Journal of Sivas Cumhuriyet University Social Sciences Institute

| https://dergipark.org.tr/tr/pub/scusbed | Founded: 2026 Available Online, ISSN: 1303-1279 Publisher: Sivas Cumhuriyet Üniversitesi

Green Bonds in Forestry Finance: A Quantile-on-Quantile and Machine Learning Perspective on Environmental and Financial Drivers

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Research Article

History

Received: 04/12/2025

Accepted: 09/02/2026

ABSTRACT

Green bonds (GBs) have emerged as a prominent sustainable finance instrument, yet their role in funding timber and forestry (TF) projects remains underexplored. This study provides one the first empirical assessments of the financial significance of GBs within the TF sector, addressing critical questions about their alignment with forestry's risk–return profile. Using daily data from May 2015 to May 2025 we analyze the dynamic and nonlinear interactions between timber and forestry returns and green bonds performance represented by GB Index and TF Index. We also include control variables that might have significant impact on timber and forestry return series. Our methodology integrates Quantile Cointegration, Quantile-on-Quantile analysis, and Random Forest machine learning to capture distributional heterogeneity, asymmetric effects in financial time series. Our results show that the green bonds exert only a modest and asymmetric impact on timber and forestry, which is becoming significant mainly at distributional extremes. Random Forest analysis identifies GB performance and water availability as key drivers of TF returns, while carbon markets exert more moderate influences. This limited role of green bonds reflects persistent sector risks, including long project durations, changing environmental conditions and a lack of standardized metrics. Our findings indicate that key control variables such as water availability and carbon credits have significant, widespread effects on TF returns. By bridging econometric and machine learning approaches, this research advances methodological innovation in green finance studies and offers actionable insights for policymakers, investors, and forest sector stakeholders seeking to align capital flows with ecological outcomes.

Keywords: green bonds, forestry finance, Machine Learning, Quantile-on-Quantile approach, carbon credits, asymmetric effects, distributional extremes.

Jel Code: G17, Q23, Q56

Orman Finansmanında Yeşil Tahviller: Çevresel ve Finansal Belirleyicilere Nicelik-Üzerine-Nicelik ve Makine Öğrenmesi Perspektifinden Bir Bakış

Süreç

Geliş: 04/12/2025

Kabul: 09/02/2026

ÖZ

Yeşil tahviller (Green Bonds, GB'ler) sürdürülebilir finansmanın önde gelen araçlarından biri olarak ortaya çıkmıştır; ancak ormancılık ve kereste (Timber and Forestry, TF) projelerinin finansmanındaki rolleri hâlâ yeterince araştırılmamıştır. Bu çalışma, TF sektöründe GB'lerin finansal önemine ilişkin ilk ampirik değerlendirmeyi sunmakta ve yeşil tahvillerin ormancılığın risk-getiri profiliyle uyumuna dair kritik soruları ele almaktadır. Günlük veriler kullanılarak, ormancılık getirileri ile yeşil tahvil performansı arasındaki dinamik ve doğrusal olmayan ilişkiler incelenmiştir. Ayrıca, TF getiri serilerini önemli ölçüde etkileyebilecek kontrol değişkenleri de analize dâhil edilmiştir. Çok aşamalı metodolojimiz, Nicelik Eşbütünleşme (Quantile Cointegration), Nicelik-Üzerine-Nicelik (Quantile-on-Quantile) analizi ve Rassal Orman (Random Forest) makine öğrenmesi tekniklerini entegre ederek finansal zaman serilerindeki dağılımsal heterojenliği ve asimetrik etkileri yakalamaktadır. Elde edilen bulgular, yeşil tahvillerin ormancılık ve kereste piyasaları üzerinde yalnızca sınırlı ve asimetrik bir etkiye sahip olduğunu, bu etkinin ise esas olarak dağılımın uç noktalarında belirginleştiğini göstermektedir. Rassal Orman analizi, GB performansı ile su kaynaklarının mevcudiyetini TF getirilerinin temel belirleyicileri olarak tanımlarken, karbon piyasalarının ise daha ılımlı bir etki yarattığını ortaya koymaktadır. Yeşil tahvillerin bu sınırlı rolü, uzun proje süreleri, değişen çevresel koşullar ve standartlaştırılmış ölçütlerin eksikliği gibi sektörel risklerin devam ettiğini yansıtmaktadır. Sonuçlar ayrıca, su mevcudiyeti ve karbon kredileri gibi temel kontrol değişkenlerinin TF getirileri üzerinde belirgin ve yaygın etkiler yarattığını göstermektedir. Ekonometrik ve makine öğrenmesi yaklaşımlarını birleştiren bu çalışma, yeşil finans araştırmalarında metodolojik yenilik sunmakta ve sermaye akışlarını ekolojik sonuçlarla uyumlu hâle getirmeyi amaçlayan politika yapıcılar, yatırımcılar ve orman sektörü paydaşları için uygulanabilir içgörüler sunmaktadır.

Anahtar Kelimeler: Yeşil tahviller, orman finansmanı, makine öğrenmesi, Nicelik-üzerine-Nicelik yaklaşımı, karbon kredileri, asimetrik etkiler, dağılımsal uçlar.

Jel Kod: G17, Q23, Q56

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How to Cite: Azimova Tarana (2026) Green Bonds in Forestry Finance: A Quantile-on-Quantile and Machine Learning Perspective on Environmental and Financial Drivers , Journal of Sivas Cumhuriyet University Social Sciences Institute, 2(1): 17-38, 2026.

Introduction

Green bonds (GBs) are key sustainable financial assets used to fund environmentally sound projects. Green finance can have a significant impact on TF and can be used to close the funding gap for restoration, conservation and sustainable management of timber and forestry. Green debt instruments have grown rapidly in the sustainable finance field over the past decade. Global green bond issuance exceeded US$1 trillion in 2024, reflecting growing investor interest in eco-labeled debt. (Climate Bonds Initiative, 2024). Zerbib (2019) argues that green bonds can successfully meet the financial and structural needs of forest enterprises and can serve as a critical financing vehicle for advancing climate action initiatives. Smith et al. (2020) demonstrate that green bonds can achieve significance when economic rewards are connected to ecological results. The prospects for sustainable forest financing are clear; however, at present the idea of sustainable financing is still controversial. (Cunha et al., 2021). Particularly ambiguous is how this applies to forests in practice. GBs differ from traditional bonds in that they are considered to be riskier, and the returns on these investments are less assured. Thus, there is a palpable mismatch between financial needs and availability of funds for green programs. (Fatica et al., 2021). Forestry projects are typically characterized by difficulties in accurately assessing environmental performance, long maturation periods, and exposure to climate risks such as fires and diseases. (Bernknopf et al., 2022; Ranjan, 2022). These scenarios threaten the delivery of environmental benefits and may also disrupt timber harvesting and diminish sales, which influence project revenues and, therefore, the probability of bond repayment, which is dependent on stable cash flows and verifiable environmental outcomes. In addition, green bonds are linked to environmental outcomes such as biodiversity conservation, carbon storage, and ecosystem restoration, whose financial benefits may be ambiguous, delayed, or difficult to verify. Consequently, investors often require a risk premium when purchasing green bonds, especially in young industries such as forestry, where financial returns are delayed and project viability is uncertain. The regulatory and certification landscape for green bonds remains in development. In the absence of defined and globally recognized standards, investors encounter the danger of greenwashing—the likelihood that bond profits are not allocated to really sustainable initiatives. This erodes market confidence and may result in undervaluation or diminished liquidity in the secondary market. In forestry, the challenge of accurately measuring and validating biodiversity outcomes exacerbates assessment and reputational risk (Bernknopf et al., 2022). Ferrando et al. (2021) observe that in areas such as Brazil, the issue of green bonds frequently prioritizes company image and its revenue potential rather than authentic ecological reform. To alleviate these risks and enhance the feasibility of green bonds in forestry, blended finance solutions were proposed. Blended-finance scholars Rode et al. (2019), Thompson (2020), Low et al. (2021), and Ferrando et al. (2021) contend that green bonds alone are insufficient for financing TF initiatives and assert that technical-assistance grants, guarantees, and subsidized tranches are essential. Although green bond portfolios are dominated by low-carbon transportation and renewable energy, the role of green bond segment is currently questionable for the TF sector. Specifically, there is a lack of direct evidence on the financial significance of the GBs in TF sector portfolio. This research is, to our knowledge, one of the first investigation using intensive empirical analysis such as Quantile-on-Quantile and Machine Learning Perspective to evaluate the degree to which the TF industry utilizes green bonds as a funding source.

The focus of this paper is to empirically evaluate the influence of green bonds on the performance of the TF sector, contributing to the continuing discourse. This study offers significant additions to the expanding corpus of research on green finance and sustainable forest development. Although previous research (Ferrando et al., 2021; Ranjan, 2022; Zerbib, 2019) has examined the theoretical and institutional functions of green bonds, there is a scarcity of empirical assessments on their financial relevance with respect to the timber and forestry (TF) sector. Assessing the degree to which TF companies employ green bonds in their financing strategy is essential for evaluating the incorporation of sustainable finance within the natural resource sector. Furthermore, we intend to investigate the subsequent inquiries: Are these instruments well aligned with the risk-return profile of forestry? Is there a nonlinear relationship between GB and TF? Are regulatory frameworks and green taxonomies adequately defined to facilitate issuance? Is there investor interest in long-term, environmentally conscious forestry bonds? By examining these inquiries, we can gain a clearer understanding of the constraints and possibilities of green bonds as a sustainable finance instrument in the TF sectors. The augmented utilization of green bonds by TF enterprises could yield substantial ecological advantages, including but not limited to superior water quality, enhanced forest management, improved biodiversity conservation and boosted carbon sequestration. Secondly, we utilize data with daily frequency, which is infrequently applied in green finance studies especially concerning the forestry and natural resource sectors. Many previous researches depends on monthly or quarterly aggregates, potentially obscuring significant short-term market dynamics or delayed interactions. This research utilizes daily data to provide a detailed and responsive analysis of the interactions between green bonds, water availability, and carbon markets with the profitability of the TF sector, particularly during turbulent, transitional and normal periods. The study utilizes a multi-stage econometric approach that integrates Random Forest (machine learning), Quantile Cointegration, and Quantile-on-Quantile approach. These analytical advancements provide a more profound understanding of the variability of relationships throughout the entire distribution of TF returns. By recognizing asymmetric impacts and tail dependencies, these methodologies enhance the methodological boundaries of green finance research, which has frequently depended on mean-based predictors that may conceal significant heterogeneity (Shahbaz et al., 2018; Xiao et al., 2009).

This article consists of several sections. Section 2 reviews the related literature. Section 3 describes the data and methodology. Section 4 presents the empirical results. Section 5 discusses policy implications, and Section 6 concludes.

Literature Review

As of the third quarter of 2024, the Climate Bonds Initiative (2024) reports that the cumulative volume of labelled sustainable debt—comprising green, social, sustainability, sustainability-linked, and transition bonds—exceeded USD 5.4 trillion, with green bonds constituting a significant share of this market. In particular, individual green bond issuance approached USD 196 billion in the first quarter of 2024, contributing to a projected record-breaking total of USD 1 trillion by the end of the year. The sustainable development of these instruments is predicated on the premise that proceeds are directed towards emissions reduction, biodiversity conservation, o the preservation of natural capital (Zerbib, 2019). Forestry is theoretically well-suited for green finance due to its essential function in climate mitigation, water regulation, and biodiversity (FAO, 2020). Zerbib (2019) provides actual evidence that green bonds might successfully align with the financial and structural needs of forestry projects. His investigations validate the concept that green bonds could function as a primary funding source for the development of nature-based climate solutions. Projects like reforestation, sustainable logging, and carbon credit generation are directly associated with the ideas of green bonds and can be structured to meet investors' specific environmental goals. Richard et al., (2020) investigate the incorporation of biodiversity, ecosystem services, and timber yields from forests into bond pricing, thereby creating a new type of forest sustainability bonds. The benefits of ecosystem services, including as carbon sequestration and water security, evolve over prolonged durations, making this sort of bond suitable for the biological timelines of forestry. Although they may be appropriate for ecosystem-based climate solutions, fewer than 3% of global green bond revenues are now allocated to forestry or nature-based solutions (FAO, 2020; Low et al., 2021). This mismatch has generated increasing scholarly interest in comprehending the obstacles to broader implementation of green bonds in timber and forestry finance.

