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Price discovery and volatility spillovers in the interest rate derivatives market

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The interest rate derivatives market is an important force in promoting the development of the bond market and is an effective tool to manage interest rate risk. The research on price discovery and volatility spillover of the market can help provide valuable reference information for investors. Based on treasury bond futures and interest rate swaps, the paper aims to discuss the price discovery function and spillover structure of the interest rate derivatives market. The paper establishes the information share model and spillover index model for empirical analysis. The results show that: First, the calculation results of the information share model show that the price discovery of treasury bond futures and interest rate swap markets is stronger than that of the spot market. Second, based on structural break analysis, treasury bond futures and interest rate swaps do not have breakpoints, while the treasury bond spot has three breakpoints. The paper divides the entire sample into four stages based on structural breakpoints and finds that the price discovery ability of the interest rate derivative market dynamically changed. Third, as a net spillover in the market, treasury bond futures have developed relatively stable. Both treasury bond futures and interest rate swaps have spillover effects on the spot market, indicating that China's interest rate derivatives market can impact the treasury bond spot market.

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Introduction

The interest rate derivatives market is an important force that promotes the development of the bond market. The interest rate derivatives market contributes to forming benchmark interest rates in the financial market and makes risk-free interest rate pricing more effective. With the continuous deepening of interest rate marketization, China's interest rate derivatives market has developed rapidly, and businesses such as interest rate swaps, forward interest rates, bond forwards, and interest rate options have been launched. Currently, China's interest rate derivatives market includes the floor market dominated by treasury bond futures and the over-the-counter market dominated by interest rate swaps. As an important tool for hedging interest rate risk, investors' demand for interest rate derivatives continuously increases (Liu et al. 2020a).[1] As an emerging market, it is worth studying whether China's interest rate derivatives have played an effective role and whether they can provide channels for investors to hedge risks. As the core function of the financial market, price discovery refers to the process of impounding new information into the security prices (Shrestha et al. 2023). An effective price discovery mechanism is a key factor in developing the derivatives market, which helps traders make scientific investment decisions (Karabiyik et al. 2018). The analysis of volatility spillover structure between markets can provide a theoretical basis for asset pricing and investment portfolios (Zhang et al. 2020). So, this paper aims to research the price discovery and volatility spillover of the interest rate derivatives market, which helps to measure the price discovery efficiency and spillover structure of the market.

Based on this, China's interest rate derivatives market is chosen as the research object. China's interest rate derivatives market is still in its infancy. Studying its development situation can help provide experience for interest rate derivatives markets in other emerging countries. From the price discovery and volatility spillover perspective, this paper chooses the most mainstream products in China's interest rate derivatives market, treasury bond futures and interest rate swaps, and conducts empirical research on the interest rate derivatives market by establishing information share (IS) model and Diebold and Yilmaz (DY) spillover index model. This paper mainly analyzes whether the treasury bond futures and interest rate swap markets effectively perform the price discovery function. Which can help scientifically evaluate the price discovery efficiency of China's interest rate derivative market. The study of volatility spillover structure can help to further understand the dynamic relationships among markets. In addition, it can provide a more theoretical basis for investment decision-making and promote the better development of the interest rate market. Therefore, the main contributions of this paper are presented in the following aspects: First, starting from the treasury bond futures, interest rate swaps, and treasury bond spot markets, this paper establishes an information share model to study the price discovery function of the interest rate derivatives market, which enriches the relevant literature. Secondly, this article uses the spillover index model to explore the volatility spillover structure of the interest rate derivative market. Static and dynamic spillover structure analysis helps to further understand the information transmission mechanism between markets. The research in this paper contributes to a more comprehensive understanding of the price discovery efficiency and volatility spillover of China's interest rate derivative market.

The remainder of this paper is structured as follows: Section 2 is a literature review, and Section 3 describes the utilized data and implemented methodology. Section 4 shows the empirical results. Section 5 concludes the research and suggests some policy implications.

Literature review

The transaction cost hypothesis suggests that the market with the lowest transaction cost has sufficient liquidity and investors, which can first reflect new information (Xuan et al. 2020). Alex and Michael's research confirmed that the lead-lag relationship between interest rate swap and treasury bond futures market was affected by transaction costs, and the market with lower transaction costs could dominate the price discovery process (Frino and Garcia, 2018). In theory, the futures market has a cost advantage; an effectively functioning futures market can lead the spot market in price discovery (Chen and Tongurai, 2023; Fassas and Siriopoulos, 2018). Most studies have confirmed that the treasury bond futures market is leading in price discovery, with most showing that the price of treasury bond futures can lead to the spot price. Park et al. (2017) examined the impact of foreign participation in KTB futures and its role in price discovery (Park et al. 2017). Ivan et al. (2019) examined price discovery in sequential markets for the 10-year US treasury note, German bund, and UK Gilt futures over the period 2010–2017 (Ivan et al. 2019). They found that price discovery increased after the opening of the US stock market. Ruan et al. (2021) used multi-fractal detrended cross-correlation analysis (MF-DCCA) methods for research and found that there is a continuous correlation between the 10-year US treasury bond spot and futures, while there is no significant correlation between the 5-year treasury bond futures and spot (Ruan et al. 2021). Regarding interest rate swaps, some scholars carried out research from the aspect of pricing (Liang and Zou, 2020; Nopporn and Sanae, 2021; Wang and Huang, 2019).

Studying the spillover effects between markets can further understand the characteristics of information transmission and risk contagion (Zhang et al. 2022). Different scholars use different methods to discuss the volatility spillovers between markets. Lu et al. (2019) used a flexible bivariate heterogeneous autoregressive model to identify short-, mid-, and long-term spillover effects (Lu et al. 2019). Mata et al. (2021) employed the exponential generalized autoregressive conditional heteroscedasticity (EGARCH) technique to develop the volatility spillover effect among pan-Asian countries (Mata et al. 2021). Elgammal et al. (2021) undertook their analysis within a bivariate GARCH (p, q) framework (Elgammal et al. 2021). Liu et al. (2020a, 2020b) used non-linear methods of Granger causality to test the mean spillover relationship between European Union Allowances (EUA) spot and futures markets and analyzed volatility spillovers between them by the non-linear time-varying parameter-vector autoregressive model (TVP-VAR) spillover index (Liu et al. 2020b). Lee and Yoon (2020) employed the vector autoregressive-generalized autoregressive conditional heteroscedasticity (VAR-GARCH) model with the Baba, Engle, Kraft, and Krone (BEKK) specification to discuss dynamic volatility spillovers between carbon and traditional fossil energy market (Lee and Yoon, 2020). In order to better explore the directional and dynamic spillovers between markets, Diebold and Yilmaz proposed a spillover index model (DY spillover index), which can better measure spillover relationships in different markets (Chen et al. 2023a). Guo and Tanaka (2022) used the DY spillover index model to analyze the relationship between the energy and food markets (Guo and Tanaka, 2022).

While there is less research on the combination of treasury bond futures, spot, and interest rate swap market, based on the theory of information overflow, Liu et al. (2021) studied the influence of the government bonds spots, government bonds futures, and interest rate swap market in China's interest rate market from the perspective of fluctuation overflow (Liu et al. 2021). Sharma and Chotia (2019) investigated the efficiency of the

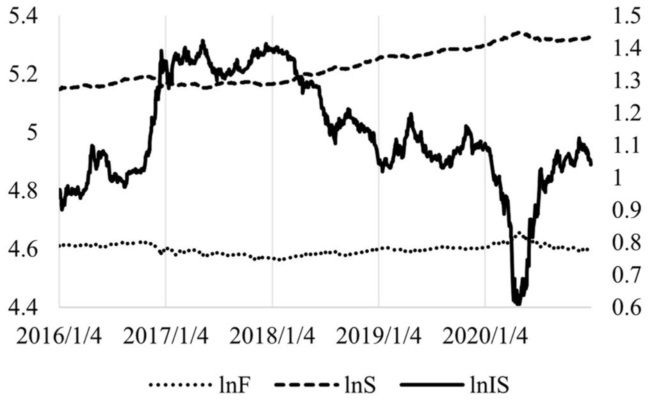

Fig. 1 Logarithmic price series. The left ordinate is the logarithmic price of treasury bond futures and spot, the right ordinate is the logarithmic price of interest rate swaps.

interest rate derivatives market by assessing its contribution to the price discovery process using spot and futures prices (Sharma and Chotia, 2019). Zhang et al. (2019) studied the price discovery mechanism using the Granger causality test, information share model and vector autoregressive model based on the three markets of treasury bond futures, spot, and interest rate swap (Zhang et al. 2019).

Existing literature has more studies on the price discovery of treasury bond futures but few on the analysis of the interest rate swap and interest rate derivatives markets and the spillover effect of volatility between derivatives markets. Therefore, this paper takes the Chinese interest rate derivatives market as the research object to study the relationship between price discovery and volatility spillover. Based on the analysis of the above literature, this paper proposes the hypothesis that the interest rate derivatives market can guide the spot market to conduct price discovery, and there is a volatility spillover effect between the markets.

