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Research Article

Carbon Market Evaluation Based on Random Walk Hypothesis in China

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According to the proposal of Kyoto protocol, carbon dioxide emission rights are traded as a commodity, and carbon emission trading market emerges as the times require. As the world's largest carbon emitter, China has established eight pilot markets for carbon emission trading. Selecting the closing price of eight carbon trading markets from the establishment to June 23, 2020, this paper analyzes the daily, weekly, and monthly return series data, using the first-order autoregressive process to adjust the daily income series to eliminate the weak trading market effect and then comprehensively uses the traditional variance ratio test and multiple variance ratio test to analyze the weak-form market efficiency of the eight carbon trading markets. The empirical results show that most of the carbon trading markets are non-weak-form market efficiency, and only Tianjin, Shanghai, and Hubei markets are weak-form market efficiency under the daily trading data. However, with the increase of carbon holding period, the weak-form market efficiency continues to strengthen. It shows that liquidity, quantity, and information transparency are important factors that affect the market efficiency.

1. Introduction

The climate change caused by the greenhouse gas effect not only affects the economic prosperity and development of all countries, but also threatens the ecological environment on which human beings rely for survival. Global warming has become a major problem that the international community urgently needs to cooperate to solve. After the Kyoto protocol was signed in 1997, carbon dioxide emission rights were regarded as a kind of trading goods; thus the carbon emission rights trading market appeared. Following the pace of energy conservation and emission reduction in the world, China actively undertakes more responsibility for emission reduction and has issued a number of policies to promote low-carbon economy. The domestic carbon trading market started late. Since 2013, China has successively established eight carbon trading markets in Beijing, Tianjin, Shanghai, Hubei, Guangdong, Shenzhen, Chongqing, and Fujian. By August 2020, the cumulative trading volume of carbon markets in China's pilot provinces and cities is more than 400 million tons, and the cumulative turnover is more than 9 billion yuan. It has effectively promoted the work of the pilot provinces and cities to cope with climate change and control greenhouse gas emissions [1].

2. Literature Review

In the capital market, "market efficiency" means that the relevant information inside and outside the market is completely reflected by the price, or various resources in the market are reasonably allocated and effectively utilized. The basic function of capital market is to distribute the ownership of capital in economic activities. The efficient market hypothesis holds that, in the stock market with sound laws, good functions, high transparency, and full competition, all valuable information has been timely, accurately, and fully reflected in the stock price trend, including the current and future value of enterprises, unless there is market manipulation. Otherwise, it is impossible for investors to obtain excess profits higher than the average level of the market by analyzing the past prices.

In 1970, Fama put forward “efficient market hypothesis,” which holds that if the price completely reflects all the available information in a market, it can be called an efficient market. According to the available information set, three types of efficient markets are defined: weak, semistrong, and strong [2]. In the weak-form efficient market, trading will not produce price fluctuations due to historical information, so investors can not obtain excess returns by virtue of historical information. In other words, the weak efficient market should conform to the “random walk” process. It will not achieve the expected purpose to analyze and predict the future market price trend by using the current or historical price, and the transaction price will not be easily influenced by speculation and other nonmarket factors.

Carbon emission trading market is a global emerging financial market. Foreign scholars have studied more the mechanism, rules, price factors, and risks of carbon market. Kruger and others called the EU carbon emission system “a great new policy experiment” and attached great importance to China’s carbon emission trading market and regarded it as “the third big policy experiment” [3]. Chevalier uses OLS method and recursive CUSUM process to study the price volatility of EU carbon market based on the EU daily price [4]. Convery studied the mechanism and performance of the EU carbon market, at the same time, which gives other countries much significant advice for establishing carbon market [5]. Shaohui Zou and Tian Zhang applied both VAR-GARCH-DCC and VAR-GARCH-BEKK models to study the correlation and dynamic volatility spillover between green investing market, coal market, and CO_2 emissions [6].

In the past, the research field of market efficiency mainly focused on the stock market, securities market, and futures market. The main research methods of market efficiency were unit root process, random run test, sequence correlation test, capital asset pricing model, and variance ratio test [7–13]. Montagnoli uses the method of variance ratio test to test the market efficiency of holding period of 2, 5 and 10 days in the first and second stages. The research results confirm the conclusion of them. It shows that the second stage of EU carbon trading market is weak efficient market [14]. Based on the cost of holding hypothesis, Charles et al. studied the factors that affect the efficiency of the EU market and found that, even in the case of structural change, the futures price, spot price, and interest rate are cointegrated, and the lack of cost of holding is the main reason for market inefficiency [15]. In addition, based on the practical research of international carbon emission market, more and more scholars put forward targeted suggestions for the problems and obstacles in the process of promoting market development in China. The research suggests that China’s carbon market should promote the development of relevant financial business from the aspects of improving the regulatory system, trading platform, and professional organization team [16–19].

On the basis of the existing research, this paper makes the following three contributions: (1) select the daily data, weekly data, and monthly data of eight pilot markets to conduct a full sample study; (2) the weak-form efficiency of carbon trading market defined as the idea that the carbon price fully reflects all the information related to carbon emissions; (3) comprehensive use of traditional variance ratio test and multiple variance ratio test for detailed empirical research.

3. Variance Ratio Tests

3.1. Lo-MacKinlay (1988) Test. The test method of variance ratio is proposed by Lo and MacKinlay (1988). Lo and MacKinlay variance ratio test is also known as the traditional variance ratio test, which allows the series to obey nonnormal distribution and heteroscedasticity [20]. If the daily return series of carbon trading price obeys martingale process, the variance of daily return series increases linearly with time: the variance of period K is k times that of period 1. If the daily return series of carbon trading price obeys martingale process, the variance of daily return series increases linearly with time: the variance of period K is k times that of period 1. The series obeys independent and identical distribution (independent identical distribution) which is the premise of the series obeying martingale process.