Risk-Return Misalignments in Forestry Investments. Forestry initiatives are fundamentally distinct from the predominant infrastructure or renewable energy investments that are funded by the green bond issuances. They are defined by extended investment timelines, unpredictable cash flows, environmental connections, and regulatory changes (Bernknopf et al., 2022; Ranjan, 2022). Forestry operations, including afforestation, sustainable timber production, and ecosystem restoration, typically require decades to yield complete economic and ecological benefits. Trees demand 10–30 years (or longer) to reach maturity, postponing wood profits and carbon credit production. Prolonged timeframes conflict with the shorter durations (5–10 years) favored by several bond investors, who necessitate prompt principal payments and reliable streams of income. There is a higher default risk and more difficulty in coupon scheduling with timber and forestry cash flows compared to traditional project bonds, and this volatility persists even beyond maturity. The profitability of forestry is closely related to environmental factors. Natural forests and plantations are vulnerable to the ecological and economic destruction that can result from natural disasters including droughts, wildfires, pest outbreaks, and diseases. The frequency and severity of these dangers are being amplified by climate change. Natural capital losses could be permanent or necessitate heavy expenditure in restoring ecosystems, putting bond repayments in peril, in contrast to the insurance or rebuilding of physical assets in most infrastructure projects. Traditional institutional investors are less interested in forestry bonds because of the increased risks associated with these traits, which are hard to standardize or hedge. Ecosystem benefits, such as carbon sequestration or watershed control, may not fully materialize for decades, which distorts the return profiles of sustainable forest initiatives. Green bonds associated with forestry continue to be a specialized product with low adoption rates due to the lack of revenue assurances and upfront risk-sharing arrangements (Fata et.al. 2021). Ojekunle et al., (2024) investigate the viability of green bonds for financing forest conservation in Southwestern Nigeria, noting that although there is significant interest from civil-society organizations and governmental bodies, commercial banks and pension funds exhibit caution due to regulatory uncertainty, limited deal sizes, and a lack of credit-enhancement procedures. This misalignment explains why green bonds struggle to integrate effectively with forestry finance.

Despite these constraints, forestry-linked green bonds also present important potential opportunities when supported by appropriate financial and institutional frameworks. Long biological growth cycles can be aligned with patient capital from sovereign wealth funds, development banks, and impact-oriented investors seeking long-term environmental returns alongside moderate financial yxields. Risk-balancing mechanisms—such as public guarantees, first-loss tranches, blended-finance structures, insurance against climate-related losses, and advance purchase agreements for carbon credits—can significantly improve bankability. Successful applications in advanced economies, particularly in parts of Europe and North America, demonstrate that forestry bonds can attract institutional investors when supported by strong regulatory clarity, credible carbon markets, and standardized monitoring, reporting, and verification (MRV) systems. In contrast, developing countries face additional barriers related to weaker institutional capacity, land-tenure uncertainty, limited access to insurance markets, and underdeveloped carbon pricing mechanisms, which elevate perceived investment risk. While pilot initiatives in countries such as Brazil, Indonesia, and Nigeria show growing momentum, forestry-based green bonds in these contexts remain heavily dependent on multilateral development banks and donor-backed credit enhancements. A comparative perspective highlights that narrowing the gap between developed and developing markets requires policy harmonization, scalable deal structures, and international risk-sharing arrangements. Strengthening these mechanisms could enable forestry-related green bonds to transition from a niche instrument to a more mainstream component of sustainable finance.

Verification and Greenwashing Risks. A major obstacle to the widespread adoption of forestry-related green bonds lies in the lack of credible verification and enforcement mechanisms. For green bonds to generate genuine environmental value, investors must be assured that proceeds are directed toward measurable and verifiable ecological outcomes. However, prevailing frameworks frequently rely on issuer-led disclosures and voluntary reporting standards, which often lack independent oversight and robust enforcement (Ferrando et al., 2021). This institutional weakness increases the risk of greenwashing, whereby bonds are labeled as environmentally sustainable without guaranteeing substantive environmental benefits.

Empirical evidence reinforces these concerns. Ferrando et al. (2021) demonstrate that, within the Brazilian forestry sector, green bonds have at times functioned more as instruments of reputational signaling than as catalysts for meaningful ecological transformation. Rather than fostering equitable and multifunctional forest landscapes, such bonds often reinforce debt-driven growth models. Similarly, Begemann et al. (2023), drawing on 51 in-depth expert interviews across financial institutions, timberland investors, global organizations, and predominantly European civil society actors, find that prevailing sustainable-finance taxonomies—most notably the EU Taxonomy—prioritize aggregated climate metrics while overlooking critical forest-specific dimensions such as biodiversity conservation, land-tenure security, and mixed-use forest management. The authors argue that effective forestry green bonds require tailored criteria encompassing sustainable harvesting rates, ecosystem service provision, and social governance indicators, including community participation and tenure rights, to be meaningfully integrated into use-of-proceeds rules and reporting standards.

Recent scholarship further highlights that environmental metrics alone are insufficient to ensure sustainable forestry finance. Xu et al. (2025) emphasize that green finance instruments, including green bonds, must be redesigned to address equity, procedural justice, and underlying power asymmetries, rather than narrowly focusing on carbon outcomes. Complementing this view, Low et al. (2021) classify green finance instruments across different forestry applications and note that despite their long-term co-benefits, forestry projects struggle to attract institutional capital due to uncertain cash flows, regulatory complexity, and illiquidity. Brockhaus et al. (2022) caution that green bonds frequently favor large landholders and highly rated corporate issuers, thereby perpetuating existing inequalities in land governance and access. As a result, most forestry-linked green bonds remain disproportionately centered on carbon sequestration, often at the expense of biodiversity protection, livelihoods, and governance outcomes.

Without rigorous third-party verification of both ecological and social co-benefits, forestry projects financed through green bonds risk converging toward monoculture plantations or minimal compliance certification schemes. Thompson (2020), in assessing biodiversity-oriented financing instruments—including traditional and green bonds—underscores the necessity of resilient project platforms, robust measurement systems, and effective risk-sharing mechanisms to align financial returns with ecological integrity. Taken together, this body of evidence supports the central thesis that while green bonds hold significant potential for financing sustainable forestry, their effectiveness ultimately depends on the integration of forest-specific verification standards, social governance safeguards, and credible enforcement mechanisms capable of translating green finance into genuine environmental outcomes.

Taxonomy and Standardization Challenges. Another challenge to incorporating green bonds into forest financing is the absence of accurate, sector-specific taxonomy. Current generic green bond frameworks, such as the EU Green Taxonomy or ICMA's Green Bond Principles, is still developing the framework necessary for biodiversity programs, sustainable forest management, and forest regeneration. For this reason, issuers and shareholders may be hesitant to engage with the forestry sector for fear of regulatory coercion or reputational harm. (Ranjan 2022; Gong et.al., 2024; Climate Bonds Initiative, 2024). Gong et al., (2024) examines a composite “green finance index” and illustrate that green finance, particularly green bonds, can enhance forestry productivity via structural and human-capital mechanisms. Their results underscore that effectively designed green bonds, aligned with industry modernization and bolstered by clear taxonomies, serve as a potent instrument for sustainable forest investment and regional advancement. Miola et al., (2021) conduct a comprehensive analysis of Brazilian forestry-sector issuances, illustrating how green-bond frameworks depend on a tailored institutional apparatus—state incentives, regulatory modifications, and private debt governance. Although promoted as instruments for sustainability, green bonds in these instances primarily finance extensive plantation growth and corporate activities, frequently to the detriment of smallholders, biodiversity, and traditional land rights. The authors contend that financialization generates not just monetary liabilities but also "social and ecological debt," as people and ecosystems incur the concealed costs of extraction and monoculture. The research emphasizes the necessity for green-bond frameworks to extend beyond carbon measures and incorporate stringent social-ecological safeguards. In the absence of reforms, green bonds may continue to support extractive forestry instead of promoting truly sustainable and equitable forest governance. Ferrando et al., (2021) conclude that the primary beneficiaries of green bonds are corporate entities possessing investment-grade ratings. Smallholder and community participants continue to be underprivileged: merely 2 percent of revenues were allocated through credit lines available to cooperatives, and certification expenses established further obstacles to involvement. The research indicates that plantation farming systems funded by bond capital provide rapid carbon sequestration per hectare but intensify biodiversity decline, water-table depletion, and labor instability. Numerous remote rural communities have experienced diminished access to clean water and traditional land, exemplifying the "metabolic rift" associated with financialized forestry. To tackle this, the Climate Bonds Standard is now working on defining standards that are specific to forestry. These criteria will evaluate carbon integrity, land tenure rights, and biodiversity safeguards. However, investor trust is limited because these regulatory structures are still emerging and do not have uniform world-wide adoption. A sustainable finance policy framework is presently in the works at the European Union. A taxonomy, a system for categorizing and defining environmentally friendly practices, is central to it. A new set of rules for disclosure, primarily aimed at businesses and financial organizations, and various instruments, such the European Union green bond standard (EUGBS), implement the taxonomy (European Commission, 2021, 2022). While the United States has just started to take initial moves, analogous regulatory actions with different scopes are happening, in the United Kingdom, China, and South Africa. (Climate Bonds Initiative, 2020, 2021; Forest Stewardship Council. 2022). Responsible forest management is promoted by certifications like the Forest Stewardship Council (FSC) and the Sustainable Forestry Initiative (SFI). Moreover, these must be met before investors will give sustainable finance practices their attention (FSC, 2022). Hybrid financing frameworks and novel financial products, such as Forest Resilience Bonds and Green Bonds, are incorporating timberland investment. While directing private funds toward ecological sustainability objectives, these methods attempt to lessen the dangers of investing in sustainable forestry. (Stanford Natural Capital Project, 2020). The absence of harmonized forestry-specific taxonomies introduces substantial heterogeneity and measurement noise into green bond datasets, which justifies the use of non-linear approaches such as quantile-on-quantile regression and machine learning techniques. The De-Risking Power of Blended Financing. Blended financing is a new strategy that shows promise for overcoming these obstacles. Investments in ecologically sound but commercially precarious industries, such as forestry, might be "blended" by making judicious use of public and charitable funds to reduce the inherent risk in such investments (Stanford Natural Capital Project, 2020). Rode et al. (2019) document blended finance applications in the “Unlocking Forest Finance” project, showing that combining concessional support with impact-linked returns can mobilize private capital in otherwise underfunded forest conservation efforts. In particular, Rode et al., (2019) recognize that in order to meet the scale, risk characteristics, and capacity-building needs of sustainable landscape investments, they must be integrated into a larger mix of commercial debt or equity, public subsidies or grants, philanthropic "first-loss" capital, guarantees, and technical assistance funding. Green bonds are one of several "innovative financing" strategies that, in addition to blended finance and crowdsourcing, might potentially aid in scaling up landscape-level conservation (Rode et al.,2019). But the authors, analyzing the Unlocking Forest Finance (UFF) projects found that green bonds' rigid payback plans, strict interest rates, and requirement for big deal amounts (often greater than US$50 million) rendered them unsuitable for the small-scale, high-risk, long-horizon initiatives that are typical of early-stage forest preservation. In contrast to UFF projects, which deal with biological risks, fluctuating commodity markets, and emerging ecosystem-service income streams, institutional investors in green bonds anticipate low-risk, assured cash flows. Therefore, the financial gap for the forestry projects cannot be filled by green bonds alone. Instead of operating on its own, green bonds are seen as one part of a blended finance portfolio that also includes state guarantees, technical assistance grants, and philanthropic first-loss capital to help reduce the overall risk of the funding. This multi-layered strategy helps meet the versatility prerequisites of landscaping initiatives as well as the scalability and security demands of green-bond investors. Thompson (2020) argues that biodiversity-linked bond models that embed outcome-based payments can improve the financial viability and ecological integrity of such instruments. Low et al., (2021) argue that forests remain underexploited in green financial markets, despite their essential contributions to climate mitigation, biodiversity preservation, and ecosystem services. Low et al., (2021) assert that green bonds hold potential for financing forestry initiatives; however, they necessitate standardized impact measurement frameworks and enhanced pipelines of investable projects.

