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Carbon Markets and Financial Risk Assessment under Global Climate Transition

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Abstract

With the transition to a low-carbon economy, agricultural carbon offsets are being sucked into the same risk universe as allowances, commodity prices, and agricultural lending. This study aims to examine how much the volatility is changing from the carbon markets to the financial markets of the agriculture sector and whether a tail risk can be quantified and hedged with reliability. A three-asset system (a series of carbon allowances, an agricultural commodity index and an agri-lender equity index) is analyzed. It features a combination of GARCH (1,1), Student-t errors, a generalized forecast-error variance decomposition based on a volatility proxy, regime-conditional Value-at-Risk (VaR) and Expected Shortfall (ES), minimum-variance hedging, and out-of-sample backtesting. The sample includes a simulated 2,600 business days with a built-in transition-stress regime. Average spillover volatility is 10.4 percent of forecast-error variance (12.3 percent in a rolling window), the majority of which is between the agricultural and lender series, and not between carbon and the lender series. The portfolio ES is 3.10 percent of portfolio value during calm times and 6.14 percent during stress. Carbon-based hedging will reduce the variance by 10-13 percent at stress levels and will increase variance at calm levels. When compared to a 1 percent target, exceedances are clustered together when the stress is at 2.4-2.8 percent while VaR satisfies unconditional coverage tests. The paper concludes with recommendations for the agricultural stakeholders, bankers, and agricultural policy makers of the regime.

Keywords: Carbon Markets, Climate Transition Risk, Volatility Spillover, Expected Shortfall, Agricultural Finance, Hedging Effectiveness.

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Introduction

Suppose there were a regional farming co-operative whose products were soil-carbon credits, the bank that would be willing to advance credit based on next crop, and the registry that would certify the credits. Each of them has own books of accounts. The cooperative enters the yields (or harvested produce), the input costs, and the credit income. The bank logs values of collateral and defaults. Issuance, vintages, and retirements are recorded in the registry. Throughout much of the history of agricultural finance, these three had followed rather independent paths with each other. Climate transition is bringing them together throughout the world.

The term "financial" has now come into usage and has been seen increasingly in the academic literature to describe this binding, rather than the environmental one. While scattered across methodologies and asset classes, the evidence has come on rapidly, and the impacts of climate risks on financial markets have been carried via a few channels, as uncovered by the field reviews (Zhai et al., 2024). In addition to the lack of physical damage, the transition itself can be a risk, in that it can have a profound impact on valuations long before any physical damage occurs, due to policy tightening, changing preferences, and technological change (Di Febo, 2025). The idea is institutionalized in reporting infrastructure in the form of systems of carbon accounting and disclosure, which assert that these systems matter to the process of 'creating' financial climate risk. The amount of exposure reported on a balance sheet can in part be influenced by how emissions are measured, reported, and priced (Folkers, 2024).

Agrarian economies have a closer integration. While agricultural production involves costs of carbon-intensive inputs, such as fertilizer and fuel, rural lenders are invested in one sector of production while agricultural land and livestock can generate offsets. The effects of carbon policy change are not confined to the market for the use of carbon allowances. Can be passed to commodity prices through input prices and passed to lenders through borrower cash flows.

The difficulty is that the carbon price is policy-driven; it is collapsible, and it can change. Deep-learning forecasters have been proposed to forecast price movements of the carbon market (Bua et al., 2024), to evaluate the risk of green finance (Zhang et al., 2025), and to improve the traditional benchmarks. Even if perfect accuracy is attained in projecting losses, it is not sufficient to adequately communicate to a risk manager what losses might be on a mixed portfolio during a stress period in the market. European financial markets indicate that investors value transition risk and physical risk separately and that the valuation of transition risk and physical risk can vary over time (evaluate different aspects of the climate risk) based on the measures of climate exposure derived from the text (Bua et al., 2024). A climate exposure-based risk framework, which is often seen as a static approach, can therefore suffer from misstatement of losses regarding both severity (how bad the loss is) and timing (when the loss occurs).

