challenges, the growing body of empirical evidence confirms that ESG engagement, when structured and sustained, can enhance risk-adjusted performance and foster broader financial resilience.

This study aims to identify which specific ESG indicators are most influential in explaining the Bank Capital to Asset Ratio across countries. Drawing from a set of 37 standardized ESG variables, we apply a two-stage empirical approach. Best subset selection and the Least Absolute Shrinkage and Selection Operator (LASSO) techniques are used to isolate key predictors, while ensemble learning models, including Gradient Boosting Machines (GBM), eXtreme Gradient Boosting (XGBoost), and Generalized Linear Models (GLM), serve as robustness checks within a meta-learning framework.

This study makes three important contributions to the literature on ESG factors and banking stability. First, it addresses a critical gap in the current literature by establishing a conceptual framework that directly links specific environmental, social, and governance elements to banking stability, offering a clearer understanding of how these dimensions influence financial resilience and capital adequacy. Second, it empirically identifies the ESG indicators most predictive of banking stability, providing policymakers and financial institutions with actionable insights on where ESG investments can have the most significant impact. Third, the study illustrates the effectiveness of advanced machine learning (ML) techniques, such as ensemble methods, within this framework to ensure that findings are both statistically rigorous and robust across diverse contexts, thereby improving the reliability and applicability of ESG analyses.

The structure of this paper is as follows: Sect. 2 presents a literature review of the impact of ESG integration on financial performance in the banking sector. Section 3 introduces the conceptual framework and the specific ESG indicators utilized in this study. Section 4 describes the data and empirical methodology. Section 5 discusses the results and their implications. Section 6 covers the robustness checks employed, and Sect. 7 concludes with policy implications and recommendations for integrating ESG factors into sustainable banking practices.

2 Literature review

Recent scholarship has increasingly examined the implications of ESG integration for financial stability in the banking industry, revealing a complex and context-specific relationship. One central insight emerging from the literature is the nonlinearity of ESG's financial effects. In the Middle East and North Africa (MENA) region, Mallek et al. (2024) demonstrate that ESG components exhibit both convex and concave relationships with bank stock returns. A similar conclusion is drawn by Teng et al. (2022), who analyze Taiwanese firms and uncover an inverted U-shaped relationship between ESG engagement and corporate financial performance.

While such analyses reveal the potential gains from ESG implementation, others emphasize the limitations of its financial influence. Gigante & Manglaviti (2022) investigate whether higher ESG scores reduce the cost of debt for European non-financial corporations. Using a sharp regression discontinuity design and ESG scores

from Refinitiv, they find no statistically significant evidence of such an effect. In the European banking context, Lupu et al. (2022) assess the relationship between ESG scores and financial stability using a cross-quantilogram approach, uncovering that the influence of ESG factors is concentrated in specific quantiles of the distribution rather than at the mean.

Firm characteristics such as size also have a major impact on ESG-related financial outcomes. Bolibok (2024) studies 668 banks assigned ESG risk ratings and finds that the relationship between bank size and ESG risk follows a U-shaped pattern. While larger banks initially benefit from economies of scale in ESG risk management, these advantages can reverse beyond a specific size due to diseconomies and increased complexity. Internal governance features further condition ESG outcomes, as shown by Jung (2024), who examines Chinese listed firms and identifies ownership concentration, not board independence, as a moderator of the ESG–financial performance relationship.

Beyond internal factors, regulatory and institutional settings have a substantial effect on the financial materiality of ESG initiatives. Bruno & Lagasio (2021) provide an overview of European policies aimed at integrating ESG principles into the banking sector, describing how regulators are increasingly viewing financial institutions as key levers for advancing sustainability goals. Meanwhile, Jucá et al. (2024) explore the consequences of ESG controversies and find that their financial impacts vary across industries and countries. In particular, banks operating in countries with stringent regulatory environments tend to incur greater costs when involved in ESG controversies.

In Asia, ESG engagement is increasingly associated with financial resilience and performance. Xing et al. (2024) find that bank competition in China enhances corporate ESG performance, particularly among non-state-owned, smaller firms and in central and eastern regions. This effect is transmitted through credit, investment, and information channels and is further amplified by higher levels of marketization and corporate reputation. The role of governance is again central in the findings of Hin & Liu (2023), who analyze A-share banks and securities firms in China. Similarly, Zhang & Liu (2022) argue that ESG performance significantly enhances financial flexibility, particularly in uncertain market conditions.

Evidence from Southeast Asia further supports the view that ESG can serve as a tool for financial enhancement, though the effects are often contingent. Ihsani et al. (2023) report that ESG performance has a positive impact on accounting-based financial indicators (e.g., return on assets) in Indonesian firms. However, the influence on market-based metrics, such as Tobin's Q, is not statistically significant. In parallel, Jamal et al. (2021), examining Malaysian firms, find that environmental factors increase return on equity, while social and governance factors show mixed effects. The work sheds light on the influence of ESG in shaping long-term market expectations and contributing to stakeholder trust.

Outside the banking sector, ESG appears especially relevant in environmentally sensitive industries. Naeem et al. (2022) examine corporations in the energy and manufacturing sectors and find that ESG performance is positively associated with financial performance, with more pronounced effects in developed countries. Naimy et al. (2021) offer a more complex view based on East Asian firms in the industrial

sector. Their results reveal that the impact of ESG on financial performance varies across ESG pillars, financial performance metrics, and industries. For example, they identify a concave relationship between social factors and accounting returns, as well as a convex relationship between governance and the price-to-book ratio.

Together, these studies converge on the conclusion that ESG factors are increasingly relevant to financial stability and resilience. However, their effectiveness is shaped by institutional, regional, sectoral, and firm-level characteristics. The literature reveals significant heterogeneity in how ESG translates into financial outcomes, with particular variation in the effects of individual ESG pillars, the influence of internal governance, and the responsiveness of financial markets and regulators. A key research gap lies in understanding how ESG performance relates explicitly to indicators of bank-level financial stability, such as capital adequacy and risk absorption, within varying regulatory and institutional contexts. This study addresses this gap by investigating the conditional impact of ESG scores on banking resilience, with a focus on firm size, ownership structures, and regional governance environments. In doing so, it seeks to clarify the mechanisms through which ESG integration contributes to financial stability in the banking sector across diverse global contexts.

3 ESG and banking: a conceptual framework

The integration of ESG frameworks with the United Nations Sustainable Development Goals (SDGs) represents a strategic convergence of corporate-level accountability and global developmental ambitions. ESG, operating as a tool for firms to manage risk and promote responsible business conduct, translates macro-level targets of the 2030 Agenda, such as poverty reduction, environmental protection, and institutional integrity, into operational corporate practices (see, for example, Radu et al., 2023). ESG scores have been empirically mapped to SDG indicators, allowing organizations to measure and communicate their contribution toward selected SDGs, especially those most pertinent to private sector action (Khaled et al., 2021).

Carbon mitigation and waste reduction strategies, central to ESG environmental performance, are increasingly aligned with SDG 13 (Climate Action) and SDG 12 (Responsible Consumption and Production). For example, Cong et al. (2022) demonstrate that ESG-related environmental investments in China result in measurable reductions in CO₂ emissions, substantiating the functional role of ESG strategies in mitigating climate change. Similarly, Saxena et al. (2023) highlight that the application of digital technologies enhances the accuracy and transparency of ESG environmental reporting, further strengthening alignment with SDG tracking frameworks. In addition, ESG data can inform and support circular economy strategies, as shown by Sardanou et al. (2023), who analyze how resource efficiency and material footprints within the circular economy affect national-level carbon performance under the SDG 13 framework. However, accurate SDG measurement remains constrained by persistent data challenges (Dang & Serajuddin, 2020).