The discussion encompasses blended finance, emphasizing the significance of public capital and philanthropic assistance in mitigating risks associated with private investment, especially in the initial phases of projects. The report delineates multiple obstacles to the expansion of forestry-related green finance. Absence of metrics to measure biodiversity and ecosystem co-benefits. Inadequate investor awareness and technical proficiency, dispersed ownership and project scale in forest landscapes, coupled with insufficient standardization in verification and reporting protocols. The authors advocate for cross-sector collaborations, more defined national strategies regarding green finance and nature investment, and the incorporation of forestry into comprehensive net-zero investment platforms to address these challenges. Moreover, according to Zerbib (2019), investors are willing to agree to somewhat lower returns in exchange for a healthier environment, as evidenced by the 2–5 basis point yield premium that green bonds trade at over analogous vanilla bonds. It is mainly unknown, though, if this lower cost of capital results in quantifiable improvements in timberland performance under various market circumstances. Thompson (2020) underscores the essential function of blended financial frameworks, including the integration of green bonds with guarantees or subsidies, to improve the bankability of green bonds. Baxter et al., (2020) demonstrate that blended green finance schemes are crucial for reconciling shareholder requirements with sustainable ecological results and long-term forestry investments.

Data, Model and Econometric Analysis

Data

The dataset of our study comprises two primary variables: Green Bonds and TF Index. Green bonds serve as the independent variable, while (TF) function as the dependent variable. We incorporate additional independent variables, including the Water Index, Carbon Credit Prices (CC), the Global Natural Resources (GNR) Index, market volatility (VIX), Infrastructure (Inf), and Clean Energy (CE), which function as explanatory variables. All dependent and independent variables in our model are S&P indices, with the exception of the VIX index. Daily series price data for all variables are acquired from DataStream. We employ an exponential logarithmic transformation on price data to derive the return data and eliminate non-stationary patterns, using the following equation: $r = ln\frac{P_t}{P_{t-1}}$. Our sample includes daily observations from May 2015 to May 2025, with the number of observations of 2605.

Table 1: Descriptive Statistics

	count	mean	std	min	max	skewness	kurtosis	JB_statistic
TF	2605	0,000197	0,012145	-0,1404	0,089007	-1,01428	13,95691	21501,5372
GB	2605	0,000025	0,003808	-0,0241	0,022717	-0,05376	4,162574	1872,672993
CC	2605	0,000367	0,009578	-0,10434	0,085519	-1,05647	17,49611	33574,04743
CE	2605	0,000013	0,016088	-0,12497	0,110346	-0,2624	6,572719	4697,676933
VIX	2605	-0,00017	0,079338	-0,39222	0,705007	1,11127	7,491517	6600,12254
GNR	2605	0,000094	0,01212	-0,12911	0,116876	-1,26049	16,44173	29910,46178

Inf	2605	0,000244	0,009629	-0,14266	0,099954	-2,08652	38,75362	164256,3784
Water	2605	0,000358	0,010019	-0,11138	0,075265	-0,73116	13,50056	19932,63727

The pronounced skewness and excess kurtosis across all series indicate the presence of fat tails and asymmetric return distributions, justifying the use of quantile-based econometric techniques and non-linear machine learning models.

Model

We begin our analysis with Machine Learning Algorithm (Random Forest Model) to estimate the non-linear relation. (Breiman 2001) A Random Forest constitutes a collection of decision trees. The prediction relies on majority voting for classification, utilizing multiple decision trees trained on various segments of the data. The Random Forest model is an ensemble of randomly created decision trees that modelled as follows:

$$Z(x) = mode\{z_1(x), z_2(x), z_3(x), \dots \dots, z_q(x)\}$$

$$Z(x) = \frac{1}{t}\sum_{q=1}^{Q} z_q\,(x)$$

Where $Z(x)$ represents the definitive forecast of the Random Forest model, $z_1(x), z_2(x), z_3(x), \dots \dots, z_t(x)$ are predictions of Q decision trees, x is the input variables.

In accordance with the equation, we obtain the output (prediction) from each of the Q decision trees for the input x, and subsequently compute the average of these outputs to derive the final prediction. This averaging mitigates the model's variance, enhancing the stability and accuracy of predictions relative to employing a solitary tree analysis.

Quantile Cointegration Test. We proceed our analysis with the Quantile Cointegration Test to confirm long-term interactions. In contrast to conventional cointegration tests (Engle-Granger or Johansen), which emphasize average relationships, the QC test analyzes the behavior of the relationship at various quantiles of the conditional distribution. Xiao (2009) modified standard cointegration tests, which are hampered by endogeneity issues, by incorporating fragmented cointegration errors into lead-lag components as follows:

$$C_Q^Y\left(Y_q \middle| U_q^Y, U_q^X\right) = \alpha(\iota) + \beta(\iota)' + \gamma(\iota)'X_q^2 + \sum_{j=-F}^{F} \Delta X'_{q-j}\,A_j + \sum_{j=-F}^{F} \Delta X_{q-j}^2\,B_j + K_e^{-1}(\iota)$$

Where $C_Q^Y\left(Y_q \middle| U_q^Y, U_q^X\right)$ represents the q-th conditional quantile of Y_q based on the information sets; U_q^Y, U_q^X ; $\alpha(\iota)$ denotes the quantile-related intercept, $\beta(\iota)'$ represents the long-term linear slope at the ι–th conditional quantile; $\gamma(\iota)'X_q^2$ estimates how the slope varies with the X_q levels; $\sum_{j=-F}^{F} \Delta X'_{q-j}\,A_j$ functions to encapsulate short-term dynamics and fix serial correlation, $\sum_{j=-F}^{F} \Delta X_{q-j}^2\,B_j$ is the quadratic lead/lags that estimate alterations in the nonlinear (quadratic) component of X. The last term $K_e^{-1}(\iota)$ represents the residual surprise from the ι-th quantile.

Quantile-on-Quantile Approach. Our final analysis includes nonlinear Quantile-on-Quantile (QQ) approach. The QQ method is a nonlinear extension of quantile regression that elucidates the complete dependence between the distributions of two variables.

We begin with conditional quantile regression estimations as follows:

$$TF_q = \beta^{\Omega}(GB) + e_q^{\Omega}$$

Where GB is green bond, TF is timber and forestry index. β^{Ω} is an nonparametric function, which represent the slope of the function, and e_q^{Ω} is an error with zero quantile.

We linearize around the ι quantile using the first-order in accordance with Sim et.al., (2015) method and obtain the following result:

$$\beta^{\Omega}(GB_t) = \beta_0(\Omega, \iota) + \beta_1(\Omega, \iota)\left(GB_q - GB^q\right)$$

Substituting $\beta^{\Omega}(GB_t)$ in TF_q gives the following model.

$$\beta^{\Omega}(GB_t) = \beta_0(\Omega, \iota) + \beta_1(\Omega, \iota)\left(GB_q - GB^q\right) + e_q^{\Omega}$$

The β_0 and β_1 represents the slope of the model and indicates how a minor fluctuation in the green bond around its ι quantile affects the Ω -quantile of timber and forestry index. The values of β_0 and β_1 may vary according to the quantiles of GB and TF. A positive slope indicates that when the green bond index approaches its ι -quantile, elevated index values correspond to increased values of TF at its own Ω quantile. A negative slope signifies an inverse effect. This enables the observation of asymmetry: perhaps low quantiles of the bond index exclusively influence high quantiles of the ecological footprint (or vice versa), which conventional regression would overlook.

This procedure, as outlined in Shahbaz et al., (2018) and Chang et al. (2022), elucidates how particular components of green bond distribution influence distinct aspects of environmental quality, extending well beyond average effects of the original QQ regression analysis. Machine Learning is used in this study because it captures complex interactions and non-linearities without imposing parametric assumptions. Next, we confirm long-term relationships under various market regimes we apply Quantile Cointegration Test.

We use Quantile Cointegration Tests because it enables to detect stable long-run linkages even in the presence of heterogeneous dynamics. Finally, we map the complete distributional influence of green-bond variations on the Green Bond, Forestry, and Timberland indices using a QQ analysis. In order to isolate the green bond signal, we also account for pertinent explanatory factors, such as the Water Index, Carbon Credit Prices, the Global Natural Resources Index, market volatility (VIX), and an Infrastructure & Clean Energy index. The QQ framework is used because it offers a granular view of how green-bond surprises affect forestry and timberland returns at extreme and median quantiles. Overall, the econometric strategy follows a complementary structure: the Random Forest model identifies key non-linear drivers, quantile cointegration tests the existence of long-run relationships under heterogeneous regimes, and the quantile-on-quantile approach maps the full distributional dependence between green bonds and forestry returns.

Econometric Analysis

Machine Learning: Random Forest Model

Table 2: Metric Assessments of Model Formation Outcomes

Metrics	Random Forest Measures
RMSE	0.008214
MSE	0.000067
MAE	0.005794
R^2	0.6030