The null assumption is that the daily return series have martingale process, that is, $VR(k) = 1$. If $VR(k) > 1$; it means that the carbon trading price fluctuates greatly; if $VR(k) < 1$, it indicates that the carbon trading price tends to be stable. $r_{1i,t}$ is the daily return series of carbon price in carbon trading market i at time t; $r_{2i,t}$ is the weekly return series of carbon price in carbon trading market i at time t; $r_{3i,t}$ is the monthly return series of carbon price in carbon trading market i at time t. i represents Beijing, Shenzhen, Shanghai, Guangdong, Tianjin, Hubei, Chongqing, and Fujian carbon markets, respectively, $T \longrightarrow \infty$. The variance ratio statistic equation is as follows:

$$\mathrm{VR}(k) = \frac{\left\{(1/T_k)\sum_{t=k+1}^{T}\left(x_{i,t} + x_{i,t-1} + \cdots + x_{i,t-k} - k\mu\right)^2\right\}}{\left\{(1/T)\sum_{t=1}^{T}\left(x_{i,t-1} - \mu\right)^2\right\}}, \tag{1}$$

where x is the adjusted return series; $\mu = (1/T)\sum_{t=1}^{T} x_{i,t}$; and k is the order of lags. The traditional variance ratio test results are divided into the same variance test and the different variance test. The same variance test formula is as follows:

$$M_1 = (\mathrm{VR}(k) - 1)\left(\frac{2(2k-j)(k-1)}{3kT}\right)^{-(1/2)}. \tag{2}$$

M_1 is asymptotically normal independent identically distributed. The premise of heteroscedasticity test is that there is heteroscedasticity in series, and the test statistic M_2 is expressed as

$$M_2 = (\mathrm{VR}(k) - 1)\left(\sum_{j=1}^{k-1}\left[\frac{2(k-j)}{k}\right]^2 \delta_j\right)^{-(1/2)}, \tag{3}$$

where j is the holding period.

$$\delta_j = \frac{\left\{\sum_{t=j+1}^{T}\left(x_{i,t}-\mu\right)^2\left(x_{i,t-1}-\mu\right)^2\right\}}{\left\{\left[\sum_{t=1}^{T}\left(x_{i,t}-\mu\right)^2\right]^2\right\}}. \tag{4}$$

The heteroscedasticity test also obeys the asymptotic normal distribution. If the statistic exceeds the critical value, the zero hypothesis that the return sequence obeys martingale process is rejected; that is, the market is a weak-form market efficiency; otherwise, the zero hypothesis is accepted. However, the traditional variance ratio test has the following three problems. First, the sample size is distorted due to the asymptotic normal distribution. The second is whether the original hypothesis is valid for all K. The third is the arbitrary selectivity of K value.

3.2. Nonparametric Test. Wright proposed the rank sum sign nonparametric test method of regression series, which solved the problem of sample size distortion [21]. When the sample size is small, the sample size has its own distribution, so it is necessary to test the nonnormality and instability. The results show that the method has better test effect. The null hypothesis: The return series follows martingale process. The rank test equation is as follows:

$$R_1 = \left[\frac{(1/T_K)\sum_{t=k+1}^{T}\left(r_{1i,t}+r_{1i,t-1}+\cdots r_{1i,t-k}\right)^2}{(1/T)\sum_{t=1}^{T} r_{1i,t}^2}-1\right] \times\left(\frac{2(2k-1)(k-1)}{3kT}\right)^{-(1/2)}, \tag{5}$$

$$R_2 = \left[\frac{(1/T)\sum_{t=k+1}^{T}\left(r_{2i,t}+r_{2i,t-1}+\cdots r_{2i,t-k}\right)^2}{(1/T)\sum_{t=1}^{T} r_{2i,t}^2}-1\right] \times\left(\frac{2(2k-1)(k-1)}{3kT}\right)^{-(1/2)}. \tag{6}$$

In this paper, r is used to express the rank of return series as follows:

$$r_{1i,t} = \frac{r_{i,t}-T+1/2}{\sqrt{(T-1)(T+1)/12}}, \tag{7}$$

$$r_{2i,t} = \Phi^{-1}\frac{r_{i,t}}{T+1}. \tag{8}$$

Using rank test instead of M_1 test value in traditional variance ratio, the test result is not limited by sample size and heteroscedasticity, which is more convincing than traditional variance ratio test result. Wright's research shows that, even in the presence of heteroscedasticity, sign test has relative accuracy. The test equation is as follows:

Table 1: Sample description.

Markets	Total obs.	Daily	Weekly	Monthly	Time range
Beijing	1361	980	301	80	2013/11/29–2020/06/23
Shenzhen	1959	1525	350	84	2013/06/18–2020/06/23
Shanghai	1274	927	273	74	2013/11/26–2020/06/23
Guangdong	1676	1286	313	77	2013/12/19–2020/06/23
Tianjin	791	575	165	51	2013/12/16–2020/06/23
Hubei	1827	1445	308	74	2014/04/28–2020/06/23
Chongqing	713	500	160	53	2014/06/19–2020/06/23
Fujian	637	478	125	34	2017/01/09–2020/06/23

$$s_1 = \left[\frac{(1/T_K)\sum_{t=k+1}^{T}\left(s_{i,t}+s_{i,t-1}+\cdots+s_{i,t-k}\right)^2}{(1/T)\sum_{t=1}^{T} s_{i,t}^2}-1\right] \times\left(\frac{2(2k-1)(k-1)}{3kT}\right)^{-(1/2)}, \tag{9}$$

where $S_t = 2\mu(x_t,0) = 2H(x_t)-1,\ H(x_t) = \begin{cases}1, & \text{if } x_t>0,\\ 0, & \text{if others.}\end{cases}$ S_t is independent identically distributed. If the statistic exceeds the critical value, the null hypothesis is rejected; otherwise, the null hypothesis is accepted.