ESG's three pillars, environmental, social, and governance, serve as distinct but interlinked dimensions for operationalizing SDGs:

1. **Environmental Dimension:** This dimension encompasses emissions reduction, energy transition, and climate resilience. Battulga & Dhakal (2023) show how long-term renewable energy planning can facilitate the transition of coal-reliant cities to low-carbon models, demonstrating the potential for ESG-linked actions to reshape local energy systems. Moreover, climate vulnerability assessments, such as those using multiscalar indices like the Standardized Precipitation Evapotranspiration Index, are vital for adaptation planning (Vicente-Serrano et al., 2010), indicating ESG's compatibility with resilience-oriented environmental indicators.
2. **Social Dimension:** ESG's social component encompasses welfare-related indicators, such as access to clean water, healthcare, and education. Baskaran (2022) illustrates the utility of geographic information systems in monitoring SDG 6 (Clean Water and Sanitation), while Anser et al. (2020) and Adeleye et al. (2020) empirically demonstrate the role of public health and social expenditures in poverty and inequality dynamics, two critical areas for SDGs 1 and 10. These results underscore that ESG-aligned corporate strategies may reinforce inclusive development if complemented by measurable social impact indicators.
3. **Governance Dimension:** Governance indicators, including anti-corruption measures, institutional quality, and legal enforcement, underpin organizational integrity. Mohd-Rashid et al. (2023) provide evidence that stronger property rights and institutional integrity reduce corruption across Asia–Pacific countries. At the firm level, Dobrzański et al. (2021) demonstrate that R&D investment efficiency, closely tied to governance structures, directly contributes to innovation-based competitiveness. Similarly, Eccles & Saltzman (2011) emphasize integrated reporting as a mechanism for creating long-term corporate value, reinforcing the enabling role of ESG governance practices in achieving the SDGs.

In the banking sector, the adoption of ESG criteria is not merely a matter of compliance but increasingly a strategic tool for sustainability-aligned governance. Dicuonzo et al. (2022) demonstrate that systematically important European banks are progressively integrating ESG into their corporate governance systems, driven in part by board-level initiatives. Moreover, ESG engagement influences financial resilience and risk. Chollet & Sandwidi (2018) find that strong social and governance performance reduces firm-specific and total financial risk, creating a reinforcing feedback loop between ESG implementation and financial stability. In banking specifically, sustainability performance has been linked to improved financial outcomes. Buallay et al. (2020) report that ESG disclosures have a positive influence on operational, financial, and market performance in MENA banks, although the relationship varies across ESG components.

However, the path to authentic ESG implementation involves significant upfront costs, including the development of disclosure infrastructure and compliance mechanisms (Horkey et al., 2024). Nizam et al. (2019) note that access to sustainable finance improves long-run bank performance, particularly through quality lending and management practices, suggesting that ESG-related costs can be offset by improved capital efficiency. From a capital structure perspective, ESG adoption can also reduce funding costs. El Ghouli et al. (2011) confirm that US firms with more substantial

corporate social responsibility (CSR) performance benefit from lower cost of equity, particularly through improvements in employee relations and environmental policies. Mackey et al. (2007) similarly argue that investor preferences for socially responsible firms can enhance firm valuation, while Waddock & Graves (1997) propose that stakeholder-focused governance correlates with better management quality and reputational gains.

These empirical findings align with theoretical models that view ESG as a source of competitive advantage. Porter (1991) famously argued that well-designed environmental regulation can spur innovation and improve competitiveness, a hypothesis relevant to ESG-driven banking reforms. Furthermore, the instrumental view of CSR articulated by Garriga & Melé (2004) emphasizes the strategic value of sustainability initiatives in attaining extended-term economic performance.

Taken together, the conceptual link between ESG and the SDGs, when filtered through the banking sector, becomes operational in the form of enhanced governance, improved financial stability, and better alignment with stakeholder expectations. In particular, the ESG framework contributes to the banking sector's capital adequacy by lowering risk exposure, enhancing reputational value, and fostering access to more stable financing channels. These mechanisms influence core indicators of financial soundness, such as the capital-to-assets ratio, which captures a bank's ability to absorb shocks while pursuing sustainability-aligned strategies. Rather than treating ESG as a broad, undifferentiated score, this study focuses on the relationship between specific ESG indicators and the Bank Capital-to-Asset Ratio. While establishing a direct causal link between ESG factors and capital adequacy remains methodologically challenging due to endogeneity and data limitations, our analysis emphasizes statistically robust associations. By identifying which ESG indicators are most predictive of capital strength, the study adds to the growing evidence that ESG integration, even if not strictly causal, plays a significant role in shaping the financial resilience of banking institutions.

4 Data and empirical strategy

This study draws on the World Development Indicators¹ and the ESG data portal² from the World Bank, which includes a range of ESG indicators across a global panel of 80 countries over four years (2013–2016). Due to substantial missing data beyond the year 2016, extending the analysis to a longer time frame was not feasible without compromising the consistency and completeness of the dataset. The period from 2013 to 2016 was therefore selected, as it represents the most recent window for which complete data coverage is available across all 37 ESG indicators and the dependent variable for all countries included. A (political) map of the countries included in the analysis is provided in Figure A1 in the Appendix together with a detailed list of all the considered variables, along with their definition, in Table A1. To ensure compat-

¹ Available at <https://databank.worldbank.org/source/world-development-indicators/>. Last accessed June 2024.

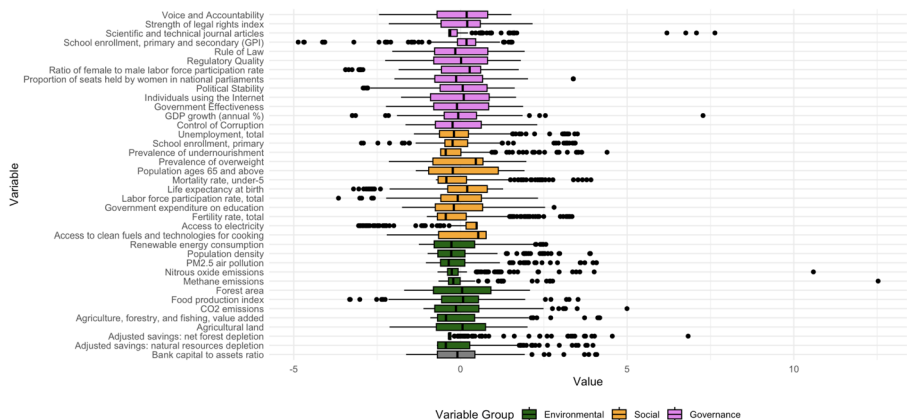
² Available at <https://esgdata.worldbank.org/>. Last accessed June 2024.

ibility across variables and improve the performance of ML, which are sensitive to differences in scale.³

Figure 1 presents the overall distribution of all ESG variables and the dependent variable, *Bank Capital to Assets Ratio*, across the dataset. Each of these variables is represented through a box plot, showing the median, interquartile range, and outliers, to understand the spread, central tendencies, and variability of the data.

In the governance category, we notice that most variables represent relatively compact distributions, although some indicators display a considerable spread with notable outliers. For example, *Voice and Accountability* and *Strength of legal rights index* display some variability, reflecting differences in governance structures across countries. *Scientific and technical journal articles*, *Rule of Law*, and *Regulatory Quality* exhibit moderately concentrated distributions with some outliers, indicating that most countries share similar governance standards in these areas, although a few countries diverge considerably. Variables such as the *Individuals using the Internet* and *Political Stability* display notable differences across countries, likely reflecting disparities in access to digital infrastructure and varying levels of political stability.

The social variables show a broader range of variability across countries. Several indicators display a widespread pattern, reflecting significant disparities in social and economic conditions. The *Prevalence of undernourishment* and *overweight* highlights distinct health and nutritional challenges in different regions, with some countries exhibiting high prevalence in one or both categories. *The Population aged 65 and above*, along with *Life expectancy at birth*, captures demographic variations, highlighting differences in aging populations and life expectancy across countries. *Mortality rate under-5* displays a wide range, with some countries experiencing significantly higher child mortality rates. *Government expenditure on education* and *Access to clean fuels and technologies for cooking* vary widely, with outliers indicating countries that invest considerably more in these areas relative to others.



Note: Box plots show the distribution of the dependent variable (light gray) and selected ESG indicators. Colors represent variable groups.

Fig. 1 Variables' Box Plot

³All variables were standardized using the *scale()* function in R. This procedure converts each variable into its Z-score, centering it at zero and rescaling it by its standard deviation.

In the environmental category, many variables exhibit notable dispersion and skewness, reflecting the diverse environmental conditions and resource utilization practices globally. *Renewable Energy Consumption* shows significant variability, with outliers indicating countries that invest heavily in renewable resources. *Population density* and *PM2.5 air pollution* also exhibit wide ranges, with densely populated or highly polluted countries appearing as outliers. *Methane* and *Nitrous Oxide Emissions* have moderate ranges, with certain countries contributing disproportionately higher emissions. *Forest areas* and *Agricultural land* display skewed distributions, as some countries dedicate extensive areas to agriculture, which impacts environmental sustainability. *Adjusted saving for net forest depletion* and *natural resources depletion* illustrate the depletion of natural resources, with some countries showing high levels of depletion.

