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Rethinking the Factors Affecting the Arrival Quantity and Price of Sawlogs in Japanese Sawmills: An ARDL Approach

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Abstract

We clarified the long- and short-term factors affecting the arrival quantity and price of sawlogs in sawmills in Akita Prefecture, the second largest producer of sugi logs (Japanese cedar, *Cryptomeria japonica* D. Don) in Japan. In this study, we applied the autoregressive distributed lag (ARDL) model to derive long-term multipliers and reparameterize error correction models (ECMs). We used monthly data from a 157-month study period from April 2009 to April 2022. Our findings showed that sawlog (sugi, 24 cm - 28 cm in diameter) price was associated with lumber price (sugi nuki, special grade) in the long term. However, price was not much affected by the arrival quantity of sawlogs in sawmills. We found the arrival quantity of sawlogs to be associated with the quantity of lumber shipment strongly but not considerably affected by sawlog price. The results showed the importance of the supply and value chains in sawmills. Finally, ECM for arrival quantity revealed a faster error correction speed than that of price shown in the price model.

Discipline: Forestry
Additional key words: long-term relationship, lumber shortage, sugi, supply chain, value chain

Introduction

A virtuous cycle of planting, tending, and harvesting is critical in plantation forests, which provide multiple resources, including timber. In Japan, plantation forests compose approximately 10 million ha of land area. This accounts for approximately 40% of Japan's total forest area. This is because after World War II, the country undertook large-scale reforestation and afforestation to recover the war-ravaged land and meet future demands. Mostly planted in the 1950s-1960s, many plantation forests have been mature for harvest since the 1990s. Although forest areas have remained almost unchanged, the growing stock is increasing. By 2017, the total growing stock reached approximately 5.2 billion m^3. Approximately 3.3 billion m^3 of the growing stock originates from plantation forests (FA 2022). By contrast, under the free-trade policy, wood production volume has been declining since the mid-1960s. Large quantities of timber were imported because of high economic growth. In 2002, industrial roundwood harvest volume was the lowest—at 15 million m^3—less than one-third of that in 1960. In 2019, this number increased to approximately 22 million m^3. However, this remains very low, less than 0.7% of the total growing stock in plantation forests, which is also less than one-third of the total annual growth in growing stock (FA 2022). Although small-scale forest owners are large in number, the scale of many logging companies and sawmills is also small. This leads to an unstable sawlog and lumber supply. House builders and other lumber consumers have relied on foreign supplies. Owing to national and prefectural policies encouraging the use of domestic timber since 2003 (e.g., in the construction of public buildings) and the countrywide construction of larger-scale sawmills, logging volume has been increasing. The ratio of domestic production to total demand quantity (i.e., the self-sufficiency rate) of wood has been increasing. By 2020, the self-sufficiency rate of total wood has reached 41.8% from that of 18.8% in 2002 (MAFF 2021), doubling in less than two decades.

Sawmills process sawlogs harvested from forests and supply lumber to house builders, precut factories, glued laminated timber factories, home centers, and so on.

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Hence, sawmills are critical in the supply chain of forest products. Traditionally, in Japan, log bidding markets play an important role in supplying sawlogs to sawmills (Endo 2013). Since the early 2000s, however, sawmills began signing loose short-term contracts with logging companies and cooperative associations of forest owners to maintain stable feedstock supplies. In these contracts, price is a critical consideration. Apart from these contracts, sawmills quote monthly prices to logging companies to sell logs to them. Currently, sawmills mainly obtain sawlogs from logging companies and various associations, with less percentage from local log bidding markets (48.0% in 2006, 36.8% in 2011, and 32.5% in 2018; MAFF 2021).

Sawmills are fundamental in the value chain of forest products and in sustainable forest management. In the supply chain, capital or fund flows are critical. End users (e.g., house buyers) pay builders when they buy houses. Part of the funds will finally go to forest owners. This value chain is as important as the supply chain. If the value chain stops, the supply chain will also need to stop. In the value chain, sawmills are close and important to forest owners. In 2021, the price of sugi sawlogs (24 cm - 28 cm in diameter and 3.65 m - 4.00 m in length) was 17,000 yen/m^3 in the national average. However, for logs sold to plywood mills and those for producing wooden chips, the prices are 12,000 and 6,600 yen/m^3, respectively (MAFF 2022a). In 2019 before COVID-19, they are 14,300, 11,300, and 6,300 yen/m^3, respectively. Although sawlogs sell at high prices, forest owners need to accumulate enough return for sustainable forest management. Therefore, sawmills and forest owners are significantly linked.

In this research, we focus on sawmills because of their important positions in the supply and value chains. Managing the arrival quantity and price of sawlogs is important in maintaining operating profit and sustainable management in sawmills. Using an autoregressive distributed lag (ARDL) approach, this study aims to clarify the factors affecting the arrival quantity and price of sawlogs in Japanese sawmills.

Traditional econometric analysis considers simultaneous relationships among arrival, price, and other variables in both the demand and supply sides under equilibrium situations. However, owing to the existence of either excess demand over supply or excess supply over demand, reflecting the real relationships between respondent and explanatory variables using the traditional simultaneous equilibrium approach is difficult. Instead, this study used single models, such as the ARDL models.