Source: Author's Estimations

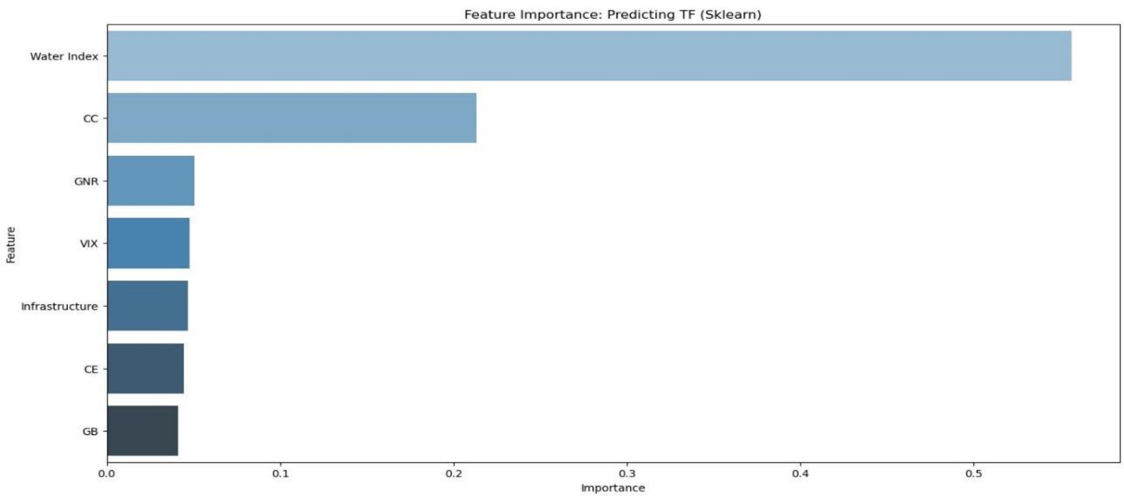

Figure 1: Feature's significance assessment

Source: Author's Estimations

A Machine Learning model was utilized to analyze the primary financial and environmental factors affecting the Timber and Forestry (TF) sector's performance, integrating Green Bonds (GB) together with various explanatory variables such as the Water Index, Carbon Credit Prices (CC), and the Global Natural Resources (GNR) Index, market volatility (VIX), Infrastructure and Clean Energy (CE). The feature's significance assessment disclosed a distinct structure of impact providing significant insights into the manner in which various environmental and economic variables impact the performance of TF Returns. GB, the main independent variable, was given low importance ((<0.1)). In addition, lower importance have been placed on infrastructure and clean energy (<0.1). Although these variables are frequently included in the more general category of sustainable finance, their comparatively low direct impact on TF returns suggests that the capital flows or policy signals they symbolizes have not yet made a obvious impact on the forestry industry. Specifically, the small impact of GB is worth mentioning. The Random Forest model indicates that there is small direct correlation between the green bond market and TF returns, despite the fact that they are becoming more and more widespread as tools for financing ecological initiatives. This result demonstrates the necessity for greater emphasis on green financing tools if the objective is to foster the conservation of forests. The Water Index's dominance, which accounted for roughly 60% of the model's explanatory power emphasize the profound reliance of timber and forestry on water connectedness. Particularly, the ecological health of forests depends on water quality and its accessibility. Extreme fluctuations in water resources, have a direct impact on the biodiversity and expected return on forestry investments. Therefore, on our model the Water Index appear not just as an explanatory variable but as a main variable in understanding TF industry dynamics. The second important variable in our model is CC. Rising carbon credit prices increase the economic value of protecting forest assets, which are essential for sequestering carbon. While some woodland- industries may profit directly from rising carbon prices through carbon offset projects, others may benefit indirectly from rising land values or traders appetite for climate-aligned investments. Consequently, changes in the carbon credit market serve as a significant indicator of the economic outlook for the TF industries. The model's use of the carbon credit index is significant because it captures broader market trends, such as the fact that rising carbon prices signal increasing enthusiasm for environmental policies and environmentally conscious capital flows, which can stimulate the carbon and forestry industries. This finding demonstrates the growing integration of climate finance tools, such as carbon credits, into market assessments of natural resource areas. The GNR Index and VIX were awarded moderate prominence, contributing 8% and 7%, respectively. The GNR Index probably indicates wider trends in commodities markets that might affect both the price and demand for timber products. Simultaneously, the VIX, an indicator of market volatility, implies that the TF sector exhibits a degree of responsiveness to investor sentiment and risk aversion, albeit it is less responsive than more cyclical industries. This aligns with the idea that the forest industry might serve as a partial protection in times of uncertainty, owing to its relatively steady and long-term investment perspective. Next, we will continue with the mean SHAP assessment model which follows Gaussian process with nonlinear regression model. SHAP analysis offer a practically sound way to evaluate the average influence of each characteristic to the output of the model and provide insight into the complex interplay between inputs and TF projections.

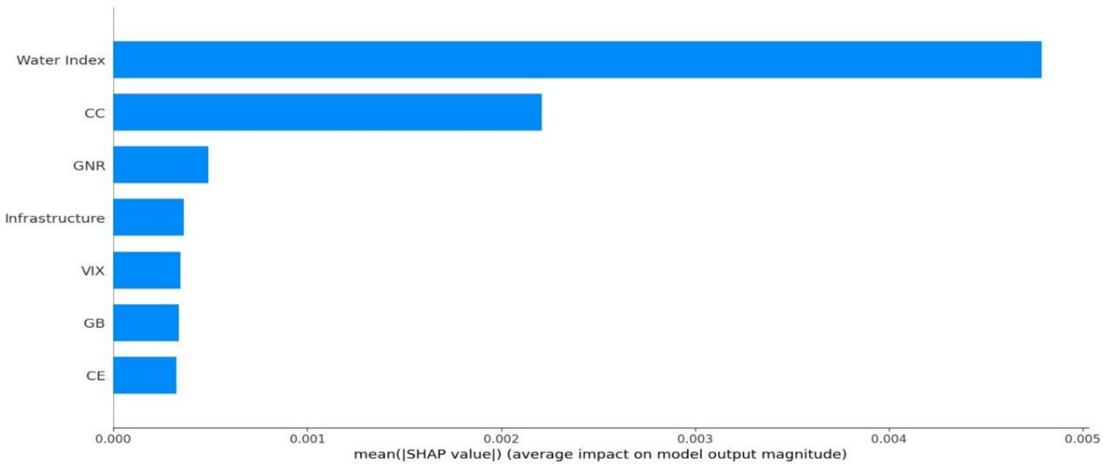

Figure 2: SHAP Assessment Outcomes of Rational Nonlinear Analysis with Gaussian Process Model

Source: Author’s Estimations

Particularly important, Green Bonds (GB) and Clean Energy (CE) exhibited the most modest mean SHAP values, recorded at 0.0003 and 0.0002, respectively. These findings suggest that sustainability-related financial instruments possess weak direct explanatory capacity for TF returns in this context. Although these are significant components of the wider green finance ecosystem, the Random Forest suggest that they may not yet be closely interconnected with TF investments. This may indicate insufficient direct financial inflows into forestry projects or a long-term impact horizon not represented in the model. The most influential variable, by a considerable margin, was the Water Index, exhibiting a mean SHAP value of 0.005. This reinforces the previous findings on feature importance and underscores the notion that water-related aspects are crucial in comprehending the performance of TF assets. The supply of water impacts the health of forests, regeneration cycles, and wildfire risk, all of which can directly effect timber yields and valuation. The substantial SHAP value indicates that minor variations in water-related factors regularly alter the model's projections of TF returns. The Carbon Credit (CC) variable exhibited a mean SHAP value of 0.0025. This suggests that CC has a significant and consistent impact on model results. This is most likely due to forests functioning as carbon sinks and producing income via engagement in carbon markets. As carbon costs increase, the value proposition of sustainable forest management enhances, positively impacting TF performance. The other variables had significantly lower SHAP values, demonstrating their relatively minor or indirect influence. The Global Natural Resources (GNR) Index exhibited a SHAP value of 0.0008, indicating that although the overall commodities market affects TF returns, its average influence is negligible in comparison to ecological variables such as water and carbon. likewise, Infrastructure and VIX exhibited low yet discernible effects, potentially indicating a slight sensitivity of the TF sector to market sentiment and economic condition. We proceed with the SHAP Beeswarm analysis of the Random Forest, which offers a comprehensive understanding of the impact of each input variable on the projections of TF returns, considering both magnitude and direction.

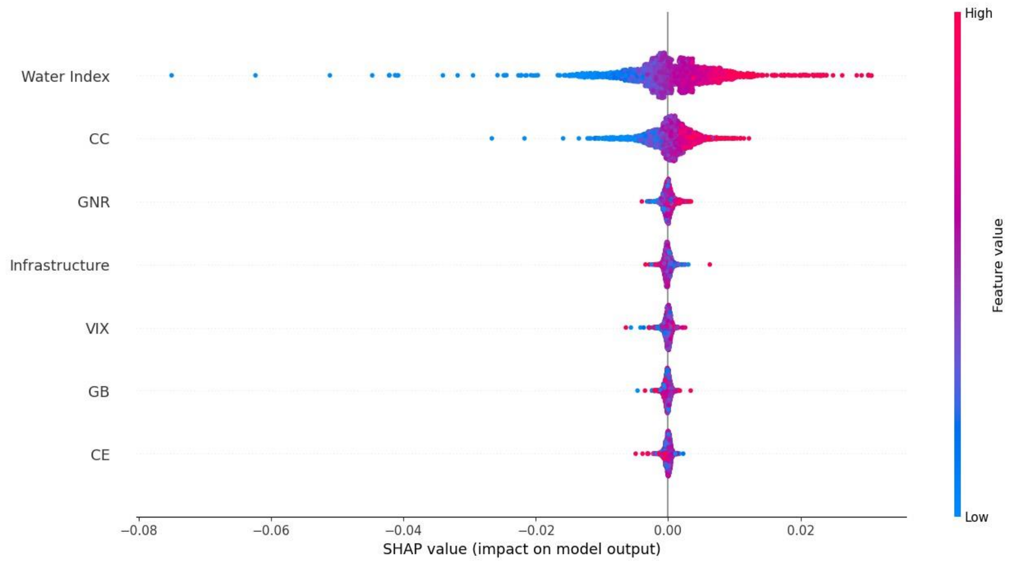

Figure 3: SHAP Beeswarm Analysis

Source: Author’s Estimations

The Water Index reemerges as the most significant component. The SHAP value within the range of -0.02 to 0.03 indicates that water-associated alterations can substantially enhance or diminish TF returns. This illustrates the twofold role of water: as a catalyst for expansion (beneficial impact) and as an agent of threat, exemplified by droughts or floods (detrimental impact). The wider distribution indicates variability in the impact of diverse water resource characteristics across different times or contexts within the sample. The values of Carbon Credits exhibit the second highest spread, but slightly narrower than those of the Water Index. Their SHAP value range suggests they influence TF returns in both directions, albeit with lower intensity. Carbon prices affect the economic feasibility of forest conservation and replanting; nevertheless, this effect is contingent upon particular policy or market conditions. The asymmetric range (more negative than positive) indicates that volatility or a decrease in carbon prices adversely affects TF performance more than an increase in prices benefits it. The remaining variables—Global Natural Resources Index, Infrastructure, VIX, and Clean Energy—exhibit SHAP values closely aligned with zero, indicating their influence on TF return forecasts is limited. Even though these data elements yet do not substantially influence the model's output in either direction, they can still have informational value and therefore rise statistical significance of the overall model. Most importantly, the SHAP indicators for green securities are tightly clustered around 0, signifying their little impact on TF performance predictions. The results presented here indicate that GBs have limited direct explanatory power on TF returns in SHAP Beeswarm analysis of the Random Forest. While they are becoming crucial elements of the broader green finance ecosystem, the Random Forest indicates that GB may not yet be strongly linked to TF investments. This may suggest inadequate direct funding inflows into forestry initiatives and or a delay in impact. Alternatively, it may indicate on a delay in impact or a long-term impact horizon not accounted for in this model. Therefore, we move into the next phase of our empirical research to examine deeper the connection between GB and the forestry sector.

Quantile Cointegration Test

The table presents the results of the quality control test. This technique investigates the quantile-dependent associations between the TF variable and several potential predictors utilizing the supremum test statistic, represented as Sup_τ $|V_n(\tau)|$, where τ represents the τth quantile of independent variables. The supremum norm coefficient affirms the parameter stability.

In particular, this metric quantifies the degree of reliance between variables throughout their conditional quantiles. To ascertain the level of statistical significance of each association, we compare the observed supremum values with critical values at the 1%, 5%, and 10% significance thresholds (C1, C5, and C10, respectively).

Table 3: Quantile Cointegration Estimation Results

Variable Pairs	Coefficient	Sup_ι |V_n(ι)|	C1	C5	C10
TF vs GB	γ	0.36	0.29	0.24	0.21
TF vs CC	γ	0.97	0.12	0.10	0.08
TF vs CE	γ	0.09	0.07	0.06	0.05
TF vs VIX	γ	0.04	0.01	0.01	0.01
TF vs GNR	γ	0.19	0.09	0.08	0.07
TF vs Infrastructure	γ	0.24	0.12	0.10	0.09
TF vs Water Index	γ	0.94	0.13	0.10	0.08

Sourse: Author's Estimations

The results reveal that there is long-run correlation, between GB and TF with a Sup_τ $|V_n(\tau)|$ value of 0.36, surpassing the 1% critical criterion (C1 = 0.29). This implies a quantile-specific relationship, presumably implying that GB influence TF more significantly during particular distributional extremes, such as during periods of elevated or diminished TF values. The long run cointegration between TF and Carbon Credits is the most robust among the factors analyzed. The Sup_τ $|V_n(\tau)|$ value is 0.97, significantly above the most restrictive critical threshold (C1 = 0.12). This outcome reveals a substantial dependence framework between the two parameters over quantiles, indicating that the influence of carbon credit patterns on TF fluctuates significantly at various quantile dimensions. The Water Index demonstrates a robust cointegration with TF, evidenced by a supremum statistic of 0.94, exceeding all crucial thresholds (C1 = 0.13, C5 = 0.10, and C10 = 0.08). This indicates that water-based components affect TF variably according to the conditional quantile, suggesting skewed (asymmetrical) impacts under extreme environmental or market conditions.