Finally, the dependent variable, *Bank Capital to Assets Ratio*, exhibits a more condensed distribution with relatively few extreme values. This compact distribution suggests that, overall, banking stability, as measured by capital adequacy, remains relatively consistent across countries, with fewer cases deviating significantly from the norm. The few outliers that do appear warrant closer examination, as they suggest that some countries experience atypical levels of banking stability or instability, potentially influenced by their unique economic and regulatory environments.

Figures 2, 3, and 4 present the correlation matrices for each category of variables—environmental, social, and governance—along with the dependent variable, *Bank Capital to Assets Ratio*. Thus, the decision to divide the analysis into three separate models, one for each ESG category, while maintaining consistency in the dependent variable, enables us to isolate the influence of each category on banking stability. Figure 2 displays the correlation matrix for environmental variables.

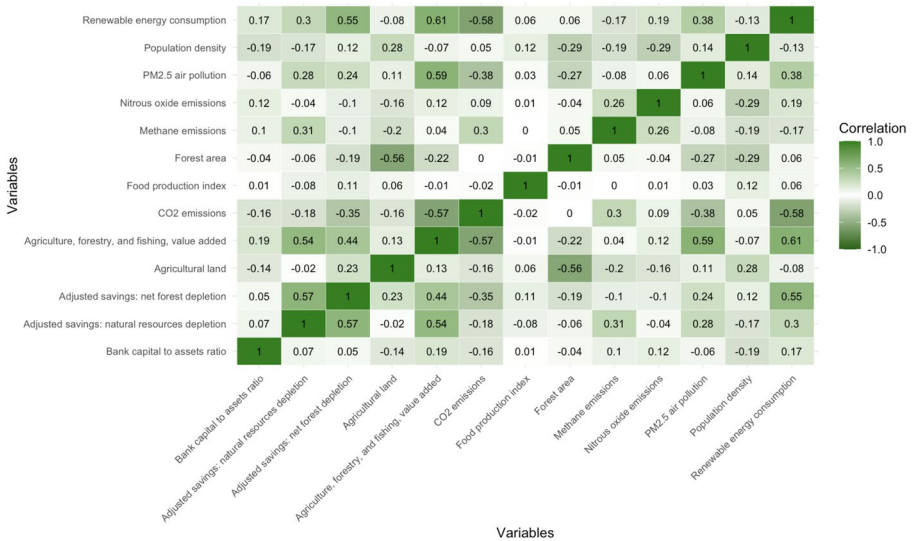


Fig. 2 Correlation Matrix for environmental variables

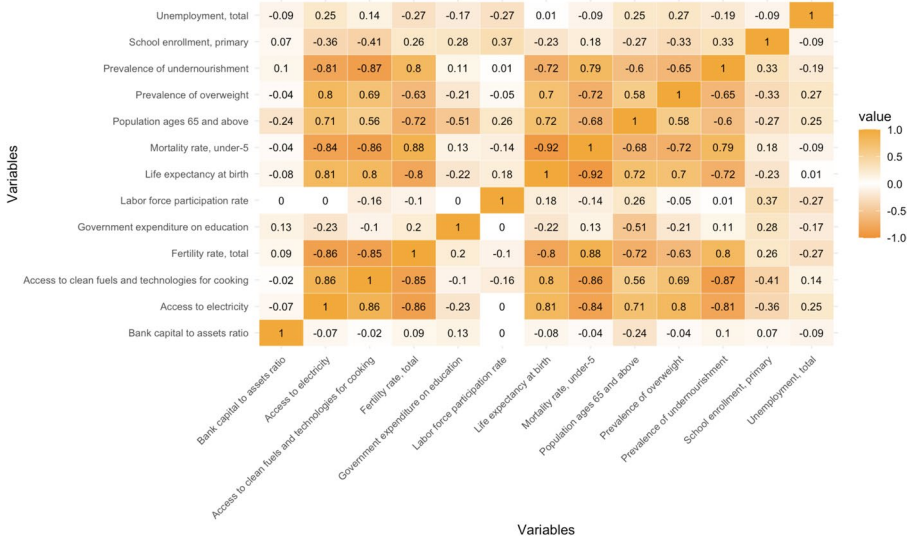


Fig. 3 Correlation Matrix for social variables

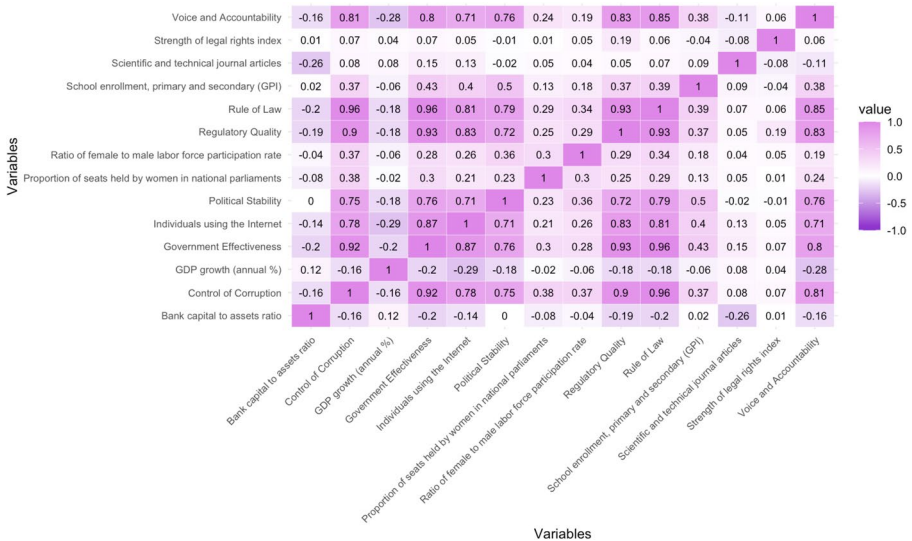


Fig. 4 Correlation Matrix for governance variables

The matrix reveals the relationships between environmental factors such as renewable energy consumption, CO₂ emissions, agricultural land, and the *Bank Capital to Assets Ratio*. Several variables exhibit strong correlations with each other, indicating interconnected environmental factors. For instance, adjusted savings metrics for net forest depletion and natural resource depletion are positively correlated, reflecting shared patterns in resource consumption. CO₂ emissions have a strong negative cor-

relation with *Renewable energy consumption*, highlighting the relationship between lower emissions and higher adoption of renewable resources. The dependent variable, *Bank Capital to Assets Ratio*, exhibits a modest positive correlation with variables such as *Adjusted Savings: natural resources depletion* and *Food production index*, suggesting that resource management and agricultural productivity may have an impact on banking stability. However, the overall correlations with the dependent variable are relatively low, indicating that environmental variables may have a more indirect impact on banking capital adequacy.

Figure 3 illustrates the correlation matrix for social variables, which encompasses indicators related to population demographics, health, education, and access to resources.

There are strong positive correlations between variables such as life expectancy at birth and access to electricity, as well as strong negative correlations between undernourishment and educational enrollment, reflecting the interdependency of social factors. Variables related to health outcomes, such as *Mortality rate under-5* and *Prevalence of undernourishment*, are highly correlated, indicating that improvements in one aspect of social well-being are often accompanied by improvements in others. The *Bank Capital to Assets Ratio*, however, exhibits low correlations with most social variables, suggesting that the direct influence of social factors on banking stability may be limited. Nevertheless, the moderate correlation with labor force participation and government expenditure on education suggests potential indirect effects of labor market conditions and public investment in education on banking stability.

Figure 4 provides the correlation matrix for governance variables, including indicators of institutional quality, regulatory effectiveness, and political stability.

Strong correlations are evident among variables such as rule of law, government effectiveness, and regulatory quality, highlighting the interconnected nature of governance structures. These correlations reflect how institutional strength tends to cluster across different dimensions of governance. The *Bank Capital to Assets Ratio* exhibits weak correlations with most governance variables. However, a slightly negative relationship is observed with variables such as *Control of Corruption* and *Regulatory Quality*, suggesting that, in some cases, better governance standards may be associated with more conservative banking practices. However, given the generally low correlations with the dependent variable, governance factors may have a limited direct effect on banking capital adequacy, though they remain essential for creating a stable operating environment.

