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Synchronized movement between US lumber futures and southern pine sawtimber prices and COVID-19 impacts

Jianbang Gan, Nana Tian, Junyeong Choi, and Matthew H. Pelkki

Abstract: We analyzed the synchronized movements of lumber futures and southern pine sawtimber stumpage prices in the United States since 2011 and their response to COVID-19 events using wavelet analysis and event study. We found that the sawtimber and lumber prices have followed complex comovement patterns in the time–frequency domain and both reacted to COVID-19 events with a higher response intensity of the lumber price. Although they reacted differently to the early COVID-19 episodes and vaccine news, the sawtimber and lumber prices responded similarly to the COVID-19 pandemic declarations by the World Health Organization and US president, the US Food and Drug Administration panel's recommendation of the first COVID-19 vaccine, and economic stimulus legislation. The patterns of synchronized movements between the sawtimber and lumber prices varied with time and frequency, but their comovement at low frequencies (>64 weeks) has strengthened since 2014 and been led by the lumber futures price; COVID-19 episodes have not changed this trend. The different magnitude of response of the two prices to the COVID-19-related events, as well as the long-term dominance of the lumber price in the comovement, reveals asymmetric price negotiation power and benefit distributions among the agents of the lumber value chain.

Key words: COVID-19, stumpage price, lumber futures price, wavelet analysis, event study.

Résumé : Nous avons analysé les mouvements synchronisés de la valeur à terme du bois de construction et la valeur du bois de sciage du bois sur pied du pin du sud aux États-Unis depuis 2011 et leur réponse aux événements de la COVID-19 en utilisant l'analyse d'ondelette et l'étude d'événement. Nous avons constaté que la valeur du bois de sciage et celle du bois d'oeuvre ont suivi des modèles de covariation complexes dans le domaine temps-fréquence et que les deux ont réagi aux événements de la COVID-19, avec une intensité de réponse plus élevée de la valeur du bois d'oeuvre. Même si elles ont réagi différemment aux premières manifestations de la COVID-19 et aux nouvelles concernant les vaccins, la valeur du bois de sciage et la valeur du bois d'oeuvre ont répondu similairement aux annonces de pandémie de COVID-19 par l'Organisation mondiale de la Santé et le Président des États-Unis, à la recommandation du groupe d'experts de la Food and Drug Administration américaine concernant le premier vaccin contre la COVID-19 et à la loi sur la relance économique. Les modèles des mouvements synchronisés entre la valeur du bois de sciage et la valeur du bois d'oeuvre ont varié avec le temps et la fréquence, mais leur covariation à de basses fréquences (>64 semaines) s'est renforcée depuis 2014 et a été guidée par la valeur à terme du bois de construction; les manifestations de la COVID-19 n'ont pas changé cette tendance. La magnitude différente de la réponse des deux valeurs aux événements reliés à la COVID-19 de même que la domination à long terme de la valeur du bois d'oeuvre dans la covariation révèlent le pouvoir de négociation de la valeur et la distribution des bénéfices asymétriques entre les agents de la chaîne de valeur du bois d'oeuvre. [Traduit par la Rédaction]

Mots-clés : COVID-19, valeur du bois sur pied, valeur à terme du bois de construction, analyse d'ondelette, étude d'événement.

Introduction

Sawtimber is the raw material for lumber production, suggesting that their prices are interrelated. Ample empirical studies have been carried out to analyze the dynamics of sawtimber and lumber prices as well as their interrelationships (e.g., Ning and Sun 2014; Klepacka et al. 2017; da Silva et al. 2020). Yet, in recent years and particularly during the COVID-19 pandemic, lumber futures and southern pine sawtimber prices in the United States (US) have demonstrated different and divergent paths of movement (Fig. 1), leading to increasing concern about their economic impacts and the health of the industry (e.g., Keegan et al. 2011; Riddle 2021). During the pandemic, for example, the lumber futures price has followed a volatile path while southern pine sawtimber price has shown minimal fluctuations (Fig. 1). The distinct trajectories of the sawtimber and lumber futures prices have yielded different impacts on market participants including consumers, traders, sawmill operators, loggers, and tree growers (Riddle 2021). Such a phenomenon calls into question whether and to what extent the sawtimber and lumber futures prices have reacted differently to COVID-19 events and how the relationship between the two prices has evolved over time.