The main motivation behind this research are three important research questions that will analyze the relationship between carbon markets, agricultural commodity and financial risk. The first question is whether the volatility of the carbon markets variables can be quantitatively measured and transmitted to agricultural commodities and financial series which have an impact on lending. Understanding the mechanism of transmission is necessary for detecting the risks associated with such kind of markets and for the assessment of agricultural and financial stability associated with the risks associated with carbon prices. The second question takes it further by examining whether the tail risk of portfolios significantly differs during the period of market stress and the period when the market behaves normally. Extreme losses, volatility and resistance to negative changes in financial portfolio are the main areas of concern. Research question three deals with the desirability and feasibility of entry of agricultural producers, farmers in particular, into carbon markets under certain circumstances. The findings from the research questions will be of great significance to financial institutions, agricultural players and the regulatory authorities. The findings will be of great use in determining appropriate capital reserves, sound processes for carbon offset contract creation and improvements in stress testing procedures. Generally, the research is aimed at providing insights regarding volatility transmission effects and the financial aspects of incorporation of the carbon market in agriculture.

This research is based on four major research objectives, which will include an examination of volatility transmission, portfolio risk, hedging effectiveness, and risk model robustness for carbon, agricultural commodities, and financial markets. First of all, the study examines volatility transmission between variables of carbon markets and agricultural commodities index, as well as between agricultural lenders equity index and agricultural commodities index both in unconditional and time-varying settings. The aim of this examination is to see how much and how volatility has spilled from one linked market to another. Secondly, the study will estimate Value at Risk (VaR) and Expected Shortfall (ES) for chosen portfolio during calm and financial stress periods. This estimation will be helpful to observe possible differences between potential losses and extreme risks exposure. First, the research evaluates the effectiveness of the minimum variance hedging strategies in terms of risk reduction in the given two scenarios. Thirdly, this work aims at

analyzing the performance of the minimum variance hedging strategies out of sample in order to check whether such strategies may be useful in risk reduction. Finally, the study employs backtesting techniques to assess the robustness and accuracy of the risk measures estimation, especially in case of large changes in the markets. The aim is to find out whether models which work under normal market conditions also remain valid under extreme market stress.

The research offers four significant contributions to the literature on volatility spillovers and risk management problems in carbon, agricultural, and financial markets. First, an integrated model framework that considers the interaction of market relationships rather than the examination of volatility spillover for each pair of markets individually is constructed. This approach helps to acquire an adequate knowledge of volatility spillovers in different market situations. Second, the results show that the tail-risk exposure is regime-dependent, while the average volatility spillovers depend less on the regime. This finding indicates the importance of considering the tail risk regime sensitivity in addition to the average volatility relationship in the context of financial risk management. Third, the study focuses on the conditional nature of carbon-based hedging strategies, showing their effectiveness under calm market conditions but inefficiency in the case of stressful market conditions. This allows for the deployment of more flexible and adaptive hedging strategies as opposed to maintaining long-term hedging strategies. Fourth, the study proposes an open, clear, and analyzable process setup with clear parameters. This will make the proposed methodology replicable and testable through actual market data. In addition, artificial intelligence in the carbon trading system has huge prospects in improving market efficiency and financial risk management (Parhamfar et al., 2025). The proposed framework will provide a replicable basis of measurement for such technological advancements and applications.

The rest of the paper will be organized into six sections to give a structured account of the research methodology, the analytical methodology, and the research findings. The literature review of the present study is presented in Section II, which comprises all literature, theories, and research advances related to carbon markets, commodity markets, volatility spillover, and financial risk management. Section III explains the research design, data set description, variable selection and methodological steps involved in the empirical research. This section also describes the analytical techniques and statistical tools utilized for the analysis of volatility spillover, portfolio risk, and hedging effectiveness. Results are described and analyzed in detail concerning past studies in Section IV. Focus is placed on the implications and relations found in the analysis of the results obtained empirically. The key results are highlighted and the findings are translated into practical implications for the financial sector, farmers and regulatory bodies in Section V. Finally, Section VI provides the summary of the key results, their significance, limitations of the study and possible directions for future research. In this way, the logic and structure of the work is ensured from the theoretical background, methodology and evaluation of the empirical results to the conclusions drawn.