3.3. Belaire-Franch and Contreras Test. Lo-MacKinlay variance ratio test and Wright variance ratio test are both single variance ratio tests. Compared with single variance ratio test, multiple variance ratio test has better effect. The specific reasons are as follows: When single variance ratio test is used, different difference sequences (i.e., different K) are selected to test whether the price series is a random walk process. If one or several difference series fail the statistical test, it can be considered that the sequence is not a random walk. Using single variance ratio test requires every difference series to pass statistical test, which will lead to overtest. In order to overcome this problem, Chow and Denning (1993) [22] proposed the idea of multiple variance ratio test. The statistics are as follows:

$$\mathrm{MV}(k_i) = \sqrt{t}\max\left|M(k_i)\right|, \tag{10}$$

where $M(k_i)$ is the Lo-MacKinlay test statistic.

Because the variance ratio statistics involved in the multiple variance ratio test proposed by Chow and Denning are based on the Lo-MacKinlay statistics, it has defects (the Lo-MacKinlay test statistics only conform to the asymptotic normality). Belaire and Contreras (2004) proposed an extended multiple variance ratio test [23]. Compared with Chow Denning's idea of multiple variance ratio test, the

Table 2: Summary statistics for carbon returns.

Markets		Obs.	Mean	Max	Min	Std. Dev.	Skewness	Kurtosis	Jb	Prob.
Daily	Beijing	979	0.000581	0.208055	−0.28305	0.07052	−0.66715	6.39830	543.707	≤0.001
	Shenzhen	1524	0.000090	2.29131	−2.25700	0.26145	0.166762	32.6348	55774.4	≤0.001
	Shanghai	926	0.000421	0.928461	−0.83873	0.07566	0.707451	45.3227	69188.2	≤0.001
	Guangdong	1285	−0.000614	0.116748	−0.23985	0.04857	−0.31575	3.47739	33.5559	≤0.001
	Tianjin	574	−0.00019	0.728239	−0.69314	0.06675	−0.07345	50.6190	54233.3	≤0.001
	Hubei	1444	0.000012	0.095602	−0.16664	0.02913	−0.18032	6.70875	835.408	≤0.001
	Chongqing	499	−0.000319	0.296493	−0.34465	0.13772	−0.22478	1.83857	32.2483	≤0.001
	Fujian	477	−0.002984	0.09575	−0.12557	0.06677	−0.15165	1.91883	25.0608	0.00004
Weekly	Beijing	300	0.001895	0.580654	−0.60244	0.12046	−0.68315	10.5841	742.331	≤0.001
	Shenzhen	349	0.000395	1.975343	−2.18505	0.32217	0.266869	21.2358	4839.90	≤0.001
	Shanghai	272	0.001299	0.928461	−0.83873	0.13321	0.288869	17.9285	2529.53	≤0.001
	Guangdong	312	−0.00252	0.333588	−0.37533	0.10025	−0.45340	5.70132	105.552	≤0.001
	Tianjin	164	−0.000757	0.728239	−0.69314	0.12149	0.194269	16.7178	1286.92	≤0.001
	Hubei	307	6.48E-05	0.335658	-0.46585	0.06751	−0.90303	18.2558	3018.87	≤0.001
	Chongqing	159	−0.001003	0.908177	−0.91821	0.32830	−0.23368	3.43784	2.71715	0.25702
	Fujian	124	−0.011705	0.477209	−0.52697	0.17200	−0.28249	4.42132	12.0867	0.00237
Monthly	Beijing	79	0.007198	0.381411	−0.42166	0.12282	−0.14361	5.43681	19.8177	0.00005
	Shenzhen	83	0.001661	0.675129	−0.63141	0.24671	0.098871	3.52679	1.09496	0.57840
	Shanghai	73	0.004841	0.928461	−0.48954	0.22110	0.947128	6.62387	50.8586	≤0.001
	Guangdong	76	−0.010347	0.615746	−0.50945	0.17946	−0.01568	5.29328	16.6570	0.00024
	Tianjin	50	−0.000059	0.728239	−1.19001	0.25581	−1.67923	11.7680	183.661	≤0.001
	Hubei	73	0.000273	0.525929	−0.29318	0.11319	1.376033	9.52035	152.353	≤0.001
	Chongqing	52	−0.003066	1.302343	−1.43408	0.60350	−0.00233	2.91958	0.01405	0.99299
	Fujian	33	−0.043104	0.975409	−0.96369	0.35809	0.153695	4.37134	2.71571	0.257212

main difference lies in the choice of basic statistics: Wright's rank sum signed statistics replace Lo-MacKinlay statistics.

The statistics of Belaire-Franch and Contreras are as follows:

$$\begin{aligned} CD(R_1) &= \max_{1\le i\le m}\left|R_1(k_i)\right|,\\ CD(R_2) &= \max_{1\le i\le m}\left|R_2(k_i)\right|,\\ CD(S_1) &= \max_{1\le i\le m}\left|S_1(k_i)\right|. \end{aligned} \tag{11}$$

The above analysis shows that Belaire-Franch and Contreras statistics have better effect than Lo-MacKinlay statistics and Wright statistics. Furthermore, Wright statistics are more effective than Lo-MacKinlay statistics. But in order to better compare the three variance ratio test ideas, the results of these three test methods in the empirical part is listed.

4. Data Sources and Summary Statistics

4.1. Data. This paper studied the daily, weekly, and monthly data of carbon market price in detail. The sample information is summarized in Table 1. All the time series data in this paper can be found on China carbon emissions trading All the data can be:found on Official website of 8 pilot carbon markets: http://www.cerx.cn/; https://www.bjets.com.cn/article/jyxx/; https://www.cneeex.com/; http://www.cnemission.com/; https://www.chinatcx.com.cn/list/43.html; http://www.hbets.cn/; https://tpf.cqggzy.com/; https://www.hxee.com.cn/. it's also free. The data involves 7716 daily, 1995 weekly, and 527 monthly observations. In this paper, the returns of the series are calculated as

$$x_t = 100 \times \ln\left(\frac{P_t}{P_{t-1}}\right). \tag{12}$$

In the formula above, P_t denotes carbon price at time t and log is the natural logarithm.

