

## Article

# Price Volatility Transmission in China's Hardwood Lumber Imports

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**Abstract:** Hardwood lumber is the principal part of the global hardwood timber trade. China has become the largest importer of hardwood lumber in the world. However, China's hardwood lumber imports are affected by price volatility. Thus, we investigated the price volatility transmission of China's hardwood lumber imports. We aimed to detect the source, path, and intensity of the volatility transmission in China's hardwood lumber imports, and reveal the intrinsic interactions between price volatilities. To date, there is little research on the price fluctuations of forest products. This paper provides an empirical analysis on the volatility transmission in China's forest product imports. We selected four types of major hardwood lumber imports to China; that is, *teak* (*Tectona grandis* L.F.), *merbau* (*Merbau*), *sapele* (*Entandrophragma*), and *casla* (*Terminalia* spp.) (The Latin names of tree species are given in parentheses), and used their daily prices from 4 August 2010 to 15 April 2020. The Baba–Engle–Kraft–Kroner (BEKK) multivariate models and dynamic conditional correlation (DCC) models were employed. The empirical results indicate that there is an intrinsic relationship between the price fluctuations in China's hardwood lumber imports. The volatility transmission chain originates from casla; it is transmitted along the *casla*→*sapele*→*merbau*→*teak* pathway. The direction of transmission is from lower prices to higher prices. The dynamic conditional correlation of each link in the chain does not exhibit any particular time trend. This suggests that volatility transmission is a crucial price mechanism in China's hardwood lumber imports. Our findings have important policy implications for hedging timber price risks and designing timber trade policies.

**Keywords:** hardwood lumber; China; volatility transmission; BEKK GARCH model; dynamic conditional correlation model



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## 1. Introduction

Hardwood generally has better properties and is more resilient than softwood [1]. Thus, its price is relatively higher. Major countries with rich hardwood forest resources, such as Indonesia, Malaysia, Philippines, Thailand, and Ghana, have banned the exporting of hardwood logs, but encourage hardwood lumber exports (to increase the value-added trade as well as employment) [2]. Therefore, hardwood lumber has become the principal part of global hardwood timber trade; it raises concerns for all parties involved in international wood trade [3].

In accordance with the data by the Food and Agriculture Organization of the United Nations (FAO) [4], global trade value of hardwood log declined from USD 8.60 billion to USD 6.50 billion from 2012 to 2017, and the corresponding trade volume decreased by 44%. However, the trade value of hardwood lumber worldwide increased from USD 9.64 billion to USD 12.55 billion in the same period, and its trade volume increased by 41%. Hence, the proportion of hardwood lumber trade to hardwood timber trade (hardwood timber includes hardwood logs and lumber) increased rapidly. The trade value of hardwood lumber accounted for 56.86% of the global hardwood timber trade in 2012; this rose

to 64.93% in 2017. Likewise, the ratio of hardwood lumber to global trade volume of hardwood timber surged, from 29.31% to 48.99% during the same period.

China has become the largest importer of hardwood lumber in the world. As shown in Table 1, China's hardwood lumber imports grew fast from 2010 to 2018. Its import value and volume of hardwood lumber soared by 11.14% and 9.08% per year, respectively. The growth rate of China was much higher than the average growth level in the world. Accordingly, the percentage of China's hardwood lumber imports in the global hardwood lumber trade increased. China's import value of hardwood lumber reached 40.61% of the global hardwood lumber trade by 2018, and the corresponding proportion of China's import volume of hardwood lumber rose to 45.42%.

**Table 1.** China's hardwood lumber imports from 2010 to 2018.

Year	Import Value of China (Billion Dollars)	Import Value of World (Billion Dollars)	Proportion of China's Import Value in the World (%)	Import Volume of China (Billion m <sup>3</sup> )	Import Volume of World (Billion m <sup>3</sup> )	Proportion of China's Import Volume in the World (%)
2010	2.26	8.92	25.36	5.99	18.93	31.62
2011	2.85	10.07	28.28	7.24	20.44	35.42
2012	2.87	9.64	29.80	6.89	18.91	36.42
2013	3.44	10.24	33.55	7.62	19.37	39.32
2014	5.20	12.81	40.55	9.84	22.70	43.34
2015	4.29	11.30	37.95	9.54	22.27	42.82
2016	4.47	11.08	40.33	10.85	23.85	45.48
2017	5.32	12.55	42.37	12.63	26.66	47.37
2018	5.26	12.96	40.61	12.01	26.43	45.42

Note: the original data were collected from FAO [4].

The structural imbalance between domestic supply and demand of hardwood lumber in China is the main reason for the growth of China's hardwood lumber imports [5,6]. The rapid development of the real estate market and wooden furniture industry in China has driven the growth of China's demand for high-grade hardwood lumber [7]. However, domestic supply of hardwood lumber is mainly low-grade timber. It leads to the high dependency of China on the imports of high-grade hardwood lumber [8]. Thus, China's hardwood lumber imports have a significant influence on the domestic hardwood lumber market. Consequently, China's hardwood lumber imports are affected by price volatility.

There could be volatility transmission among related commodities [9]. Volatility transmission refers to the relevance of price volatility. That is, the price fluctuation of one commodity spurs the similar fluctuation of another [10,11]. The substitutability between commodities is one important reason for volatility transmission [12]. Hardwood lumber is mainly used in wooden furniture manufacturing, wooden floor production, and indoor decorating [13]. Accordingly, different types of hardwood lumber are generally in demand, and share common market information. Southeast Asia and Central Africa are China's chief origins of hardwood lumber [14]. Due to the identical or adjacent geographical distribution, the hardwood lumber imported by China usually has similar input costs. This could bring about volatility transmission between hardwood lumbars, resulting in a price of diffusion risk in the entire timber market. It would increase the risk of decision making for timber traders, increase the difficulty of cost management for wood processing enterprises, and disturb the purchasing plans of domestic consumers. Hence, we explored the volatility transmission in China's hardwood lumber imports to provide theoretical references to minimize the price risk of China's timber trade.