Price interactions across different forest products and markets have been extensively studied. Most of the existing studies have examined the relationships among the prices of a similar product in different locations and markets, commonly known as horizontal

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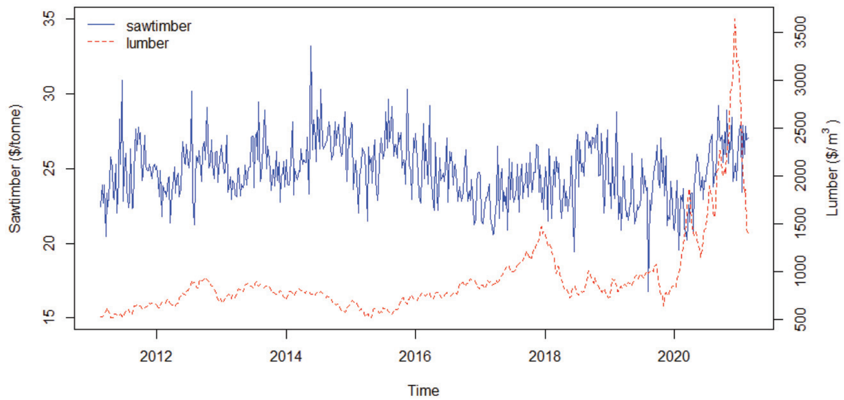
Fig. 1. The weekly prices of southern pine sawtimber stumpage and lumber futures prices (US$) in the United States from the first week of August 2011 to the last week of July 2021. [Color online.]



price transmission or the law of one price (Isard 1977). Although the law of one price is not universally held for all forest products across all markets, the evidence of horizontal price transmissions has been found among various forest products, including stumpage and sawlogs (Nagubadi et al. 2001; Daniels 2011), lumber (Jung and Doroodian 1994; Yin and Baek 2005; Shahi and Kant 2009), and pulp and paper products (Buongiorno and Uusivuori 1992; Tang and Laaksonen-Craig 2007).

A small number of studies have also explored vertical price transmission of forest products, and their results are mixed. Cointegration between pine stumpage and lumber prices in the southern US is reported to be weak or non-existing (Zhou and Buongiorno 2005; Ning and Sun 2014). On the other hand, hardwood sawtimber and lumber prices in the US state of Ohio are found to be closely interrelated though following different fluctuation patterns (Luppold et al. 1998). These studies primarily used cointegration and regression analysis that can capture the price dynamics over time but is unable to incorporate the frequency dimension. Additional insights can be gained when the price dynamics and comovement are portrayed in the two-dimensional time–frequency domain.

Besides cointegration analysis, researchers have also assessed the impacts of individual events on the prices of forest products. Natural disturbances like hurricanes, wildfires, pest infestations, and droughts can affect both short- and long-term timber supply and thus its price. These natural disturbances often entail salvage harvest, increasing the short-term timber supply and thus suppressing its short-term price; however, these disturbances may reduce the long-term timber inventory, potentially boosting the long-term timber price (Prestemon and Holmes 2000; Boucher et al. 2018). International trade disputes, housing starts, and environmental protection regulation and enforcement can also influence timber and lumber prices. The US–Canada softwood lumber trade disputes are found to contribute to lumber price volatility in the US (Zhang and Sun 2001; Karali 2011). The lumber futures price is reported to react more quickly to news on housing starts than to news on trade disputes and court rulings on the cases related to the Endangered Species Act (Rucker et al. 2005). Yet, COVID-19 episodes are unlike any of these previous events and will have broader and more profound and complex impacts on all market participants. Because COVID-19 episodes are still evolving, their long-term impacts are yet to reveal. But their short-term impacts, though having emerged, are not well understood and analyzed.

Here, we attempt to examine (*i*) the short-term response of lumber futures and southern pine sawtimber stumpage prices to COVID-19-related events in the US, and (*ii*) the comovement between the two prices in the time–frequency domain. Specifically, this study aims to answer the following questions: (*i*) How have the lumber futures and pine sawtimber stumpage prices reacted to COVID-19-related events including the official announcements of COVID-19 pandemic, vaccine news, and government economic stimuli? (*ii*) How have the sawtimber and lumber prices evolved synchronically, if at all? and (*iii*) Has the COVID-19 pandemic altered the historical comovement pattern of the sawtimber and lumber prices?

Answers to these questions will enhance our understanding of the dynamics of and relationships between these prices during and before the COVID-19 pandemic. The results derived from our event study and wavelet analysis offer new insights into the interrelationships between the lumber futures and pine sawtimber stumpage prices, and confirm the fundamental linkage between the two prices although the lumber futures price has reacted more substantially to COVID-19-related events than the sawtimber price has. Our findings help fill a knowledge gap about the COVID-19 impacts on forest product markets and prices and their implications for different agents of the wood product value chain. As the pandemic is still unfolding and likely to have far-reaching impacts, the results of this study will be of interest to researchers, policy makers, and market participants alike.

Materials and methods

Wavelet analysis

Wavelet analysis was employed to examine the comovement patterns between the southern pine sawtimber stumpage and lumber futures prices in the US. This method has advantages over other alternatives like correlation and cointegration analyses as it allows for detecting and analyzing comovement between two time series in both frequency and time dimensions (Percival and Walden 2000; Rua 2010). In addition, the stationarity of time series is not required in wavelet analysis. Thus, it has been widely used in engineering, physics, and other fields, and its applications in economics have also gained steams in recent years, particularly in the analysis of asset prices and business cycles (Crowley 2007; Yogo 2008; Rua and Nunes 2009).