The ARDL model has been applied widely in many fields. The ARDL model uses a dynamic form with lag terms for both respondent and explanatory variables and can better reflect the relationships for time series data compared to static models. Many economic time series have strong serial correlations. Without including lag terms, complicated dynamic relationships remain in the residuals of the regression model (Greene 2000).

Harris & Sollis (2003) reported that the strength of the ARDL model is that it provides a good approximation to the unknown data-generating process and unknown form of dynamic adjustment process. Moreover, confirming whether the variables are exogeneous or not is unnecessary.

Michinaka (2022) used the same theme and approach, but this study first renewed the January 2005-December 2020 study period to that of April 2009-April 2022. This included the lumber shortage period from the beginning of 2021. This study added new variables (e.g., bidding entry quantity in the local log bidding market, dummy variables of consumption tax increase, and lumber shortage) and substituted lumber shipment for sawlog consumption. Since 2021, the Japanese lumber market has experienced a sticker shock of lumber price because of COVID-19, which hampered the supply chain. However, whether a structural change in the timber market occurred remains difficult to say. Moreover, this study implemented a unit root test to the residuals of the ARDL models to avoid spurious regression relationships. We hope that the results of our study could help forest owners, logging companies, sawmills, and policymakers better understand the relevant factors and make good decisions in sustainably managing forests and businesses.

Materials and methods

1. Study site

Sugi (Japanese cedar, *Cryptomeria japonica* D. Don) is the most important tree species in Japanese plantation forests. Sugi accounts for over 40% of plantation forest areas and nearly 60% of the production volume of industrial roundwood (MAFF 2021). In this study, we took Akita Prefecture as our study site. Akita Prefecture is located in the northeast and faces the Sea of Japan. Akita is the second largest producer of sugi, next to Miyazaki Prefecture in Kyushu. In Akita Prefecture in 2021, the production of industrial roundwood was 1.18 million m^3. Approximately 41%, 47%, and 12% of logs were sent to sawmills that needed high-quality sawlog, plywood production, and raw materials for woodchips for pulp or electricity generation, respectively. Among the raw materials received by sawmills in Akita Prefecture in 2021, sawlogs harvested in Akita (which is 97.5% sugi), sawlogs harvested in other prefectures, and imported logs accounted for approximately 80.3%, 18.4%, and 1.3%, respectively (MAFF 2023). Aomori Prefecture is the largest exporter of sawlogs (91.1% of which are sugi) to Akita Prefecture. As sugi consists the highest percentage of all raw materials received, we believe that setting the price of sugi as the price for all sawlogs in Akita Prefecture is reasonable.

2. Conception frame of the research

The demand and supply quantities of sawlogs are determined by the demand and supply relationships between the sawmills and sawlog suppliers. Conversely, the quantity and price of lumber are determined by relationships between lumber consumers and sawmills (Fig. 1). Owing to Japan's demand-side leading timber market (Endo 2013, Fujikake 2016, Michinaka 2022), we focus on the factors affecting the arrival quantity and price of sawlogs and hypothesize that the volume of lumber shipped out and the price of lumber are predetermined by the supply and demand relationship between sawmills and lumber buyers.

Weather affects sawlog supply. Rainfall and snowfall decrease the productivity in logging and extracting logs from logging sites. Logging safety is another issue. Continued heavy rainfall may cause landslides, causing potential problems in logging and transportation. Another factor in the supply side is the quantity of bidding entry in the local log bidding markets. Akita Prefectural Federation of Forest Owners' Cooperative Association (APFFOCA) operates seven local log bidding markets, with member cooperative associations of forest owners from the local area. For each log market, at least one market day in 1 month can be used to sell logs through bidding. At the beginning of each month, the logs ready to sell will be announced. Sawmills can tender a bid to buy logs, and sawmills that pay higher prices secure these deals. Log markets prepare these sawlogs for sawmills and constitute one factor in the supply side of the sawlog demand and supply relationship. However, this has never been addressed in quantitative analysis in Japanese forestry economics.

The next factor is the inventory of sawlogs in sawmills. Torii (1973) highlighted that firms' motives for holding inventory can be divided into three types—transactional, reserve, and speculative motives. Yukutake (1977) considered inventory adjustment as an effective short-term market adjustment mechanism. Sawlogs require large volumes, occupy a large amount of space, and need considerable capitalization. Therefore, sawmills need to control the inventory of sawlogs. Winter is the best season for logging in northeastern Japan, and winter logs are good to be kept in the yard in sawmills. Owing to the hot weather and high moisture in summer, sawmills need to process summer logs quickly to avoid insect damage. Some sawmills maintain their inventory at the level of half month of consumption. However, many sawmills in Akita Prefecture maintain inventory at a 2- to 3-month level of consumption. Keeping an adequate inventory of sawlogs is important in both the sustainable operation of production lines and profit management. Conversely, the level of inventory, as shown in its three motives, may affect the arrival quantity and price of sawlogs for purchase.