Volatility transmission of commodities is of great interest in regard to price [15–17]. Scholars have studied volatility transmission along the same industrial chain. An, Qiu, and Zheng [18] examined volatility transmission in the beef cattle supply chain of western Canada. They found that volatility transmission was unidirectional from the feed barley market to the feeder cattle market. Saghaian et al. [19] discovered that positive and negative price changes caused an asymmetric volatility transmission between corn and ethanol in the United States. Ben Abdallah et al. [20] studied whether price volatility flowed along

the Finnish meat supply chain. They observed a unidirectional volatility transmission chain from consumers to producers in the Finnish pork market. Ferrer-Pérez and Gracia-de-Rentería [21] investigated volatility transmission in the fresh wild hake supply chain in Spain. Their studies indicated that price volatility was transmitted backward, from retailers to auction, in an asymmetric way.

Studies have focused on volatility transmission of the same commodity across various markets. Yan et al. [22] discussed volatility transmission among international and domestic prices of rice, wheat, and maize in 24 developing countries. They found that volatility of international rice and wheat markets exerted momentous positive effects on the volatility of domestic rice and wheat markets in countries with high import dependence. Sinha et al. [23] found that volatility transmission existed among different onion markets in India. Kakhki et al. [24] conducted an empirical analysis on the volatility transmission of barley between the Iran Mercantile Exchange and the world. Their results suggested that the price volatility of barley transmitted from the world to the Iran Mercantile Exchange. Capitano, Rivieccio, and Adinolfi [25] discovered that the price fluctuation of wheat between Morocco and the world regularly moved together.

Some researchers focus on volatility transmission in substitute commodities. Fakari et al. [26] explored volatility transmission in beef, mutton, and chickens in Iran. They disclosed that beef mutton with a higher degree of substitution had more drastic volatility transmission, compared with other meat pairs. Gardebroek, Hernandez, and Robles [12] estimated the volatility transmission across the price returns of corn, wheat, and soybeans in the United States. Their studies showed that there was a bidirectional volatility interaction between corn and wheat, and wheat had a one-way volatility spillover effect on soybeans. Perifanis and Dagoumas [27] examined the volatility transmission between the wholesale markets of natural gas and crude oil in the United States. Their results showed an evident two-way volatility transmission path between both markets. Živkov, Kuzman, and Subić [28] measured the volatility transmission between four agriculture futures, i.e., corn, wheat, soybean, and rice, indicating that the price volatility of soybean and wheat was greatly affected by the exogenous shocks from others. Chen, Zheng, and Qu [29] detected volatility transmission among rare earth, crude oil, and new energy markets in China. It was inferred that price volatility was transmitted between crude oil and new energy markets.

The research on volatility transmission among goods focus on agricultural products and energy. To date, however, there have been few papers concerned with the volatility transmission of forest products. Due to the leading position of China in global hardwood lumber imports, we conducted an empirical analysis on volatility transmission on the major types of hardwood lumber imported by China to reveal the inherent interaction of price volatility.

The rest of the paper is organized as follows: we analyze the characteristics of the price volatility in China's hardwood lumber imports in Section 2. The methodology is specified in Section 3. In Section 4, the empirical results are presented to analyze the volatility transmission of hardwood lumber imported by China. The reasons for volatility transmission and the corresponding policy implications are discussed in Section 5.

## 2. Materials and Methods

### 2.1. Overall Trend of Price Volatility

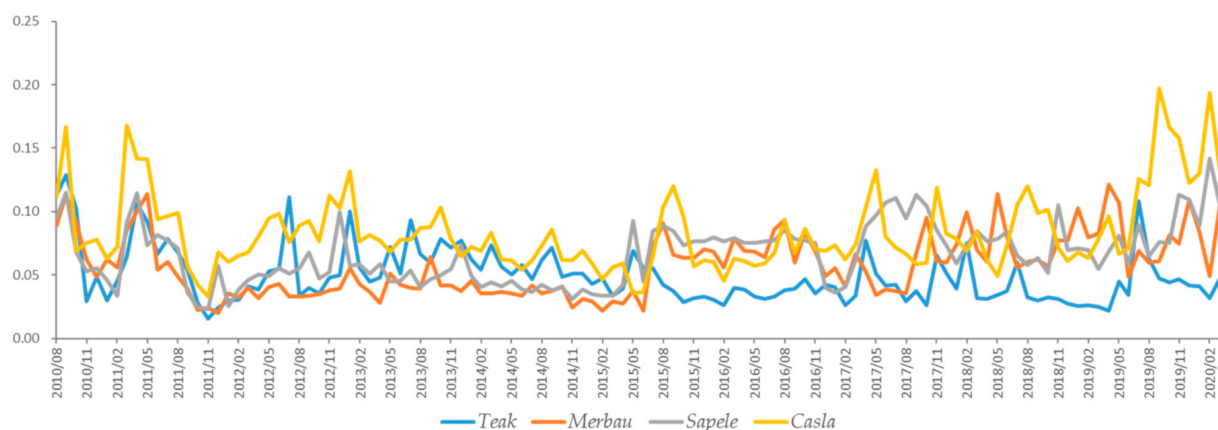
We collected the daily import prices of hardwood lumber from Yuzhu International Timber Market (Yuzhu International Timber Market is located in the city of Guangdong, and has become one of the largest timber trading centers in China. The import prices of timber issued by Yuzhu International Timber Market are important references of decision-making for domestic and foreign timber traders). The time series spanned from 4 August, 2010 to 15 April, 2020. The dataset includes four types of major hardwood lumber imports to China; that is, *teak*, *merbau*, *sapele*, and *casla*. Their names are listed in the descending order of prices. They are mostly used in furniture making and indoor decoration [30].

*Teak* is regarded as first-class timber with a high price because of its excellent wood properties [31]. It is distributed in Southeast Asia. Indonesia, Thailand, and Burma are its main origins. *Merbau* originates in Southeast Asia and the Pacific Islands [32]. Its physical performance is similar to *teak*, but its price is relatively lower. Indonesia and Malaysia are major sources of *merbau*. *Sapele* is widespread in the African tropical zone. Cameroon, Gabon, Congo, and Equatorial Guinea are its principal exporters [33]. The price of *sapele* is lower than *merbau*. *Casla* is widely distributed in Southeast Asia as well as Africa. Its price is the cheapest among the hardwood lumber mentioned above.