Methods

Data. Spot price is the price reached by the buyer and seller (Goetz et al. 2021). This paper uses the China Securities index aggregate bond index to represent the spot price of the inter-bank and Shanghai and Shenzhen stock Exchange bond markets, which is compiled by the China Securities Index company. The data is from the China Securities Index company's official website[2](Mao et al. 2022). The index comprehensively reflects the trend of price changes in the inter-bank bond market and the bond market of the Shanghai and Shenzhen Stock Exchanges and can truly reflect the actual value and yield characteristics of bonds, so this paper uses it to represent the spot price. The swap contract linked to the seven-day repo fixed interest rate (FR007) is the most active in the interest rate swap market. Therefore, this paper selects the continuous daily average fixed interest rate data of five-year interest rate swaps based on FR007 to represent the interest rate swap market, and the data is from the China Stock Market & Accounting Research Database (CSMAR) (Chen et al. 2023b; Gao et al. 2019). Treasury bond futures are an important link to the interest rate market and a good tool for hedging risks (Liu et al. 2019; Ruan et al. 2021). Correspondingly, this paper selects the daily closing price of the five-year treasury bond futures (TF) main contract as the price of treasury bond futures. The data is from the China Financial Futures Exchange. The period is from January 4, 2016, to December 31, 2020. After data curation, 1215 groups of data remained. To reduce the heteroscedasticity of time series, before empirical analysis, we take the natural logarithm of treasury bond futures price, spot price, and interest rate swap price, marked as lnF, lnS, and lnIS (Mao et al. 2022). Figure 1 shows the logarithmic time series of the employed price variables.

As shown in Fig. 1, interest rate swaps show a clear V-shaped trend in 2020. In order to hedge the impact of COVID-19, the People's Bank of China increased monetary policy easing from February to April 2020 and reduced the cost of funds through measures such as lowering the interest rate of open market operations. As a result, interbank liquidity was extremely abundant, money market interest rates accelerated downward, and the market's 7-day repo rate fell to around 1.5%, driving the downward acceleration of swap rates. Hence, the swap rate from the beginning of 2020 to mid-April decreased unilaterally. After April, the Covid-19 situation was basically under control. As market interest rates were far lower than policy rates, open market operations were suspended, and market liquidity was gradually consumed, resulting in a rapid rise in interest rates. The 7-day repo rate rose to 2.2%, and the swap rate rose rapidly. Figure 1 shows that the swap rate from late April to late June 2020 rose rapidly. At the same time, on April 3, 2020, the People's Bank of China reduced the deposit reserve ratio by 1 percentage point and lowered the excess reserve ratio to 0.35%, injecting liquidity into the market, leading to a rise in the price of treasury bond futures. Also, in Fig. 1, there was a slight increase in treasury bond futures and spot in April 2020.

The logarithmic rate of return is obtained by taking the first-order difference of the logarithmic price series, denoted as RF, RIS, and RS (Ballestra et al. 2023).

$$R_{i,t} = \left(\ln\left(P_{i,t}\right) - \ln\left(P_{i,t-1}\right)\right) * 100\%, i = F, S, IS \quad (1)$$

Research methods. Regarding price discovery and volatility spillover, both essentially transmit information between markets. Most existing literature uses the vector autoregression model, information share, GARCH, or DY spillover index models for empirical research. The information share model can calculate the contribution degree of price discovery, which helps measure the speed and efficiency of market response to new information (Chen and Tongurai, 2023). This model is widely used in studying price discovery (Chen and Tongurai, 2023; Karmakar and Inani, 2019; Papavassiliou and Kinateder, 2021). The spillover index model can demonstrate the volatility transmission mechanism between markets. Many scholars used it to explore the volatility spillover relationship between the stock, energy, or commodity markets (Sheng et al. 2023; Walid et al. 2020; Zhang et al. 2022). Therefore, this article uses the two models for empirical analysis.

Information share model. When closely linked securities are traded in multiple markets, it is often necessary to determine where the price discovery occurred. Hasbrouck proposed an information share model based on a vector error correction (VEC) model, which can measure the contribution of price discovery in different markets (Fernandez-Perez et al. 2023; Su, 2023). The contribution ratio of each market is called the information share of the market. Therefore, this paper adopts the information-sharing model proposed by Hasbrouck for analysis.

First, the paper establishes a vector error correction model, which is suitable for analyzing non-stationary time series.

$$\Delta Y_t = \alpha\beta' Y_{t-1} + \sum_{i=1}^{p-1} \Gamma_i \Delta Y_{t-i} + \varepsilon_t, t = 1, 2, \ldots \ldots, T \quad (2)$$

where $\beta' Y_{t-1}$ is an error correction vector reflecting the long-term equilibrium relationship between variables. The coefficient matrix α reflects the speed at which the variable is adjusted to an equilibrium state. In order to measure the contribution of each market to price discovery, Hasbrouck converted the VEC model into vector moving average (VMA) form and its single integer form:

$$\Delta Y_t = \Psi(L)\varepsilon_t \tag{3}$$

$$Y_t = Y_0 + \Psi(1)\sum_{i=1}^{t}\varepsilon_i + \Psi^*(L)\varepsilon_t \tag{4}$$

where $\Psi^*(L)$ is the matrix polynomial of a lag operator. The condition for the existence of a cointegration relationship requires that $\beta^T\Psi(1) = 0$, $\Psi(1)$ is the sum of moving average coefficients in Eq. 3. $\Psi(1)\varepsilon_t$ constitutes the long-term impact of the innovation item (disturbance item) on the price of each market. Assuming that ψ is the common row vector of $\Psi(1)$, the Eq. 4 can be written as:

$$Y_t = Y_0 + \psi\left(\sum_{i=1}^{t}\varepsilon_i\right)\iota + \Psi^*(L)\varepsilon_t \tag{5}$$

where $\psi\varepsilon_t$ is defined as a common effective price, the variance is $\psi\Omega\psi'$. Ω is a residual covariance matrix, $\Omega = \begin{pmatrix} \sigma_1^2 & \rho\sigma_1\sigma_2 \\ \rho\sigma_1\sigma_2 & \sigma_2^2 \end{pmatrix}$.

When there is no relation between innovation items, Ω is a diagonal matrix, and the information share of the market i is:

$$IS_i = \frac{\psi_i^2\sigma_i^2}{\psi\Omega\psi'} = \frac{\psi_i^2\sigma_i^2}{\psi_1^2\sigma_1^2 + \psi_2^2\sigma_2^2} \tag{6}$$

When there is a relation between innovation items, we need to use the Cholesky decomposition method to decompose Ω. At this time, the information share of market i is:

$$IS_i = \frac{\left(\left[\psi M\right]_i\right)^2}{\psi\Omega\psi'} \tag{7}$$

where $\Omega = MM'$, $M = \begin{pmatrix} m_{11} & 0 \\ m_{12} & m_{22} \end{pmatrix} = \begin{pmatrix} \sigma_1 & 0 \\ \rho\sigma_2 & \sigma_2(1-\rho^2)^{\frac{1}{2}} \end{pmatrix}$, $[\psi M]_i$ is the ith element of the row vector ψM. Cholesky decomposition can give a larger information share to the first market, so the upper and low limits of information share can be obtained by changing the order of variables in the model. The larger the relation between the innovation of markets, the higher the upper limit and the lower the low limit. The average of the upper and low limits can be used as a reasonable estimate of the information shared. According to the IS model, the upper and low limits of the two markets' information share are:

$$IS_1^U = \frac{(\alpha_2\sigma_1 - \alpha_1\sigma_2\rho)^2}{\alpha_2^2\sigma_1^2 - 2\rho\alpha_1\alpha_2\sigma_1\sigma_2 + \alpha_1^2\sigma_2^2}, IS_1^L = \frac{\alpha_2^2\sigma_1^2(1-\rho^2)}{\alpha_2^2\sigma_1^2 - 2\rho\alpha_1\alpha_2\sigma_1\sigma_2 + \alpha_1^2\sigma_2^2} \tag{8}$$

$$IS_2^U = \frac{(\alpha_1\sigma_2 - \alpha_2\sigma_1\rho)^2}{\alpha_2^2\sigma_1^2 - 2\rho\alpha_1\alpha_2\sigma_1\sigma_2 + \alpha_1^2\sigma_2^2}, IS_2^L = \frac{\alpha_1^2\sigma_2^2(1-\rho^2)}{\alpha_2^2\sigma_1^2 - 2\rho\alpha_1\alpha_2\sigma_1\sigma_2 + \alpha_1^2\sigma_2^2} \tag{9}$$