To further understand the relationship between ESG indicators and *Bank Capital to Assets Ratio*, we analyze both the trend of the dependent variable over time, shown in Fig. 5, and Sankey diagrams for each ESG category, depicted in Fig. 6. These figures are important in providing a granular view of the data. The time series plot in Fig. 5 illustrates the temporal pattern or shift in banking stability. The Sankey diagrams presented in Fig. 6 visually represent the influence of each category of ESG variables on the dependent variable, highlighting the complexity and interconnectedness of these relationships.

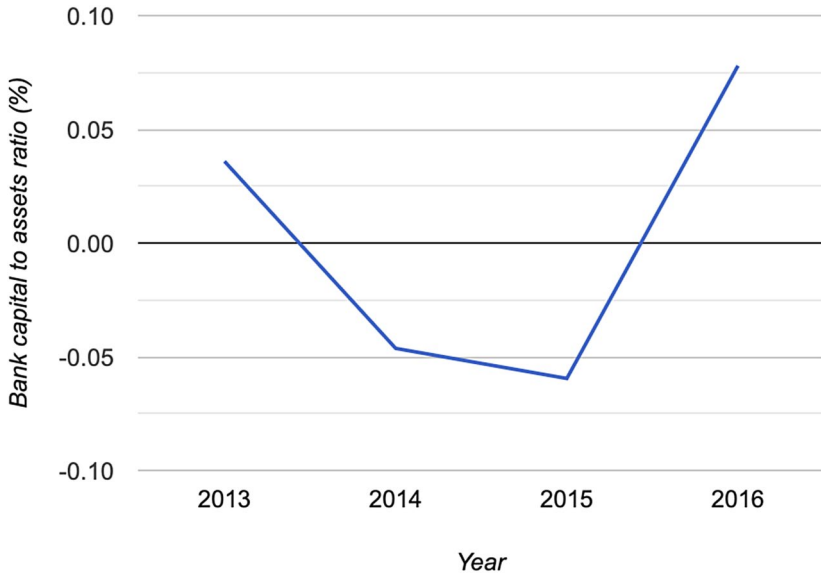


Fig. 5 Bank Capital to Assets Ratio (%)

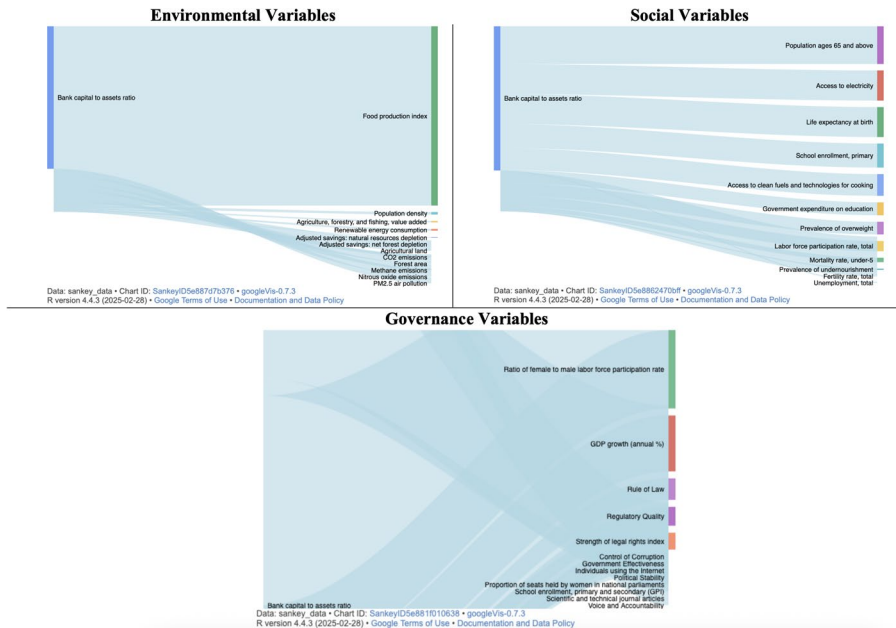


Fig. 6 Sankey Diagrams: Environmental, Social, and Governance variables

Figure 5 displays the trend of the Bank Capital to Assets Ratio over the four-year period considered.⁴

The series reveals a downward trend from 2013 to 2015, followed by a marked recovery in 2016. This decline may reflect persistent macro-financial vulnerabilities in the post-global financial crisis environment, including tightening regulatory requirements (e.g., Basel III implementation) and declining asset quality in several emerging markets. In 2015, sharp downturns in commodity prices and capital flow volatility may have further weakened banks' balance sheets, contributing to a deterioration in Tier 1 capital as a percentage of total assets. The recovery in 2016 may be connected to more regulatory recapitalization efforts and improved earnings performance across banking systems in both advanced and middle-income countries. The negative values observed in 2015 for some observations likely indicate instances where reported Tier 1 capital turned negative, typically a result of accumulated losses, signaling systemic stress or regulatory breaches in specific banking systems. Overall, this figure offers a snapshot of financial resilience dynamics across countries over the short panel period. The *Bank Capital to Asset Ratio*, according to the World Bank definition, measures the financial strength of banks by comparing their Tier 1 capital, such as common equity, retained earnings, and disclosed reserves, to their total assets, meaning the full value of everything the bank owns as reported on its balance sheet. Unlike ratios based on risk-weighted assets, this indicator uses total assets as the denominator, providing an unadjusted view of capitalization. Negative values, as shown in Fig. 5, may occur when a bank's Tier 1 capital becomes negative due to accumulated losses exceeding its core capital, indicating severe financial weakness or a regulatory breach during those periods. Figure 6 consists of three Sankey diagrams,⁵ Each corresponds to one of the ESG categories. The width of each flow from a predictor to the outcome variable represents the relative importance of that ESG indicator based on variable importance scores derived from ensemble ML models. In the environmental panel, the most prominent flows come from the *Food production index*, showcasing the role of agrifood system productivity in supporting bank capitalization in economies reliant on natural resource sectors. Additional variables like *Population density*, *PM2.5 air pollution*, and *Renewable energy consumption* also contribute, reflecting potential environmental risks or adaptive capacities that influence banking stability.

In the social panel, key predictors include access to electricity, life expectancy, and school enrollment rates. These variables capture demographic and welfare conditions that affect household stability, labor productivity, and ultimately the credit environment in which banks operate. Notably, indicators related to health and human capital emerge as key determinants, suggesting that social vulnerability may translate into macroeconomic and financial fragility.

In the governance panel, the strongest influences are linked to the *Regulatory Quality*, *Control of Corruption*, and the *Strength of legal rights index*. These findings emphasize the role of institutional quality in shaping the risk environment faced by banks. Good control appears critical for enforcing contracts, managing regula-

⁴ Generated using the *googleVis* package in RStudio to track changes over time visually.

⁵ Sankey diagrams were constructed using *gvisSankey()* to illustrate the relative magnitude of each ESG indicator's average value and its conceptual link to the banking stability proxy.

tory compliance, and maintaining investor confidence, all of which influence bank capital adequacy. Innovation-related indicators such as scientific publication output and internet penetration also emerge, suggesting a connection between knowledge infrastructure and financial resilience.

The empirical framework for this analysis involves a two-step approach to identify the most significant ESG factors that influence the Bank Capital to Assets Ratio. Regarding the structure of the dataset, while it spans four years, the panel is short in time and wide in cross-section, making the analysis primarily cross-sectional in nature. As such, the ML models were not intended to capture temporal dynamics or forecast future values, but rather to identify the importance of variables and cross-sectional heterogeneity in ESG determinants of the Bank Capital to Asset Ratio. Given these premises, a standard 80:20 train-test split was adopted to ensure that all ML models are evaluated out-of-sample. This choice is informed by guidance from Cerqua et al. (2024), who demonstrate that disregarding the panel's cross-sectional and longitudinal dependencies can inflate out-of-sample performance and lead to misleading conclusions about a model's real-world applicability. Given the absence of dynamic modeling and the explicitly cross-sectional aim of our analysis, the use of a temporally agnostic random split remains methodologically sound.

To ensure transparent and robust variable selection, both best subset selection model and LASSO were applied as complementary, rather than interchangeable, techniques. The best subset selection model provides a baseline for interpretable subset selection, while LASSO is employed to handle high-dimensional predictor sets and enforce sparsity through penalization. The purpose of applying both methods is not only to compare consistency in selected predictors but also to enhance confidence in the variables fed into subsequent ML models.