The monthly price volatility can be measured according to Equation (1) [34].

$$vm = SD\left(\ln \frac{p_t}{p_{t-1}}\right) \sqrt{n} \quad (1)$$

where  $vm$  stands for volatility amplitude,  $p_t$  is the import price of hardwood lumber on date  $t$ ,  $n$  denotes the number of trading days in one month,  $\ln$  denotes the natural logarithm operator, and  $SD$  refers to the operator of standard deviation. From Figure 1, four types of hardwood lumber have a similar volatility trend overall. In terms of the volatility range, the price volatility of *casla* is higher than the others (most of the time). The price volatility of *merbau* and *sapele* grew sharply since May 2015. The price volatility of *teak* dropped to the lowest level among them after August 2015.



**Figure 1.** The monthly price volatility ratio of major hardwood lumber imported by China.

## 2.2. Methodology

We utilized the Baba–Engle–Kraft–Kroner (BEKK) generalized autoregressive conditional heteroskedasticity (GARCH) models and dynamic conditional correlation (DCC) models to evaluate the volatility transmission across hardwood lumber types. The GARCH models are the principal empirical methods for probing the volatility characteristics of the time series, thus far [35,36]. The BEKK GARCH model proposed by Engle and Kroner [37] is a powerful tool to capture the joint co-movement of conditional volatilities among multi-variables. It does not impose any restriction on the conditional correlation structure of variables, so that, to some extent, the bias of model specification could be avoided [38]. Besides, the number of its parameters is smaller than other multivariate GARCH models [39]. This shows the convenience of its estimation process. The DCC model introduced by Engle [40] allows us to evaluate the dynamic evolution of the interdependence between price volatilities. It is fit to identify the time trend of the estimated conditional correlation [41,42].

The price series are converted into price returns by Equation (2). This logarithmic transformation is a standard method for measuring price returns [43].

$$r_{it} = \ln(p_{it}/p_{i,t-1}) \quad (2)$$

where  $p_{it}$  is the import price of hardwood lumber  $i$  on date  $t$ ,  $r_{it}$  is the corresponding price return after the conversion, and  $\ln$  denotes the natural logarithm operator.

Then, the following conditional mean equation in the form of the vector autoregressive (VAR) model, is considered:

$$r_t = \gamma_0 + \sum_{j=1}^p \gamma_j r_{t-j} + \varepsilon_t, \varepsilon_t | I_{t-1} \sim (0, H_t) \quad (3)$$

where  $r_t$  is a  $2 \times 1$  vector of price returns.  $\gamma_0$  is a  $2 \times 1$  vector of long-term drifts.  $\gamma_j$ , with  $j = 1, \dots, p$ , are  $2 \times 2$  matrices of parameters.  $\varepsilon_t$  is a  $2 \times 1$  vector of innovations conditional on past information  $I_{t-1}$  with zero mean.  $H_t$  is the  $2 \times 2$  conditional variance matrix of  $\varepsilon_t$  to assess the price volatility of hardwood lumber. The stationarity of the return series hereinafter rules out the necessity to account for the vector error correction (VEC) model (the VEC model is applied to the modeling of the non-stationary time series with co-integration relations [44]).

The BEKK GARCH model with one-time lag is specified as:

$$H_t = C'C + A'\varepsilon_{t-1}\varepsilon'_{t-1}A + B'H_{t-1}B \quad (4)$$

where  $H_t$  is the corresponding conditional variance matrix.  $C$  is a  $2 \times 2$  upper triangular matrix with constants. Volatility transmission across commodities consists of volatility spillover and persistence effects [45] (Arenas and Lafuente, 2021). The elements of  $a_{ij}$  ( $i \neq j$ ) in the  $2 \times 2$  matrix  $A$  quantify the volatility spillover effect from an innovation in hardwood lumber  $i$  to hardwood lumber  $j$ . The off-diagonal parameters  $b_{ij}$  ( $i \neq j$ ) of the  $2 \times 2$  matrix  $B$  evaluate the volatility persistence effect in conditional variance between hardwood lumber  $i$  and  $j$ .

The DCC model is used to probe the time-varying feature of volatility interaction between hardwood lumber.  $H_t$  is decomposed as follows:

$$H_t = D_t R_t D_t \quad (5)$$

$$R_t = (\rho_{ij,t}), \quad i, j = 1, \dots, N \quad (6)$$

where  $R_t$  is the time-dependent conditional correlation matrix.

$$D_t = \text{diag}(h_{11,t}^{1/2} \dots h_{NN,t}^{1/2}) \quad (7)$$

$$h_{ii,t} = \omega_i + \alpha_i \varepsilon_{i,t-1}^2 + \beta_i h_{ii,t-1} \quad (8)$$

i.e.,  $h_{ii,t}$  is defined as the GARCH (1, 1) specification.

$$R_t = \text{diag}(q_{ii,t}^{-1/2}) Q_t \text{diag}(q_{ii,t}^{-1/2}) \quad (9)$$

The elements  $u_{it}$  of the vector  $u_t$  are defined as:

$$u_{it} = \frac{\varepsilon_{i,t}}{\sqrt{h_{ii,t}}} \quad (10)$$

$$Q_t = (1 - \alpha - \beta) \bar{Q} + \alpha u_{t-1} u'_{t-1} + \beta Q_{t-1} \quad (11)$$

where  $\bar{Q}$  is the  $N \times N$  unconditional covariance matrix of  $u_t$ , and  $\alpha$  and  $\beta$  are non-negative adjustment parameters satisfying  $\alpha + \beta < 1$ .

### 3. Results

We employed the BEKK GARCH model to measure the mean levels of the volatility spillover and persistence effects in China's hardwood lumber imports on the full sample. As illustrated in Table 2, the kurtosis indexes are all greater than 3. This points to a leptokurtic distribution of every price return. The skewness coefficients are close to zero. It

implies that the distributions of the price returns are all symmetrical. The Jarque–Bera tests indicate that none of the return series followed a normal distribution. These tests suggest that the Student T distribution is suitable for the specification of the BEKK GARCH model. The Ljung–Box statistics denote that there is autocorrelation for each price return. Lagrange Multiplier tests verify that all of the price returns have the ARCH effect. The Augmented Dickey–Fuller tests signify that the return series are all stationary at a 1% significance level (see Table 3). These results support that it is proper to choose the VAR and BEKK GARCH models for data fitting.