4.2. Summary Statistics. The descriptive statistics of income series from Beijing, Shanghai, Guangdong, Hubei, Shenzhen, Chongqing, and Fujian carbon exchanges to June 23, 2020, are shown in Table 2. The mean value of the eight carbon trading market return series is around 0, which means that the carbon price is fixed for a period of time and the market is not active. From the fluctuation range of daily income series, that is, the difference between the maximum and the minimum, the minimum difference is 0.22132, and the maximum difference is 4.548318, indicating that the long-term volatility of carbon price is large. In terms of standard deviation, the standard deviation of monthly return series is larger than that of daily return series and weekly return series. The standard deviation of monthly return rate of Chongqing carbon trading market is 0.603508, which is larger than that of Guangdong, Beijing, Hubei, Tianjin, Fujian, Shenzhen, and Shanghai carbon trading markets, indicating that the price volatility of Chongqing carbon trading market is greater than that of other seven cities.

The carbon trading markets in Beijing, Guangdong, Hubei, Tianjin, Chongqing, and Fujian all show negative skewness and high kurtosis, among which the negative skewness indicates that the carbon trading market returns have a thick tail on the left. The skewness of Shenzhen and Shanghai carbon trading markets is 0.166762 and 0.707451,

Table 3: VR test daily returns.

Market		$k = 2$	$k = 5$	$k = 10$	$k = 30$
Beijing	L-M	0.461103***	0.234983***	0.118685***	0.057705***
	z-Statistic	−8.543156	−6.946726	−5.572058	−4.389915
Tianjin	L-M	0.39803**	0.183431**	0.089899*	0.062416
	z-Statistic	−2.485202	−2.15884	−1.861805	−1.487925
Shanghai	L-M	0.493802***	0.239946***	0.110478***	0.057196***
	z-Statistic	−3.010141	−2.922434	−2.837119	−2.684569
Shenzhen	L-M	0.33162***	0.14837***	0.089614***	0.045523**
	z-Statistic	−5.855641	−4.370003	−3.257013	−2.492294
Guangdong	L-M	0.495881***	0.24509***	0.121924***	0.062874***
	z-Statistic	−13.14374	−10.95438	−8.489376	−6.375676
Hubei	L-M	0.438173***	0.216592***	0.120986***	0.058237***
	z-Statistic	−11.23657	−9.326487	−7.594706	−6.188488
Chongqing	L-M	0.628142***	0.354641***	0.192052***	0.103572***
	z-Statistic	−7.126948	−6.645722	−5.402258	−4.128351
Fujian	L-M	0.562276***	0.314032***	0.170541***	0.088683***
	z-Statistic	−7.537041	−6.63919	−5.265964	−4.05519

respectively, which indicates that the right side of the normal distribution is thick tailed. For monthly data, the skewness of return series in Beijing, Guangdong, Chongqing, and Tianjin markets is left to the normal distribution, while the other four markets are opposite. The return series of 8 carbon trading markets show the characteristics of peak and thick tail, and they have the characteristics of abnormal distribution. It further shows that the market can not fully reflect the market information, which leads to information accumulation.

5. Empirical Results

5.1. Empirical Test of Lo-MacKinlay

5.1.1. The Daily Data Results. The test results of traditional variance ratio (Lo-MacKinlay) of daily return series of 8 carbon trading markets are shown in Table 3. According to the treatment method of weak trading market by Ibikunle et al. [24], this paper adjusts the daily return series of eight carbon trading markets. If the statistics of two or more holding periods are larger than the critical value, the null hypothesis of martingale process is rejected, that is, non-weak-form market.

The results show that Beijing, Shanghai, Shenzhen, Guangdong, Hubei, Chongqing, and Fujian markets all refuse the null hypothesis during the holding period. Therefore, Beijing, Shanghai, Shenzhen, Guangdong, Hubei, Chongqing, and Fujian carbon markets are non-weak-form market. The null hypothesis is accepted only when the holding period is 30 days in Tianjin carbon market; also, the statistics of the other three holding periods are higher than the critical value to varying degrees, and the null hypothesis of martingale process is rejected. In the daily return series of Tianjin carbon market, the statistics of three holding periods are greater than the critical value, which indicates that Tianjin carbon market has not reached the weak-form market efficiency. However, when the holding period is 30 days, the statistics are not significant, which indicates that the weak-form efficiency trend of the market is gradually increasing.

To sum up, the statistics of carbon markets in Beijing, Shanghai, Shenzhen, Guangdong, Hubei, Chongqing, and Fujian are greater than the critical value in varying degrees and do not reach the weak-form market efficiency level; Tianjin carbon trading market is a non-weak-form market efficiency, but the trend of weak-form market efficiency is increasing.

5.1.2. The Weekly Data Results. This paper used variance ratio test to do empirical research on weekly return series. The frequency of weekly data is lower than that of daily frequency data. The test results of traditional variance ratio (Lo-MacKinlay) of weekly return series of 8 carbon trading markets are shown in Table 4.

It can be seen from Table 4 that each holding period of weekly return series of Beijing and Guangdong carbon trading markets rejects the original hypothesis at the significance level of 1%, indicating that Beijing and Guangdong carbon trading markets are non-weak-form market efficiency. At the significance level of 10%, the weekly return series of Shanghai, Hubei, Chongqing, and Fujian carbon markets reject the original hypothesis, indicating that these four markets are non-weak-form market efficiency. The test results show that the weekly return series data of Tianjin and Shenzhen carbon trading markets only accept the null hypothesis when the holding period is 30 days, and other holding periods reject the null hypothesis.

5.1.3. The Monthly Data Results. From Table 5, some important implications were obtained. For pilots in Beijing, Tianjin, Shanghai, Shenzhen, Guangdong, and Hubei, we can reject the zero hypothesis of random walk, which illustrates these pilots are non-weak-form market efficiency,

Table 4: VR test weekly returns.