To reduce dimensionality and to conduct an initial screening of relevant predictors, we implement a constrained version of best subset selection using the *regsubsets* function. This procedure evaluates all combinations of variables of a given size and selects those that optimize a fit criterion, typically adjusted R² or Bayesian Information Criterion. Although this procedure is sometimes informally labeled as “step-wise,” it differs conceptually and computationally from forward or backward best subset selection models, which iteratively add or remove one variable at a time. Best subset selection is exhaustive within a constrained model size and offers greater flexibility in identifying optimal predictor sets. We apply this method separately within each of the ESG categories, limiting the number of selected variables to five per group to maintain parsimony and control the risk of overfitting. As described by James et al. (2021), subset selection methods are instrumental in exploratory settings where the analyst aims to determine which predictors provide the best explanatory performance for a given outcome.

Following the variable screening stage, we estimate penalized linear regression models using the LASSO, which minimizes the residual sum of squares subject to an ℓ_1 -norm constraint on the coefficient vector. The LASSO estimator, introduced by Tibshirani (1996), induces sparsity by shrinking some coefficients exactly to zero,

thereby serving simultaneously as a variable selection and regularization technique. While LASSO does not explicitly resolve multicollinearity, it can partially reduce its effect by selecting one variable among a group of highly correlated predictors and discarding the rest. However, this selection can be unstable in the presence of strong multicollinearity. The primary advantage of LASSO in our context lies in its capacity to augment model interpretability by identifying the most influential predictors and mitigating overfitting, particularly when working with a high-dimensional set of ESG indicators. Zou & Hastie (2005) extend this framework by proposing the elastic net, which combines ℓ_1 and ℓ_2 penalties and encourages the inclusion or exclusion of groups of correlated predictors together. Although the elastic net is not employed in our baseline model, its comparative advantages highlight a limitation of the LASSO that informs our interpretation of the results. To ensure efficient estimation and computational tractability, we adopt the algorithm developed by Friedman et al. (2010), which uses coordinate descent for convex penalty functions and accommodates both sparse features and large-scale problems. The theoretical appeal of penalized likelihood methods is further supported by Fan & Li (2001), who develop a class of nonconcave penalization functions that enable simultaneous estimation and variable selection in high-dimensional models.

To assess the robustness of our findings and to capture potential nonlinearities or higher-order interactions among variables, we implement three additional supervised learning algorithms: GBM, XGBoost, and GLM. GBM, as developed by Friedman (2001), represents a function approximation strategy in which models are built sequentially through additive expansions that minimize a specified loss function using the gradient descent method. Building on the GBM framework, XGBoost (see Chen & Guestrin, 2016) introduces a suite of enhancements, including sparsity-aware algorithms, regularization, and parallel processing capabilities, allowing it to scale to large datasets with high computational efficiency. The model is widely used for structured data tasks and is known for its high predictive accuracy. Natekin & Knoll (2013) offer an exhaustive tutorial on gradient boosting techniques, showing their flexibility and strength in capturing nonparametric regression relationships without requiring prior knowledge of the functional form.

As a complementary specification, we estimate a GLM using canonical link functions to evaluate whether the relationships captured by the ML models are preserved in a classical statistical framework. GLMs, as formalized by McCullagh & Nelder (1989), generalize linear regression by allowing for non-normal response distributions and link functions suitable for binary, count, or skewed outcomes. To integrate the strengths of each individual model and minimize generalization error, we adopt a stacked generalization (stacking) approach, wherein the predictions from GBM, XGBoost, and GLM are used as inputs into a meta-model, specifically a GLM. Wolpert (1992) introduces stacking as a method to reduce the error rate of one or more base learners by modeling their residuals in a second-level learning task. Rather than relying on a single model or selecting one algorithm based solely on performance,

stacking enables the synthesis of complementary predictive strengths while correcting for algorithm-specific biases.

This multi-stage empirical design, comprising exploratory variable reduction, penalized estimation, flexible model comparison, and meta-learning, ensures both interpretability and robustness in identifying ESG indicators that matter the most to banking sector resilience.

5 Results and discussion

The results of the best subset selection and LASSO regressions for each ESG category are presented in Tables 1, 2, and 3. Each model utilizes the selected variables from the best subset selection⁶ and LASSO⁷ Methods within a linear regression framework, incorporating fixed effects for countries and years.

Table 1 Environmental variables and Bank Capital to Assets Ratio

	Estimate	Std. Error	t value	P-Value
Best Subset Selection Model				
Agricultural land	0.2693	0.5834	0.4620	0.6450
Agriculture, forestry, and fishing, value added	-0.2437	0.4067	-0.5990	0.5499
CO ₂ emissions	-1.1434	0.3280	-3.4850	0.0006
Forest area	-0.8319	1.6392	-0.5080	0.6125
PM2.5 air pollution	-0.2224	0.1859	-1.1960	0.2333
Intercept	-1.3043	2.8651	-0.4550	0.6496
Country FE	Yes			
Year FE	Yes			
Adjusted R-squared	0.9239			
LASSO Regression				
Agricultural land	0.1833	0.5807	0.3156	0.7527
Agriculture, forestry, and fishing, value added	-0.2019	0.4015	-0.5030	0.6157
CO ₂ emissions	-1.3646	0.3445	-3.9612	0.0001
Population density	0.0307	1.0272	0.0299	0.9762
Renewable energy consumption	-0.8212	0.4085	-2.0102	0.0461
Intercept	-0.9985	1.0742	-0.9295	0.3541
Country FE	Yes			
Year FE	Yes			
R-squared	0.9520			

⁶ Performed using the *regsubsets()* function from the *leaps* package to identify the most influential ESG variables within each category. The optimal model was chosen based on the adjusted R-squared value.

⁷ Implemented via the *glmnet* package with cross-validation to penalize irrelevant predictors and retain only the most influential variables. Dummy variables for fixed effects (country and year) were excluded

Table 2 Social variables and Bank Capital to Assets Ratio

	Estimate	Std. Error	t value	P-Value
Best Subset Selection Model				
Fertility rate, total	-0.6000	0.5953	-1.0080	0.3150
Life expectancy at birth	2.1270	0.9500	2.2390	0.0266
Mortality rate, under-5	1.2839	0.8555	1.5010	0.1355
Population ages 65 and above	2.1847	1.0043	2.1750	0.0311
Prevalence of undernourishment	0.0633	0.2256	0.2810	0.7795
Intercept	5.6015	2.4056	2.3290	0.0212
Country FE	Yes			
Year FE	Yes			
Adjusted R-squared	0.9258			
LASSO Regression				
Mortality rate, under-5	0.0298	0.6202	0.0481	0.9617
Population ages 65 and above	1.9701	1.0102	1.9501	0.0529
Intercept	3.2290	2.2303	1.4478	0.1497
Country FE	Yes			
Year FE	Yes			
R-squared	0.9492			

In Table 1, we observe the results for the Environmental category.

The best subset selection model identifies five environmental variables that contribute to explaining the Bank Capital to Assets Ratio. Among these variables, *CO₂ emissions* exhibit a statistically significant adverse effect, with an estimate of -1.1434 ($p < 0.001$), suggesting that higher values in this environmental indicator are associated with a lower *Bank Capital to Assets Ratio*. This result is consistent with findings in the literature, which indicate that certain environmental factors, such as carbon emissions or resource depletion, can pose risks to financial stability (e.g., Dietz et al., 2016). The adjusted R^2 of 0.9239 indicates a strong fit for the best subset selection model.

In the LASSO regression model, which applies a penalty to reduce the influence of less significant variables to zero, a slightly different set of environmental variables is retained. *CO₂ emissions* remain significant, with an even more substantial negative impact (-1.3646 , $p < 0.001$). Additionally, *Renewable energy consumption* is selected with a significant adverse effect (-0.8212 , $p < 0.05$). This LASSO selection reinforces the importance of *CO₂ emissions* and suggests that *Renewable energy consumption* also plays a role in affecting the dependent variable. The R -squared of 0.952 in the

from penalization. The variables selected by LASSO were used in an Ordinary Least Squares (OLS) model to estimate the final coefficients and R^2 while including country and year fixed effects.