**Table 2.** The statistical characteristics for the price returns of major hardwood lumber imported by China.

Statistics	<i>Teak</i>	<i>Merbau</i>	<i>Sapele</i>	<i>Casla</i>
Skewness	−0.1321	−0.1944	−0.0153	0.1427
Kurtosis	8.1481	5.3153	3.2984	4.0750
Jarque–Bera	3664.8460	760.1679	12.4100	170.6131
<i>p</i> value	0.0000	0.0000	0.0020	0.0000
LB (10)	201.8507	302.4614	372.7716	411.6194
<i>p</i> value	0.0000	0.0000	0.0000	0.0000
LB (20)	218.7662	310.7639	407.2827	422.0256
<i>p</i> value	0.0000	0.0000	0.0000	0.0000
LM (10)	333.2700	371.7200	446.8800	609.0400
<i>p</i> value	0.0000	0.0000	0.0000	0.0000
LM (20)	402.9600	452.0400	513.1000	657.6800
<i>p</i> value	0.0000	0.0000	0.0000	0.0000
Observations	3310	3310	3310	3310

Note: LB and LM stands for the corresponding Ljung–Box and Lagrange Multiplier test statistics, separately.

**Table 3.** The stationary tests for the return series of major hardwood lumber imported by China.

Coefficient	<i>Teak</i>	<i>Merbau</i>	<i>Sapele</i>	<i>Casla</i>
Augmented Dickey–Fuller test	−48.9197	−44.9719	−32.4749	−39.2390
<i>p</i> value	0.0001	0.0001	0.0000	0.0000

As reported in Table 4, the maximum likelihood technique is used to estimate the parameters of the BEKK GARCH model according to the BHHH algorithm. The optimal lag number is chosen based on Schwarz’s Bayesian information criterion (SBIC). The diagnostic tests are implemented with 10 and 20 lags. The statistics of the Ljung–Box tests hint that we cannot reject the null hypothesis of no autocorrelation in squared residuals. The results of the Lagrange Multiplier tests indicate that the ARCH effect does not exist in squared residuals in all instances. The Hoking Multivariate Portmanteau tests prove that there is no cross-correlation in squared residuals in most cases. These results verify the adequacy of the model specification.



**Table 4.** The empirical results of the Baba–Engle–Kraft–Kroner (BEKK) GARCH model.

Coefficient	Teak–Merbau		Teak–Sapele		Teak–Casla		Merbau–Sapele		Merbau–Casla		Sapele–Casla	
	Teak (i = 1)	Merbau (i = 2)	Teak (i = 1)	Sapele (i = 2)	Teak (i = 1)	Casla (i = 2)	Merbau (i = 1)	Sapele (i = 2)	Merbau (i = 1)	Casla (i = 2)	Sapele (i = 1)	Casla (i = 2)
$a_{i1}$	0.4121 ** (0.0258)	−0.0245 ** (0.0091)	0.4137 ** (0.0290)	−0.0039 (0.0107)	0.4244 ** (0.0270)	−0.0113 (0.0135)	0.2462 ** (0.0357)	0.0416 ** (0.0154)	0.3094 ** (0.1134)	0.0037 (0.0189)	0.2892 ** (0.0264)	−0.0248 ** (0.0055)
$b_{i1}$	0.9006 ** (0.0121)	0.0098 ** (0.0034)	0.9007 ** (0.0135)	0.0034 (0.0044)	0.8980 ** (0.0129)	−0.0020 (0.0058)	0.9659 ** (0.0098)	−0.0175 ** (0.0064)	0.9483 ** (0.0386)	−0.0042 (0.0080)	0.9499 ** (0.0097)	0.0111 ** (0.0007)
$a_{i2}$	−0.0079 (0.0135)	0.2442 ** (0.0240)	−0.0134 (0.0153)	0.2883 ** (0.0208)	−0.0190 (0.0353)	0.2703 ** (0.0210)	−0.0180 (0.0205)	0.3140 ** (0.0230)	−0.0103 (0.0630)	0.2836 ** (0.0780)	0.0218 (0.0185)	0.3139 ** (0.0272)
$b_{i2}$	0.0034 (0.0042)	0.9676 ** (0.0063)	0.0022 (0.0061)	0.9518 ** (0.0072)	0.0054 (0.0160)	0.9587 ** (0.0063)	0.0050 (0.0073)	0.9428 ** (0.0082)	0.0093 (0.0291)	0.9503 ** (0.0282)	−0.0036 (0.0085)	0.9422 ** (0.0105)
$v$		0.6796 (0.7119)		1.3644 (0.5055)		0.3544 (0.8376)		0.8944 (0.6394)		1.1083 (0.5746)		5.6343 (0.0598)
Wald test for non-causality in variance on each lumber ( $H_0: a_{ij} = b_{ij} = 0, \forall i \neq j$ )												
Chi-square	0.6796	9.1814	1.3644	0.8535	0.3544	2.2932	0.8944	7.7655	1.1083	0.5632	5.6343	269.9785
$p$ value	0.7119	0.0101	0.5055	0.6526	0.8376	0.3177	0.6394	0.0206	0.5746	0.7546	0.0598	0.0000
Ljung–Box test for autocorrelation ( $H_0$ : no autocorrelation in squared residuals)												
LB(10)	10.8187	14.9557	12.7454	15.8845	10.4391	14.0465	15.1120	17.6378	11.7988	15.4885	9.7354	14.3347
$p$ value	0.3718	0.1337	0.2383	0.1030	0.4029	0.1709	0.1280	0.0614	0.2987	0.1152	0.4640	0.1583
LB(20)	20.6939	23.7140	21.0241	23.3431	18.8858	20.7599	22.6329	24.2523	20.2505	21.8676	18.8081	21.7692
$p$ value	0.4153	0.2551	0.3957	0.2723	0.5293	0.4114	0.3072	0.2315	0.4424	0.3477	0.5343	0.3532
Lagrange Multiplier test for ARCH residuals ( $H_0$ : no ARCH effects in squared residuals)												
LM(10)	0.2500	0.3600	0.2700	8.1600	0.2200	1.6700	0.1700	3.9700	0.0700	2.5100	7.8500	1.5000
$p$ value	1.0000	1.0000	1.0000	0.6129	1.0000	0.9983	1.0000	0.9487	1.0000	0.9908	0.6433	0.9990
LM(20)	2.6400	0.4200	1.5500	10.7100	1.5100	2.1700	0.2300	6.2700	0.1300	2.9700	10.2700	2.1000
$p$ value	1.0000	1.0000	1.0000	0.9535	1.0000	1.0000	1.0000	0.9985	1.0000	1.0000	0.9631	1.0000
Hosking Multivariate Portmanteau test for cross-correlation ( $H_0$ : no cross-correlation in squared residuals)												
HM(10)	62.0694		56.3292		38.1603		48.5193		42.8500		53.6636	
$p$ value	0.0142		0.0450		0.5533		0.1671		0.3499		0.0729	
HM(20)	85.2241		79.6160		83.7114		74.6684		62.5951		83.4487	
$p$ value	0.3239		0.4911		0.3664		0.6474		0.9246		0.3740	
Log Likelihood	−22,103.6027		−21,628.0652		−20,821.3768		−21,263.2434		−20,456.6258		−20,031.6627	
SBIC	4.2076		4.1594		3.9897		4.0934		3.9271		3.8787	
Observations	3306		3302		3306		3304		3304		3302	