Component share model. The paper also used the Component Share (CS) proposed by Gonzalo and Granger to analyze price discovery (Fernandez-Perez et al. 2023). The information share and component share measures adopt cointegration to constrain multiple price series to share a common efficient price (Gemayel et al. 2023). CS is calculated based on the vector error correction model, as shown in Eq. 2. The formula is shown as follows:

$$CS_1 = \frac{\alpha_2}{\alpha_2 - \alpha_1}, CS_2 = \frac{\alpha_1}{\alpha_1 - \alpha_2} \tag{10}$$

Vector autoregression model. As an econometric model, the vector autoregression (VAR) model realizes the regression of each time series to all the time series lag terms (Kang and Lee, 2019). It overcomes the shortcomings of a single-variable autoregressive model and is suitable for multiple time series variables. It can estimate the dynamic relationship of joint endogenous variables. The VAR model established in this paper is as follows:

$$\begin{bmatrix} RF \\ RS \\ RIS \end{bmatrix}_t = \varphi_1\begin{bmatrix} RF \\ RS \\ RIS \end{bmatrix}_{t-1} + \ldots\ldots + \varphi_p\begin{bmatrix} RF \\ RS \\ RIS \end{bmatrix}_{t-p} + \begin{bmatrix} \varepsilon_{RF} \\ \varepsilon_{RS} \\ \varepsilon_{RIS} \end{bmatrix} \tag{11}$$

$\phi_1, \ldots\ldots, \phi_p$ are 3×3 dimensional matrices.

Diebold and Yilmaz spillover Index model. The spillover index is a measure of the sensitivity of a financial market to fluctuations from other markets. This paper uses Diebold and Yilmaz's spillover index model to analyze the spillover relationship among treasury bond futures, treasury bond spot, and interest rate swap markets. The traditional orthogonal variance decomposition usually adopts Cholesky decomposition, and its result strictly depends on the order of variables. When there is a contemporaneous relationship between the disturbance items in the vector autoregressive model, different variables will produce different results (Wu et al. 2023). Diebold and Yilmaz used a generalized vector autoregressive model proposed by Koop, Pesaran and Potter and Pesaran and Shin (KPPS) to calculate variance decomposition that is insensitive to the order of variables (He et al. 2023). In a broad sense, the model can be expressed as n-market vector autoregression. The model uses the forecast error variance decomposition (FEVD) based on VAR to calculate the overflow index (Ahmad et al. 2018). The FEVD does not depend on the variable ordering and can intuitively show the spillover relationship between multiple variables. The model is specified as follows: let the return and volatility of sample variables be specified as a VAR process.

First, establish a p-order vector autoregressive model with N variables:

$$X_t = \sum_{i=1}^{p}\Phi_i X_{t-i} + \varepsilon_t \tag{12}$$

where X_t represents the yield vector of treasury bond futures, spot and interest rate swap market, which is $(R_{F,t}, R_{IS,t}, R_{S,t})^T$, Φ_i is the coefficient matrix, $\varepsilon_t \sim (0, \sum)$ is a vector of independent and identically distributed disturbance. The moving average form of the above stationary model is:

$$X_t = \sum_{i=0}^{\infty}A_i\varepsilon_{t-i} \tag{13}$$

Where the $N\times N$ coefficient matrices A_i are expressed as $A_i = \Phi_1A_{i-1} + \Phi_2A_{i-2} + \ldots + \Phi_pA_{i-p}$, with $A_0 = I_n$ and with $A_i = 0$ for $i < 0$.

Second, to avoid the problem of variable ordering, the generalized VAR framework of KPPS is used for variance decomposition. Consider the H-step-ahead forecast error variance, define self-variance share as the share of the H-step forecast error variance of a variable X_i impacted by themselves, and define cross-variance shares as the share of the H-step forecast error variance of the variable X_i impacted by the variable X_j. The latter is the volatility spillover of market j to market i, which is

Table 1 Descriptive statistics.

Variable	Mean	Median	Maximum	minimum	Std.dev.	Skewness	Kurtosis
lnF	4.598369	4.599957	4.655816	4.560539	0.017504	0.12047	2.897855
lnIS	1.134798	1.098612	1.423108	0.609766	0.171723	−0.298344	3.055859
lnS	5.22663	5.209814	5.342478	5.146797	0.062815	0.370464	1.576729
RF	−0.0000064	0.0000494	0.010934	−0.013715	0.001762	−0.653972	12.13423
RIS	0.000067	0.000000	0.058182	−0.113867	0.011145	−0.692229	15.27594
RS	0.000148	0.000171	0.007277	−0.007302	0.000787	0.279981	20.76528

expressed as:

$$\theta_{ij}^{g}(H)=\frac{\sigma_{jj}^{-1}\sum_{h=0}^{H-1}\left(e_i'A_h\Sigma e_j\right)^2}{\sum_{h=0}^{H-1}\left(e_i'A_h\Sigma A_h'e_i\right)},H=1,2,\ldots\ldots,N \tag{14}$$

Where σ_{jj}^{-1} is the reciprocal of the standard deviation of the error term of the j-th equation of the VAR model, e_i is the selection vector (the i-th element is 1, the rest are 0), Σ represents covariance matrices of ε_t. Since the errors based on the generalized VAR framework are not orthogonal, the sum of the contributions of the forecast error variance is not necessarily equal to 1: $\sum_{j=1}^{N}\theta_{ij}^{g}(H)\neq 1$. In order to make better use of the error variance decomposition matrices, the formula after standardization is:

$$\tilde{\theta}_{ij}^{g}(H)=\frac{\theta_{ij}^{g}(H)}{\sum_{j=1}^{N}\theta_{ij}^{g}(H)} \tag{15}$$

where $\sum_{j=1}^{N}\tilde{\theta}_{ij}^{g}(H), 1,\ \sum_{i,j=1}^{N}\tilde{\theta}_{ij}^{g}(H)=N$. Furthermore, the total spillover index, directional spillover index and net spillover index can be obtained. Thus, construct the total volatility spillover index based on KPPS variance decomposition:

$$S^{g}(H)=\frac{\sum_{i,j=1(i\neq j)}^{N}\tilde{\theta}_{ij}^{g}(H)}{\sum_{i,j=1}^{N}\tilde{\theta}_{ij}^{g}(H)}*100=\frac{\sum_{i,j=1(i\neq j)}^{N}\tilde{\theta}_{ij}^{g}(H)}{N}*100 \tag{16}$$

The total spillover index can measure the contribution of spillover between markets to the error variance. The larger the index, the higher the contribution and the more obvious the spillover effect between markets.

As mentioned above, the variance decomposition based on the generalized VAR framework is invariant to variables ordering, so the directional spillover of market i from other markets can be calculated as:

$$S_{i\cdot}^{g}(H)=\frac{\sum_{j=1(j\neq i)}^{N}\tilde{\theta}_{ij}^{g}(H)}{\sum_{i,j=1}^{N}\tilde{\theta}_{ij}^{g}(H)}*100=\frac{\sum_{j=1(j\neq i)}^{N}\tilde{\theta}_{ij}^{g}(H)}{N}*100 \tag{17}$$

The directional spillover from market i to other markets is:

$$S_{\cdot i}^{g}(H)=\frac{\sum_{j=1(j\neq i)}^{N}\tilde{\theta}_{ji}^{g}(H)}{\sum_{i,j=1}^{N}\tilde{\theta}_{ji}^{g}(H)}*100=\frac{\sum_{j=1(j\neq i)}^{N}\tilde{\theta}_{ji}^{g}(H)}{N}*100 \tag{18}$$

Then, get the net volatility spillover of market i to other markets as:

$$S_{i}^{g}(H)=S_{\cdot i}^{g}(H)-S_{i\cdot}^{g}(H) \tag{19}$$

Table 2 Phillips−Perron test results.

variable	1% critical value	5% critical value	10% critical value	ADF test value	*P* value
lnF	−3.4355	−2.8637	−2.5680	−1.7711	0.3952
RF	−3.4355	−2.8637	−2.5680	−35.8885***	0.0000
lnIS	−3.4355	−2.8637	−2.5680	0.1877	0.9718
RIS	−3.4355	−2.8637	−2.5680	−21.9180***	0.0000
lnS	−3.4355	−2.8637	−2.5680	−1.5812	0.4919
RS	−3.4355	−2.8637	−2.5680	−26.9980***	0.0000

*** denotes statistical significance at the 1% level.

Table 3 Correlation matrix.

	lnF	lnS	lnIS
lnF	1.0000		
lnS	0.4640***	1.0000	
lnIS	−0.9000***	−0.6110***	1.0000

*** denotes statistical significance at the 1% level.

The net volatility spillover represents the difference between the volatility spillover from one market to all other markets and the volatility shocks received from other markets. And the volatility spillover between two markets can be expressed as:

$$S_{ij}^{g}(H)=\left(\frac{\tilde{\theta}_{ji}^{g}(H)}{\sum_{i,k=1}^{N}\tilde{\theta}_{ik}^{g}(H)}-\frac{\tilde{\theta}_{ij}^{g}(H)}{\sum_{j,k=1}^{N}\tilde{\theta}_{jk}^{g}(H)}\right)*100=\left(\frac{\tilde{\theta}_{ji}^{g}(H)-\tilde{\theta}_{ij}^{g}(H)}{N}\right)*100 \tag{20}$$

That is, the difference between the volatility spillover from market i to market j and those overflow from market j to market i.