Table 3 Governance variables and Bank Capital to Assets Ratio

	Estimate	Std. Error	t value	P-Value
Best Subset Selection Model				
Control of Corruption	-0.0823	0.2876	-0.2860	0.7751
Political Stability	0.2829	0.1387	2.0400	0.0431
Rule of Law	-0.1885	0.3054	-0.6170	0.5381
Scientific and technical journal articles	-0.1359	0.2562	-0.5300	0.5965
Voice and Accountability	-0.5427	0.3189	-1.7020	0.0908
Intercept	0.0956	0.7257	0.1320	0.8953
Country FE	Yes			
Year FE	Yes			
Adjusted R-squared	0.9214			
LASSO Regression				
GDP growth (annual% %)	0.0779	0.0290	2.6827	0.0081
Regulatory Quality	0.6535	0.2521	2.5922	0.0104
Rule of Law	-0.4606	0.2828	-1.6286	0.1054
Scientific and technical journal articles	-0.1034	0.2450	-0.4220	0.6736
Voice and Accountability	-0.5136	0.3011	-1.7060	0.0900
Intercept	0.0487	0.6545	0.0744	0.9408
Country FE	Yes			
Year FE	Yes			
R-squared	0.9533			

LASSO model is slightly higher than in the best subset selection model, indicating that the penalized regression has achieved a more precise fit by reducing model complexity.

The results for the Social category are shown in Table 2.

In the best subset selection model, five social variables are selected, with two variables, *Life expectancy at birth* and *Population ages 65 and above*, demonstrating statistical significance. *Life expectancy at birth* has a positive effect (2.1270, $p < 0.05$), as does *the proportion of the population aged 65 and above* (2.1847, $p < 0.05$), suggesting that these social factors may positively contribute to banking stability. This result matches with previous studies indicating that higher levels of social development can indirectly support financial stability by promoting economic growth and resilience (e.g., Beck et al., 2007). The model yields an adjusted R-squared value of 0.9258, indicating a strong fit.

In the LASSO model, only *Population ages 65 and above* remains marginally significant, with an estimate of 1.9701 ($p \approx 0.053$), while *Life expectancy at birth* loses its significance. The LASSO approach reduces the selection to a smaller subset, highlighting *Population ages 65* as the primary social variable influencing the dependent variable. Again, the LASSO model's R^2 of 0.9492 supports the notion that

penalized regression yields a high model fit with fewer predictors. Table 3 provides the results for the Governance category. In the best subset selection model, five governance variables are selected. Among them, *Political Stability and the Absence of Violence/terrorism* are statistically significant ($0.2829, p < 0.05$), suggesting a positive association with *Bank Capital to Assets Ratio*. This result may reflect how robust governance structures, such as effective regulatory quality and control of corruption, can enhance financial stability by fostering a favorable operating environment for banks (e.g., Kaufmann et al., 2009; Laeven & Levine, 2009). The adjusted R^2 of 0.9214 indicates that the model explains a substantial portion of the variance in the dependent variable. The LASSO regression for governance retains *GDP growth* and *Regulatory Quality* as significant predictors, with *GDP growth* showing a positive effect ($0.0779, p < 0.01$) and *Regulatory Quality* also exhibiting a positive influence ($0.6535, p < 0.05$). The slightly higher R-squared value of 0.9533 in the LASSO model indicates that this method's variable selection provides a well-fitting model with fewer predictors, thereby emphasizing the most impactful governance variables.

In each ESG category, both best subset selection and LASSO regressions identify key variables influencing the Bank Capital to Assets Ratio. The best subset selection model provides a broader set of variables, while the LASSO regression narrows the selection, enhancing model interpretability and focusing on variables with the most substantial impact. The environmental results highlight the potential risks associated with specific environmental factors, while the social and governance results emphasize the stabilizing effects of development and institutional strength on banking stability. The combination of these techniques ensures a rigorous and interpretable model, consistent with empirical best practices in econometrics and ML.

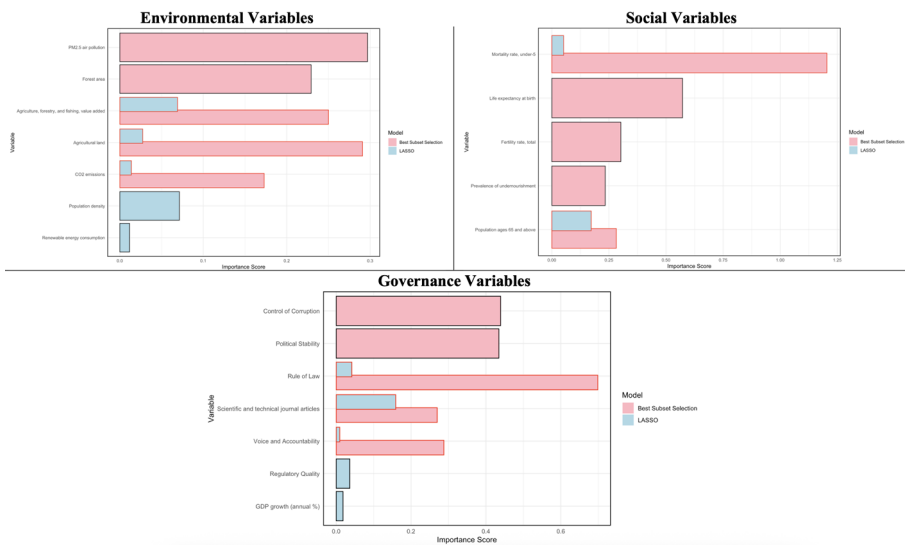


Fig. 7 Best subset selection and LASSO Importance Scores

Figure 7 presents a consolidated view of the variables identified as influential by both the best subset selection and LASSO regression models across the ESG categories.⁸ By juxtaposing the results from each model, we can observe the consistency or divergence in variable selection across different analytical approaches, thus providing insights into the robustness of our findings.

In the Environmental category, the best subset selection model identified indicators such as PM2.5 air pollution, forest area, and the value added from agriculture, forestry, and fishing as having considerable importance in predicting banking stability. Notably, *PM2.5 air pollution*, which serves as a proxy for environmental stress and urban-industrial externalities, matches with the concern raised by Dietz et al. (2016), who estimate the financial risks posed by climate change on global asset values. Similarly, forest areas and agricultural activities represent key components of natural capital and the economic structure.

In the Social category, the best subset selection model retained health-related features, such as the under-5 mortality rate and life expectancy at birth, underscoring the role of demographic and public health conditions in shaping macroeconomic stability, which can, in turn, influence financial systems. This finding is consistent with Bloom et al. (2004), who argue that health, as a fundamental component of human capital, exerts a statistically significant positive effect on aggregate output, independent of other labor market factors. Similarly, Acemoglu & Johnson (2007) analyze international health improvements during the mid-twentieth century and find that higher life expectancy leads to population growth. However, the impact on per capita income is more modest. In contrast, the LASSO model retained variables such as the *Prevalence of undernourishment* and the share of the *5.1 Population aged 65 and above*.

In the Governance category, the best subset selection consistently selected *Control of Corruption* and *Political Stability*, reaffirming the importance of governance quality in sustaining banking and financial sector stability. The inclusion of these variables receives strong support in the work by Kaufmann et al. (2009), which shows the importance of institutional quality, including regulatory frameworks, control of corruption, and political stability, in shaping the development process. Additionally, the best subset selection model identified *Rule of Law*, and the LASSO model selected *Regulatory Quality*, both of which are central in shaping financial sector functionality. The emphasis on legal and regulatory institutions matches with the findings of La Porta et al. (1999), who examine the determinants of government performance across countries. Finally, the inclusion of scientific and technical journal articles in the LASSO model indicates the potential function of innovation and knowledge generation in financial stability. In summary, the alignment in certain key variables, such as *Mortality rate*, across different models highlights their robust impact. Meanwhile, the divergence in other variables, such as *Population density*, suggests that different methodologies may capture additional dimensions of ESG's influence on financial stability. This comparative analysis strengthens our understanding of which ESG

⁸ While the regression tables report estimated coefficients (which indicate the direction and magnitude of the effect under *ceteris paribus* conditions), the importance scores plotted here represent the absolute magnitude of these coefficients and are not adjusted for statistical significance or multicollinearity.