Conversely, the other four variable pairs—TF vs CE (Clean Energy), TF versus VIX (Volatility Index), TF versus GNR (Global Natural Resources), and TF versus Infrastructure—do not demonstrate statistically significant quantile-based interactions. Their Sup_τ $|V_n(\tau)|$ measures are under the 10% critical limit, suggesting that any apparent change in TF between quantiles is not adequately unique to establish a robust interdependence on these variables. The Sup_τ $|V_n(\tau)|$ statistic of 0.19 for the TF-GNR combination surpasses all critical values, with the minimum cutoff (C1) at 0.09. This outcome offers evidence of a quantile-dependent link, indicating that GNR exert differential influence on TF based on the conditional distribution of TF. This may indicate TF's vulnerability to commodity cycles or shocks associated to natural resources. The associations with Clean Energy (CE), Volatility Index (VIX), and Infrastructure are statistically significant at the 1% level; nevertheless, their Sup_τ values of 0.09, 0.04, and 0.24, respectively indicate moderate to weak quantile dependence. These data continue to suggest quantile effects; however, they may signify diminished or more localized influences throughout the range of TF. The TF–GNR association is notable for its marginal strength. Despite the Sup_τ value of 0.19 above the criteria of C1(0.09), the margin remains comparatively slim when contrasted with more robust correlations such as TF–CC. This indicates that although there is statistical proof for quantile dependence, the economic relevance of the relationship may be more constrained. It may indicate particular quantile zones where dependency arises, as opposed to widespread, substantial impacts throughout the whole distribution.

Quantile-on-Quantile Approach.

We further analyze the connectiveness between GB and the TF variables and other variables with TF using Quantile-on-Quantile (QQ) technique. This method analyzes the conditional probability distribution of TF in relation to various quantiles of GB, offering a more nuanced comprehension of asymmetric and nonlinear interactions. The results of the QQ analysis are illustrated via a heatmap and a 3D surface plot, with the horizontal axis denoting GB quantiles from q= 0.1 to q=0.9, the vertical axis indicating TF quantiles, and the color/height of the surface reflecting the size of the relationship between variables (effect coefficient).

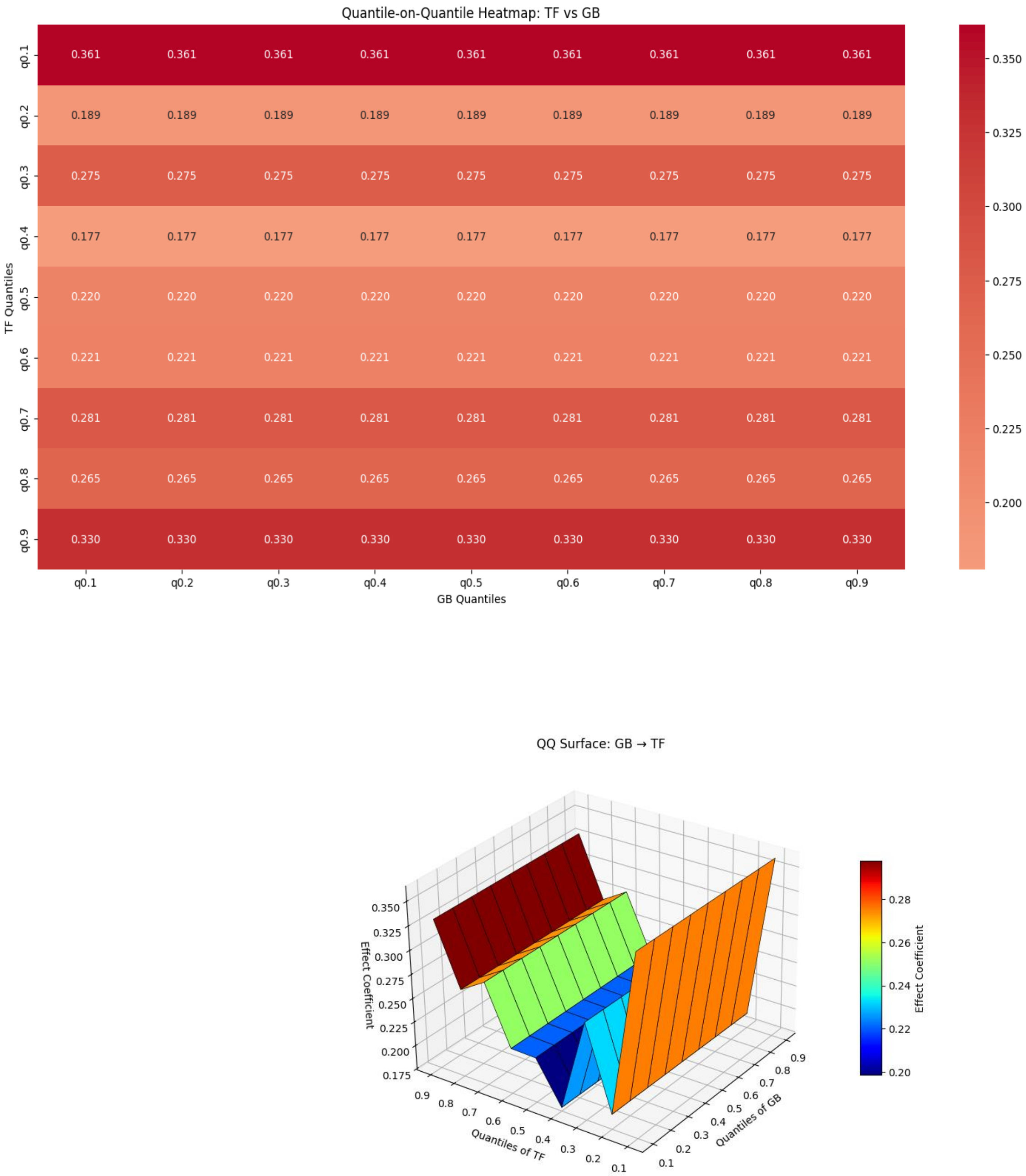

Figure 4: Quantile on Quantile Heatmap and Plot TF and GB

Source: Authors Estimation

At bottom quantile 0.1, GB demonstrates the most robust relationship, with impact values continuously reaching 0.361 throughout all GB quantiles. This suggests that when TF underperforms, Green Bond markets consistently stabilize TF. The influence diminishes significantly around the middle range of TF quantiles between 0.4 and 0.6, with values decreasing to roughly 0.177 to 0.221. This diminished susceptibility indicates that under regular economic circumstances, TF's behavior exhibits lower sensitivity to GB fluctuations. As we progress towards elevated TF quantiles of 0.9, the influence of GB intensifies once more, attaining a value of

0.330. This increasing pattern indicates that GB gains influence when TF is already excelling, perhaps due to connected dynamism in environmentally-driven capital movements and favorable market conditions. A notable feature in both the surface and heatmap is the relative consistency between GB quantiles for each fixed TF quantile. The effect at TF at 0.3 quantile is 0.275 over all GB quantiles. This indicates that GB's influence on TF is more dependent on TF's condition than on its own variations. TF's response to GB is contingent upon quantiles; yet, GB's own condition does not substantially modify that impact. Important conclusion from QQ analysis is that GB seems to exert greater influence during favorable TF movements, likely indicating a convergence of sentiment among shareholders about sustainability and ecological problems. Overall, by analyzing diverse effects throughout the complete return distribution, we reveal a stabilizing influence of green bonds during forestry downturns and an amplifying effect during upswings, which illustrate both the counter-cyclical support and growth-enhancing roles anticipated by blended-finance theory. Our research provides novel insights for policymakers, investors, and communities aiming to harmonize carbon, biodiversity, and financial goals in environmentally friendly forestry. We apply Quantile-on-Quantile analysis to other explanatory variables. The findings from the 3D surface plot and heatmap indicate a predominantly persistent and positive relationship between CC and TF variables.

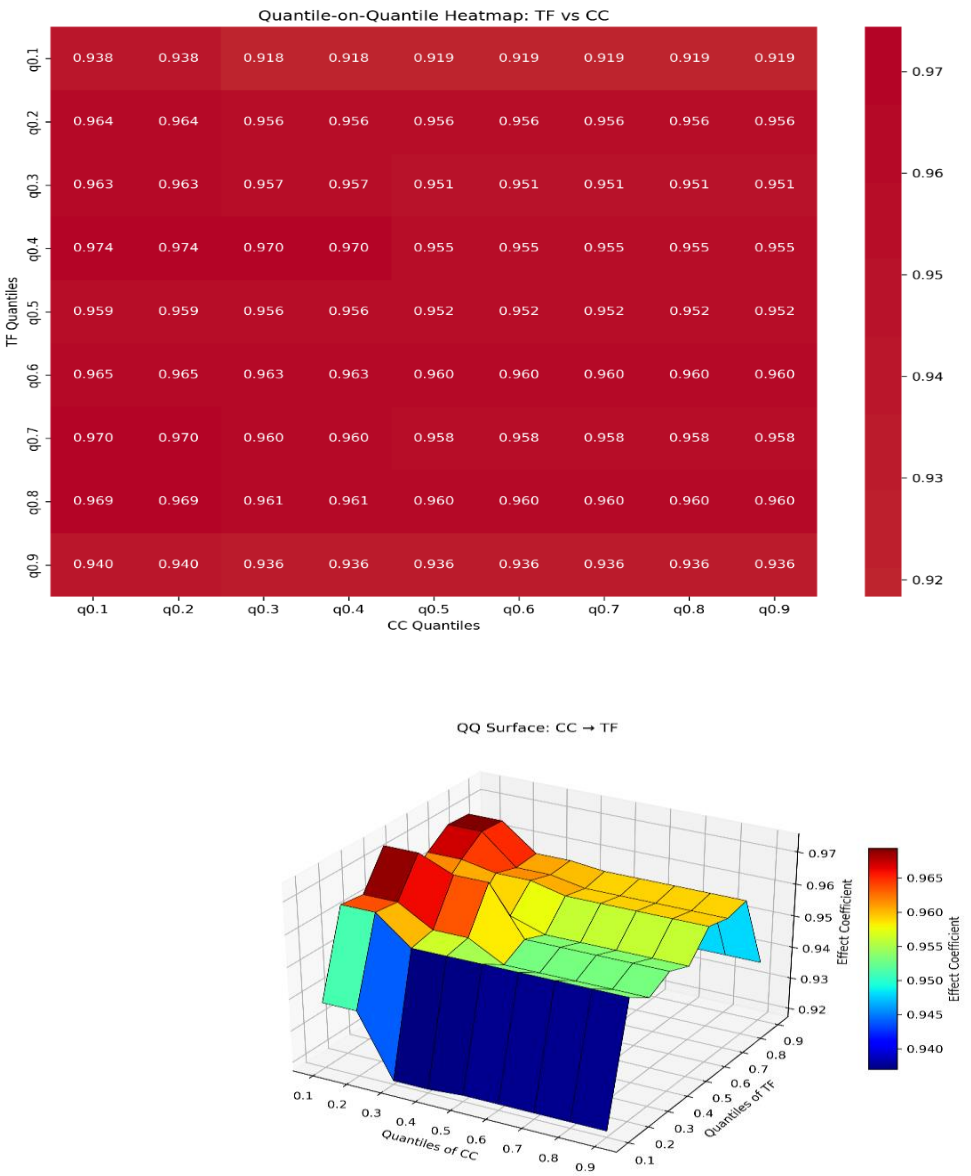

Figure 5: Quantile on Quantile Heatmap and Plot TF and CC

Source: Authors Estimation

Notable the outcomes are seen when the TF Index lies in its middle-to-upper quantiles between 0.4 and 0.7 and CC prices are positioned in the lower-to-middle quantiles of 0.1 and 0.4. In this region, impact values reach their zenith, signifying that moderate carbon credit prices exert the most significant impact on the TF Index while it operates at average to above-average concentrations. Overall, the findings highlight carbon credit markets can significantly influence the TF sector, especially under steady or relatively normal market conditions.