Empirical results

Descriptive statistics. Table 1 is a summary of the descriptive statistics. According to Table 1, compared with other variables, interest rate swap yields fluctuate more; the three groups of yields all have peak distributions, and the skewness and kurtosis of treasury bond spot yields are the largest.

After performing descriptive statistics on the data, this paper adopts the Phillips-Perron (PP) test to check the stability of the variables (Karmakar and Inani, 2019). The test is a way to find the root of the unit and explain sequence stationarity in time series data (Li et al. 2024). According to Table 2, the logarithmic price series of treasury bond futures, spot and interest rate swaps are unstable. The yield series obtained after the first-order difference rejects the null hypothesis at the 1% significance level, so the three series are stable.

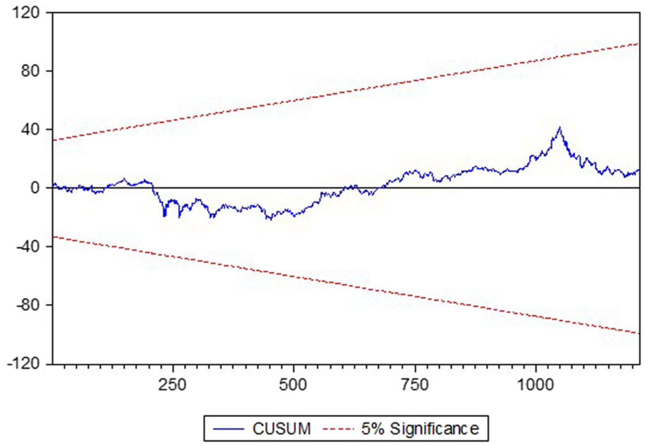

Fig. 2 CUSUM test-treasury bond futures. The figure shows the CUSUM test results of treasury bond futures with significance not exceeding 5%.

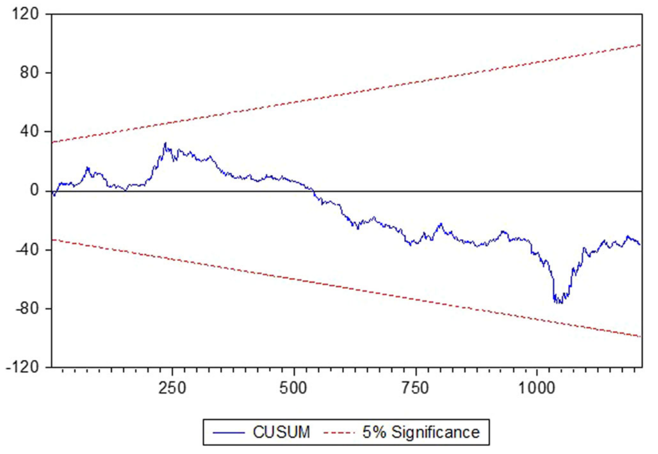

Fig. 3 CUSUM test-interest rate swap. The figure shows the CUSUM test results of interest rate swap with significance not exceeding 5%.

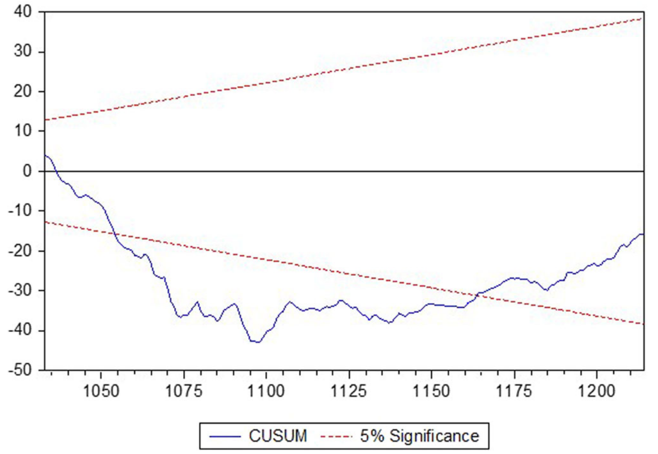

Fig. 4 CUSUM test-treasury bond spot. The figure shows the CUSUM test results of treasury bond spot with significance exceeding 5%.

Table 4 Structural breakpoint test results.

	Break test	F-statistic	scaled F-statistic	critical value**
RF	0 vs. 1	2.5393	2.5393	8.5800
RIS	0 vs. 1	7.3996	7.3996	8.5800
RS	0 vs. 1*	18.2383	18.2383	8.5800
	1 vs. 2*	21.6746	21.6746	10.1300
	2 vs. 3*	20.8635	20.8635	11.1400
	3 vs. 4	5.7236	5.7236	11.8300

*denotes statistical significance at the 5% level. ** denotes Bai-Perron critical value.

A correlation test is also conducted, and Table 3 displays the outcome.

Structural break analysis. Structural break analysis can be applied to solve the problems of slope heterogeneity and cross-sectional dependence (Shao et al. 2021). The paper uses the cumulative sum (CUSUM) to test the stability of the parameters (Stauvermann et al. 2018). At the same time, it provides a foundation for analysing the following text. Compared with the Chow test, this method doesn't need to assume the structural breakpoint in advance. As shown in Figs. 2, 3, the CUSUM test results of treasury bond futures and interest rate swaps do not exceed the significance level of 5%, indicating that the time series of treasury bond futures and interest rate swaps are stable. In Fig. 4, the CUSUM test result of spot treasury bonds exceeds the 5% critical line, indicating that the parameters are unstable. The treasury bond spot time series may have a structural break in the process of fluctuation. Based on this, the paper uses the Bai-Perron multiple breakpoint test to test the structural breakpoints of sequences (Cuestas et al. 2024). Compared with other structural fracture methods, this method has the advantage of explaining the non-stationarity and cross-sectional dependence simultaneously and the influence of time dimension on the structural fracture of each cross-section (Shao et al. 2021). As shown in Table 4, the results indicate no breakpoint in treasury bond futures and interest rate swaps, but there are three breakpoints in treasury bond spots. The dates corresponding to the three structural breakpoints are October 25, 2016, January 22, 2018, and April 3, 2022.

Information share model. This paper uses the Johansen cointegration test to analyze the cointegration relationship between variables (Mishra et al. 2023; Papavassiliou and Kinateder, 2021). The Johansen cointegration test helps analyze whether the causal relationship described by the equation belongs to pseudo regression. If there is a cointegration relationship between variables, an error correction model can be established (Li and Chau, 2016). As shown in Tables 5, 6, there is a long-term stable cointegration relationship between the two variables of treasury bond futures and spot, and the same is true for interest rate swaps and treasury bond spot.

Based on the long-term equilibrium relationship between the two variables, this article uses the information share model to analyze the market's price discovery ability. Table 7 shows the calculation results of the full-sample information share model. It can be seen that the price discovery capability of the treasury bond futures and interest rate swap markets is higher than that of the spot market. This shows that the interest rate derivatives market has a price discovery function.

Based on the structural breakpoints, the paper divides the time series into four parts and calculates the information shared. Table 8 shows the calculation results. Table 8 shows that the price discovery ability of treasury bond futures fluctuates and is lower than that of the treasury bond spot market in the second stage. The price discovery contribution of interest rate swap is lower than that of treasury bond spot in the second and fourth periods.

Table 5 Johansen cointegration test (Trace statistic).

	Hypothesis of cointegration	Eigenvalue	Trace Statistic	0.05 Critical Value	P value
(lnF, lnS)	None	0.032281	40.35848	12.3209	0.0000***
	At most 1	0.000485	0.588264	4.129906	0.5047
(lnIS, lnS)	None	0.031705	40.78344	12.3209	0.0000***
	At most 1	0.00143	1.734204	4.129906	0.2208

*, **, *** denote statistical significance at the 10, 5, and 1% level, respectively.

Table 6 Johansen cointegration test (Max-eigen statistic).

	Hypothesis of cointegration	Eigenvalue	Max-Eigen Statistic	0.05 Critical Value	P value
(lnF, lnS)	None	0.032281	39.77021	11.2248	0.0000***
	At most 1	0.000485	0.588264	4.129906	0.5047
(lnIS, lnS)	None	0.031705	39.04923	11.2248	0.0000***
	At most 1	0.00143	1.734204	4.129906	0.2208

*, **, *** denote statistical significance at the 10, 5, and 1% level, respectively.

Table 7 Full-sample information share analysis.