Review of Literature

There were two sources for the development of carbon markets. These limits on emissions and the allocation of tradable allowances create a compliance market, and the price of an allowance is linked to abatement costs, the level of pollution allowed in the regulations, and the expected number of allowances. The voluntary markets have grown organically, in response to corporate pledges and project-based offsets, many of which are in the forestry and agriculture sector. The two are different in terms of standardization, liquidity and verification. The value of compliance allowances would be in quality, additionality and permanence; while the value of voluntary credits would be in these features.

Questions have been raised regarding these markets' infrastructure. A recent literature review on blockchain for the carbon market explores the potential of blockchain to enhance traceability, mitigate double counting and simplify the operation of a registry, and pinpoints technical and governance challenges that still need to be addressed (Merlo et al., 2025). It's not directly relevant to financial risk, but it is relevant. There are a number of potential risks, such as counterparty risk and integrity shocks, which could cause a short-notice price change in the voluntary segment even if there is no price change in the compliance segment.

The financial environment is provided by green finance. A stocktaking on climate change and decarbonization in green finance shows how capital markets, banks and policy instruments are being mobilized for the transition and what financing gaps there are (Fu et al., 2024). Projects a linkage between the cost of carbon and cost of capital for low-carbon investment, which means that companies that do not buy or sell a single carbon allowance can be affected by a carbon market shock.

Technological aspects are added. Within the carbon trading space, the potential for AI to assist in price discovery, market efficiency, and risk management, and how model risk and data constraints can impede these applications, have been explored (Parhamfar et al., 2025). The important point in the current paper is that the co-movement of many

users in the signal space is amplified during stress periods in the carbon markets, and algorithmic tools are used to help navigate the markets.

The empirical question is whether the carbon transition brings a co-movement in terms of volatility for the markets. The results indicate that there could be an asset-wide shock to volatility, not only in the carbon market, but in a wide asset class, in response to a common shock from the carbon transition (Campos-Martins & Hendry, 2024). This is important because, at the time of a common shock, diversification is already a weak point. There is no offsetting exposure of a carbon price and the agricultural lender's share price on the same underlying policy.

A complementary strand traces the losses resulting from the climate through the financial system. The financial network, as a system of exposures that magnify the effect of a loss in one region to creditors and investors in the other region, is the global financial risk map of climate change (Mandel et al., 2025). In agricultural finance, the network view suggests that a regional lender might be a stress transmitter to other markets, and a stress absorber to the markets of the region.

The regulatory route is also very important. In the EU, the regulatory regime of the banking channel for financing an orderly transition aims to examine how prudential regulation and requirements, supervisory expectations and disclosure requirements influence the way banks take on and price transition risk (Nieto & Papathanassiou, 2024). Such a disorderly transition, in which policy changes happen in a stop-start manner or at random points in time, would pose a serious challenge to that framework, which is only being tested by the volatility peaks and correlation rises that this paper explores.

Studies revealing such volatility linkages don't have to be constant. A network of similar carbon-transition shocks (Campos-Martins & Hendry, 2024) and the propagation of losses (Mandel et al., 2025), as well as a banking system that shapes how losses are absorbed (Nieto & Papathanassiou, 2024), suggest that it should be more likely and more strongly correlated for losses to be larger and higher when policy uncertainty is greater. Therefore, it seems that the regime-conditional approach discussed below is attractive.

Data and Methodology

The analysis is carried out using the structure in fig 1. A 'carbon-price and policy-uncertainty signal' is at the heart of it. Has effects on compliance allowances, on voluntary and agricultural offsets, which affect commodity price volatility and agri-lender balance sheets. The effects impact the tail risk of a portfolio (tail risk), and the measured tail risk affects the way in which it is hedged and acted on (tail risk response), which affects the signal (tail risk response). The framework is designed to be circular, with risk-management decisions in stress (such as hedge purchases or tightened loan limits) having an impact on market behavior, and thus the next round of volatility.