Market		$k = 2$	$k = 4$	$k = 8$	$k = 16$
Beijing	L-M	0.654493***	0.373247***	0.179679***	0.222856***
	z-Statistic	−3.568279	−3.168659	−3.232521	−2.132748
Tianjin	L-M	0.508498**	0.199109**	0.102121*	0.040291
	z-Statistic	−2.115261	−2.035371	−1.905071	−1.505145
Shanghai	L-M	0.410908***	0.168162*	0.084994**	0.037706*
	z-Statistic	−2.855362	−2.393971	−2.209673	−1.75355
Shenzhen	L-M	0.397243***	0.118289**	0.064635*	0.027196
	z-Statistic	−3.037446	−2.443292	−1.886342	−1.276251
Guangdong	L-M	0.51726***	0.243247***	0.132656***	0.05559***
	z-Statistic	−4.920838	−4.574642	−3.663555	−2.844785
Hubei	L-M	0.545944***	0.174654***	0.094933**	0.033483*
	z-Statistic	−3.192883	−2.873131	−2.466674	−1.957215
Chongqing	L-M	0.588219***	0.305006***	0.153959***	0.0544*
	z-Statistic	−3.8407	−3.266235	−2.675175	−1.729808
Fujian	L-M	0.663552***	0.342464***	0.15692***	0.075063**
	z-Statistic	−2.89223	−3.28576	−2.821544	−2.20439

Table 5: VR test monthly returns.

Market		$k = 2$	$k = 4$	$k = 5$	$k = 8$
Beijing	L-M	0.429718***	0.191804**	0.093079**	0.039567*
	z-Statistic	−3.26232	−2.352633	−1.843054	−1.285965
Tianjin	L-M	0.447671**	0.145181*	0.116835*	0.037386*
	z-Statistic	−1.68352	−1.555983	−1.320808	−1.133245
Shanghai	L-M	0.547518**	0.286775**	0.124463*	0.099739*
	z-Statistic	−2.572429	−2.211541	−1.852491	−1.383688
Shenzhen	L-M	0.526742***	0.271877***	0.175267**	0.086916 ∗
	z-Statistic	−3.4036	−2.931565	−2.135711	−1.655951
Guangdong	L-M	0.477374**	0.165066**	0.103202*	0.045582*
	z-Statistic	−2.54605	−2.046049	−1.580276	−1.113698
Hubei	L-M	0.381251**	0.264047**	0.126275**	0.082816*
	z-Statistic	−2.544513	−1.885446	−1.76267	−1.484773
Chongqing	L-M	0.579718**	0.233738**	0.129381*	0.060139
	z-Statistic	−2.283644	−2.017855	−1.568811	−1.023908
Fujian	L-M	0.318991**	0.190508	0.074262	0.429526
	z-Statistic	−2.296156	−1.489103	−1.249386	−0.559659

Table 6: Multiple variance ratio test daily returns.

Market		$k = 2$	$k = 5$	$k = 10$	$k = 30$
Beijing	MV*	0.855219***	0.765296**	0.5791**	0.327714***
	z-Statistic	−2.582753	−2.326537	−2.835249	−3.254458
Tianjin	MV*	0.823469	0.754047	0.688023	0.671746
	z-Statistic	−0.851179	−0.776355	−0.774332	−0.636679
Shanghai	MV*	0.891813	0.721833	0.617111	0.652238
	z-Statistic	−0.644325	−1.049579	−1.175289	−0.940869
Shenzhen	MV*	0.545556***	0.304225***	0.187486***	0.129181**
	z-Statistic	−4.946023	−4.195001	−3.219969	−2.415345
Guangdong	MV*	0.977622	0.939453	0.865519*	0.694647**
	z-Statistic	−0.580622	−0.854024	−1.2375	−1.962708
Hubei	MV*	0.896629	0.884268	0.865104	0.687674
	z-Statistic	−2.184306	−1.388532	−1.127249	−1.921894
Chongqing	MV*	1.338718***	1.774427***	2.16038***	2.312009***
	z-Statistic	6.591535	8.155265	7.88103	6.062376
Fujian	MV*	1.245093***	1.553289***	1.726864***	1.520605**
	z-Statistic	4.455762	5.410534	4.547625	2.227063

Table 7: Multiple variance ratio test weekly returns.

Market		$k=2$	$k=4$	$k=8$	$k=16$
Beijing	MV*	0.481274***	0.16136***	0.07543**	0.027335**
	z-Statistic	−4.547082	−3.59526	−2.975808	−2.011372
Tianjin	MV*	0.938769	0.769341	0.586697	0.484148
	z-Statistic	−0.258347	−0.566016	−0.845348	−0.799943
Shanghai	MV*	0.762357	0.648489	0.795515	1.014917
	z-Statistic	−1.182321	−1.075543	−0.493368	0.03044
Shenzhen	MV*	0.638717**	0.242447**	0.172405*	0.100163
	z-Statistic	−2.344503	−2.411365	−1.764301	−1.207583
Guangdong	MV*	0.912492	0.726244**	0.623283	0.477681
	z-Statistic	−1.059057	−1.801725	−1.632179	−1.558962
Hubei	MV*	0.874062	0.625463*	0.590202	0.692027
	z-Statistic	−1.18299	−1.654001	−1.281003	−0.778588
Chongqing	MV*	0.588219***	0.402421***	0.196758**	0.09251*
	z-Statistic	−3.8407	−3.223077	−2.878752	−2.238048
Fujian	MV*	0.663552***	0.342464***	0.15692***	0.075063**
	z-Statistic	−2.89223	−3.28576	−2.821544	−2.20439

while Chongqing and Fujian pilots are weak-form market efficiency.

Obviously, the empirical results of monthly returns are better than the results of daily data and weekly data. The results show that the carbon market price series of Chongqing and Fujian obey a random walk process. It can be seen that the monthly return series can overcome the disadvantage of thin daily return.