Wavelet transform can decompose a time series like the sawtimber or lumber price into some elementary wavelets:

$$\psi(t) = \frac{1}{\sqrt{s}}\psi\left(\frac{t-\tau}{s}\right) \tag{1}$$

where t denotes time, τ represents the center of the wavelet's energy, and s indicates the scale. $\psi(\cdot)$ shown in eq. 1 is centered at τ with scale s. The shift of the energy center of a wavelet over time reflects its translation property while the scale indicates its dilation property (Percival and Walden 2000; Crowley 2007; Rua 2010).

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The continuous wavelet transform of a time series, $x(t)$, can be represented by

$$W_x(\tau,s)=\frac{1}{\sqrt{s}}\int_{-\infty}^{+\infty}x(t)\,\psi\left(\frac{t-\tau}{s}\right)dt \quad (2)$$

Thus, an inverse wavelet transform will give $x(t)$:

$$x(t)=\frac{1}{c}\int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty}w_x(\tau,s)\,\psi\left(\frac{t-\tau}{s}\right)\frac{d\tau ds}{s^2} \quad (3)$$

where c is a constant related to $\psi(\cdot)$.

For two time series, $x(t)$ and $y(t)$, their cross-wavelet spectrum can be calculated as

$$w_{xy}(\tau,s)=w_x(\tau,s)\,w_y(\tau,s) \quad (4)$$

which is a complex conjugate that consists of both real and imaginary parts. Then, the comovement between the two time series, $x(t)$ and $y(t)$, can be measured by

$$\rho_{xy}(\tau,s)=\frac{\mathcal{R}(w_{xy}(\tau,s))}{\sqrt{|w_x(\tau,s)|^2|w_y(\tau,s)|^2}} \quad (5)$$

where $\mathcal{R}(\cdot)$ is the real part of $w_{xy}(\tau,s)$, and $|w(\tau,s)|^2$ is the wavelet power spectrum. ρ_{xy}, which is similar to the Pearson correlation coefficient but in the frequency–time domain and indicative of comovement, is referred as to wavelet coherence.

In addition to the magnitude of comovement, wavelet analysis can also reveal a phase difference, if any, between two time series. Phase differences suggest which series is leading or lagging. For instance, if the phase difference between x and y is zero, then x and y move together in the same direction with neither leading nor lagging; if the phase difference between x and y is equal to π, then x and y move together but in opposite directions with y leading. More detailed descriptions of the wavelet analysis method can be found in Percival and Walden (2000) and Crowley (2007).

Event study

We also conducted an event study to assess the impact of COVID-19-related events on the pine sawtimber stumpage price in the southern US and the lumber futures price at the Chicago Merchandise Exchange (CME). Event studies have been extensively used to investigate the effect of an event on economic and financial market performance including stock prices (MacKinlay 1997; Binder 1998). This method allows researchers to compute the cumulative abnormal return (CAR) from an investment within a time period (event window). It seeks to uncover whether the CAR, the sum of deviations of actual returns from the normal or expected returns within an event window, is attributable to an event.

The CAR from an investment during the event window (T_1, T_2) can be expressed as

$$\mathrm{CAR}_{T_1,T_2}=\sum_{T_1}^{T_2}\mathrm{AR}_t=\sum_{T_1}^{T_2}[R_t-E(R_t)] \quad (6)$$

where t denotes time; and AR, R, and $E(R)$ represent the abnormal return, actual return, and expected or normal return from the investment, respectively.

There are several approaches for estimating the abnormal return, including the average adjusted return rate model, the market index adjusted return rate model, and the market model, among others. The average adjusted return rate model could generate large deviations if a bear or bull market occurs (Klein and Rosenfeld 1987). The results derived from the market index adjusted return rate model could be case-sensitive (Huang and Li 2018). The market model has been most widely used and considered the best alternative although there are often weak statistical relationships between the expected return and the market reference (Armitage 1995). The market model for estimating the expected return of an asset can be written as

$$E(R_t)=\alpha+\beta R_{mt}+\mu_t \quad (7)$$

where R_{mt} is the return of the market reference at time t, a and b are regression coefficients, and μ is the error term.

We used two approaches to estimate the normal return of pine sawtimber and lumber: the market model and the autoregressive integrated moving average (ARIMA) model. In the market model, we selected the S&P 500 index as the market reference. Unlike lumber, pine sawtimber is not traded at CME and thus may not be closely related to the market reference. Hence, we also estimated the ARIMA models for both the sawtimber and lumber prices and used them to project the sawtimber and lumber prices during the COVID-19 pandemic. The ARIMA models essentially assume that the sawtimber and lumber prices would follow their pre-pandemic trajectories if COVID-19 did not emerge.