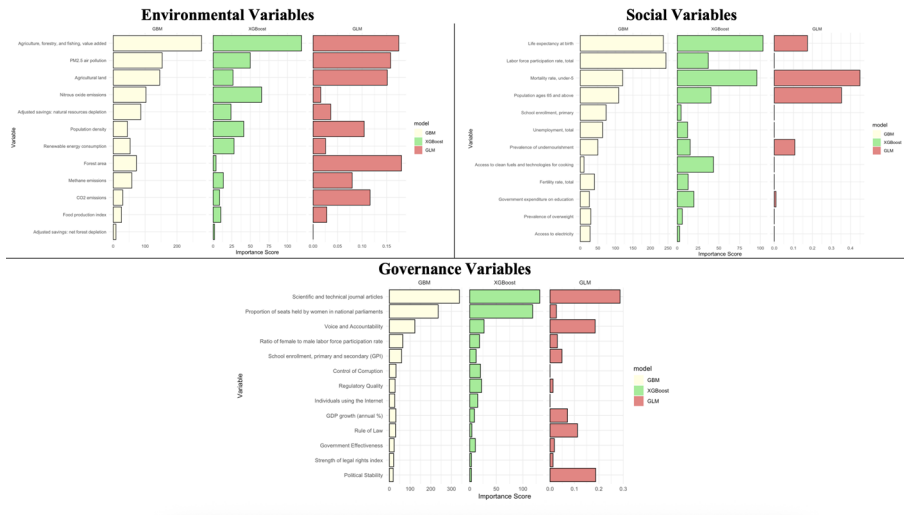


Fig. 8 GBM, XGBoost, and GLM Importance Scores

factors consistently impact banking stability and which may vary depending on the model employed.

6 Robustness checks

In the robustness check section, we apply three ML models (GBM, XGBoost, and GLM)⁹ On each ESG category, evaluate the robustness of the variable selection achieved through the best subset selection and LASSO regression models. Figure 8 presents the combined importance scores for each category across the three ML models, enabling us to assess which variables consistently influence the Bank Capital to Assets Ratio. For the Environment category, both GBM and XGBoost models identified *Agriculture, forestry, and fishing*, as well as *PM2.5 air pollution* and *Agricultural land*, as important predictors, aligning with previous findings from best subset selection and LASSO regressions. The GLM model, however, highlighted *CO₂ emissions* and *Population density* alongside *Agriculture, forestry, and fishing*, indicating a slight variation in variable importance, likely due to the model’s linear assumptions. In the Social category, the GBM and XGBoost models highlighted variables such as *Life expectancy at birth*, and *Mortality rate*, consistent with the best subset selection results. The GLM model, however, gave more weight to the *Prevalence of undernourishment* and *Population ages 65 and above*, suggesting that GLM places a dif-

⁹H2O package applications’ *h2o.gbm*, *h2o.xgboost*, and *h2o.glm* models were trained with sevenfold cross-validation to assess variable importance through ensemble and regularized methods. Models were trained using the H2O framework for scalable ML. The code also appropriately captures the variable importance through the *h2o.varimp* function, with visualizations generated for each model. The GLM model specifies a Gaussian family, aligning it with the continuous nature of the dependent variable *Bank Capital-to-Assets Ratio*.

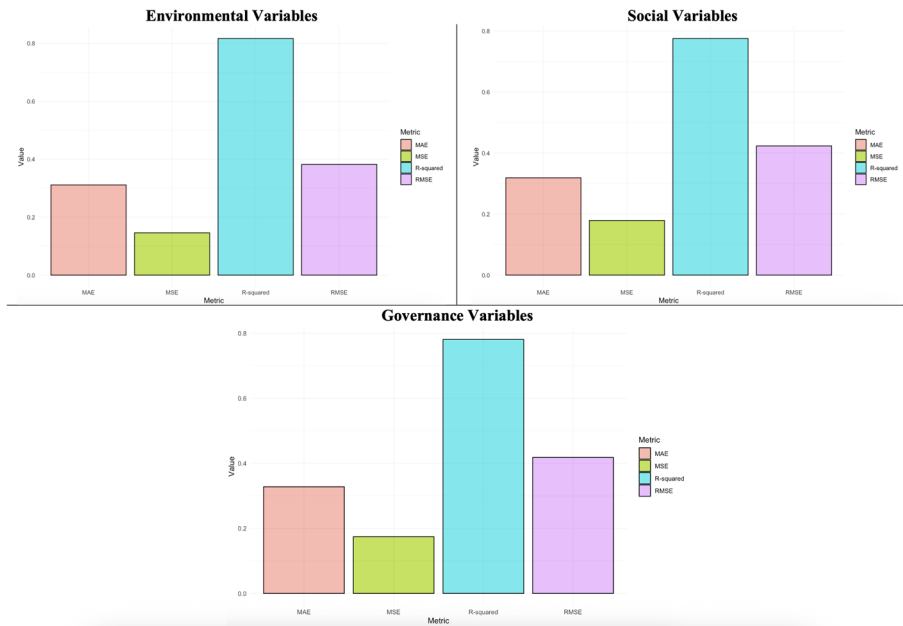


Fig. 9 Meta-Learner Performance Metrics

ferent emphasis on long-term social indicators affecting the financial system. Within the Governance category, the importance scores from GBM and XGBoost strongly reflected variables *such as Scientific and technical journal articles*, and the *Proportion of seats held by women in national parliaments*, reflecting previous findings. The GLM model's emphasis on *Political Stability* further corroborates the impact of governance quality on banking stability.

In summary, Fig. 8 validates the robustness of our previous findings, with consistent variable importance scores across different models, especially in the GBM and XGBoost frameworks. Following the singular model outcomes, we implemented a stacked ensemble model combining GBM, XGBoost, and GLM algorithms. The meta-learner algorithm, set to "GLM" for the ensemble, helped in weighting each base model's predictions, ultimately producing a combined prediction with reduced error.¹⁰ Figure 9 displays the performance metrics for the ensemble model across the environmental, social, and governance categories.

Examining Fig. 9, the R-squared value indicates the accuracy of the stacked ensemble, which reaches approximately 0.8 across all categories. This high R-squared suggests that the model accounts for a substantial portion of the variance for the Bank Capital to Assets Ratio, confirming the robustness of our results. Both the RMSE and Mean Absolute Error (MAE) values indicate acceptable levels of prediction error, underscoring the model's accuracy.

¹⁰A stacked ensemble model was developed using `h2o.stackedEnsemble()` with GBM, XGBoost, and GLM as base learners and a GLM meta-learner. This model leveraged the predictive strengths of each algorithm to boost efficiency.

The application of the stacked ensemble method and the model's performance metrics reinforce the consistency of our findings from the best subset selection and LASSO regression analyses, further validating the selected predictors within each ESG category. Through this ensemble model, we offer a robust and comprehensive analysis that matches well with the identified significant variables across the environmental, social, and governance dimensions.

7 Conclusions and policy implications

This research offers empirical evidence on the role of ESG factors in strengthening banking sector stability, operationalized through the Bank Capital to Asset Ratio, a key indicator of financial resilience. By employing a combination of ML techniques and statistical modeling, including LASSO regression and a subset selection procedure, we identify a parsimonious set of ESG indicators with significant predictive power. Specifically, we find that environmental variables related to value added in primary industries, social indicators concerning child health and survival, and governance-related metrics reflecting scientific and technical capacity contribute meaningfully to explaining variation in banking capital adequacy.

These findings are consistent with the expanding corpus of research pointing to the stabilizing influence of ESG strategies within the financial sector (e.g., Chiamonte et al., 2022; Citterio & King, 2023). Beyond risk mitigation, ESG adoption also interacts with profitability dynamics in ways that are non-linear and context-dependent (e.g., Yuen et al., 2022). While initial ESG engagement may incur short-term costs, sustained adoption enhances long-term performance. This lends credence to the view that ESG integration, when appropriately calibrated, can support both financial and operational resilience. Our findings support this interpretation by indicating that strategic ESG investments, particularly in governance and social domains, may yield long-term benefits in terms of stability. In the context of emerging economies, where ESG frameworks and data environments are often less developed, our results are echoed by Azmi et al. (2021), who document a non-linear relationship between ESG activity and bank value. Complementarily, Arun et al. (2022) point out the need for worldwide sustainability frameworks and mandatory disclosure policies in improving ESG adoption among banks.

Our assessment additionally indicates that governance-related ESG dimensions exert a particularly robust influence on banking stability. Esteban-Sánchez et al. (2017) find that corporate governance structures and employee relations have a positive impact on financial performance. However, their effectiveness may weaken under systemic stress, such as financial crises. Meanwhile, the relational dimension of ESG is highlighted by Houston & Shan (2022), who demonstrate that banking relationships influence borrower ESG profiles. Banks with stronger ESG standards are more likely to lend to similarly aligned firms and, over time, contribute to improvements in borrowers' ESG behaviors. This relational transmission mechanism supports the

argument that ESG integration is not only internally beneficial to banks but also externally generative of more sustainable financial ecosystems.