5.2. Multiple Variance Ratio Test

5.2.1. The Daily Data Results. The purpose of this test is to solve the problem of sample size distortion caused by the traditional variance ratio test, which is more credible than the traditional variance ratio test. In the multiple variance ratio test, the null hypothesis VR $(k)=1$ holds for all k values, and the alternative hypothesis VR (km) $\neq 1$ holds for some holding periods, where $m=1,\ldots,m$. Kim uses traditional variance ratio and Chow and Denning test as reference and introduces wild bootstrap into variance ratio test and sets the repetition times equal to 1000 [23, 24]. Because MV statistics have the characteristics of approximate sampling distribution, the problem of sample distortion caused by less sample size is solved. The multiple variance ratio test results of daily return series of 8 carbon trading markets are shown in Table 6.

The multiple variance ratio test method solves the problem of K arbitrary selection with the optimal lag time. The test results of multiple variance ratio are shown in Table 5. Beijing, Shenzhen, and Fujian carbon markets reject the null hypothesis at the significance level of 10%, indicating that Beijing, Shenzhen, and Fujian carbon trading markets are non-weak-form market efficiency. Tianjin, Shanghai, and Hubei carbon trading markets are weak-form market efficiency with insignificant holding periods at 1%, 5%, and 10%. The daily return series of Chongqing carbon trading market rejects the original hypothesis at the level of 1%, indicating that Chongqing carbon trading market is a non-weak-form market efficiency. The test results show that the original hypothesis is rejected only when the holding period is 10 days or 30 days, while the null hypothesis is accepted in other holding periods.

5.2.2. The Weekly Data Results. In this part, this paper used multiple variance ratio test to study the weekly returns of 8 carbon markets. The multiple variance ratio test results are shown in Table 7.

It can be seen from Table 7 that the carbon markets in Beijing, Chongqing, and Fujian reject the null hypothesis at the level of 10% significance. The research results show that the carbon markets in Beijing, Chongqing, and Fujian are non-weak-form market efficiency. Each holding period of weekly return series of Tianjin and Shanghai carbon trading markets is not significant at the level of 1%, 5%, and 10%, and they are weak-form market efficiency. The test results show that the weekly return series data of Shenzhen carbon trading market only accept the null hypothesis when the holding period is 30 days, and other holding periods reject the null hypothesis.

5.2.3. The Monthly Data Results. In our research, we also test the monthly returns using multiple variance ratio test. The empirical test results are shown in Table 8.

From Table 8, obviously, the null hypothesis of random walk in Tianjin and Shanghai, Shenzhen, Guangdong, Hubei, and Chongqing markets can be accepted, which illustrates these pilots are weak-form market efficiency; however, Beijing and Fujian markets are non-weak-form market efficiency.

5.3. Discussion

5.3.1. Carbon Price Volatility. Large price fluctuation and price instability are the prominent factors of the low efficiency of carbon market. Figure 1 shows the price fluctuation characteristics of eight carbon markets from the first trading

Table 8: Multiple variance ratio test monthly returns.

Market		$k=2$	$k=4$	$k=5$	$k=8$
Beijing	MV *	0.695192 * *	0.480591 *	0.343364	0.211074
	z-Statistic	−2.072848	−1.69775	−1.459785	−1.119355
Tianjin	MV *	0.739338	0.399241	0.415626	0.668487
	z-Statistic	−0.938343	−1.308469	−1.011917	−0.412345
Shanghai	MV *	1.093257	1.180996	1.190165	1.191703
	z-Statistic	0.465174	0.528045	0.380225	0.278525
Shenzhen	MV *	0.957645	0.880725	0.466108	0.464588
	z-Statistic	−0.357585	−0.469223	−1.371396	−0.804113
Guangdong	MV *	0.770781	0.683639	0.755878	1.100152
	z-Statistic	−1.519169	−0.87732	−0.459207	0.120964
Hubei	MV *	0.893936	1.075171	1.123346	1.315522
	z-Statistic	−0.555874	0.220587	0.27472	0.436051
Chongqing	MV *	1.059403	0.899872	0.691642	0.68386
	z-Statistic	0.349964	−0.28344	−0.584621	−0.351965
Fujian	MV *	0.450513 * *	0.256212	0.27613	0.127265
	z-Statistic	−1.985703	−1.608904	−1.102051	−1.021691