Prior to fitting the models, we tested the stationarity of the data series using the augmented Dickey–Fuller (ADF) test (Dickey and Fuller 1979) and Kwiatkowski–Phillips–Schmidt–Shin (KPSS) test (Kwiatkowski et al. 1992). Both the ADF and KPSS tests suggested that the return from pine sawtimber is stationary. For the return from lumber, the ADF test failed to reject the null hypothesis of the existence of a unit root, whereas the KPSS test indicated that it is stationary. Both the ADF and KPSS tests, however, confirmed that the first-order difference of the return from lumber is stationary. The stationary data series were then used to fit the models.

The events considered in this study included the COVID-19 pandemic events, vaccine news, and economic stimulus acts enacted in the US (Table 1). Many COVID-19-related events have taken place. We focused on only the major events, including the first COVID-19 case reported in the US and the declarations of COVID-19 a global pandemic by the World Health Organization (WHO) and a national emergency by the US president, the earliest positive news on COVID-19 vaccine development and the first recommendation of COVID-19 vaccines by the US Food and Drug Administration (FDA) advisory panel, and the three largest economic stimulus packages (Acts) enacted in the US. The confirmations of the first US COVID-19 case by the Centers for Disease Control and Prevention and human transmission by Chinese scientists happened on the

Table 1. COVID-19-related events included in the event study.

Date	Event
21 January 2020	Centers for Disease Control and Prevention (CDC) confirmed the first COVID-19 case in the US, and Chinese scientists confirmed COVID-19 human transmission
11 March 2020	World Health Organization (WHO) declared COVID-19 a global pandemic
13 March 2020	US president declared COVID-19 a national emergency
27 March 2020	The Coronavirus Aid, Relief, and Economic Security (CARES) Act was enacted (US$ 2 trillion)
14 July 2020	Moderna early data showed its vaccine efficacy
10 December 2020	US Food and Drug Administration (FDA) advisory panel recommended Pfizer–BioNTech COVID-19 vaccine
27 December 2020	The Consolidated Appropriations Act was enacted (US$ 880 billion)
11 March 2021	The American Rescue Plan Act was enacted (US$ 1.9 trillion)

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same day, and the COVID-19 declarations by WHO and the US president occurred in the same week. The events occurring on the same week were combined. All other events occurred in different weeks and several weeks apart from one another, and each of them was treated as a separate event.

Three event windows were considered. They included the same week (0, 0) when the event occurred (the event week), and the week before (–1, 0) and the week after (0, 1) the event took place. A *t* test was performed to test whether the CAR within each event window was statistically significant.

Data

The CME lumber futures price is a well-documented and widely used lumber price indicator although it is primarily based on the contracts of softwood lumber in the northwestern United States and western Canada (CME Group 2009). Given the lack of southern pine lumber futures price, we were curious about how the southern pine sawtimber stumpage price was related to the CME lumber futures price, particularly as the US South has been a dominant supplier of softwood lumber in the country. In fact, there is strong evidence of the law of one price across major US domestic softwood lumber markets and (or) species including southern pines (Yin and Baek 2005), and US and Canadian softwood lumber markets are also interconnected (Shahi and Kant 2009). We also preferred the CME lumber futures price over lumber spot prices, because the futures price plays a more important role in the price discovery of softwood lumber than the spot price (Parajuli and Zhang 2016).

The daily market-closing lumber futures price (US$/MBF) was retrieved from the NASDAQ (2021), which is based on the CME Random Length lumber futures price (CME Group 2009). The price series reflects continuous futures contracts by rolling "front-month" contracts with consecutive expiration dates using the first-of-month roll method. The daily prices were then converted to their weekly averages for this study. The use of the weekly averages rather than daily prices was because the most frequent pine sawtimber stumpage price available was a weekly series. The pine sawtimber price (US$/ton; 1 ton (short) = 0.907 tonnes (i.e., metric tons)) dataset was purchased from Forest2Market (2021). The daily market-closing S&P 500 index price was obtained from the Wall Street Journal (2021) and converted to its weekly average as well. All three data series covered 522 weeks from the first week of August 2011 to the last week of July 2021 (Fig. 1). With the intention of excluding the impact of the Great Recession of 2008, we did not choose a longer time series for the pre-pandemic historical data. All these data were nominal prices. They were not converted to real prices in this study for two reasons. First, our focus was on the comovement of the sawtimber and lumber prices, and they were affected similarly by inflation. Second, the conventional deflators available are quarterly series that are much less frequent than the weekly data used in this study. Using any of these deflators may distort our price data. The original units of timber futures (US$/MBF) and sawtimber stumpage (US$/ton) prices were converted to international units (US$/m^3 and US$/tonne) for our analyses, respectively.