Note: Standard errors are reported in parentheses. LB, LM, and HM denote the Ljung–Box, Lagrange Multiplier, and Hosking Multivariate Portmanteau tests, respectively.  $v$  symbolizes the estimated degree of freedom. SBIC denotes Schwarz’s Bayesian information criterion. \*\* represents the levels of significance at 1%.

The parameters  $a_{21}$  and  $b_{21}$  in the groups of *teak-merbau*, *merbau-sapele*, and *sapele-casla* are all statistically significant at a 1% level. The Wald tests for these groups reject the null hypothesis that  $a_{21}$  and  $b_{21}$  are jointly equal to zero at 5% significance level. It means that the volatility spillover and persistence effects simultaneously exist in China's hardwood lumber imports. The paths of both effects are highly consistent by comparison. Therefore, we infer that the overall volatility transmission chain is *casla*→*sapele*→*merbau*→*teak*. The volatility in China's hardwood lumber imports is transmitted from a lower price to a higher price. The source of volatility transmission is *casla*. Through the comparison of the coefficients along the volatility transmission path, the absolute values of  $a_{21}$  and  $b_{21}$  are positively correlated, and the former are larger than the latter. This demonstrates that the volatility spillover and persistence effects move together, and intensify the price volatility of the entire market. The impact of exogenous shocks plays a dominant role in the process of the volatility transmission.

The foregoing analysis uncovers that the volatility transmission in China's hardwood lumber imports conforms to "meteor shower hypothesis" instead of a "heat wave hypothesis". Both hypotheses are put forward by Engle, Ito, and Lin [46]. Exogenous shocks follow a process like a meteor shower hitting the Earth. The impact of this process is displayed as the volatility spillover from one kind of hardwood lumber to another one. In contrast, in the "heat wave hypothesis", the interdependence of volatility across commodities does not exist. A volatile day of one good tends to be followed by another volatile day of itself, but not a volatile day of others.

We investigate the dynamic change of interrelation between price volatility of hardwood lumber via the DCC model. The diagnostic tests illustrate that there is no autocorrelation, ARCH effect, or cross-correlation in the squared residuals (see Table 5). The estimated coefficients  $\alpha$  and  $\beta$  in each link of the volatility transmission chain are both significant at the 1% level. The null hypotheses that the parameters  $\alpha$  and  $\beta$  are jointly equal to zero are rejected by the Wald tests at the 1% significance level. These signify the appropriateness of the DCC model assumption. Figure 2 displays the time-variant characteristics of the conditional correlation between the price volatility of hardwood lumber. The conditional correlation of each hardwood lumber pair does not exhibit any particular time trend. The variability in the conditional correlation of *teak-merbau* and *sapele-casla* is higher than *merbau-sapele*. In light of constant conditional correlation, the interdependence of *merbau-sapele* is the greatest, followed by *sapele-casla* and *teak-merbau*. This coincides with the results of the BEKK GARCH model.