On October 1, 2013, the Prime Minister announced that the consumption tax rate would be increased from 5 to 8% in April 2014 (Nikkei 2013). Following the

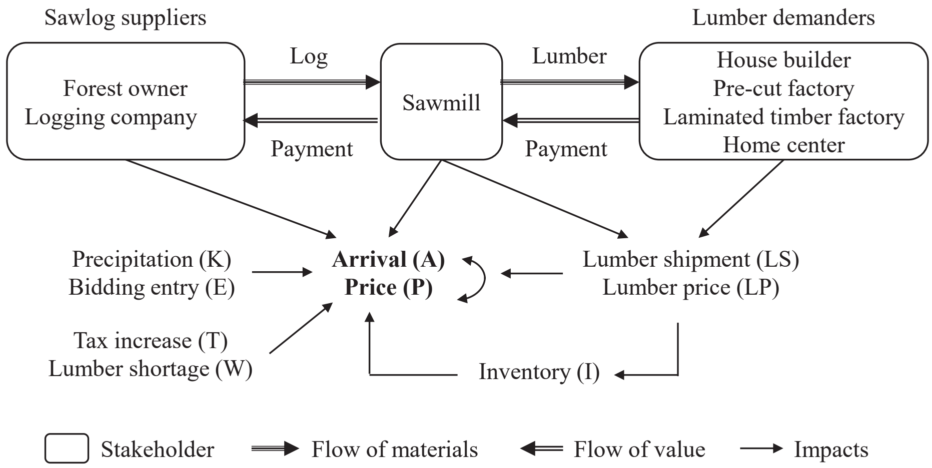

Fig. 1. Conceptual framework of the research

Note: Items with abbreviations are variables to be incorporated in modeling, and arrival quantity and price of sawlogs are target variables.

announcement, the demand for sawlogs and lumber increased. As rush demand did not last long, we added a dummy variable in the analysis. For the period from October 2013 to March 2015, we assigned a value of 1 and 0 if otherwise. Since 2021, the COVID-19 pandemic had caused a considerable increase in lumber prices. Hence, we added another dummy variable, that is, lumber shortage. For the period from January 2021 to April 2022, we assigned a value of 1 and 0 if otherwise. Although this is not shown in Figure 1, we also incorporated a monthly dummy variable to reflect seasonal changes.

In Figure 1, the double arrow shows that sawlog price may affect the arrival quantity of sawlogs and vice versa. When one variable is a respondent variable, the other may be a cause variable.

3. Method

In economics, the general equilibrium theory presents the ideal relationship of supply and demand. Practically, however, a true equilibrium between demand and supply may never be realized. Disequilibrium may be an ordinary state, and this may represent either an excess of demand over supply or excess of supply over demand. In the timber market, demand generally drives and leads the market in both quantity and price, and supply attempts to meet demand. The absence of historical planting and tending cost of forests makes it difficult for forest owners to determine the break-even price in selling logs and standing trees. National forests play an important role in providing wood and maintaining a stable wood supply in Japan. However, this may make their nominal owner—the national government—compete with the private forest owners. Logging companies' need to maintain continuous operations because of their high fixed costs weakens their bargaining position in quantity and price negotiations. However, sawmills must provide qualified lumber or veneer lamina at a low cost to continuously meet the needs of consumers. Determining which factors affect the arrival quantity and price of sawlogs in sawmills in the long term and short term and how they affect sawlog quantity and price is important as these relate to sustainable operation and profit management in sawmills and forest owners.

On econometric analysis, the supply, demand, and defining functions of the equilibrium of demand and supply quantities are commonly seen. However, most studies did not define supply and demand correctly because of the existence of sawlogs in the log market and in sawmills. Traditional equilibrium analysis cannot distinguish long-term impacts from short-term ones. In addition, simultaneous equilibrium equations do not reflect the effects of various factors in the previous periods well. In this research, we did not apply simultaneous equilibrium but we used single models—ARDL models—to clarify the factors affecting the arrival quantity and price of sawlogs.

ARDL models are also called dynamic models, ADL models, or AD models. The static model is more restrictive and may lead to erroneous inferences that do not adequately reflect relationships among variables (De Boef & Keele 2008). It may include lag terms in regression models for technological (production and its preparation need time), institutional (through law or custom), and subjective (imperfect knowledge of the market and psychological inertia) reasons (Koyck 1954). Uncertainty in the aforementioned three reasons is also a reason for the existence of lag terms (USDA 1958). Moreover, this is true for forest industry. For models that include lags, Koyck (1954) highlighted that the individual slope of the lag term is not important. However, he emphasized that the long-term elasticity derived from the slope and speed of recovery of deviations from the equilibrium state are important. He presented equations that include lag terms for explanatory and explained variables.

Pesaran & Shin (1995) were the first to introduce the ARDL model as an abbreviation for the autoregressive distributed lag model to the best of our knowledge. Pesaran et al. (2001) then developed a bounds test method to test for the existence of a long-term relationship (cointegration relationship), regardless of whether the time series is a stationary process (I(0)) or a unit root process (I(1)). The application of the bounds tests has popularized the ARDL model.

However, autoregressive distributional lag models have already existed before 1995. Davidson et al. (1978) showed that difference-in-difference models may exhibit information loss. Moreover, they showed that distributional lag models include past values of the explained variable that can estimate the model at the variable level without differencing and can reflect adjustments for long-term relationships and deviations from equilibrium conditions by transforming the model. Hendry et al. (1984) theoretically described dynamic models (e.g., ARDL models) from general expression to nine restricted specific cases. Hendry (1995) demonstrated that the number of specific equations was increased from 9 to 10. By 1995, many other studies (e.g., Wickens & Breusch 1988) derived (reparameterized) long-term multipliers and error correction models (ECMs) from dynamic models. Essentially, the long-term relationship and ECM analysis do not rely on bounds tests.