	(1)		(2)	
	lnF	lnS	lnIS	lnS
Upper limit	99.77%	44.92%	99.77%	57.40%
Low limit	55.08%	0.23%	42.60%	0.23%
Mean	77.43%	22.57%	71.19%	28.81%

Table 8 Contribution of price discovery at different stages.

Stage	Treasury bond futures		Interest rate swap	
	lnF	lnS	lnIS	lnS
2016.1.4-2016.10.25	89.34%	10.66%	73.76%	26.24%
2016.10.26-2018.1.22	15.90%	84.10%	13.18%	86.82%
2018.1.23-2020.4.2	88.88%	11.12%	83.09%	16.91%
2020.4.3-2020.12.31	50.20%	49.80%	31.25%	68.75%

Table 9 Component share calculation result.

	(1)		(2)	
	F	S	IS	S
CS	85.27%	14.73%	−6.0143	7.0143

This indicates that the price discovery ability of China's interest rate derivative market has not been stable in recent years, and it was impacted by unstable external factors.

Componenet share model. Table 9 is the result of the calculation of the CS model. It can be seen that the price discovery function of the treasury bond futures market is stronger than that of the spot market. In contrast, the result of the interest rate swap market did not prove that it has the price discovery ability.

VAR model. The PP test (Table 2) concluded that the rate of return series is stable, and a VAR model can be established for further analysis. According to Table 10, the best lag order is 2; the VAR(2) model is established. Table 11 shows the parameter estimation result of the VAR model. It can be seen from Table 11:

$$RF_t = -0.043RF_{t-1} - 0.104RF_{t-2} - 0.297RS_{t-1} + 0.311RS_{t-2} \\ -0.024RIS_{t-1} + 0.006RIS_{t-2} - 0.0 \quad (21)$$

Table 10 Lag order test.

Lag	LogL	FPE	AIC	SC	HQ
0	17317.856	0.000	−37.039	−37.026	−37.034
1	17743.278	0.000	−37.749	−37.699	−37.73
2	17770.472	0.000	−37.803	−37.715*	−37.77*
3	17767.762	0.000	−37.808	−37.682	−37.76

* indicates lag order selected by the criterion.

Table 11 Parameter estimation table of the VAR model.

Argument	Estimator	RF	RS	RIS
RF_{t-1}	Coefficient	−0.043	0.141	−2.073
	Std.dev.	0.039	0.014	0.229
	t-value	−1.094	9.811	−9.072
RF_{t-2}	Coefficient	−0.104	−0.005	0.637
	Std.dev.	0.038	0.014	0.226
	t-value	−2.705	−0.374	2.82
RS_{t-1}	Coefficient	−0.297	0.135	3.275
	Std.dev.	0.114	0.042	0.671
	t-value	−2.605	3.185	4.883
RS_{t-2}	Coefficient	0.311	0.231	−2.456
	Std.dev.	0.101	0.038	0.597
	t-value	3.063	6.146	−4.117
RIS_{t-1}	Coefficient	−0.024	−0.01	0.246
	Std.dev.	0.007	0.003	0.042
	t-value	−3.277	−3.807	5.818
RIS_{t-2}	Coefficient	0.006	0.002	−0.062
	Std.dev.	0.007	0.002	0.039
	t-value	0.892	0.842	−1.56
Constant	Coefficient	0.000	0.000	0.000
	Std.dev.	0.000	0.000	0.000
	t-value	−0.149	4.873	−0.243

Table 12 Results of variance decomposition.

Rank	RF				RS				RIS			
	Std.dev.	RF%	RS%	RIS%	Std.dev.	RF%	RS%	RIS%	Std.dev.	RF%	RS%	RIS%
1	0.002	100.000	0.000	0.000	0.001	39.747	60.253	0.000	0.010	37.584	16.551	45.865
2	0.002	99.046	0.084	0.871	0.001	52.685	46.443	0.873	0.011	44.001	14.449	41.550
3	0.002	98.786	0.322	0.893	0.001	53.38	45.593	1.027	0.011	44.277	14.452	41.270
4	0.002	98.773	0.330	0.897	0.001	53.485	45.473	1.042	0.011	44.269	14.484	41.247
5	0.002	98.769	0.333	0.898	0.001	53.555	45.403	1.042	0.011	44.298	14.482	41.220
6	0.002	98.768	0.334	0.898	0.001	53.593	45.363	1.043	0.011	44.307	14.481	41.212
7	0.002	98.767	0.335	0.898	0.001	53.604	45.352	1.044	0.011	44.307	14.481	41.212
8	0.002	98.767	0.335	0.898	0.001	53.608	45.348	1.044	0.011	44.307	14.482	41.211
9	0.002	98.767	0.335	0.898	0.001	53.609	45.347	1.044	0.011	44.307	14.482	41.211
10	0.002	98.767	0.335	0.898	0.001	53.609	45.346	1.044	0.011	44.307	14.482	41.211

RS is spot price, RF is futures price, RIS is interest rate swap price, and Std.dev is the standard deviation.

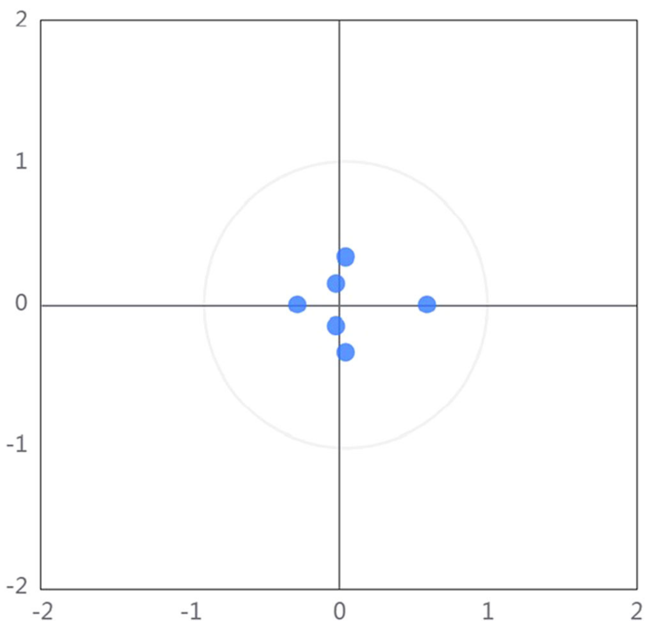

Fig. 5 AR root test.

$$RS_t = 0.141RF_{t-1} - 0.005RF_{t-2} + 0.135RS_{t-1} + 0.231RS_{t-2} - 0.01RIS_{t-1} + 0.002RIS_{t-2} + 0.0 \tag{22}$$

$$RIS_t = -2.073RF_{t-1} + 0.637RF_{t-2} + 3.275RS_{t-1} - 2.456RS_{t-2} + 0.246RIS_{t-1} - 0.062RIS_{t-2} - 0.0 \tag{23}$$

As shown in Fig. 5, all roots fall within the unit circle, so the stability condition is satisfied, and the model can further perform impulse response analysis and variance decomposition.

Figure 6 is an impulse response analysis plot depicting the effect of a shock on one endogenous variable (the shock variable) in the model on another endogenous variable (the variable subject to the shock). As can be seen from Fig. 6, RF is affected by itself, RS, and RIS in the first five phases and gradually converges to 0 in the sixth phase. RS is affected by RF and RIS in the first seven periods and gradually converges to 0 from the eighth period. RIS is affected by RF, RS, and itself in the first five periods and gradually converges to 0 from the sixth period.

Table 12 shows the variance decomposition results. From the variance decomposition results of RF, it can be seen that in the first phase, the fluctuation of RF is completely affected by itself, and by increasing the number of phases, RS and RIS will have a slight impact on it, but it is mainly affected by itself. As can be seen from the variance decomposition results of RS, the fluctuation of RS in the first period is affected by itself and RF, but mainly by itself. With the increase in the number of periods, RF has an increasing influence on RS and becomes the most important influencing factor, while RIS also has a slight influence on it. From the variance decomposition results of RIS, it can be seen that in the first period, the fluctuation of RIS was mainly influenced by itself, and RF and RS also impacted it. However, with the increase in the number of periods, RF had an increasing impact on RIS and became the most important influencing factor, which was also influenced by itself and RS.

Empirical results based on the spillover index model

Static spillover analysis. The analysis of the spillover index is based on the second-order VAR model and uses $H = 10$-step-ahead forecast error variance deposition (Fasanya et al. 2020). Table 13 shows the volatility spillovers among the three markets. The total spillover index in the lower right corner shows that the spillover index for the entire sample period is 49.0%, indicating that 49.0% of the variance of the forecast error between treasury bond futures, spot, and interest rate swaps comes from the spillover among variables. The contribution to others in this row shows that the treasury bond futures market has the largest spillover to other markets at 51.1%, followed by the interest rate swap market. It can be seen from the column contribution from others: spillover from other markets to the treasury bond spot market is the largest, at 54.5%, followed by the interest rate swap market. Judging from the net volatility spillover in the last row, the largest is from treasury bond futures to other markets, at 7.5% (51.1–43.6%), and from other markets to the spot market, at −7.5% (47.0–54.5%). In addition, the spillovers between treasury bond futures and spot are smaller than the spillovers between interest rate swaps and spot, indicating that the impact between treasury bond futures and spot is less than between interest rate swaps and the spot market.