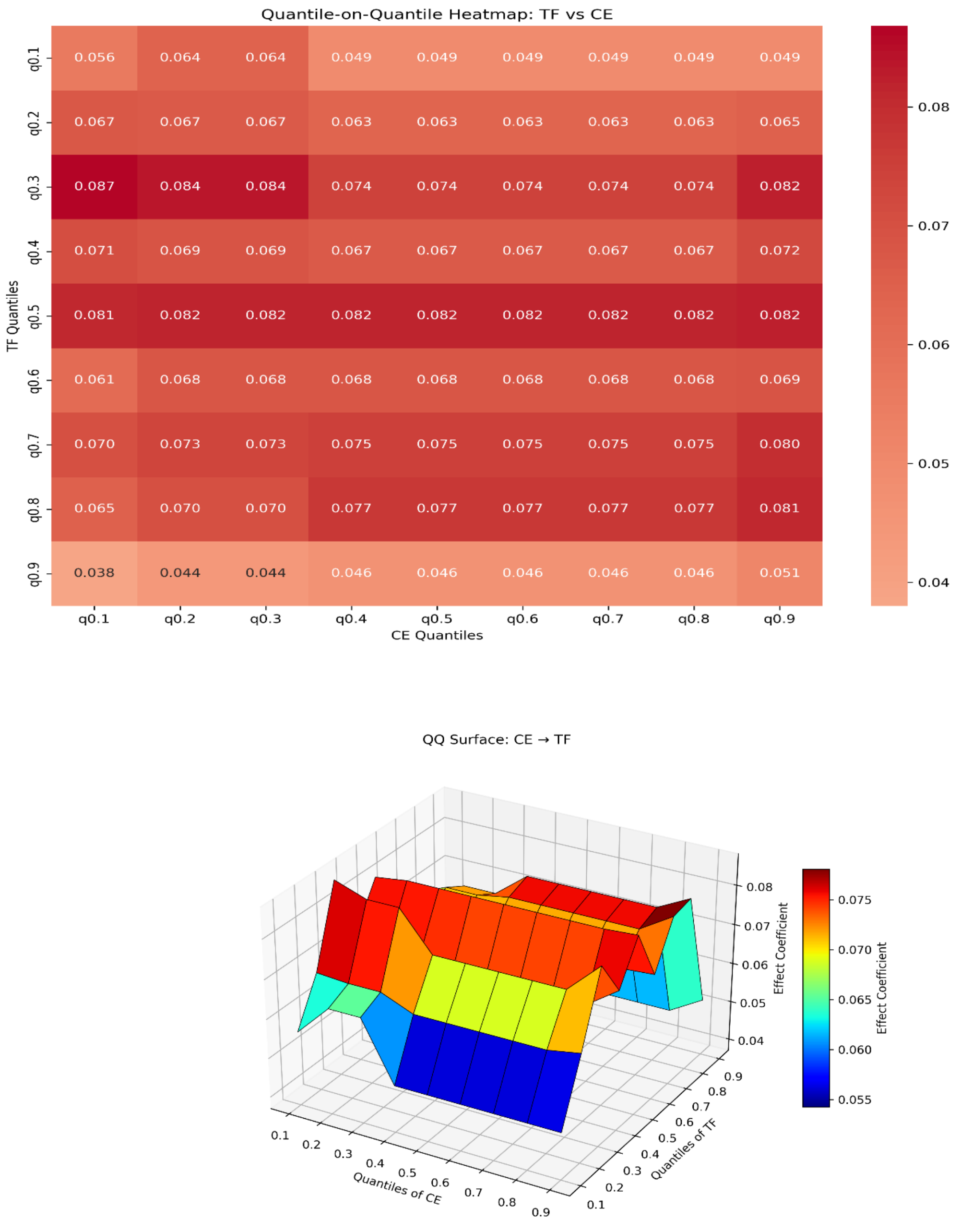

Figure 6: Quantile on Quantile Heatmap and Plot TF and CC

Source: Authors Estimation

The results indicate that when the TF Index lies in its lowest quantiles between 0.01 and 0.03 the impact parameter varies from 0.049 to 0.064, signifying a small positive impact of CC variable. The small effect continues across all quantiles, indicating that clean energy movements do not significantly predict TF returns. This result is consistent with the findings from the Random Forest model.

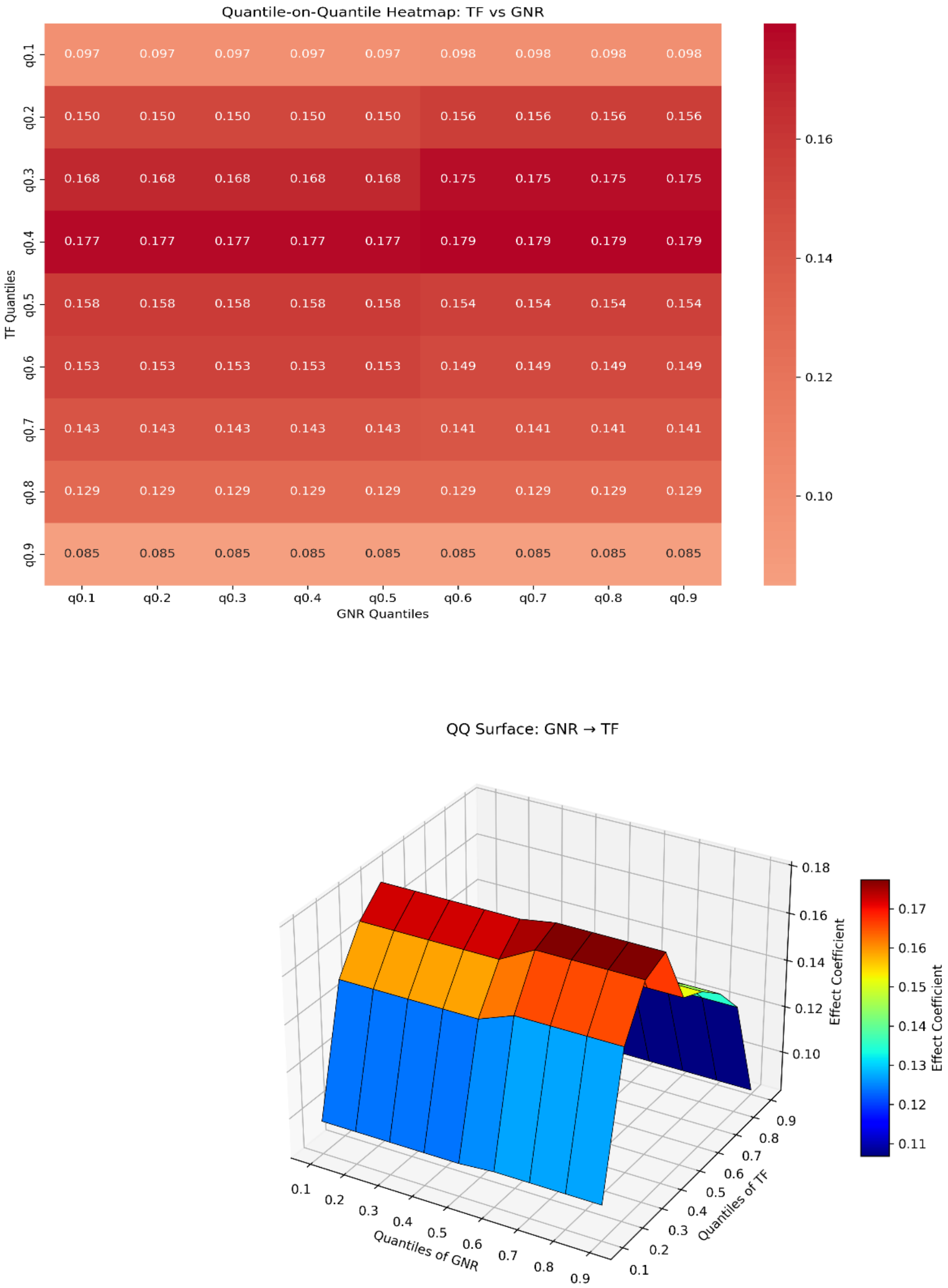

Figure 7: Quantile on Quantile Heatmap TF and GNR
Source: Authors Estimation

The results from QQ analysis indicate on a small impact of GNR variable. This impact continues across all quantiles, and varies between 0.15-0.23, indicating that GNR movements do not significantly predict TF returns. This result is also consistent with the findings from the Random Forest model.

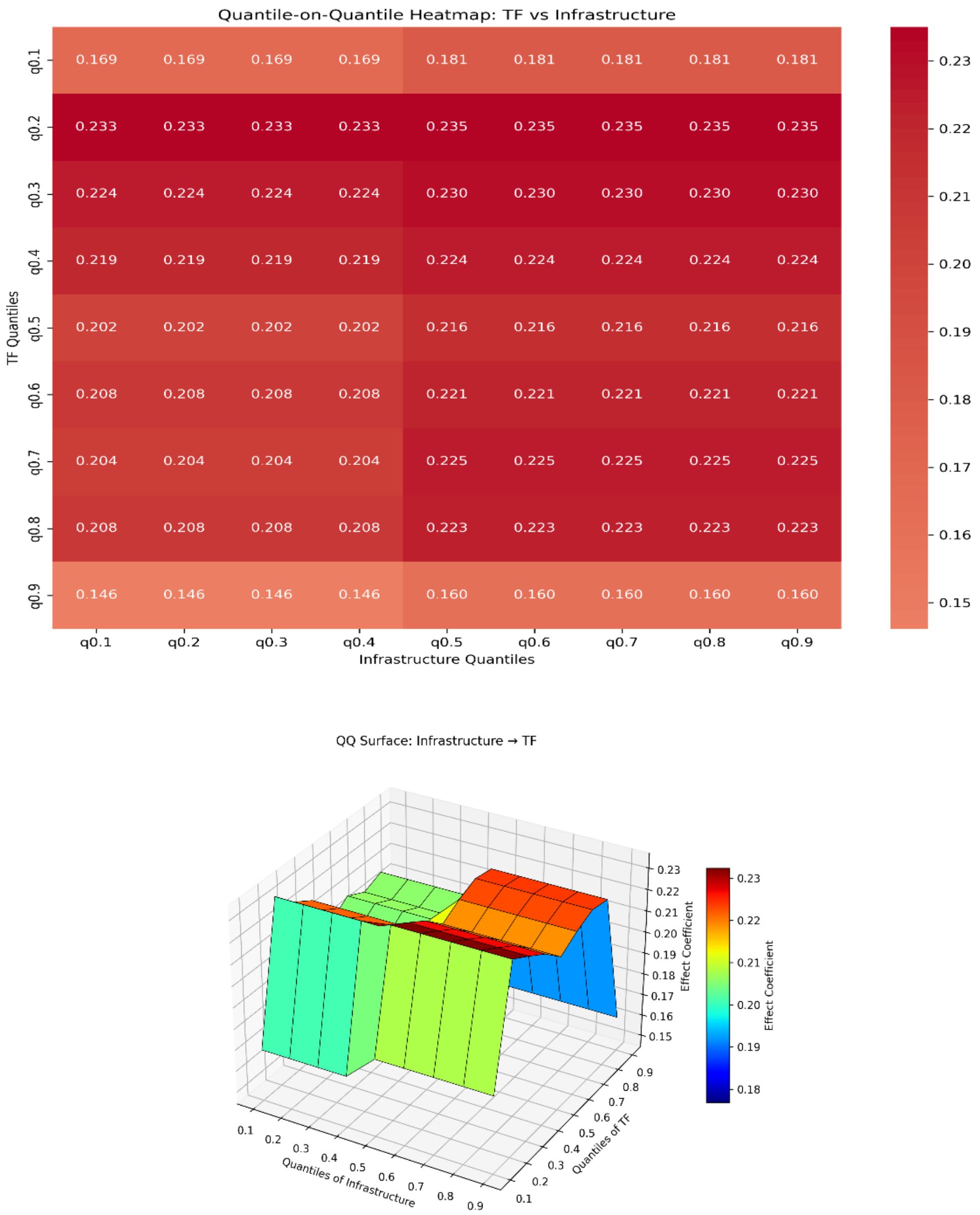

Figure 8: Quantile on Quantile Heatmap and Plot TF and Infrastructure

Source: Authors Estimation

The Infrastructure Index exerts a minimum effect on the TF Index across all quantiles, indicating that this estimator is not statistically significant in our model.