The pre-pandemic data covering the period from the first week of August 2011 to the last week of 2019 were used to fit both the market and ARIMA models. The best fit models were then used to predict the expected or normal return during the pandemic (from the first week of 2020 to the last week of July 2021) if the COVID-19 did not occur.

Results

Comovement between pine sawtimber stumpage and lumber futures prices

The estimated Pearson correlation coefficients indicate that the pine sawtimber stumpage and lumber futures prices were negatively correlated at a low magnitude during the study period (from August 2011 to July 2021). Additionally, the lumber futures price was more strongly correlated with S&P 500, though in an opposite direction, than the pine sawtimber stumpage price was (Table 2).

Table 2. Pearson correlation coefficients between weekly average southern pine sawtimber stumpage and lumber futures prices and S&P 500 index value (first week of August 2011 – last week of July 2021).

	S&P 500	Lumber future price
Lumber future price	0.61	
Pine sawtimber price	−0.19	−0.19

The wavelet analysis results show more detailed and complex connection between the sawtimber stumpage and lumber futures prices at the frequency–time domain (Fig. 2). The comovement between the two prices has varied with frequency and over time. Since 2014, at low frequencies (64 weeks or longer) the comovement between the two prices has become stronger and been led by the lumber futures price; however, at higher frequencies (between 32 and 64 weeks), the comovement has weakened over time. It appears that their comovement at the frequency of >64 weeks has replaced that at the lower frequency of 32–64 weeks since 2014. This trend has not changed due to the COVID-19 pandemic.

At high frequencies (<32 weeks), there are no clear patterns of long-term comovement between the two prices although the comovement has occurred irregularly for various short time periods. Interestingly, during the COVID-19 pandemic, the short-term comovement between the two prices has strengthened at some high frequencies. Specifically, from July 2020 to February 2021 the two prices showed strong synchronized movement with almost no phase difference at the frequency of 5–8 weeks. Since January 2021, the comovement between the two prices has also been strong at the frequency of 14–25 weeks but with a phase difference between $\pi/2$ and $-\pi$, indicating the sawtimber stumpage price leading the comovement.

These wavelet analysis results provide new insights into the comovement and transmission between the pine sawtimber stumpage and lumber futures prices in the US. Their comovement patterns consist of both short- and long-term comovements at different frequencies and have evolved over time. Simple correlation or cointegration analysis may not be able to uncover all these details and the complexity of their comovement patterns. Although their comovements at higher frequencies are varying and last for only a short period, the strong evidence of their comovement at the frequency of >64 weeks over the last 7 years suggests that the pine sawtimber and lumber futures prices are fundamentally linked to each other. And, the lumber price has led this comovement, implying that the lumber price has driven the sawtimber price in the long term. The long-term dominant role of the lumber price in the comovement also indicates that lumber market players have more price negotiation power than tree growers. In the short term, however, the sawtimber price can influence the lumber price as well, as shown by the leading role of the sawtimber price in the comovement for a short period during the pandemic. This may be partly because the abundant supply of pine sawtimber (Fu 2018; Oswalt et al. 2019) or relatively small fluctuations in the sawtimber price may have served as resistance to further abnormal increases in the lumber price.

We were also curious about the comovement pattern during the economic recovery from the Great Recession of 2008. Thus, we added the data from the trough month (June 2009) of the Great Recession (Radlin 2021) to July 2011 to the original dataset and redid the wavelet analysis. The comovement pattern between the two prices during the Great Recession recovery period did not show any noticeable difference from the far left part of Fig. 2. The event study, on the other hand, entailed avoiding this unusual

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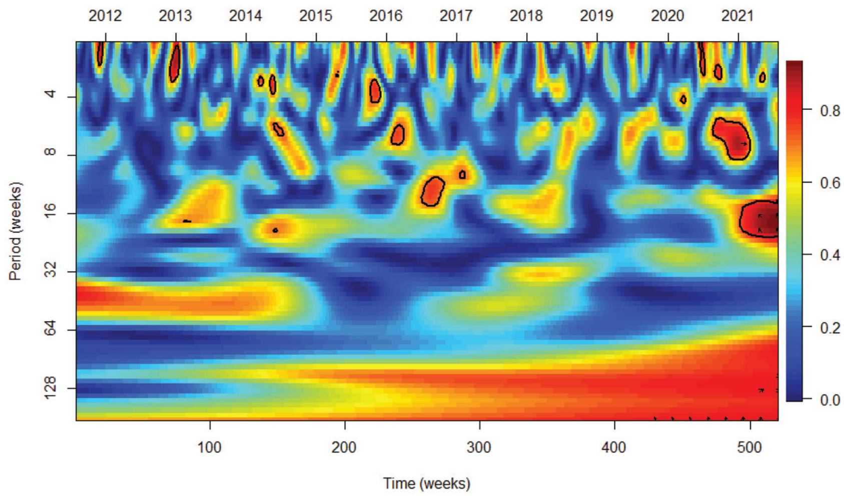
Fig. 2. Wavelet coherence between the southern pine sawtimber stumpage and lumber futures prices in the United States in the frequency–time domain from the first week of August 2011 to the last week of July 2021. The color indicates the magnitude of wavelet coherence with red indicating high coherence. The arrows denote the phase difference of the lumber futures price over the pine sawtimber stumpage price.