**Table 5.** The empirical results of the dynamic conditional correlation (DCC) model.

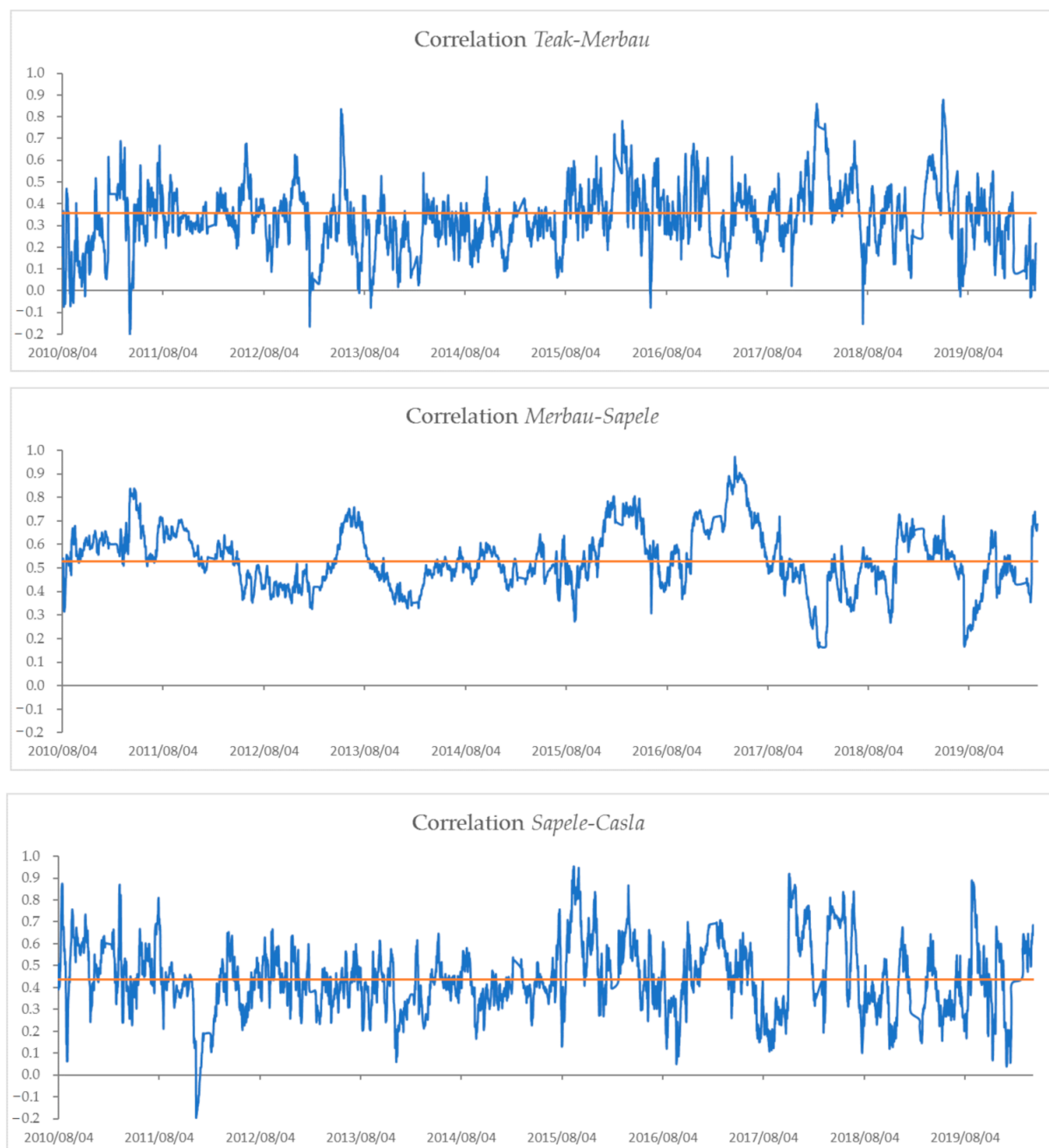
Coefficient	<i>Teak–Merbau</i>		<i>Merbau–Sapele</i>		<i>Sapele–Casla</i>	
$\alpha$	0.0666 **		0.0229 **		0.0547 **	
	(−0.0139)		(−0.0020)		(−0.0150)	
$\beta$	0.8898 **		0.9705 **		0.9185 **	
	(−0.0293)		(−0.0027)		(−0.0321)	
$v$	2.0097 **		2.9847 **		6.3803 **	
	(−0.3578)		(−0.7964)		(−1.5652)	
Wald joint test for adjustment coefficients ( $H_0$ : $\alpha = \beta = 0$ )						
Chi-square	3166.3455		139546.4342		4137.7509	
$p$ value	0.0000		0.0000		0.0000	
Lung–Box test for autocorrelation ( $H_0$ : no autocorrelation in squared residuals)						
	<i>Teak</i>	<i>Merbau</i>	<i>Merbau</i>	<i>Sapele</i>	<i>Sapele</i>	<i>Casla</i>
LB(10)	10.9129	7.7272	7.5170	11.1469	11.5540	9.2500
$p$ value	0.3643	0.6555	0.6759	0.3462	0.3160	0.5086
LB(20)	19.9054	15.8634	16.0866	19.5684	21.4179	18.5363
$p$ value	0.4639	0.7251	0.7112	0.4852	0.3729	0.5521
Lagrange Multiplier test for ARCH residuals ( $H_0$ : no ARCH effects in squared residuals)						
LM(10)	0.2200	0.0600	0.0600	2.4900	4.7800	0.8300
$p$ value	1.0000	1.0000	1.0000	0.9910	0.9054	0.9999
LM(20)	1.2900	0.1200	0.1300	7.0900	9.1700	1.4500
$p$ value	1.0000	1.0000	1.0000	0.9964	0.9808	1.0000



Table 5. Cont.

Coefficient	<i>Teak–Merbau</i>	<i>Merbau–Sapele</i>	<i>Sapele–Casla</i>
Hosking Multivariate Portmanteau test for cross-correlation ( $H_0$ : no cross-correlation in squared residuals)			
HM(10)	35.9322	24.9311	30.9594
<i>p</i> value	0.6539	0.9701	0.8468
HM(20)	59.1247	53.2128	65.4146
<i>p</i> value	0.9614	0.9909	0.8806
Log Likelihood	−22,121.0674	−21,292.7373	−20,051.0249
Observations	3306	3304	3302

Note: Standard errors are reported in parentheses. LB, LM, and HM denote the Ljung–Box, Lagrange Multiplier, and Hosking Multivariate Portmanteau tests, respectively. *v* symbolizes the estimated degree of freedom. \*\* represents the levels of significance at 1%



**Figure 2.** The dynamic conditional correlations of major hardwood lumber imported by China. Note: The dynamic conditional correlations are estimated with the DCC model. The solid lines are the constant conditional correlations on the grounds of Bollerslev (1990).

#### 4. Discussion

The empirical analysis confirms that there is an intrinsic interconnection between the price fluctuations in China's hardwood lumber imports. The volatility transmission chain originates from *casla*, and is transmitted along the *casla*→*sapele*→*merbau*→*teak* path. The direction of transmission is from lower to higher prices. This phenomenon could be explained as follows. Low-priced hardwood lumber would have generally wider geographical distribution and larger living wood growing stock than high-priced hardwood lumber. For example, *casla* stems from Southeast Asia and Africa, and *sapele* is distributed in a number of countries in Central Africa. However, the main production of *teak* is in Myanmar, and the chief origin of *merbau* is Indonesia. Consequently, their stock would be smaller than *casla* and *sapele*. In line with the classical price theory, price is the dominant influencing factor of demand [47–49]. The lower the price, the greater the demand. These would result in a higher proportion of cheap hardwood lumber in China's imports, and accordingly, cheap hardwood lumber would have a larger influence on the import price system, compared to expensive hardwood lumber. This could be the main reason why the volatility transmission from less expensive hardwood lumber to more expensive hardwood lumber occurs.

This study has important policy implications. It suggests that volatility transmission is a crucial price mechanism of the timber trade. Thus, it is beneficial to consider volatility transmission for hedging timber price risk and designing timber trade policies. Firms could forecast the fluctuation trends of timber import prices more accurately by means of the insights gained from volatility transmission. It would help timber traders to optimize the price strategies, considering risk aversion, and assist wood processing enterprises in managing the costs of imported timber. For the government, it may provide policy reference to control the overall timber market import price risk. The restriction on the source of volatility transmission or the disconnection of the volatility transmission chain might be feasible approaches to mitigate the market price risk.