In an interview with Ericsson (2004), Hendry stated that "Nonsense regressions are only a problem for static models or for those patched up with autoregressive errors.

If one begins with a general dynamic specification, it is relatively easy to detect that there is no relationship between two unrelated random walks" (p. 766). Ghouse et al. (2018) and Ghouse et al. (2021) showed that using Monte Carlo methods, the lag variables are found to be missing variables. Moreover, they demonstrated that the ARDL model can reveal a spurious regression relationship between those unrelated variables.

The ARDL (p, q) model can be shown as in Equation (1) (De Boef & Keele 2008, IHS Markit 2022).

$$y_t = \alpha_0 + \alpha_1 t + \sum_{i=1}^{p} \varphi_i \, y_{t-i} + \sum_{j=1}^{k} \sum_{l_j=0}^{q_j} \omega_{j,l_j} \, x_{j,t-l_j} + \varepsilon_t. \quad (1)$$

Here, t is the trend term, followed by the autoregressive (AR) parts of the response variable. These are followed by the explanatory variables for the current period and lags, and finally, the error term. p and q are the orders of the lags for the response and explanatory variables, respectively. For k explanatory variables, different lag numbers (q_j) can be set. The sum of the coefficients of the lag terms of the response variables must be met as $\left|\sum_{i=1}^{p} \varphi_i\right| < 1$. This means that y_t is not an explosive process (De Boef & Keele 2008, Hendry 1995). For ARDL models, the respondent variable and the variable expressed by a single equation can be easily distinguished. Parameters can then be estimated by the standard least squares method (Greene 2000).

After the general ARDL model is specified, the long-term effect or long-term multipliers for k explanatory variables can be derived or reparameterized from Equation (1), as shown in Equation (2). When all long-term multipliers are combined, the long-term equilibrium relationship between the response variable and all explanatory variables can be shown in Equation (3). Here, in Equation (2), β_j denotes the slopes of the long-term influencing factors and does not include the slopes of the short-term factors. Equation (4) shows the deviation between the actual value of the response variable and its expectation value at a long-term equilibrium based on long-term multipliers. Equation (5) is an ECM where p and q lag terms can be found for the respondent and explanatory variables, respectively. ECM presentation shows the short-term relationships and adjustment to the last-period's deviation from a long-term equilibrium. Coefficient θ is the error adjustment parameter that indicates the speed of adjustment to restore the equilibrium state and is expected to have a negative and statistically significant sign. Higher θ implies that the faster the speed of adjustment is, the less periods are needed to restore to the equilibrium state. However, when deriving ECMs from ARDL models, standard errors must be calculated separately. In this research, standard errors were calculated using the delta method (IHS Markit 2022).

$$\beta_j = \frac{\sum_{l_j=0}^{q_j} \omega_{j,l_j}}{1 - \sum_{i=1}^{p} \varphi_i}, \quad (2)$$

$$y_t = \beta_1 x_{1,t} + \cdots + \beta_k x_{k,t}, \quad (3)$$

$$ECT_t = y_t - (\beta_1 x_{1,t} + \cdots + \beta_k x_{k,t}), \quad (4)$$

$$\Delta y_t = \alpha_0 + \sum_{i=1}^{p-1} \gamma_i \, \Delta y_{t-i} + \sum_{j=1}^{k} \sum_{l_j=0}^{q_j-1} \delta_j \, \Delta x_{j,t-l_j} + \theta ECT_{t-1} + \varepsilon_t. \quad (5)$$

During model estimation, we used the natural logarithm for each variable, except dummy variables, and selected explanatory variables, including lag terms by AIC. We used the software Eviews 12 for the analysis (IHS Markit 2022). Pesaran and Shin (1995) argued that the problems of residual serial correlation and endogenous regressors in ARDL models can be solved by an appropriate selection of lags. Ghouse et al. (2018) and Ghouse et al. (2021) argued that the ARDL model solves the spurious regression relationships.

Because determining whether the estimated model meets the necessary assumptions is necessary, this study tested the residuals of the ARDL models for 1) independence of error terms, 2) independence of explanatory variables and error terms, 3) residual vs. fitted values, 4) homoscedasticity, and 5) stationarity of residuals.

In this study, we took arrival quantity (A) and price of sawlogs (P) in sawmills as target or response variables. When one of these two variables is the response variable, all other variables can be considered explanatory variables (Fig. 1). Both long- and short-term effects are considered for bidding entry quantity (E) in the sawlog bidding market, inventory of sawlogs in sawmills (I), lumber shipment (LS), lumber price (LP), and the arrival quantity and price of sawlogs in sawmills. As Akita Prefecture did not experience extreme weather conditions during the study period, we believe that we only need to account for the short-term effects of precipitation (K). Similarly, we only considered the short-term effects of the consumption tax increase (T), lumber shortage (W), and monthly dummy variables. The effect of lumber shortage weakened in the summer of 2022, and its long-term effect needs to be considered in the future. Finally, owing to monthly seasonality, we incorporated monthly dummy variables in modeling.