Moreover, the role of corporate governance in reducing risk is reinforced by Gangi et al. (2019), who find that environmentally engaged banks with sound governance structures are significantly less risky. However, the effectiveness of such strategies ultimately hinges on the quality of underlying ESG data. In this respect, our combined use of subset selection, penalized regression, and ML robustness checks delivers a thorough strategy to identifying which ESG indicators matter most, and when, in supporting capital adequacy and institutional resilience.

Taken together, these findings advance the empirical understanding of ESG's role in financial stability. They suggest that ESG factors, when embedded in strategic decision-making and backed by reliable data and regulatory support, can serve not merely as reputational signals but as substantive contributors to financial health. For policymakers, the implications include the need to promote standardized ESG disclosure requirements and enhance the capacity of financial institutions to assess ESG-related risks. For banks, the insights highlight the value of tailoring ESG investments to reflect core dimensions of operational stability, particularly governance quality and long-term social impact. The evidence assembled here confirms the evolving role of ESG, not as a peripheral concern, but as an integral component of sustainable banking strategy.

For future research, further exploration of ESG dynamics across diverse regulatory frameworks and economic contexts would be particularly valuable. Examining the longer-term consequences of ESG investments on banks' profitability, competitiveness, and resilience helps clarify the strategic value of ESG integration beyond capital adequacy. Moreover, future studies could consider more granular ESG indicators and investigate potential interaction effects across dimensions to capture better the mechanisms through which ESG factors shape financial performance. One promising direction would be to expand the set of outcome variables. Incorporating the Capital to Risk-Weighted Assets Ratio, a commonly used metric in prudential regulation, could offer insights into how ESG performance relates to risk-adjusted capital adequacy and facilitate comparisons with regulatory benchmarks. This would also facilitate discussion of how ESG integration matches with or deviates from existing capital regulation standards.

While our analysis provides robust evidence of a statistically significant association between ESG indicators and the Bank Capital-to-Asset Ratio, we caution that our cross-sectional design does not permit strong causal claims. In particular, the possibility of reverse causality, where banks with weaker capital buffers may underperform on environmental indicators due to limited investment capacity, cannot be entirely ruled out. However, the risk of such reverse causality is limited in our case, for three reasons. First, the ESG indicators used in the analysis are independently compiled by third-party institutions and are unlikely to reflect short-term capital positions directly. Second, the standardization of variables and the modeling framework

are designed to identify structural patterns rather than capture reactive dynamics. Third, the direction and significance of effects are consistent across multiple ML models, which reduces the likelihood of spurious correlations. Nonetheless, we acknowledge this limitation and encourage future research to explore these relationships using longitudinal or instrumental variable approaches that are better suited for causal identification.

In conclusion, this study highlights the strategic importance of ESG integration in banking by demonstrating its correlation with capital adequacy, a key dimension of financial stability. By identifying which ESG dimensions are most strongly associated with capital strength, the findings provide practical guidance to financial institutions and regulators seeking to align their banking practices with sustainability goals. As the role of ESG in finance continues to expand, institutions that proactively embed ESG considerations into their governance and risk frameworks may be better equipped to withstand emerging systemic risks and foster long-term, sustainable growth.

Appendix

Fig. A1 and Table A1.



Fig. A1 Map of Selected Countries

Table A1 Variables' list

ESG Group (if any)	Variable Name	Definition	Source
	Bank capital to assets ratio	The ratio of a bank's capital to its total assets is a key indicator of financial stability	World Bank
Environment	Renewable energy consumption	The share of renewable energy in total final energy consumption	World Bank
Environment	Population density	The number of people living per square kilometer of land area	World Bank
Environment	PM2.5 air pollution	The population-weighted exposure to ambient PM2.5 pollution is measured in micrograms per cubic meter	World Bank
Environment	Nitrous oxide emissions	Emissions of nitrous oxide, expressed in thousand metric tons of CO ₂ equivalent	World Bank
Environment	Methane emissions	Emissions of methane, expressed in kilotons of CO ₂ equivalent	World Bank
Environment	Forest area	The proportion of land area covered by forests	World Bank
Environment	Food production index	An index measuring the relative level of food production compared to a base period (2014–2016)	World Bank
Environment	CO ₂ emissions	Carbon dioxide emissions resulting from the burning of fossil fuels and the production of cement, divided by mid-year population	World Bank
Environment	Agriculture, forestry, and fishing, value added	The value added by the agriculture, forestry, and fishing sectors as a percentage of GDP	World Bank
Environment	Agricultural land	The share of land area that is arable, under permanent crops, and under permanent pastures	World Bank
Environment	Adjusted savings: net forest depletion	The monetary value of net forest depletion, expressed as a percentage of Gross National Income	World Bank
Environment	Adjusted savings: natural resources depletion	The monetary value of energy, mineral, and net forest depletion, expressed as a percentage of Gross National Income	World Bank
Social	Unemployment, total	The share of the labor force that is without work but available for and seeking employment	World Bank
Social	School enrollment, primary	The total enrollment in primary education, regardless of age, expressed as a percentage of the population of official primary education age	World Bank
Social	Prevalence of undernourishment	The percentage of the population whose food intake is insufficient to meet dietary energy requirements continuously	World Bank
Social	Prevalence of overweight	The percentage of adults with a body mass index (BMI) of 25 or higher	World Bank
Social	Population ages 65 and above	The proportion of the population aged 65 and older	World Bank
Social	Mortality rate under-5	The probability per 1,000 that a newborn baby will die before reaching age five, if subject to age-specific mortality rates of the specified year	World Bank
Social	Life expectancy at birth	The average number of years a newborn is expected to live, assuming mortality patterns at the time of birth remain constant	World Bank
Social	Labor force participation rate, total	The proportion of the population aged 15 and older that is economically active	World Bank

Table A1 (continued)

ESG Group (if any)	Variable Name	Definition	Source
Social	Government expenditure on education	The total public expenditure on education is expressed as a percentage of Gross Domestic Product	World Bank
Social	Fertility rate, total	The average number of children a woman would have, assuming she lives through her reproductive years and bears children according to age-specific fertility rates	World Bank
Social	Access to clean fuels and technologies for cooking	The percentage of the population that primarily uses clean cooking fuels and technologies	World Bank
Social	Access to electricity	The percentage of the population with access to electricity	World Bank
Governance	Voice and Accountability: Estimate	Reflects perceptions of the extent to which a country's citizens can participate in selecting their government, as well as freedom of expression, freedom of association, and a free media	World Bank
Governance	Strength of legal rights index	Measures the degree to which collateral and bankruptcy laws protect the rights of borrowers and lenders	World Bank
Governance	Scientific and technical journal articles	The number of scientific and engineering articles published	World Bank
Governance	School enrollment, primary and secondary (gross), gender parity index (GPI)	Gender parity index for gross enrollment, i.e., the ratio of girls to boys enrolled at primary and secondary levels in public and private schools	World Bank
Governance	Rule of Law	Reflects perceptions of the extent to which agents have confidence in and abide by the rules of society, including the quality of contract enforcement, property rights, the police, and the courts, as well as the likelihood of crime and violence	World Bank
Governance	Regulatory Quality	Reflects perceptions of the government's ability to formulate and implement sound policies and regulations that facilitate and promote private sector development	World Bank
Governance	Ratio of female to male labor force participation rate	The labor force participation rate of females is a percentage of the labor force participation rate of males	World Bank
Governance	Proportion of seats held by women in national parliaments	The percentage of parliamentary seats in a single or lower chamber held by women	World Bank
Governance	Political Stability	Reflects perceptions of the likelihood of political instability and/or politically motivated violence, including terrorism	World Bank
Governance	Individuals using the Internet	The percentage of individuals who have used the Internet from any location in the last three months	World Bank
Governance	Government Effectiveness	Reflects perceptions of the quality of public services, the quality of the civil service and its degree of independence from political pressures, the quality of policy formulation and implementation, and the credibility of the government's commitment to such	World Bank
Governance	GDP growth (annual%)	The ratio of a bank's capital to its total assets is a key indicator of financial stability	World Bank

Table A1 (continued)

ESG Group (if any)	Variable Name	Definition	Source
Governance	Control of Corruption	The share of renewable energy in total final energy consumption	World Bank

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Declarations

Conflict of interest The authors have not disclosed any competing interests.

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