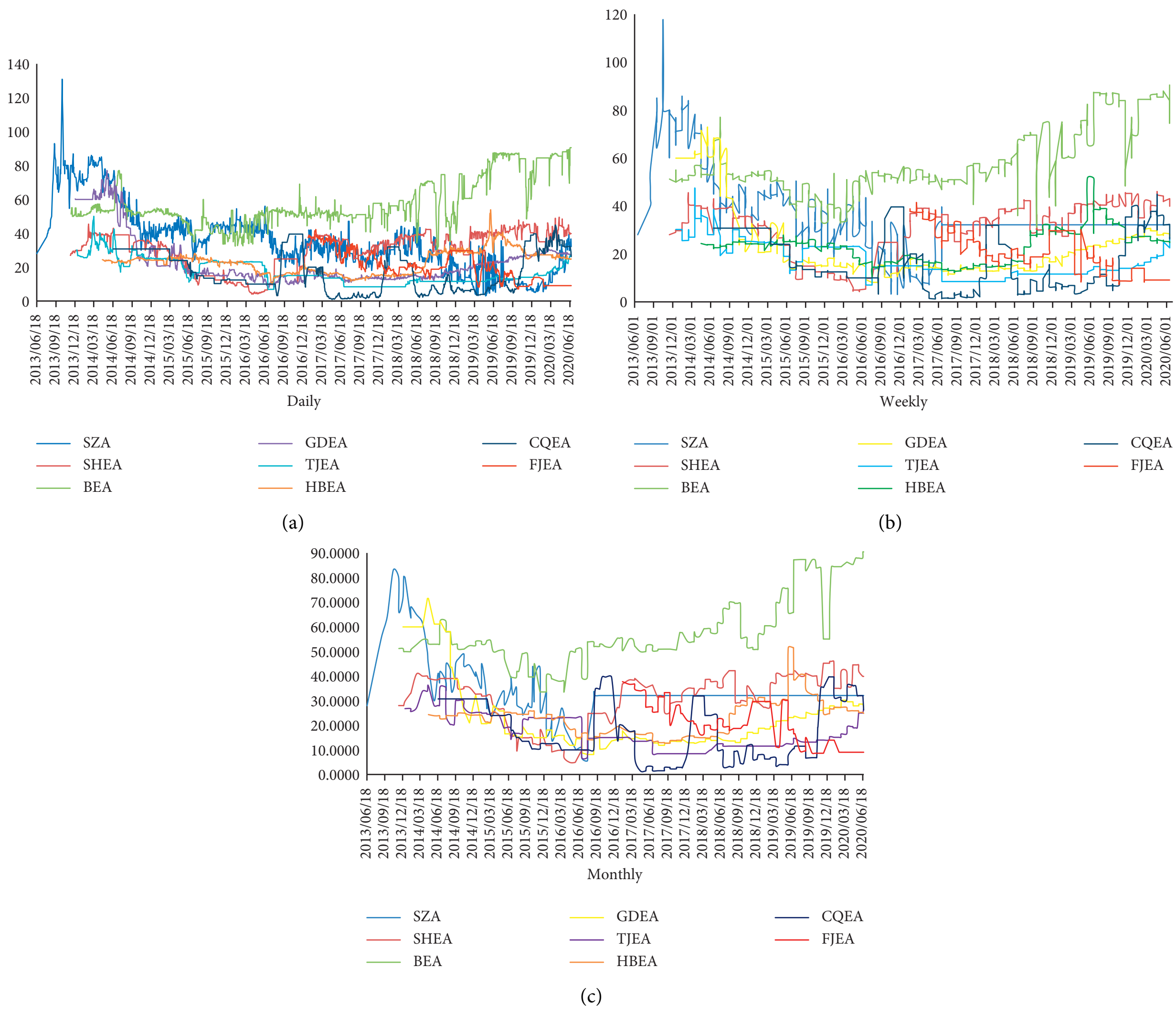

Figure 1: Price volatility of 8 pilots: (a) Daily. (b) Weekly. (c) Monthly.

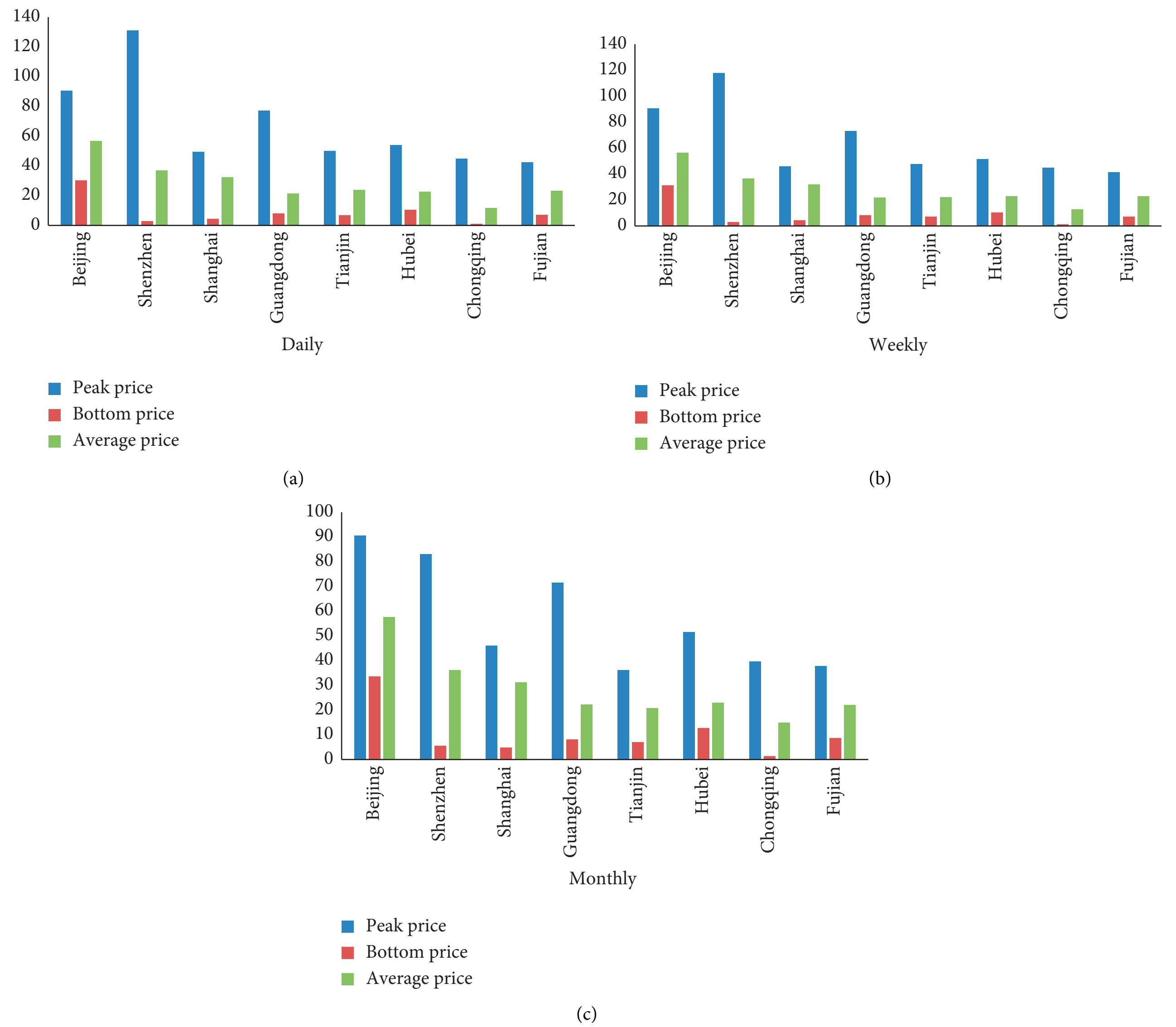

FIGURE 2: The average, peak, and bottom prices of the eight pilot ETS. (a) Daily. (b) Weekly. (c) Monthly.

day to June 23, 2020. The results show that the prices of China's eight carbon markets are very different.