4. Data

For this study, we gathered data from April 2009 to April 2022 from the Ministry of Agriculture, Forestry and Fisheries (MAFF), Meteorological Agency, Akita Prefecture, and APFFOCA. Figure 2 shows the movements of the monthly quantity of the arrival of sawlogs and shipment of lumber in sawmills in Akita Prefecture. The period from 2009 to 2016 exhibited a slightly increasing trend in arrival quantity. After that, some fluctuations in arrival quantity occurred.

Lumber will be shipped out according to orders from consumers (e.g., house builders and glued laminated timber companies). The period from 2009 to 2016 exhibited a slight increase, but after that period, this moved to a lower level. A decrease in lumber shipments could be due to 1) rising shares of kiln dry and biomass electricity generation, 2) an increase in wooden houses built differently from traditional post-and-beam construction, and 3) plywood competition.

Figure 3 shows the prices of sawlogs and lumber in Akita Prefecture. Sawlogs in Akita (sugi sawlogs) are 24 cm - 28 cm in diameter (medium size) for both grades A and B (Note: Grade A is of the best quality. A lower grade may be used for plywood). Sawmills also purchase sawlogs at other sizes (e.g., 14 cm - 22 cm or 30 cm - 36 cm). However, sawlogs at 24 cm - 28 cm are preferred because of their efficiency in processing and, hence, their profitability. Additionally, their prices are higher. On lumber, sugi nuki at a special grade (Note: Nuki is one of the wooden house materials used to reinforce walls and floors by connecting pillars horizontally), an important construction material for wooden houses, was chosen because of its higher proportion in total lumber and data availability. Under Japan's policy of encouraging the use of domestic timber, the decreasing trend in domestic sawlog production had stopped. In the entire period, a slight increasing trend can be found for both prices of sawlogs and lumber. In the period from October 2013 to 2014, price increases due to the rush demand were caused by increased consumption tax. Since 2021, price rose considerably because of the COVID-19 pandemic, and this was considered a lumber shortage.

Figure 4 shows the monthly inventory of sawlogs in sawmills and bidding entry quantity of sawlogs in the log market. Inventory increased sharply in 2019, which may

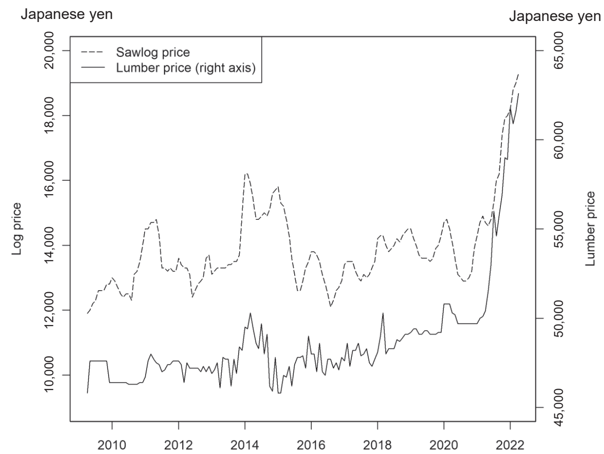

Fig. 3. Monthly prices of sawlogs and lumber in Akita Prefecture
Sources: Prices of sawlogs are from MAFF (2022a), and prices of lumber are from APFFOCA (2022).

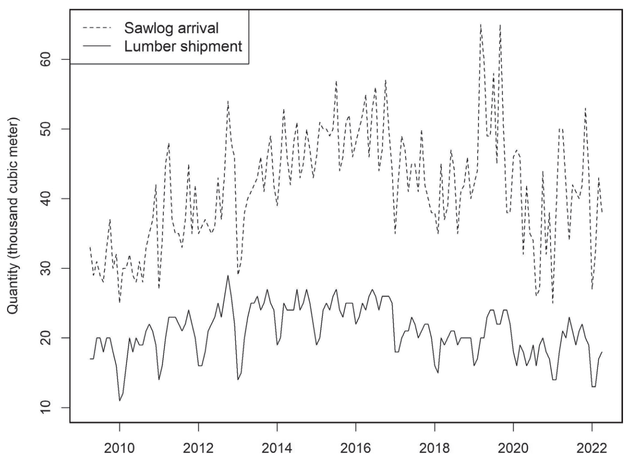

Fig. 2. Monthly arrival of sawlogs and shipment of lumber in sawmills in Akita Prefecture
Source: MAFF (2022b)

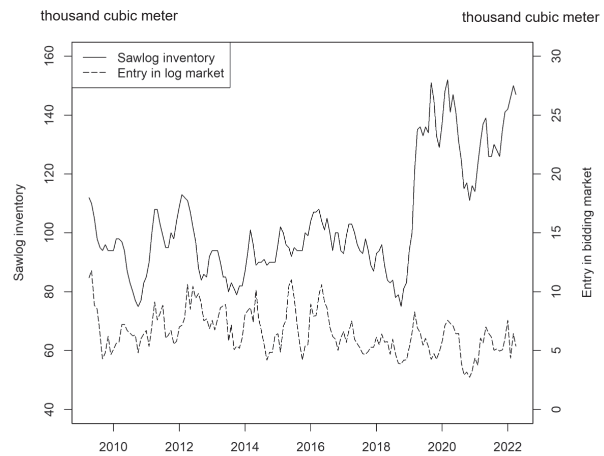

Fig. 4. Monthly inventory of sawlogs in sawmills and bidding entry of sawlogs in the log market in Akita Prefecture
Sources: MAFF (2022b) and APFFOCA (2022)

be due to the increase in demand for sawlogs. Since 2020, the level of arrival has lowered, but the level of inventory was high because of COVID-19. As for bidding entry, since 2017, this has moved at a lower level than that of the past. This is because more sawlogs are being sent directly from logging companies to sawmills and not sent to the bidding market.