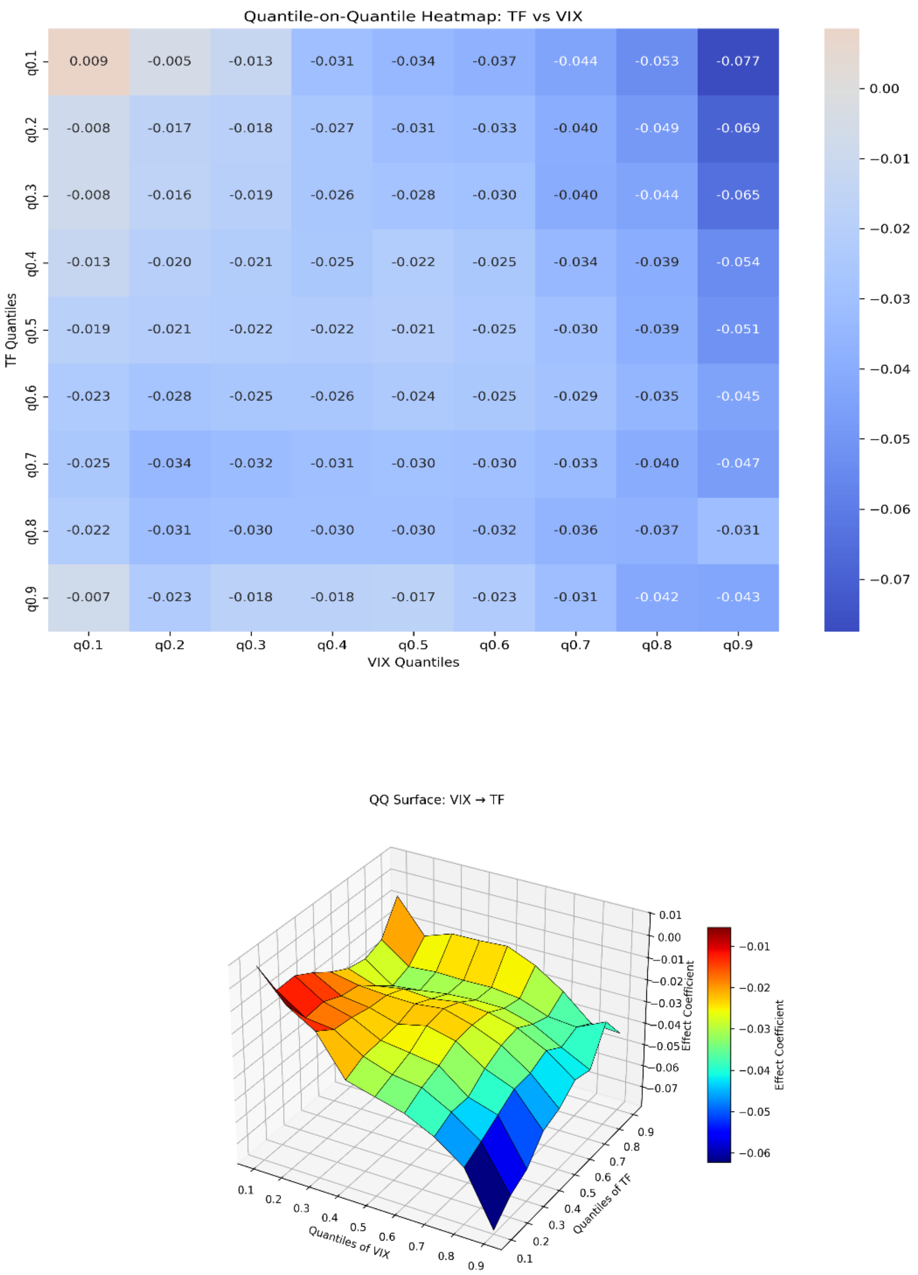

Figure 9: Quantile on Quantile Heatmap and Plot TF and VIX

Source: Authors Estimation

The findings from the QQ analysis suggest a minimal effect of the VIX variable. This effect persists across all quantiles, suggesting that VIX fluctuations do not meaningfully forecast TF returns. This outcome aligns with the results from the Machine Learning algorithm.

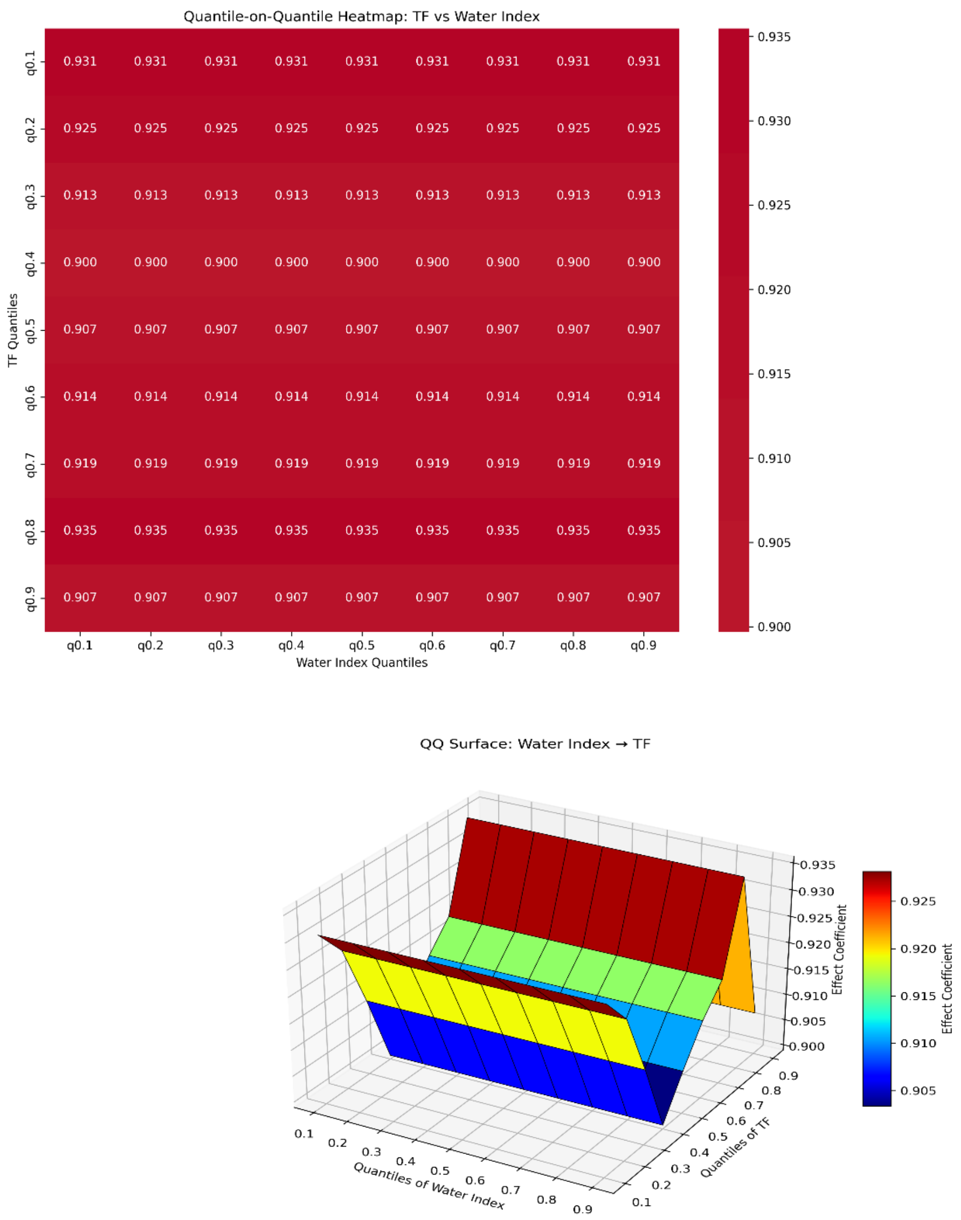

Figure 10: Quantile on Quantile Heatmap and Plot TF and Water Index

Source: Authors Estimation

The impact values vary from 0.900 to 0.935, constantly displaying high positive values, signifying a robust and durable positive connection between the Water Index and TF Index across nearly all quantile combinations. At the lowest quantiles of 0.1 the impact values are greatest, suggesting that when TF is low, increases in the Water Index are positively and significantly associated with rises in TF values. In middle range the impact values are still positive and robust, but display slightly diminished influence of Water Index. At upper quantiles the connectedness becomes very strong again, with the values ranging between 0.907-0.919. These results coincide with the findings from the Random Forest analysis in our model.