As can be seen from Figure 1, the price of carbon market fluctuates sharply. By the middle of October 2013, the price in Shenzhen had reached a high level of 120 yuan/ton and then dropped sharply, with the price approaching 80 yuan/ton. In the year of 2017, the lowest price is approached to 20 yuan/ton. From 2013 to May 2016, the price of carbon market in Shanghai showed a downward trend, with a fluctuation range of 5–50 yuan/ton, showing an overall upward trend. From Figure 1, it can see that the prices of 8 pilots have similar fluctuation trend whenever it is daily data, weekly data, or monthly data.

5.3.2. Liquidity and Trading Volume. Liquidity is an important indicator to measure the development activity and maturity of the financial market. The stronger the liquidity is, the more attractive it is to all kinds of participating institutions, and the more perfect the price discovery function of the market is.

Transaction prices in an efficient financial market should contain fully available information, which has no empirically verifiable effect on predicting future prices or returns. In this research, this paper calculated the peak price, bottom price, and average price of 8 carbon markets.

Figure 2 shows the average price, peak price, and bottom price of China's eight carbon markets. In terms of the daily peak price, Shenzhen ranked the highest, at 130 yuan/ton, followed by Beijing and Guangdong where the prices were 87 yuan/ton and 78.91 yuan/ton, respectively. Regarding the bottom price, most of the prices are less than 10 yuan/ton. Beijing had the highest at 32 yuan/ton. Nationwide, the average price of carbon market is 25.68 yuan/ton. For the monthly data, Beijing had the highest at 90.5 yuan/ton; Tianjin, Chongqing, and Fujian's are lower, at 36.17 yuan/ton, 39.74 yuan/ton, and 37.74 yuan/ton, respectively.

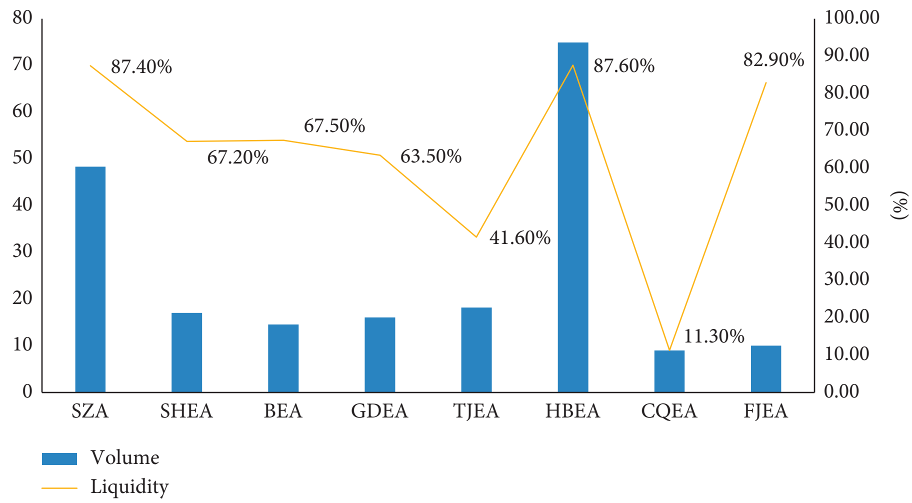

FIGURE 3: The liquidity and volume of the eight carbon markets.

At present, the pilot carbon markets of the eight provinces and cities are still in the early stage of market development, and the liquidity is generally weak. It can only make a preliminary analysis on the trading activity of the eight pilot carbon markets according to the ratio of the trading volume of the spot secondary market to the total amount of its quota. Lack of market liquidity is also the main problem in China's carbon market. Figure 3 shows the liquidity and trading volume of China's carbon market. The eight carbon markets are strikingly different. From our research, it can be concluded that these transactions have been carried out almost every day since Hubei ETS was launched. The trading frequency and activity of carbon market in Hubei Province are the highest among the eight carbon markets. The liquidity of Hubei market is as high as 87.6%, followed by Shenzhen and Fujian, indicating that Hubei and Shenzhen markets are active.

6. Conclusion

Weak-form market efficiency is a good performance of market operation. The basic judgment on the weak efficiency of carbon market is of great significance for building a national unified carbon market. In the empirical analysis, based on the data availability and effectiveness, the paper selects the closing price data of Beijing, Shanghai, Guangdong, and Hubei carbon trading markets from the establishment to June 23, 2020, to test the market weak-form efficiency test. Based on the sample period from June 18, 2013, to June 23, 2020, this paper tests the efficiency of all carbon markets in China (Beijing, Tianjin, Shanghai, Shenzhen, Guangdong, Hubei, Chongqing, and Fujian) and analyzes the factors influencing the efficiency.

The empirical results show that there are significant differences in carbon price levels among domestic carbon markets, and the development of domestic carbon market is unbalanced. The empirical results show that China's carbon market does not achieve weak-form efficiency. At the same time, Tianjin, Hubei, and Shanghai are rich in carbon resources, stable carbon prices, and strong market liquidity, forming a weak efficiency market. On the whole, the market is gradually implemented. In addition, liquidity, trading volume, carbon price, and allocation subsidies also affect market efficiency. The results show the following:

(1) There are many days when the carbon trading volume is zero, and the domestic carbon market is weak.

(2) The daily return series of carbon price follow non-normal distribution, with obvious characteristics of peak and thick tail. Carbon price can not truly reflect market supply and demand and is easier to be manipulated, resulting in higher market investment risk.

(3) The results of validity test are different with different carbon holding periods, and the weak-form efficiency of carbon trading market is phased. The price of carbon trading guides the behavior of the participants, and the weak efficiency of the market plays an important role in the healthy operation of the market. Compared with the research results of the first stage of non-weak efficiency of EU carbon trading market, China's carbon markets have achieved initial success by learning from the successful experience of foreign carbon trading markets and combining with the actual situation in China, which has laid the foundation for building a unified national carbon trading market [25-26].

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest.

Authors' Contributions

All authors contributed equally to this work. All authors read and approved the final manuscript.

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