Figure 1 depicts how the global climate transition will shape the dynamics of the carbon market, and the relevant transmission channels of the impact on agricultural commodity markets and financial risks in the context of lending. The framework illustrates the potential impact of shifts in carbon market conditions on market volatility, financial linkages, and risk exposure in agriculture and lending. These relationships are assessed systematically via Volatility Modelling, Spillover Analysis, Tail-risk Assessment, Hedging Performance Evaluation and Model Back-test. The analytical process can be used to determine potential risk transmission, to estimate extreme financial losses and to evaluate hedge effectiveness in varying markets. In addition, the framework highlights the need to build confidence in the measurement of risks, robust financial protection in times of market stress, and market-specific risk reduction measures. The resulting insights aid in well-informed decision-making, bolster financial resilience, and assist in comprehensive risk management in the interdependent carbon, agricultural, and lending markets.

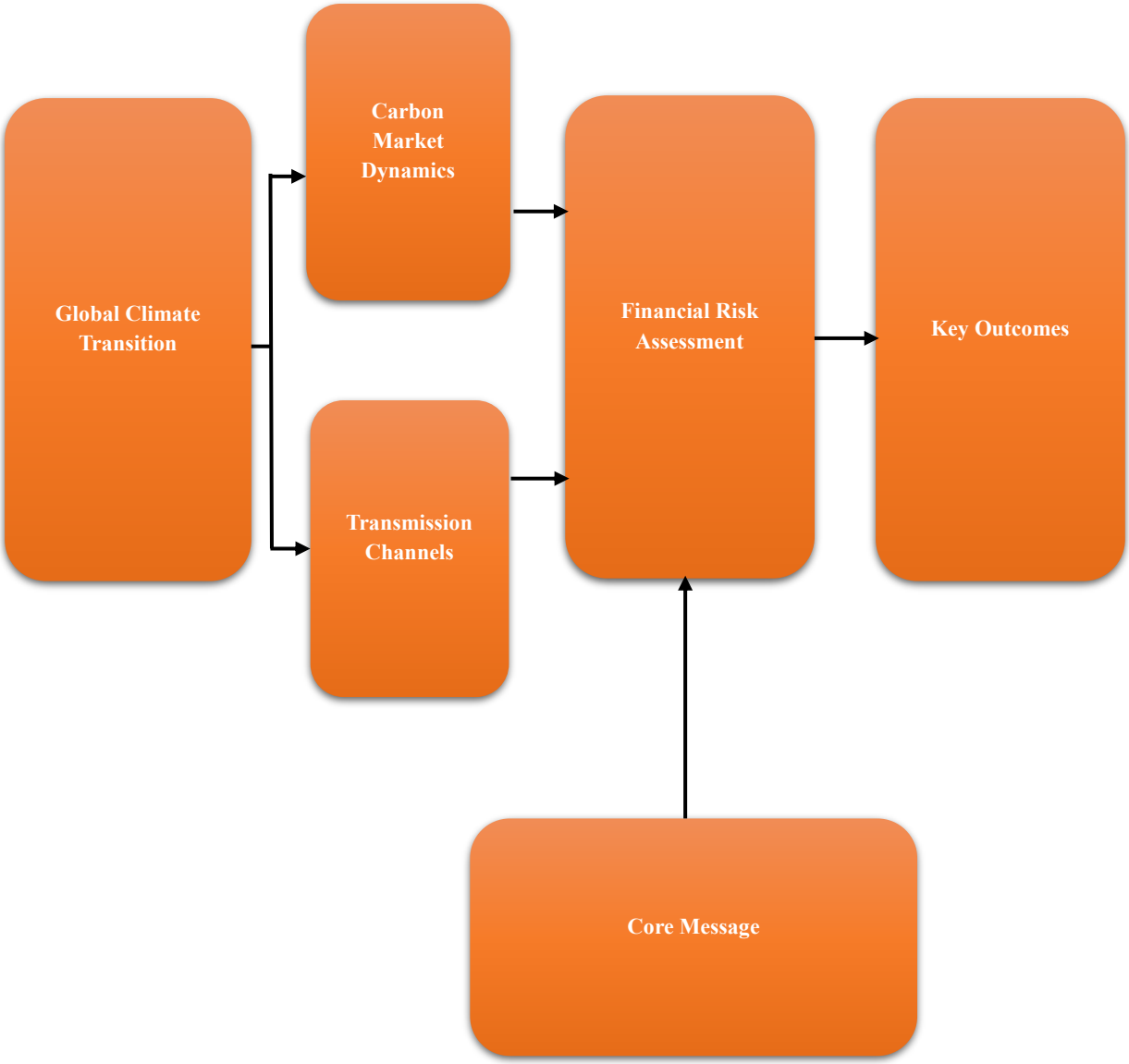


Fig. 1: Conceptual Framework for Carbon Markets and Financial Risk Assessment under Global Climate Transition