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period for estimating the normal or expected return. Hence, for data consistency, the Great Recession recovery period was not included in Fig. 2.

Price response to COVID-19-related events

The earliest COVID-19 cases were found in Wuhan, China, in December 2019, and soon its infection cases were reported in other countries including the US. The event study result shows the early COVID-19 event, the first COVID-19 case in the US and the human transmission confirmation in China, had a different impact on the sawtimber and lumber prices. The sawtimber price reacted negatively to the event, whereas the lumber price was irresponsive during the event week, the event window (0, 0). Both the sawtimber and lumber prices responded negatively when WHO and the US president declared the COVID-19 a global pandemic and a national emergency, respectively. Yet, the sawtimber market tended to ignore the declarations in the following week, (0, 1), with no significant abnormal rise in its price while the lumber price continued to drop. This might be largely because lumber market players perceived that COVID-19 would suppress lumber demand with worsening economic conditions as they experienced during the Great Depression (Riddle 2021). The sawtimber and lumber prices also reacted differently to the first positive news on COVID-19 vaccine development. During the week when Moderna released the research finding of its vaccine candidate's efficacy, the lumber price jumped while the sawtimber price reacted negatively according to the market model but showed no significant abnormal movement based on the ARIMA model. However, based on both the market and ARIMA models, both the sawtimber and lumber prices responded positively to the FDA panel's recommendation of Pfizer–BioNTech COVID-19 vaccine. Overall, the sawtimber and lumber prices responded differently to the early COVID-19 episodes and vaccine news, but they reacted similarly to the official COVID-19 declarations by WHO and the US government and the FDA panel's recommendation of the first COVID-19 vaccine.

The FDA panel's vaccine recommendation led to significant abnormal rises in both the sawtimber and lumber prices in all three event windows, including the week when the recommendation was made and 1 week before and after the recommendation. This implies that both the sawtimber and lumber markets anticipated the vaccine approval and that the FDA panel's recommendation had a positive impact on the sawtimber and lumber markets for at least 2 weeks. Additionally, in terms of the magnitude of CARs, the response of the lumber price to the FDA panel's recommendation was much greater than that of the sawtimber price, except for the result based on the ARIMA model at the event window (0, 1). The results based on both the market and ARIMA models are quite consistent for this group of events shown in Table 3, suggesting the robustness of the findings on the impacts of COVID-19 episodes and vaccine news on the sawtimber and lumber markets.

During the pandemic, several events associated with US–Canada softwood lumber trade disputes also occurred. These events did not overlap the COVID-19 events included in this study, except that in late November 2020 the US Department of Commerce announced to hike tariffs on softwood lumber imported from Canada and shortly Canada appealed under the Canada – United States – Mexico Agreement (CUSMA). The US announcement was close to the event window (−1, 0) of the FDA panel's vaccine recommendation. Such tariff increases usually tend to lift lumber prices in the US and reduce the prices in Canada (Buongiorno 2018), but the Canadian appeal might also dim the effect.

Table 4 shows the impacts of the COVID-19-related economic stimuli on the sawtimber and lumber prices. When the first stimulus, the Coronavirus Aid, Relief, and Economic Security (CARES) Act was enacted, the sawtimber price reacted negatively during the week and the lumber price responded negatively in the following week. The CARES Act was developed and enacted in a short period, 2 weeks after the US president declared COVID-19 a national emergency. Thus, it might have been perceived by the market players as a sign of concern or uncertainty about the potential adversary impacts of COVID-19 rather than an adequate stimulus. The unprecedented government economic stimulus may have intensified the fear about COVID-19, and thus the markets reacted negatively.

However, both the sawtimber and lumber prices responded positively and strongly to the second and third economic stimuli, particularly based on the market model. The magnitude of impacts of these two economic stimuli was far bigger on the lumber price than on the sawtimber price. The difference in their response magnitude may be attributable to several factors related to their general supply and demand conditions as well as the conditions induced by the COVID-19 pandemic. First, there is an abundant supply of pine sawtimber given the large and sustainable inventory of pine forests on timberlands in the southern US (Oswalt et al. 2019). Commercial forests in the region have been adding 42.5 million m^3 of sawtimber annually (Fu 2018), creating a surplus

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Table 3. Response of southern pine sawtimber stumpage and lumber futures prices to COVID-19 events and vaccine news.