Dynamic spillover analysis. The previous volatility spillover table shows the spillover structure during the entire sample period, but it cannot describe the time-varying characteristics of spillovers between markets. Next, a rolling window method is adopted for dynamic analysis. The rolling sample analysis based on the VAR model can obtain the dynamic spillover index, which helps characterize the dynamic changes of risk spillovers among variables. This article uses a 100-day rolling sample. Figure 7 is a

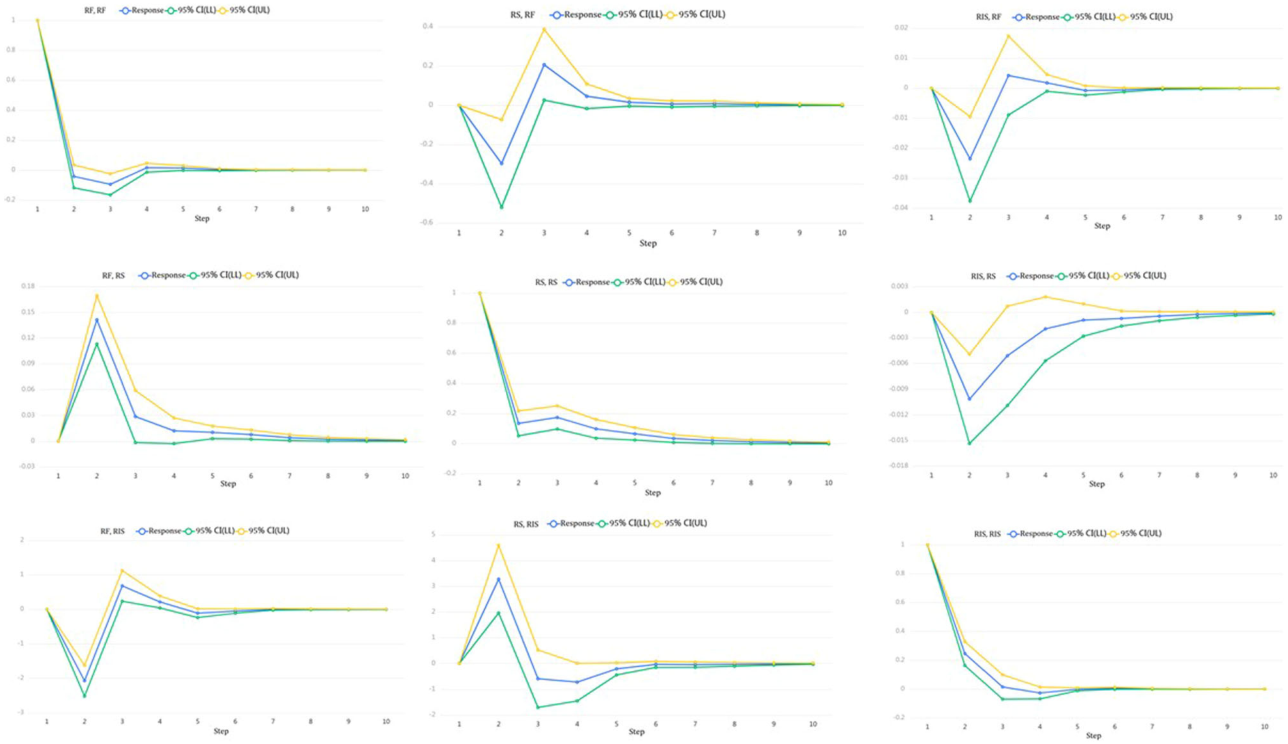

Fig. 6 Pulse response analysis diagram (In each figure, the former variable is the shock variable and the latter is the variable subject to the shock).

Table 13 Spillover index between three markets.

	RF	RIS	RS	Contribution from others
RF	56.37	21.22	22.41	43.6
RIS	24.28	51.13	24.59	48.9
RS	26.82	27.64	45.54	54.5
Contribution to others	51.1	48.9	47.0	Total spillover index: 49.0%
Net volatility spillovers	7.5	0	−7.5	

Fig. 7 Total spillover index. The figure shows the total spillover index between the various markets.

graph of the total spillover index between markets. According to Fig. 7, it can be seen that the total spillover index between the markets changed significantly at the end of 2016 and then showed an upward trend in the following years, indicating that the linkage between the markets has strengthened. The V-shaped trend appeared at the end of 2016, possibly due to the poor fundamental indicators of domestic economic data, the overall loose capital, and a low-interest rate in the money market. After November, due to factors such as the Fed rate hike, the market capital gradually tightened, and some indicators of economic fundamentals improved. Since 2018, the market's total spillover index has continued to rise, suggesting a stronger link between the interest rate derivatives market and the treasury bond spot market, which is possibly related to the launch of two-year treasury bond futures and the participation of commercial banks and insurance institutions in treasury bond futures trading.

Figures 8, 9 are the directional spillover index. The former is the directional spillover of each market to other markets, and the latter is the directional spillover of other markets to a certain market. It can be seen from Fig. 8 that the degree of spillover in the treasury bond futures and interest rate swap market has strengthened, and the spillover of the treasury bond spot market has been relatively small. This shows that the treasury bond futures and interest rate swap markets have gradually increased their impact on other markets in recent years. Figure 8 shows the volatility spillovers from other markets. The spot market is the most obvious (Fig. 9b). The spillover effect of other markets on treasury bond futures is smaller than that on the interest rate swap market. In addition, the spillover effect has increased over time, indicating that the spot market is vulnerable to the spillover effects of other market risks, and the linkage between markets has strengthened. Figure 10 shows the spillover situation of each market. It can be seen that the treasury bond futures market has almost always been in a state of net spillover (Fig. 10a), while the treasury spot market has almost always been affected by spillovers from other markets (Fig. 10c). The above shows that compared with the interest rate swap market, the treasury bond futures market has stronger volatility spillover effects and has a greater impact on other markets. Figure 10 shows the spillover situation between the two markets, where TF refers to treasury bond futures, S is treasury bond spot, and IRS is an interest rate swap. If

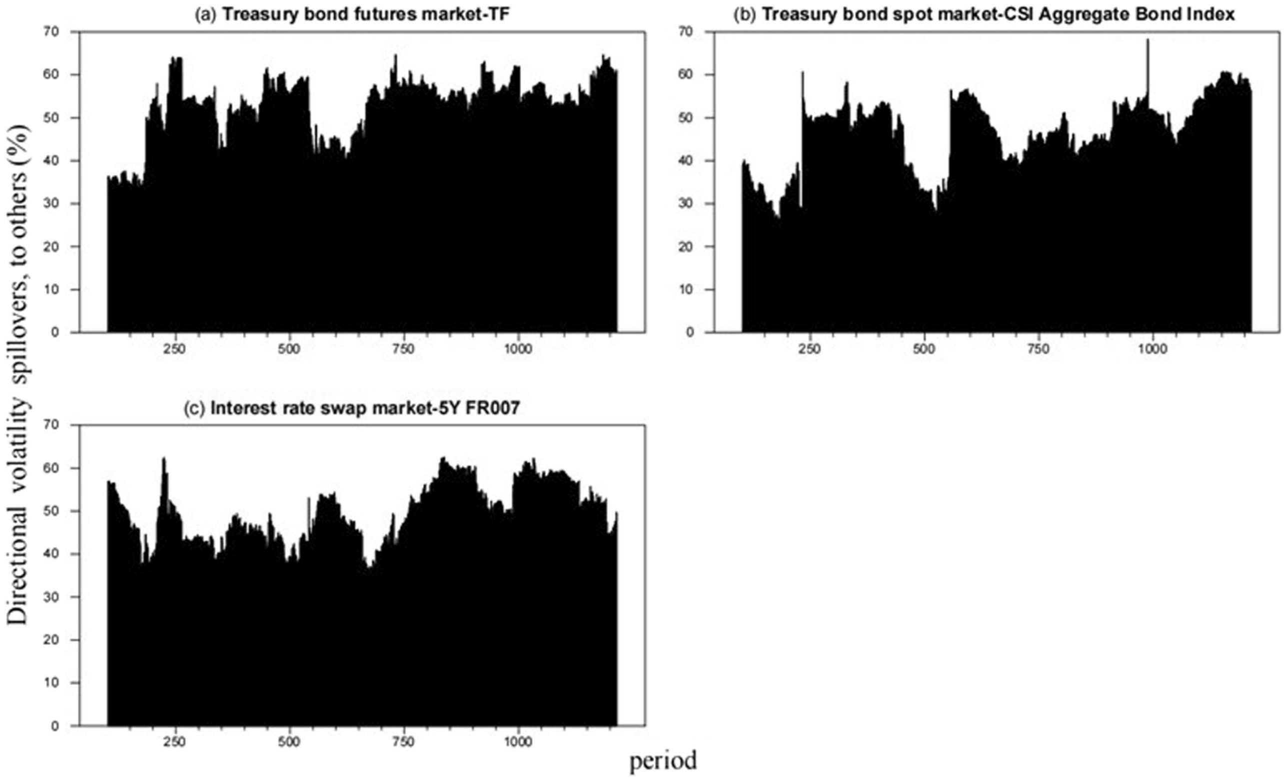

Fig. 8 Directional spillover index to others. It has three panels labeled as (**a**–**c**) to other markets. It can be seen that the degree of spillover in the treasury bond futures (**a**) and interest rate swap market (**c**) has strengthened, and the spillover of the treasury bond spot market (**b**) has been relatively small.