#### 5. Conclusions

We employed the BEKK GARCH and DCC models to explore the price volatility transmission in China's hardwood lumber imports. The empirical results demonstrate that volatility transmission, as a vital price mechanism, exists in China's hardwood lumber imports. Volatility transmission presents unidirectional diffusion characteristics. The influence of exogenous shock plays a key role in the process of volatility transmission. The dynamic change of volatility transmission has no obvious time trend. The finding reflects the formation patterns of price risks in China's hardwood lumber market. This provides theoretical references for price risk control. It is helpful for timber traders to optimize a price risk aversion strategy, for wood processing enterprises to manage the costs of timber, and for the government to control the price risk of the overall timber market.

Further research on this topic could be expanded to include other forest products imported by China, such as logs, paper pulp, and paper products. This would assist us in examining whether volatility transmission is widespread in China's forest product imports. On this basis, we would verify the underlying factors driving volatility transmission across forest products through quantitative methods. These studies would help us to understand the nature of price fluctuation in China's forest product imports more completely.

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**Data Availability Statement:** Data available in a publicly accessible repository that does not issue DOIs. Publicly available datasets were analyzed in this study. This data can be found here: <http://www.fao.org/faostat/en/#data/FT>, accessed on 4 July 2021.

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## References

1. State Forestry Administration in China. *China Forestry Statistical Yearbook*; Translated title into English; China Forestry Publishing House: Beijing, China, 2018.
2. Liu, F.; Wheeler, K.; Ganguly, I.; Hu, M. Sustainable Timber Trade: A Study on Discrepancies in Chinese Logs and Lumber Trade Statistics. *Forests* **2020**, *11*, 205. [CrossRef]
3. Parajuli, R.; Zhang, D.W. An Econometric Study of the Hardwood Sawtimber Stumpage Market in Louisiana. *For. Prod. J.* **2017**, *67*, 91–100. [CrossRef]
4. Food and Agriculture Organization of the United Nations. Available online: <http://www.fao.org/faostat/en/#data/FT> (accessed on 28 October 2020).
5. Yang, L.; Yin, Z.; Gan, J.; Wang, F. Asymmetric Price Transmission of Hardwood Lumber Imported by China after Imposition of the Comprehensive Commercial Logging Ban in All Natural Forests. *Forests* **2020**, *11*, 200. [CrossRef]
6. Zhu, G. Status, problems and development suggestions of China's wood market (Translated Title into English). *For. Prod. Ind.* **2003**, *2*, 3–7. [CrossRef]
7. State Forestry Administration in China. *The Report of Forestry Development in China*; Translated title into English; China Forestry Publishing House: Beijing, China, 2016.
8. State Forestry Administration in China. *The Report of Forestry Development in China*; Translated title into English; China Forestry Publishing House: Beijing, China, 2017.
9. Kavussanos, M.G.; Visvikis, I.D.; Dimitrakopoulos, D.N. Economic spillovers between related derivatives markets: The case of commodity and freight markets. *Transp. Res. Part E Logist. Transp. Rev.* **2014**, *68*, 79–102. [CrossRef]
10. Abdelradi, F.; Serra, T. Asymmetric price volatility transmission between food and energy markets: The case of Spain. *Agric. Econ.* **2015**, *46*, 503–513. [CrossRef]
11. Apergis, N.; Rezitis, A. Agricultural price volatility spillover effects: The case of Greece. *Eur. Rev. Agric. Econ.* **2003**, *30*, 389–406. [CrossRef]
12. Gardebreek, C.; Hernandez, M.A.; Robles, M. Market interdependence and volatility transmission among major crops. *Agric. Econ.* **2016**, *47*, 141–155. [CrossRef]
13. State Forestry Administration in China. *China Forestry Statistical Yearbook*; Translated title into English; China Forestry Publishing House: Beijing, China, 2017.
14. Mao, C.; Yan, X. Analysis of the status quo and development trend of broadleaved lumber market in China (Translated title into English). *Int. Wood Ind.* **2019**, *49*, 25–27.
15. Bergmann, D.; O'Connor, D.; Thümmel, A. Price and volatility transmission in, and between, skimmed milk powder, livestock feed and oil markets. *Outlook Agric.* **2017**, *46*, 248–257. [CrossRef]
16. Nazlioglu, S.; Erdem, C.; Soytaş, U. Volatility spillover between oil and agricultural commodity markets. *Energy Econ.* **2013**, *36*, 658–665. [CrossRef]
17. Sendhil, R.; Kar, A.; Mathur, V.C.; Jha, G.K. Price Discovery, Transmission and Volatility: Evidence from Agricultural Commodity Futures. *Agric. Econ. Res. Rev.* **2013**, *26*, 41–54.
18. An, H.; Qiu, F.; Zheng, Y. How do export controls affect price transmission and volatility spillovers in the Ukrainian wheat and flour markets? *Food Policy* **2016**, *100*, 142–150. [CrossRef]
19. Saghaian, S.; Nemati, M.; Walters, C.; Chen, B. Asymmetric Price Volatility Transmission between U.S. Biofuel, Corn, and Oil Markets. *J. Agric. Resour. Econ.* **2018**, *43*, 46–60.
20. Ben Abdallah, M.; Fekete Farkas, M.; Lakner, Z. Analysis of meat price volatility and volatility spillovers in Finland. *Agric. Econ.* **2020**, *66*, 84–91. [CrossRef]
21. Ferrer-Pérez, H.; Gracia-de-Rentería, P. Asymmetric Price Volatility Transmission in the Spanish Fresh Wild Fish Supply Chain. *Mar. Resour. Econ.* **2020**, *35*, 65–81. [CrossRef]
22. Yan, S.; Kameyama, H.; Isoda, H.; Qian, J.; Shoichi, I. Effects of international grain prices on volatility of domestic grain prices in 24 developing countries. *J. Fac. Agric.* **2016**, *61*, 225–232.
23. Sinha, K.; Panwar, S.; Alam, W.; Singh, K.N.; Gurung, B.; Paul, R.K.; Mukherjee, A. Price volatility spillover of Indian onion markets: A comparative study. *Indian J. Agric. Sci.* **2018**, *88*, 114–120.
24. Kakhki, M.D.; Farsi, M.M.; Fakari, B.; Kojori, M. Volatility Transmission of Barley World Price to the Domestic Market of Iran and the Role of Iran Mercantile Exchange: An Application of BEKK Model. *New Medit* **2019**, *18*, 97–108. [CrossRef]
25. Capitanio, F.; Riviello, G.; Adinolfi, F. Food Price Volatility and Asymmetries in Rural Areas of South Mediterranean Countries: A Copula-Based GARCH Model. *Int. J. Environ. Res. Public Health* **2020**, *17*, 5855. [CrossRef] [PubMed]