Event	Event window	Sawtimber stumpage price				Lumber futures price			
		CAR_Market	t value	CAR_ARIMA	t value	CAR_Market	t value	CAR_ARIMA	t value
CDC confirmed first COVID-19 case in the US; China confirmed human transmission (21 January 2020)	(−1, 0)	−0.052*	−4.04	0.041*	4.56	−0.032	−0.45	0.024	1.49
	(0, 0)	−0.082*	−6.40	−0.045*	−5.00	−0.035	−0.50	−0.006	−0.37
	(0, 1)	−0.012	−0.97	0.056*	6.22	−0.015	−0.21	0.009	0.60
WHO declared global pandemic (11 March 2020); US declared national emergency (13 March 2020)	(−1, 0)	0.011	0.95	−0.010	−1.16	−0.043	−0.50	−0.087*	−4.51
	(0, 0)	−0.030*	−2.55	−0.032*	−3.88	−0.118	−1.36	−0.121*	−6.35
	(0, 1)	0.103*	8.50	0.110*	13.00	−0.138	−1.58	−0.047*	−2.44
Moderna early data showed its vaccine efficacy (14 July 2020)	(−1, 0)	−0.040*	−3.18	0.017*	1.99	0.084	1.43	0.075*	5.77
	(0, 0)	−0.056*	−4.51	0.008	0.88	0.166*	2.84	0.060*	4.67
	(0, 1)	−0.018	−1.46	0.052*	5.89	0.172*	2.92	−0.018	−1.38
FDA advisory panel recommended Pfizer–BioNTech COVID-19 vaccine (10 December 2020)	(−1, 0)	0.051*	4.59	0.031*	3.91	0.242*	5.97	0.044*	4.86
	(0, 0)	0.067*	6.02	0.044*	5.62	0.373*	9.28	0.116*	13.14
	(0, 1)	0.110*	9.81	0.075*	9.53	0.444*	10.96	0.024*	2.69

Note: CAR is the cumulative abnormal return (ratio), with Market and ARIMA denoting that it is based on the market and ARIMA models, respectively. The event window (0, 0) denotes the week when the event occurred, and (−1, 0) and (0, 1) represent the 1 week before and the 1 week after the even occurred, respectively. An asterisk (*) indicates statistical significance at a 5% or better significance level.

Table 4. Response of southern pine sawtimber stumpage and lumber futures prices to COVID-19-related economic stimuli.

Event	Event window	Sawtimber stumpage price				Lumber futures price			
		CAR_Market	t value	CAR_ARIMA	t value	CAR_Market	t value	CAR_ARIMA	t value
The Coronavirus Aid, Relief, and Economic Security (CARES) Act was enacted on 27 March 2020	(−1, 0)	0.101*	8.57	0.109*	13.01	−0.152	−1.58	−0.052*	−2.44
	(0, 0)	−0.023*	−1.93	−0.051*	−6.13	−0.165	−1.73	0.035	1.69
	(0, 1)	0.050*	4.18	0.056*	6.73	−0.325*	−3.38	−0.141*	−6.65
The Consolidated Appropriations Act was enacted on 27 December 2020	(−1, 0)	0.113*	10.83	0.068*	9.22	0.404*	9.96	−0.065*	−7.28
	(0, 0)	0.131*	12.61	0.073*	10.05	0.368*	9.18	−0.018*	−2.00
	(0, 1)	0.003	0.30	−0.044*	−6.02	0.290*	7.16	−0.066*	−7.39
The American Rescue Plan Act was enacted on 11 March 2021	(−1, 0)	0.063*	6.13	−0.034*	−4.72	0.411*	11.92	−0.011	−1.39
	(0, 0)	0.140*	13.58	0.056*	7.77	0.448*	13.14	0.055*	7.32
	(0, 1)	0.086*	8.28	−0.025*	−3.45	0.413*	12.02	−0.045*	−5.87

Note: CAR is the cumulative abnormal return (ratio), with Market and ARIMA denoting that it is based on the market and ARIMA models, respectively. The event window (0, 0) denotes the week when the event occurred, and (−1, 0) and (0, 1) represent the 1 week before and the 1 week after the event occurred, respectively. As asterisk (*) indicates statistical significance at a 5% or better significance level.