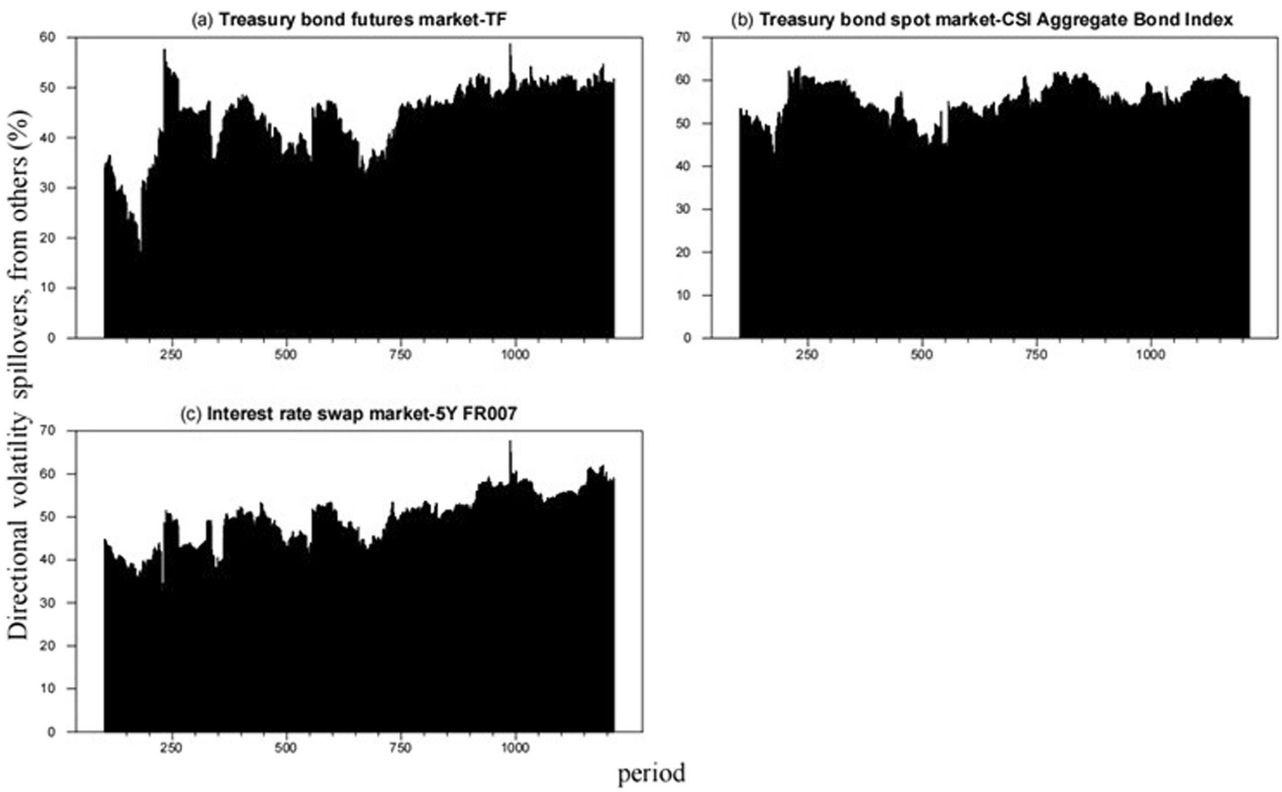

Fig. 9 Directional spillover index from others. It shows the volatility spillovers from other markets. It has three panels labeled as (**a**–**c**), showing the directional spillover of other markets to a certain market. The spot market (**b**) is the most obvious. Also, the spillover effect of other markets on treasury bond futures (**a**) is smaller than that on the interest rate swap market (**c**). In addition, the spillover effect has increased over time, indicating that the spot market is vulnerable to the spillover effects of other market risks, and the linkage between markets has strengthened.

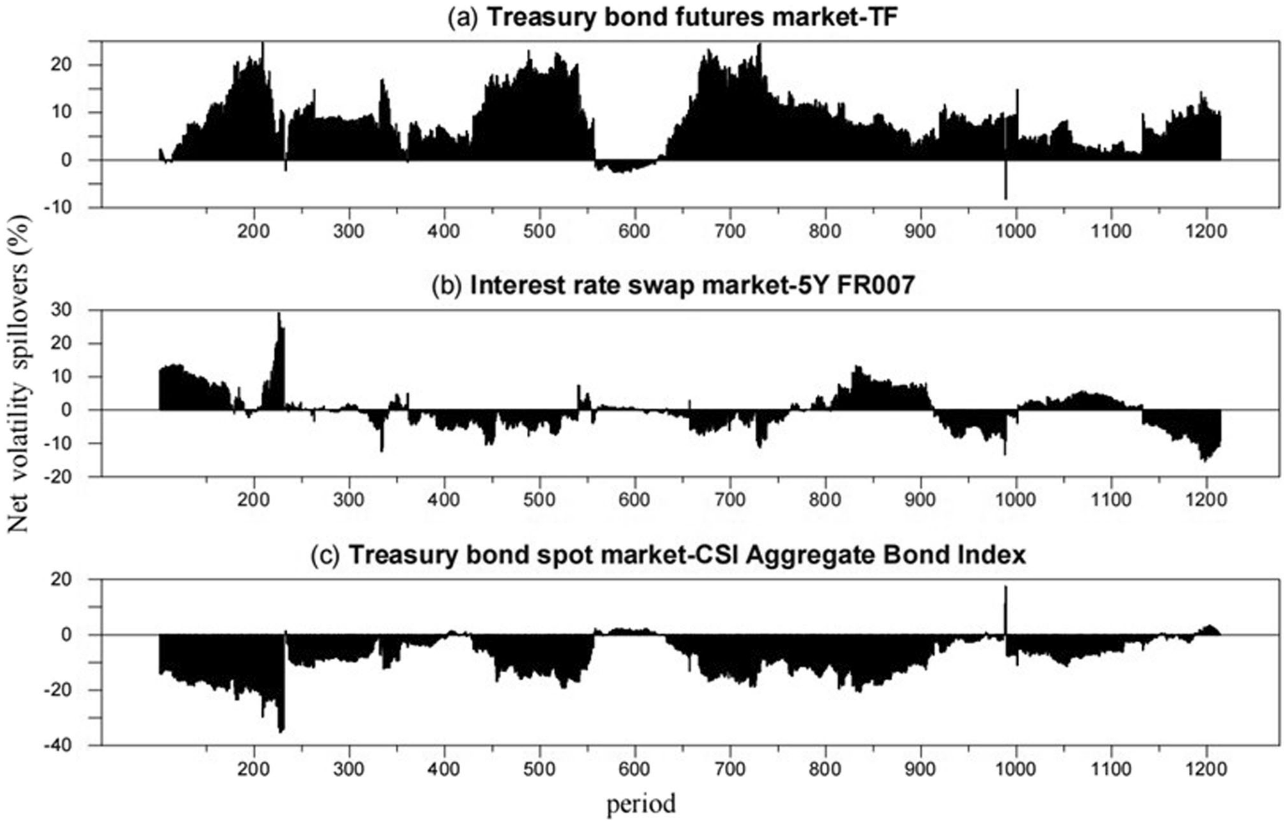

Fig. 10 The net spillover index. It shows the spillover situation of each market labeled as (**a**–**c**). It can be seen that the treasury bond futures market (**a**) has almost always been in a state of net spillover, while the treasury spot market (**c**) has almost always been affected by spillover from other markets. Compared with the interest rate swap market, the treasury bond futures market has stronger volatility spillover effects and has a greater impact on other markets.

it is positive, it indicates that the previous market has a net spillover to the next market. According to Fig. 11, it can be seen that treasury bond futures and interest rate swaps have a net spillover to the spot market, and treasury bond futures have a stronger impact on the spot market (Fig. 11b, c).Treasury bond futures also have net volatility spillovers on interest rate swaps (Fig. 11a). Through the above analysis, it can be concluded that the treasury bond futures and interest rate swap markets have developed in recent years, which can have a greater impact on other markets, and their influence has increased, indicating that China's interest rate derivatives market has a volatility spillover effect on the spot market. Thus, there is a strong linkage between derivatives markets.