26. Fakari, B.; Aliabadi, M.M.F.; Mahmoudi, H.; Kojori, M. Volatility spillover and price shocks in Iran's meat market. *Custos Agronegocio* **2016**, *12*, 84–98.
27. Perifanis, T.; Dagoumas, A. Price and Volatility Spillovers Between the US Crude Oil and Natural Gas Wholesale Markets. *Energies* **2018**, *11*, 2757. [[CrossRef](#)]
28. Živkov, D.; Kuzman, B.; Subić, J. What Bayesian quantiles can tell about volatility transmission between the major agricultural futures? *Agric. Econ.* **2020**, *66*, 215–225. [[CrossRef](#)]
29. Chen, Y.; Zheng, B.; Qu, F. Modeling the nexus of crude oil, new energy and rare earth in China: An asymmetric VAR-BEKK (DCC)-GARCH approach. *Resour. Policy* **2020**, *65*, 1–11. [[CrossRef](#)]
30. Grushecky, S.T.; Buehlmann, U.; Schuler, A.; Luppold, W.; Cesa, E. Decline in the US furniture industry: A case study of the impacts to the hardwood lumber supply chain. *Wood Fiber Sci.* **2006**, *38*, 365–376.
31. Lookose, S. Traditional teak wood articles used in households of Nilambur and Malapuram areas of Kerala. *Indian J. Tradit. Know.* **2008**, *7*, 108–111.
32. Ratnasingam, J.; Liat, L.C.; Ramasamy, G.; Mohamed, S.; Senin, A.L. Attributes of sawn timber important for the manufacturers of value-added wood products in Malaysia. *BioResources* **2016**, *11*, 8297–8306. [[CrossRef](#)]
33. Chen, X.; Guo, X.; Ran, J.; Zhu, Y.; Du, G.; Xu, Y.; Pan, B. *Imported Wood Primary Color Manual*; Translated title into English; Shanghai Science and Technology Publishing House: Shanghai, China, 2004; ISBN 7-532-37452-1.
34. Isabelle, P.; Robert, M. *Methods to Analyse Agricultural Commodity Price Volatility*; Springer: New York, NY, USA, 2010; Chapter 4; pp. 45–61. ISBN 978-1-4419-7633-8.
35. Aktan, B.; Korsakienė, R.; Smaliukienė, R. Time-varying volatility modelling of Baltic stock markets. *J. Bus. Econ. Manag.* **2010**, *11*, 511–532. [[CrossRef](#)]
36. Sanjuán-López, A.I.; Dawson, P.J. Volatility effects of index trading and spillovers on US agricultural futures markets: A multivariate GARCH approach. *J. Agric. Econ.* **2017**, *68*, 822–838. [[CrossRef](#)]
37. Engle, R.F.; Kroner, K.F. Multivariate simultaneous generalized ARCH. *Econom. Theory* **1995**, *11*, 122–150. [[CrossRef](#)]
38. Lv, X.; Lien, D.; Yu, C. Who affects who? Oil price against the stock return of oil-related companies: Evidence from the U.S. and China. *Int. Rev. Econ. Finance* **2020**, *67*, 85–100. [[CrossRef](#)]
39. Liu, X.; An, H.; Li, H.; Chen, Z.; Feng, S.; Wen, S. Features of spillover networks in international financial markets: Evidence from the G20 countries. *Phys. A* **2017**, *100*, 265–278. [[CrossRef](#)]
40. Engle, R. Dynamic conditional correlation: A simple class of multivariate generalized autoregressive conditional heteroskedasticity models. *J. Bus. Econ. Stat.* **2002**, *20*, 339–350. [[CrossRef](#)]
41. Gardebroek, C.; Hernandez, M.A. Do Energy Prices Stimulate Food Price Volatility? Examining Volatility Transmission between Us Oil, Ethanol and Corn Markets. *Energy Econ.* **2013**, *40*, 119–129. [[CrossRef](#)]
42. Bauwens, L.; Laurent, S.; Rombouts, J.V.K. Multivariate GARCH models: A survey. *J. Appl. Econom.* **2006**, *21*, 79–109. [[CrossRef](#)]
43. Joscha, B.; Robert, C. Non-linearities in the relationship of agricultural futures prices. *Eur. Rev. Agric. Econ.* **2014**, *41*, 1–23. [[CrossRef](#)]
44. Lütkepohl, H. *New Introduction to Multiple Time Series Analysis*; Springer Science and Business Media: Berlin, Germany, 2005; ISBN 3-540-26239-3.
45. Arenas, L.; Gil Lafuente, A.M. Impact of emerging technologies in banking and finance in Europe: A volatility spillover and contagion approach. *J. Intell. Fuzzy. Syst.* **2021**, *40*, 1903–1919. [[CrossRef](#)]
46. Engle, R.F.; Ito, T.; Lin, W.L. Meteor showers or heat waves? Heteroskedastic intra-daily volatility in the foreign exchange markets. *Econometrica* **1990**, *58*, 525–542. [[CrossRef](#)]
47. Rahman, M.M. Analyzing the contributing factors of timber demand in Bangladesh. *For. Policy Econ.* **2012**, *25*, 42–46. [[CrossRef](#)]
48. Kayacan, B.; Kara, O.; Ucal, M.S.; Ozturk, A.; Bali, R.; Kocer, S.; Kaplan, E. An econometric analysis of imported timber demand in Turkey. *J. Food Agric. Environ.* **2013**, *11*, 791–794.
49. Gonzalez-Gomez, M.; Bergen, V. Estimation of timber supply and demand for Germany with non-stationary time series data. *Allg. Forst Jagdztg.* **2015**, *186*, 53–62.