Data Design

The empirical sample is a calibration simulation, and not a vendor downloads. The intent is to show and test an assessment pipeline with all parameters open. There are 2600 business day observations in the sample. There is a two-state Markov chain for the market regime. On average, 67 trading days of calm periods and 22 trading days of stress periods, which leads to a stress share of 25 percent in the long run. A share of stress is realized of 25.9 percent, or 673 days. Stress vs Calm correlation for the carbon series goes from low to very high; stress volatility goes from low to about 2x with stress. Both the agricultural and lender series have squared carbon shocks which increase the variance of the series at the following time point, and the impact of the squared carbon shock is larger when in stress. By running the same pipeline, one can execute on the actual market series as well, with the simulated file replaced by the market series.

The following series are modeled: a carbon-allowance series, an agricultural commodity index, and an agri-lender equity index. The risk portfolio has 15 percent carbon exposure, 55 percent agricultural, and 30 percent lender, which means that the portfolio is an agricultural holder with a modest direct carbon stake. The portfolio's main exposure is the agricultural and lender exposure, which is being hedged.

Descriptive Statistics

Table 1: Descriptive Statistics of Daily Returns (%), n = 2,600

Series	Mean	Std. dev.	Min	Max	Skewness	Excess kurtosis
Carbon	0.044	1.953	−9.098	8.696	0.070	1.675
Agri	−0.029	1.453	−10.864	12.055	0.065	9.295
Bank	−0.037	1.600	−8.726	9.047	−0.109	3.410

None of the three series are normally distributed, and all exhibit important volatility clustering. The agricultural series has the highest amount of excess kurtosis with 9.3, because the stress events are likely to occur on a few days with large moves. These features make non-normality of the volatility model and tail-risk measures worthwhile (Table 1).

Methods in Brief

The modeling of each return series is done in a standard GARCH (1,1) specification with Student-t errors to induce volatility persistence and heavy-tailed error distribution. Volatility spillovers are derived using a generalized forecast-error variance decomposition (FEVD) model using the smoothed absolute-return proxy and a two-lag vector autoregressive (VAR) model. The generalized decomposition is not sensitive to the ordering of variables, and is therefore a good measure of cross-market transmission. The total spillover index is the mean of the spillover components of the forecast-error variance of all series over the 250-day horizon, and represents the overall average share of the forecast-error variance of each series that can be attributed to the other series. Tail risk is calculated as "Expected Shortfall" (ES), which is the expected loss if loss occurs beyond the "99% Value-at-Risk" (VaR), which is the loss with an expected probability of 1%. Both are estimated by historical simulation in the full sample and separately in the calm and stress periods. Three hedge ratio strategies are explored: a static minimum-variance hedge ratio based on the first 1,000 observations, a 120-day rolling hedge ratio, and an exponentially weighted dynamic hedge ratio. These three hedge ratio approaches are considered: a static minimum-variance hedge ratio computed from the first 1,000 observations, a 120-day rolling hedge ratio, and the exponentially weighted dynamic hedge ratio. The effectiveness of the hedges is determined as the hedge's reduction of portfolio variance, and it is assessed out of sample, based on the remaining 1600 observations. Finally, nominal 1% exceedance rates are computed using conventional historical simulation and a volatility-filtered approach and then backtested over the nominal exceedance rate of 1%, and exceedance frequencies are reported in various market regimes.