Results and discussion. The paper establishes an information share and spillover index model to research price discovery and volatility spillover of the interest rate derivatives market. First, the information share calculation results show that the price discovery ability of treasury bond futures and interest rate swaps is stronger than that of the spot market. This finding is similar to Tang et al. (2018) and Park et al. (2017), who also proved that the treasury bond futures market leads the price discovery process (Park et al. 2017; Tang et al. 2018). Low transaction costs, leverage trading, and liquidity make the futures markets dominant in the process of price discovery (Raju and Shirodkar, 2020).

Second, based on the structural break analysis, the paper finds that the price discovery contribution of interest rate derivatives declined and is lower than the spot market in stages 2 and 4. Moreover, the price discovery of interest rate derivatives changed over time, similar to Paolo et al., who found that the information share dynamically changed. Also, Dobrev and Meldrum's (2020) studies further proved that the treasury bond futures market could recover faster when facing external impact because it has higher liquidity than the spot market (Dobrev and Meldrum, 2020).

Finally, the total spillover index calculated by the spillover index model is 49%, indicating that the risk spillover between markets is obvious. The dynamic spillover analysis shows that the treasury bond futures market has the most obvious spillover effect, and the interest rate swap market also has a certain degree of spillover effect, while the treasury bond spot market is most subjected to spillover effects from other markets. Overall, the linkage between the three markets is strong, substantiating Ruan et al. (2021) study, which found a persistent correlation between treasury bond futures and the spot market (Ruan et al. 2021) and Hsiang-Hsi et al. (2019) research, which studied the stock market, treasury bond futures and cash market and found that the treasury bond futures market was affected by the volatility of the other two markets (Hsiang-Hsi et al. 2019).

Conclusions and policy implications

From the perspective of price discovery and volatility spillover, this paper studies the linkage characteristics between China's interest rate derivatives market and the treasury bond spot market. First, the paper establishes an information share model to analyze the price discovery contribution of markets. Second, the paper uses the DY spillover index model to analyze the static and dynamic spillover relationships among markets. The results show that: First, compared with treasury bond spot, the price discovery function of treasury bond futures and interest rate swaps is stronger. Second, based on structural break analysis, the price discovery ability of the interest rate derivative market is unstable. Third, as a net spillover in the market, treasury bond futures have

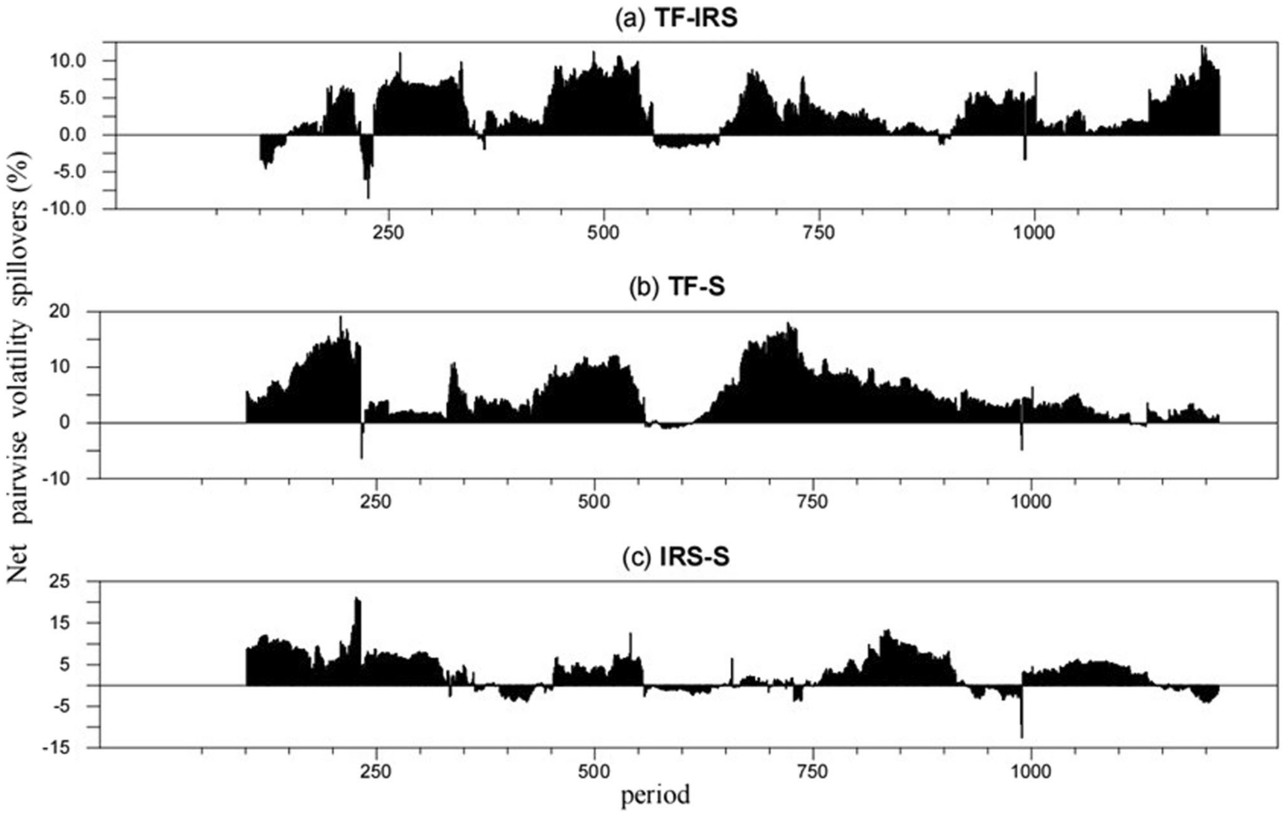

Fig. 11 Net pairwise spillovers. It shows the spillover situation between the two markets elaborated in (**a**–**c**). In the figure, TF refers to treasury bond futures, S is treasury bond spot, and IRS is the interest rate swap. If it is positive, it indicates that the previous market has a net spillover to the next market. The treasury bond futures and interest rate swaps (**a**) have a net spillover to the spot market as shown in (**b**, **c**). Also, the treasury bond futures have a stronger impact on the spot market as shown in (**b**). Treasury bond futures also have net volatility spillovers on interest rate swaps as indicated in (**a**).

developed relatively stable. Both treasury bond futures and interest rate swaps have spillover effects on the spot market, indicating that China's interest rate derivatives market can impact the treasury bond spot market.

The empirical findings of this paper have some policy implications: First, it's necessary to promote the synergy between treasury bond futures and the interest rate swap market. More varieties of interest rate derivative products can be launched to meet the diversified needs of market participants. It's important to introduce treasury bond futures with different maturities, which helps improve the market yield curve and provides a more useful pricing reference for market transactions. Second, paying more attention to the risks during derivative trading is very important. In the process of regulating the interest rate derivative market, it is necessary to pay attention to the situation of the spot market and achieve information integration and collaborative supervision of different markets. The government should focus on preventing systemic risks in the market and strengthen transparency in information disclosure. Third, by understanding the risk spillover structure among treasury bond futures, interest rate swaps and treasury bond spot markets, market participants should adjust their portfolio plans according to the dynamic changes of different markets, which can help mitigate the associated losses caused by risk spillovers.

There are some limitations in this paper. First, there are many kinds of treasury bond futures. This paper only selects five-year products, which may be too limited. Second, the paper does not consider macroeconomic factors that affect price discovery and volatility spillovers. So, future research can focus on exploring more external factors that affect the interest rate derivatives market. Additionally, high-frequency data and other interest rate derivative products can be selected for further empirical analysis.

Data availability

Data used can be accessed at the Journals' data repository via https://doi.org/10.7910/DVN/FADFGU.

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Notes

1 http://www.pbc.gov.cn/
2 https://www.csindex.com.cn/

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Conceptualization, C.C. and D.T.; methodology, W.C.; software, W.C.; validation, L.S., C.C., and H.W.; formal analysis, W.C., C.C., L.S., D.T., and H.W.; investigation, W.C. and C.C.; resources, D.T.; data curation, C.C.; writing—original draft preparation, W.C.; writing—review and editing, W.C., C.C., L.S, H.W., D.T., and D.D.L.; visualization, C.C.; supervision, D.D.L. and L.S; project administration, D.T.; funding acquisition, C.C.

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The authors declare no competing interest.

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Ethical approval was not required as the study did not involve human participants.

Informed consent

Informed consent was not required as the study did not involve human participants.

Additional information

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