of sawtimber supply. The large timber inventory in the region can easily absorb a rising demand for sawtimber, limiting its price increase. In fact, the pine sawtimber market in the southern US has been slowly responding to improved economic conditions resulting from the recovery from the Great Recession in the past decade, with the stumpage price averaging around US$27.5/tonne with slight fluctuations (Fig. 1). On the other hand, lumber supply is also limited by the capacity of logging and sawmills, which was undermined during the COVID-19 pandemic due to lockdowns and labor shortage (Riddle 2021). The COVID-19-induced lockdowns forced some sawmills to close temporarily, and even after the lockdowns were lifted, the shortage of labors (e.g., loggers and truck drivers) still confined some sawmills from operating at their full capacity (Nicholson and Skerritt 2021). This caused reductions in lumber supply, driving its price up. Second, on the demand side, reduced sawmill and logging operations due to the COVID-19-induced lockdowns and labor shortage led to a decrease in demand for sawtimber stumpage and imposed pressure on its price. Tree growers, however, could delay harvesting or selling their timber at a minimal or no extra cost when its price was dropping. Thus, less dramatic fluctuations in the stumpage price, compared to the lumber price, were observed during the pandemic. On the other hand, the lockdowns and work-from-home resulting from COVID-19 spurred a new wave of demand for residential houses and home improvements (Anenberg and Ringo 2021), escalating lumber demand and price.

Compared to the impacts of COVID-19 episodes and vaccine news (Table 3), the results on the price response to the second and third economic stimuli appear less consistent between the market model and the ARIMA model, particularly for the impact of the second stimulus on the lumber price (Table 4). This is likely related to both the ARIMA model and the legislative process of the economic stimulus acts. Unlike the first stimulus (the CARES Act), the legislative process of the second and third stimuli took several months. The market players had anticipated their enactment, and thus these Acts were no longer a surprise when they finally became effective. Additionally, the ARIMA model relies on previous observations (actual return) to predict future return. Thus, the return of previous periods was embedded in the return of the current and future periods. Consequently, the CARs in all three event windows may be subdued, at least partially, underestimating the impacts of the economic stimuli. For this type of events (less surprising events), the market model seems a better choice than the ARIMA model. As discussed previously, both the market and ARIMA models produced quite consistent results for the events associated with the COVID-19 episodes and vaccine news. Those events were unlikely to accurately predict one or several weeks in advance. Therefore, both the market and ARIMA models worked well there.

Finally, among the consistent responses of the sawtimber and lumber prices to the COVID-19 declarations by WHO and the US president, the FDA panel's recommendation of the first COVID-19 vaccine, and the economic stimuli, the lumber price reacted more substantially than the sawtimber price. This asymmetric price response demonstrates the disparity in the price negotiation power and the resultant disproportional benefit distribution across agents of the lumber value chain. The rising lumber price has passed onto consumers but did not benefit tree growers

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proportionally (Dezember and Monga 2021). Such a disparity, if not resolved, could discourage forestry production (reforestation) and encourage the conversion of forestlands to other uses in the long run (Li and Zhang 2007). This is not in the interest of society as a whole because forests provide, in addition to timber, many other ecosystem services, including water regulation, carbon storage and sequestration, and wildfire habitat (Hanson et al. 2010).

Conclusion

We investigated the synchronized movement between the southern pine sawtimber stumpage and lumber futures prices in the US and their response to COVID-19-related events. The comovement between the two prices is complex, varying over time and across the frequency spectrum and with the short- and long-term comovements overlapped. Although their comovement in high frequencies is varying and lasts only for a short period, the synchronized movement between the two prices at low frequencies (>64 weeks) has strengthened and been led by the lumber price since 2014. Hence, the two prices are fundamentally connected with the lumber price driving the sawtimber price in the long term.

Although the sawtimber stumpage and lumber futures prices reacted differently to the early COVID-19 episodes and vaccine news, they responded similarly to the official COVID-19 declarations by the WHO and US president, the FDA approval of the first COVID-19 vaccine, and the economic stimuli. This points to further evidence of connection between the sawtimber stumpage and lumber future prices even during the COVID-19 pandemic. The most noticeable and important difference, however, is the magnitude rather than speed (based on weekly data) of their response to the COVID-19-related events. In general, the lumber future price tended to react more substantially to the events than the sawtimber stumpage price. This may be attributable to both their general (long-term) supply and demand conditions and short-term market disruptions induced by COVID-19.

The different magnitude of response to the COVID-19-related events between the sawtimber and lumber prices, as well as the long-term dominance of the lumber price in the comovement between the two prices, reveals asymmetric price negotiation power among the agents of the lumber value chain and has resulted in asymmetric benefit distributions among them particularly during the COVID-19 pandemic. This calls for research to identify mechanisms for mitigating the impact disparity and particularly for minimizing the negative and polarized impacts of market disruptions in the future. Additionally, this study examines only the short-term responses of the sawtimber and lumber prices to COVID-19 events. Because COVID-19 episodes are still unfolding, follow-up studies are in order as the recovery from the pandemic progresses.

Competing interests

The authors declare there are no competing interests.

Author contributions

JG designed the study, collected and analyzed the data, and wrote and edited the manuscript. NT collected data and wrote and edited the manuscript. JC analyzed the data. MHP collected data and reviewed the manuscript.

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