Empirical Results and Discussion

Volatility Dynamics and Regime-Dependent Co-Movement

These estimates suggest that the carbon, agricultural, and lender series are characterized by high volatility persistence: the GARCH (1,1) models indicate that the series have a high degree of persistence. The value of α plus β lies in the range of (0.954, 0.969), indicating a gradual dissipation of volatility shocks. The most important ARCH coefficient is that of Agriculture (0.107), and it is the series with the fewest degrees of freedom (5.59) so it is the most sensitive to new information and has the longest tails. Moreover, there are substantial differences in 'regime-specific' correlations. The ‘regime-specific' correlations are also quite different. The correlation between carbon and agriculture is 0.06 for calm periods and 0.32 for stress periods; the correlation between carbon and lenders is 0.09 for calm periods and 0.39 for stress periods; and the correlation between agriculture and lenders is 0.23 for calm periods and 0.46 for stress periods. The changes here indicate that when it comes to times of transition stress, the benefits of diversification are significantly reduced.

Volatility Spillovers

The overall spillover index for the generalized forecast-error variance is 10.41%, suggesting that the vast majority of the volatility in the model has been due to shocks in own markets. The contribution from own funds is 92.5%, 88.9% and 87.3% for the carbon, agriculture and lenders respectively. The cross-market contribution of agriculture to the lenders and vice versa is the highest (8.2% and 7.6%), respectively. Carbon causes Agricultural volatility = 2.8%, and Lender volatility = 5.1%. There are still low net spillovers – which is to say that there is still no single market that dominates the system on a regular basis. The rolling spillover index has averaged 12.3% and has peaked at 30.6%, whereas the stress windows have averaged 13.6% compared with 11.8% during calm periods.

Portfolio Tail Risk by Regime

When subjected to stress conditions, the tail event risk is extremely high. 99% VaR grows from 2.37% to 4.79% and 99% Expected Shortfall increases from 3.10% to 6.14% during stress. The full-sample ES of 4.46% thus understates

the losses that are happening during the stress period by approximately 27%. The results reveal that risk assessments based on the pooling might not be adequate to reflect the severity of the loss in a poor market.

Hedging Effectiveness Under Stress Scenarios

The hedge is better at times of stress than in times of calm. Variance reduction may be 10-13% in stress markets and variance from hedging may be as much as 8% in calm markets. The static HR = 0.196 is pretty good, and is near the optimum stress regime. The dynamic rolling and EWMA strategies take longer to respond to brief periods of stress. The static hedge does not have as much impact on the 99% VaR (from 3.76% to 3.43%), but does have a slight effect on the ES (from 4.14% to 4.20%) so variance minimizing hedges are not necessarily designed to protect against the worst losses.

Backtesting

The back testing results indicate that VaR models can satisfy the condition of unconditional coverage, but can not satisfy the condition in the stress period. The stress-period exceedance rate remains at 2.4% to 2.8% of the time, which is in line with the 1% target. This indicates that the validation should be specific to the regime as there may be significant underestimation of risk during bad times, even though the average is not.

The empirical results obtained in this study have revealed important nuances in terms of the propagation of climate transition risks through interconnected markets with important implications for risk management, capital allocation, and macroprudential policy. In contrast to previous environmental finance literature that viewed carbon allowances and agriculture markets as two different areas of regulation, we have found that climate transition policies have created an intersection point where carbon prices' volatilities become directly related to the value of agricultural commodities and financial institutions' balance sheets. An important finding from the analysis of the generalized forecast-error variance decomposition (FEVD) approach is that unconditional volatility spillovers are rather low, ranging from an average of 10.41% over the entire sample period to a peak of 12.3% in rolling estimates. This means that under normal market conditions, own-market dynamics continue to be more important than spillovers for price discovery and risk creation processes related to carbon, agricultural commodities, and bank stocks. Nevertheless, the low level of average spillovers should not be considered a sign of market isolation. The sharp increase in rolling spillovers to 30.6% in transition stress periods proves that cross-market contagion effects are very much state-dependent.

One such important lesson can be learned from studying the particular transmission channels involved in these asset groups. The bulk of bilateral spillovers is observed in terms of transmission between agricultural commodities and agricultural lending equities (8.2% and 7.6%, respectively), while the direct spillover from carbon to lending equities is a relatively smaller one (5.1%). Through this particular structure of transmission hierarchy, it can be seen that shocks in carbon markets have a more indirect impact on financial institutions through balance-sheet effects than any direct market exposure. When there is increased volatility in carbon prices because of some changes in policies or regulations, farmers will see the effects in terms of increases in their input costs—like those associated with carbon-intensive fertilizer, fuel, and energy—plus valuation dynamics of carbon offset on land. In this way, the costs of operation create a problem in servicing debt, which will show up as non-performing loans on the balance sheet of regional agricultural lenders.