Discussion

The central goal of this paper is to assess the influence of green bonds on the performance of the TF sector. Our results suggest that while green bonds play a role in shaping the returns of timber and forestry (TF) companies, their influence remains modest. The machine-learning analysis indicates that, on average, green bonds exhibit a negligible importance (mean SHAP≈0.0003) on total returns, implying that, thus far, green bond markets have not significantly contributed to forestry outcomes. The quantile-cointegration test between Timber-Forestry (TF) returns and Green Bond (GB) issuance produces a supremum statistic of 0.36, which slightly exceeds the 1%, 5% and 10% thresholds (0.29, 0.24 and 0.21, respectively). For certain quantiles, this supports a statistically noteworthy long-run connection, but its strength is only modest. Investors often seek a risk premium when investing in green bonds, particularly in emerging sectors such as forestry where financial returns are long-term and project viability is uncertain. The perception of increased risk and ambiguity about returns partly reveals the present underuse of green bonds in timber and forestry portfolios, as evidenced by the empirical estimations of this study. Our findings align with Fata et al. (2021), who assert that forestry-related green bonds remain a niche product with limited acceptance owing to insufficient revenue guarantees and inadequate upfront risk-sharing mechanisms. A well-established discrepancy between pure green debt and actual forestry outcomes is also reflected in the research of Ferrando et al., (2021). The authors show that stand-alone green bonds in the Brazilian forest industry often serve financial engineering purposes instead of direct sustainability financing, resulting in inconsistent performance during periods of market volatility. QQ approach also provides low to modest impact on timber and forestry sector returns. In particular, GB's effect remains at 0.361 for all GB quantiles at the 0.1 TF percentile, indicating that when forestry performs poorly the project funding with green bonds is at its highest level. However, this funding is still moderate and constitutes less than 40 percent. Our results reflect Rode et al. (2019) conclusion that blended structures (public guarantees, first-loss capital, technical help) are crucial for stabilizing highly unpredictable. Especially the project risk is very high at early-stages and during downturns. According to the authors green bond capital combined with other traditional finance techniques, may offer a reliable safeguard in these risk-sharing layers. On the other hand, the GB impact drops to 0.177–0.221 values within the 0.4-0.6 TF mid-range (quantiles). Diminishing value of green bonds, indicate a range where the use of green bonds does not maintain significant funding under moderate forestry performance. This decline reflects the findings of Ferrando et al., (2021), who indicate that stand-alone green debt in the Brazilian forestry industry often prioritizing financial returns over environmental outcomes and therefore generate more benefits for capital markets than actual conservation efforts. This result is also in line with Gong et al., (2024) theory that the success of green finance depends on how mature the industry is and how skilled the workers are. If you go below these levels, green funding doesn't help the environment very much. The fact that GB and TF pair sensitivity is lowest in the mid-quantile range, where timber and forestry operate under "normal" conditions, is also consistent with their finding that green-bond capital only brings small extra benefits when the industry and human capacity are not fully developed or modernized. Lastly, the GB effect increases to 0.330 at the 0.9 TF quantile, where forestry already performs well. GBs affects TF primarily during significant booms or busts in forestry, potentially through wider risk shifts, but not during normal economic condition of the industry. These results show that environmental benefits of green financial instruments are quantile-dependent, with stronger effects in specific market and policy contexts. This supports the idea that green debt does not operate consistently across all performance states. This result mirrors a recent finding by Chang et al., (2022), who show that green finance improves environmental quality only at certain quantiles, and that this relationship exhibits significant asymmetry. Our findings are further supported with Rode et al., (2019) results who demonstrate how traditional private finance ignores forest projects under "normal" circumstances and only becomes involved during booms or crises. In the absence of risk-sharing and catalytic support (such as first-loss capital, guarantees, and technical assistance), green bonds find it difficult to maintain forestry investments in mid-performance states. A similar conclusion is given by Gong et.al. (2024) in the context of Chinese green finance: stronger firms experience diminishing marginal gains from subsidized finance, while weaker firms (lower quantiles) benefit the most. In the same vein, our QQ and Machine Learning analysis show that green bonds contribute to TF returns only to a limited extent. The empirical estimations from our study represent a U-shaped profile where GBs anchor TF during peaks and troughs, with statistically significant impacts largely confined to distribution tails, which are the periods of extreme market performance. However, the green bonds are unable to support the sector in normal circumstances, this difference suggests that green bonds are not yet a common way to fund for timber and forestry projects.

Furthermore, our empirical calculations highlight significant distributional (quantile) impacts of key environmental variables on the wood and forestry (TF) sector. In particular, water availability and carbon credits have significant, widespread effects: the water index and carbon credit index show strong long-term correlations of 0.94–0.97 with TF across the distribution. This corresponds with the understanding that the vitality of forests, and consequently timber yields, is intricately linked to hydrological variables and carbon markets. Reforestation of narrow riparian buffers can significantly enhance water quality and increase carbon sequestration with minimal alteration of land use. This discovery aligns with the FAO's evaluation that ‘forest hydrology and carbon sequestration are intricately linked ecosystem services', indicating that even modest riparian buffer plantings can enhance watershed quality by over 80% while augmenting on-site carbon reserves with negligible land use alteration (FAO, 2020). Low et.al., (2021) contend that water-related services frequently constitute the foundation of forest finance, as investors acknowledge that robust watersheds support both timber production and enduring ecological resilience. Our findings align with those of Baxter et al., (2020) who examined case studies that combine carbon and water payments and asserts that the Southeast Asia project with blended structures attracted more than $25 million outside funding by combining offtake agreements for carbon and water services with small government support grants. Our findings are also reflected in Bernknopf et.al. (2022) study, which demonstrates that forest sustainability bonds, when accurately aligned with carbon-offset revenues, attain enhanced pricing and investor interest due to their ability to monetize an ecosystem service with evident market demand. According to the authors, carbon storage can have a big impact on forest revenues, as shown by the fact that bond yields can go up by as much as 50 basis points when conservation projects produce proven carbon credits.

Conclusion

The results from this study suggest that while green bonds do play a role in shaping the returns of timber and forestry (TF) companies, their impact remains modest. Empirical results obtained using the QQ approach and Machine Learning analysis show that green bonds are included in TF returns only to a low or moderate extent, and statistically significant effects are mostly limited to the tails of the distribution – periods of extreme market performance. This asymmetry implies that green bonds are not yet functioning as a primary financing mechanism for forestry investments. Instead, they appear to supplement broader capital structures in isolated circumstances rather than form an integral part of corporate funding strategies. This finding is consistent with the observed underutilization of green bonds in the TF sector, which can be explained by a combination of sector-specific risks. Firstly, forestry projects are often associated with long investment horizons and delayed or uncertain cash flows. Maturity and cash flow risks remain uncertain for sustainable timber manufacturing, afforestation and ecosystem restoration. Secondly, there are climate and environmental risks, such as forest fires, pests, and climate change, which exacerbate investor concerns. Third, forestry initiatives face regulatory and certification barriers, such as difficulties in providing credible verification of carbon offsets or sustainability outcomes, which are critical components for green bond compliance. These factors combined discourage both issuers and investors from adopting green bonds as a dominant financing instrument in TF sector. In light of these challenges, there is a clear need for government support to enable the broader uptake of green bonds in forestry finance. Governments can play a catalytic role by creating clear taxonomies for green forestry projects, offering preferential tax treatment for green bond interest income, and establishing minimum environmental performance standards to improve market confidence. Additionally, public institutions can offer partial credit guarantees or first-loss coverage to de-risk green bond investments in early-stage forestry ventures. In addition, market-based solutions, such as standardized green bond platforms, third-party forestry-specific rating and certification mechanisms, and improved disclosure standards, can significantly reduce information asymmetries and investment risk. These private-sector innovations complement public policies by enhancing comparability, credibility, and scalability in forestry-related green bond markets. This would address the risk asymmetries that currently limit private sector participation. However, it must be acknowledged that financing forestry entirely through green bonds remains difficult, particularly during the early or transitional phases of project development. This underscores the continued importance of blended finance, where concessional funding—such as grants or subsidized loans—is combined with private capital. Blended models offer risk-sharing arrangements that make forestry projects more attractive to private investors. Nevertheless, moving forward, the weight of green finance within blended structures should increase, with the goal of transitioning toward more market-based, environmentally aligned investment solutions over time. In summary, while green bonds currently play only a supporting role in financing the TF sector financing, their potential remains high. With targeted government support and thoughtful integration of green instruments into blended finance mechanisms, green financial assets can be used on a larger scale as a core instrument to finance sustainable forestry. The policy focus should now shift to reducing sectoral risks, standardizing green certificates, and integrating green bonds more deeply into the investment portfolios of timber and forestry companies.

Genişletilmiş Özet

Yeşil tahviller (Green Bonds, GB'ler), son yıllarda sürdürülebilir finans literatüründe çevresel hedeflerle uyumlu sermaye mobilizasyonunun en önemli araçlarından biri olarak öne çıkmaktadır. Enerji, ulaşım ve altyapı gibi sektörlerde yoğun biçimde incelenmiş olmalarına karşın, doğal kaynak temelli ve uzun vadeli yatırım döngülerine sahip ormancılık ve kereste (Timber and Forestry, TF) sektöründeki rolleri ampirik olarak büyük ölçüde göz ardı edilmiştir. Oysa ormancılık projeleri; karbon yutakları, biyoçeşitlilik ve su döngüsü üzerindeki kritik etkileri nedeniyle yeşil finansmanın potansiyel hedef alanlarından biridir. Bu çalışma, TF sektöründe yeşil tahvillerin finansal önemini sistematik biçimde analiz eden ilk ampirik çalışmalardan biri olmayı amaçlamakta ve yeşil tahvillerin ormancılığın kendine özgü risk-getiri yapısıyla ne ölçüde uyumlu olduğunu sorgulamaktadır.

Çalışmada, günlük frekansta elde edilen finansal zaman serileri kullanılarak ormancılık getirileri ile yeşil tahvil performansı arasındaki ilişkiler hem dinamik hem de doğrusal olmayan bir çerçevede incelenmiştir. Analizin sağlamlığını artırmak amacıyla, TF getirilerini etkileyebileceği düşünülen makro-finansal ve çevresel kontrol değişkenleri de modele dâhil edilmiştir. Bu bağlamda, özellikle su kaynaklarının mevcudiyeti ve karbon piyasalarındaki gelişmeler, sektörel getiriler üzerindeki potansiyel etkileri nedeniyle ön plana çıkarılmıştır.

Metodolojik olarak çalışma, finansal zaman serilerindeki dağılımsal heterojenliği ve asimetrik etkileşimleri yakalamayı amaçlayan çok aşamalı ve yenilikçi bir yaklaşım benimsemektedir. Nicelik Eşbütünleşme (Quantile Cointegration) yöntemi ile değişkenler arasındaki uzun dönemli ilişkilerin dağılım boyunca nasıl farklılaştığı analiz edilirken, Nicelik-Üzerine-Nicelik (Quantile-on-Quantile) analizi sayesinde yeşil tahvil piyasasındaki farklı piyasa koşullarının ormancılık getirileri üzerindeki etkileri ayrıntılı biçimde ortaya konulmuştur. Bu ekonometrik çerçeve, Rassal Orman (Random Forest) makine öğrenmesi tekniği ile desteklenerek değişkenlerin göreli önemleri ve doğrusal olmayan etkileşim yapıları değerlendirilmiştir.

Elde edilen bulgular, yeşil tahvillerin TF piyasaları üzerindeki etkisinin genel olarak sınırlı olduğunu ve bu etkinin simetrik bir yapıya sahip olmadığını göstermektedir. Yeşil tahvil performansının ormancılık getirileri üzerindeki etkileri, ağırlıklı olarak getiri dağılımının uç bölgelerinde—özellikle aşırı olumlu veya olumsuz piyasa koşullarında—belirginleşmektedir. Bu durum, yeşil tahvillerin TF sektöründe istikrarlı ve yaygın bir finansman aracı olmaktan ziyade, belirli piyasa koşullarında tamamlayıcı bir rol üstlendiğine işaret etmektedir. Rassal Orman sonuçları ise, su kaynaklarının mevcudiyeti ile yeşil tahvil performansını TF getirilerinin en güçlü belirleyicileri olarak öne çıkarırken, karbon piyasalarının daha sınırlı fakat anlamlı bir etkiye sahip olduğunu ortaya koymaktadır.

Yeşil tahvillerin ormancılık sektöründeki bu görece sınırlı etkisi; projelerin uzun yatırım ufukları, iklim ve çevresel belirsizlikler, piyasa likiditesinin düşüklüğü ve sektöre özgü standartlaştırılmış performans ölçütlerinin eksikliği gibi yapısal risklerle ilişkilendirilmektedir. Buna karşılık, su mevcudiyeti ve karbon kredileri gibi temel çevresel faktörlerin TF getirileri üzerinde daha yaygın ve güçlü etkiler yarattığı bulgusu, doğal kaynak temelli sektörlerde çevresel değişkenlerin finansal göstergeler kadar belirleyici olabileceğini göstermektedir.

Sonuç olarak bu çalışma, geleneksel ekonometrik yöntemler ile makine öğrenmesi yaklaşımlarını bir araya getirerek yeşil finans literatürüne hem metodolojik hem de sektörel açıdan özgün bir katkı sunmaktadır. Bulgular, sermaye akışlarını ekolojik sürdürülebilirlik hedefleriyle daha etkin biçimde uyumlu hâle getirmek isteyen politika yapıcılar için önemli çıkarımlar sağlarken, yatırımcılar ve ormancılık sektörü paydaşları açısından da yeşil tahvillerin sınırlarını ve potansiyelini daha gerçekçi bir çerçevede değerlendirme imkânı sunmaktadır.

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