Finally, Figure 5 shows monthly precipitation quantity. No extreme precipitation events occurred during the period.

Results

1. Results of the general ARDL model and long-term relationships

As shown in Equation (1), we first specified the ARDL models for the arrival quantity and price of the sawlogs in sawmills in Akita Prefecture. We selected variables and their lag terms in the right side of the function using the AIC criteria. We incorporated monthly dummy variables in all alternative models. For these two models, the sums of the coefficients of the lag terms of the respondent variables were 0.61 and 0.82, which are smaller than 1. This implies that these two variables are not explosive.

Then, on the basis of Equation (2), long-term multipliers or long-term elasticities were reparameterized (Table 1). For the arrival model, price and bidding entry quantity had negative impacts whereas inventory and LS had positive impacts. However, multipliers of price and inventory were rather small and not significant. Bidding entry had significant impacts on arrival quantity, but its elasticity value was only 0.326, which denotes that it is inelastic. The multiplier of LS was 1.274, larger than 1, which denotes that it is elastic. Additionally, the estimate is significant at the 1% level. Over the long term, arrival

Table 1. Estimates of long-term multipliers (β)

Variables	Arrival model	Price model
*ln*P	−0.017 (0.197)	
*ln*A		0.024 (0.048)
*ln*I	0.048 (0.097)	−0.137 * (0.070)
*ln*E	−0.326 *** (0.058)	
*ln*LS	1.274 *** (0.067)	
*ln*LP		1.332 *** (0.208)

P: the price of sawlogs; A: arrival of sawlogs in sawmills; I: inventory of sawlogs in sawmills; E: entry in the bidding markets; LS: lumber shipment; LP: lumber price
Values in parentheses are robust standard errors.
***, *: significant at 1% and 10% levels, respectively

quantity was found to be mainly affected by LS and to some extent by bidding entry. However, arrival quantity was not affected by price and inventory levels.

The price model showed that sawlog price was mainly affected by LP and much less affected by arrival quantity and inventory levels. As expected, arrival quantity and inventory had positive and negative impacts, respectively. However, their impacts were found to be rather small and not statistically significant.

2. Short-term model results

Table 2 shows the results of the ECM presentations derived from the ARDL models. First, the arrival model showed that in the short term, arrival quantity was not affected by sawlog price. However, it was negatively affected by the previous arrivals. The high elasticity of the current month inventory (2.143) denotes that the inventory in the end of the current month had a considerable positive impact on current arrivals. However, the previous inventory negatively affected arrivals. This result reflected the fact that the foreseeing increase in demand for sawlogs affected current arrivals. Bidding entry also affected arrivals, but its impacts were rather limited. The positive and significant signs of the monthly dummy variables indicated that arrivals were higher in that month compared to January. This is true for spring. Actually, for summer (e.g., June to August), we expected negative signs. Their coefficients were rather small. The last but most important parameter was error correction or adjustment coefficient θ. For arrival model, θ was estimated as -0.390; its sign is in line with our expectations and the value is significant at the 1% level. Hence, deviations of actual values from long-term equilibrium values that occurred in the previous period were adjusted by 39.0% in the current period.

The price model shows that in the short term, prices are positively affected by those in the previous period,

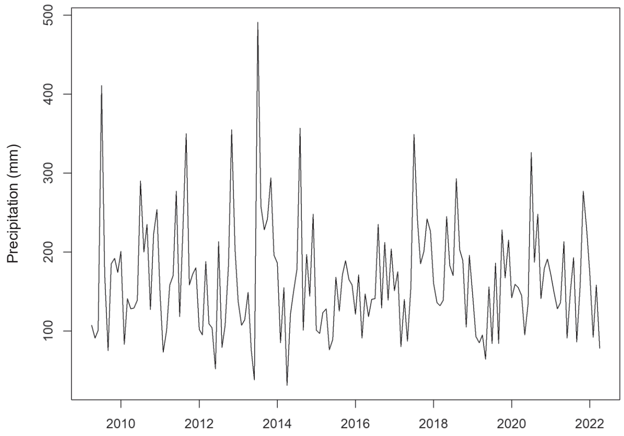

Fig. 5. Monthly precipitation in Akita Prefecture
Source: Japan Meteorological Agency (2022)