The dramatic disparity between calm and stress regime environments further illuminates the inadequacies of conventional full-sample risk measures. Tail risk estimates in regime conditional environments show that 99% VaR rises dramatically from 2.37% in calm environments to 4.79% in stressed regimes, while ES increases from 3.10% to 6.14%. Calculating risk based on the pool sample would yield a combined ES of 4.46%, which vastly underestimates the tail losses in transition regimes by about 27%. The above finding poses serious consequences for risk management at financial institutions and regulatory authorities. Conventional risk modeling through full-sample averaging creates a dangerous illusion of adequate capital in tranquil environments and risks putting the institutions at danger of undercapitalization when sudden policy changes or carbon prices collapse occur. Moreover, the backtest results illustrate that although historical simulation models generally pass unconditional coverage test, they consistently fail in stress regimes where the exceedance rate hits 2.4% to 2.8% compared to a 1% target rate.

The examination of minimum-variance hedging strategies involving carbon assets serves as additional evidence of the conditional nature of managing climate risk. Although adding carbon assets to a hedging portfolio leads to a 10% to 13% decrease in the variance of a portfolio in stress periods, the same hedging strategy causes the variance of a portfolio to increase by up to 8% in calm regimes. The reason is that the correlation between carbon assets and agricultural/lender series changes drastically—from 0.06 in calm periods to 0.32-0.39 in stress periods. Fixed hedge positions are counter-productive because hedging positions taken during calm periods add noise and tracking error to a portfolio. In an era of climate transition, risk mitigation requires a regime-sensitive approach to hedging when the

exposure to carbon markets is adjusted to current stress levels. Moreover, since minimum-variance hedges minimize total variance of a portfolio and not tail risk, such strategies offer little protection from tail events since regime-conditional Expected Shortfall does not improve much.

In conclusion, such results call for a change in paradigm with respect to how climate transition risks are assessed by agricultural lenders, bankers and policymakers. Credit risk assessment by agricultural banks should include scenario stress tests that take into account how carbon price fluctuations affect agricultural cash flow. The supervisory bodies should stop relying on exposure-based static capital requirements, and require regime-dependent stress testing in order to make sure that the banks have enough loss-absorbent buffers against nonlinear transition risks. Last but not least, market makers and carbon registry operators should concentrate their efforts on increasing market liquidity and transparency.

Conclusion

This study explored the relationship between carbon market volatility, agricultural risk and the potential risk to the lender under conditions of climate transition with regard to spillovers and tail risks, effectiveness of hedging and model back-testing. The results show that the three-market system is coupled but that carbon risk is not the primary factor behind the overall transmission. The overall spillover index for the sample period and for the rolling estimation is 10.4 percent and 12.3 percent respectively, respectively, with the highest bilateral dependence between series of agriculture and lender. The carbon–agriculture correlation increases during the stress condition with an increased dependency on markets, rising from 0.06 in calm conditions to 0.32 in stress. The tail risk is also much larger, at 99% Expected Shortfall at 6.14% during a stress period compared to 3.10% during a calm period. The carbon-based hedge will offer a moderate level of protection in stress with a reduction in portfolio variance of around 10-13%, but can potentially raise the variance by up to 8% during calm conditions. Furthermore, this level of stress-period exceedance rates (2.4-2.8% to the target of 1%) is still high for VaR models that meet the unconditional coverage tests, meaning that do not provide enough protection during extreme events. Limitations of the study include the calibrated nature of the simulation, the structure of the three series and the lack of transaction cost, liquidity, and basis risk. In the future, the framework must be further tested with observed carbon, agricultural and financial data, and with the use of real-time regime detection and dynamic correlation models and be extended to voluntary and agricultural carbon offsets. Overall, the outcomes indicate that the carbon-transitions risk of agricultural financing is very sensitive to the regime and therefore regime-sensitive measurement and mitigation approaches are desirable.

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