Table 2. Results of error correction representation

Variables	Arrival model (ΔlnA)	Price model (ΔlnP)
C	0.915 *** (0.127)	−0.794 *** (0.144)
ΔlnA		0.024 ** (0.010)
$\Delta ln A_{-1}$	−0.132 ** (0.053)	
$\Delta ln A_{-2}$	−0.140 *** (0.047)	
$\Delta ln A_{-3}$	−0.148 *** (0.041)	
$\Delta ln P_{-1}$		0.242 *** (0.073)
ΔlnI	2.143 *** (0.119)	
$\Delta ln L_{-1}$	−0.967 *** (0.180)	
ΔlnE	−0.051 (0.035)	
ΔlnE_{-1}	0.043 (0.037)	
ΔlnE_{-2}	0.057 (0.036)	
ΔlnE_{-3}	0.091 *** (0.034)	
lnK		0.008 ** (0.004)
T		0.020 *** (0.005)
W		0.018 *** (0.005)
M_2	0.177 *** (0.029)	−0.022 *** (0.007)
M_3	0.206 *** (0.030)	−0.023 *** (0.008)
M_4	0.153 *** (0.031)	−0.024 *** (0.007)
M_5	0.139 *** (0.030)	−0.028 *** (0.007)
M_6	0.140 *** (0.032)	−0.031 *** (0.007)
M_7	0.128 *** (0.032)	−0.034 *** (0.008)
M_8	0.035 (0.033)	−0.025 *** (0.007)
M_9	0.138 *** (0.036)	−0.026 *** (0.008)
M_{10}	0.139 *** (0.037)	−0.018 ** (0.007)
M_{11}	0.045 (0.034)	−0.013 * (0.007)
M_{12}	0.080 *** (0.029)	−0.010 (0.007)
θ_{-1}	−0.390 *** (0.043)	−0.180 *** (0.033)
Adj. R^2	0.884	0.495
F-statistic	56.008 ***	9.871 ***

K: precipitation; T: consumption tax increase; W: lumber shortage; Ms: monthly dummy variables
Values in parentheses are robust standard errors.
***, **, *: significant at 1%, 5%, and 10% levels, respectively

current arrivals, and monthly precipitation in the current period. Price also increased because of consumption tax increase and the lumber shortage caused by COVID-19. Although their short-term elasticities were statistically significant, their impacts were small as shown by their dimensions of the coefficients. Most of the monthly dummy variables had statistically significant estimates. However, their impacts were small. Negative estimates indicated that the price in January was higher than that in other months. Adjustment coefficient θ value was −0.180; its sign is in line with our expectations and the value is statistically significant at 1%. This means that the deviation that occurred in the previous period was adjusted by 18.0% in the current period. Compared with arrival ECM, the speed of adjustment in price model was slow.

3. Residual diagnostics

Regression analysis is a useful tool based on some assumptions. Residual diagnostics is necessary to verify specified models. In this research, we examined the residuals of the ARDL models in the following aspects: 1) independence of residuals, 2) independence of explanatory variables and residuals, 3) residuals vs. fitted values, 4) homoscedasticity, and 5) stationarity of residuals. Our results are as follows.

(1) Residual vs. fitted values

Figure 6 shows the scatterplot of residuals vs. fitted values. Residuals spread randomly around the 0 line, and no nonlinear pattern was found. This indicates that the assumption of a linear relationship is not violated.

(2) Independence of residuals

First, the null hypothesis of no serial correlation was tested up to 2 lags to the two residuals of ARDL models to test that the residuals are independent of each other using the Breusch–Godfrey LM test (Breusch & Pagan 1979, Godfrey 1978). The F-statistics for serial correlation up to 2 lags were 0.298 (P-value = 0.743) and 1.042 (P-value = 0.356) for arrival and price ARDL models, respectively. This implies that the estimates were not significant at the 5% level and did not reject the null hypothesis of no autocorrelation for both models.

(3) Independence of explanatory variables and residuals

Table 3 shows the correlation relationships between the explanatory variables and residuals of the ARDL models. For each ARDL, we included all explanatory variables in the specified model, except the dummy

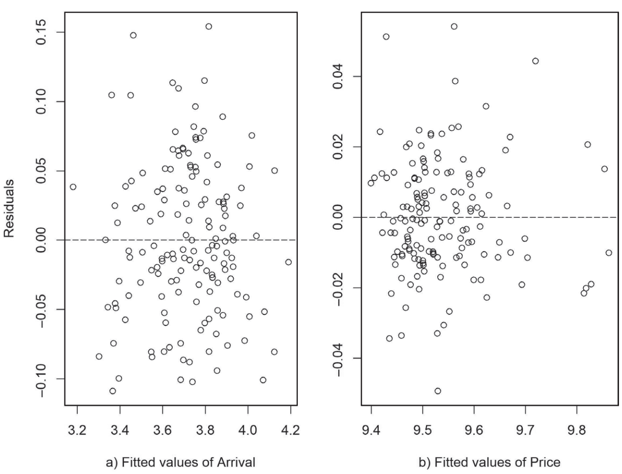

Fig. 6. Residuals vs. fitted values from arrival and price ARDL models

Table 3. Correlation coefficients between explanatory variables and residuals of ARDL models

Explanatory variables	Residuals from arrival model	Residuals from price model
P	0.006 (0.939)	
A		−0.012 (0.884)
I	0.012 (0.880)	0.012 (0.881)
LS	0.003 (0.967)	
E	0.003 (0.971)	
LP		0.000 (0.998)
K		0.000 (0.996)

For abbreviations, same as Tables 1 and 2. Values in parentheses are *P*-values.

variables. Results show that the correlation coefficients were considerably small and not significant at 5%. This implies that the residuals were independent of the explanatory variables.

(4) Homoscedasticity test

To verify the homoscedasticity of the variances, we performed the Breusch–Pagan test (Breusch & Pagan 1979). The *F*-statistics for the arrival and price models were 1.168 (*P*-value = 0.282) and 0.908 (*P*-value = 0.578), respectively. This implies that the null hypothesis of homoscedasticity was not rejected at 5%. Even so, we computed the Newey–West HAC robust standard errors and covariance using Bartlett kernel and the *t*-values and *P*-values. Tables 1 and 2 show our results.

(5) Unit root tests to check stationarity in residuals

Spurious regression can be a problem in time series analysis when the residuals of specified models are nonstationary or present a unit root process. Ghouse et al. (2018) and Ghouse et al. (2021) argued that the ARDL model can reveal a spurious regression relationship between those unrelated variables. We implemented unit root tests to determine whether the residuals are unit root processes. We implemented three traditional tests, namely, ADF (Elliott et al. 1996, Said & Dickey 1984), PP (Peter & Perron 1988), and KPSS (Kwiatkowski et al. 1992), with two situations differencing in containing only constant or both constant and linear trend terms. Table 4 shows the results. We then implemented a unit root test with a breakpoint and seasonal unit root test.

In ADF and PP tests, the null hypothesis of the unit root process was rejected at a 1% significant level. In the KPSS test, the null hypothesis of the stationary process was not rejected at the 5% level. Results show that both time series of residuals from the arrival model and price model are stationary. Hence, the spurious regression problem was not detected for both arrival and price ARDL models.

When the results from these traditional unit root tests show that both residuals are stationary, there is little doubt that they are not. However, unit root with structural break tests and a seasonal unit root test were still implemented. For the former test, we obtained ADF = −13.615 (*P*-value <0.01) and ADF = −13.119 (*P*-value <0.01) for the residuals of arrival and price, respectively. Thus, we rejected the null hypothesis of the unit root at the 1% level. A traditional HEGY method (Hylleberg et al. 1990) was adopted in the seasonal unit test. The test statistics for both residuals are 10.455 and 18.818 for all seasonal frequencies and 10.420 and 19.334 for all frequencies. As the critical values are approximately 7.50 and 7.00 at 5% in these two situations, the null hypothesis of unit root at combined frequency was rejected at 5%. We concluded that both residuals are stationary.

Discussion

First, we discussed the results of long-term multipliers. By arranging the positions of related respondents and explanatory variables based on the long-term multipliers, we formulated a diagram of long-term relationships (Fig. 7). Although the price and arrival quantity of sawlogs are expected to affect each other and to be simultaneously decided by other related factors, our empirical results show that impacts between these two variables were considerably weak. Inventory also had weak impacts on arrival in the long term. The impact of inventory on sawlog price in the long term is larger than that on arrival. However, it remained inelastic and not significant at the 5% level. Interestingly, sawlog price was strongly affected by LP and arrivals were

Table 4. Results of unit root test to residuals

Residuals	ADF		PP		KPSS	
	C	C, T	C	C, T	C	C, T
Arrival model	−12.78 ***	−12.89 ***	−12.79 ***	−12.90 ***	0.23	0.06
Price model	−12.58 ***	−12.54 ***	−12.58 ***	−12.54 ***	0.06	0.06

***: Significant at 1% level; others: not significant at 1%, 5%, and 10% levels; C: constant; T: trend

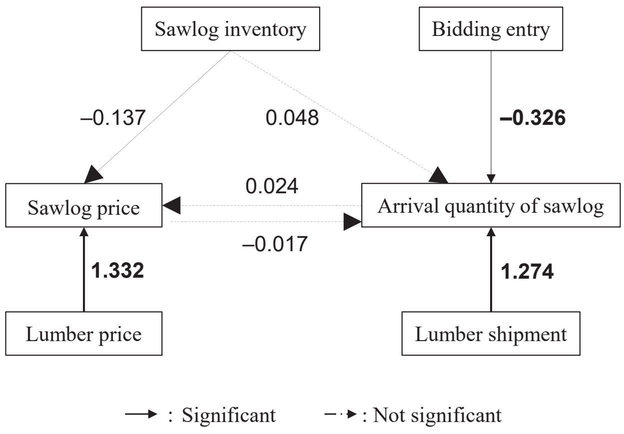

Fig. 7. Diagram of long-term relationships
Note: The width of the lines represents their impact.

strongly affected by LS. Bidding entry also affected arrival, inelastic but higher than that of sawlog inventory and statistically significant at 5%. In this way, we found that two chains were available: supply and value chains. The sustainability of management and operations in sawmills is supported by the sustainability of the supply and value chains. Bidding entry is less important than LS but also plays a role. Inventory is a factor within sawmills that can play a role in adjusting arrival and price, but it does not impose a considerable impact in the long term.

On the basis of the short-term model results, the adjustment coefficients in the ECM of arrival and price were 0.390 and 0.180, respectively. The former is more than twice the latter. This result shows that when the deviation of the actual arrival from the long-term arrival equilibrium occurred, 39% of this deviation in the current month was adjusted toward equilibrium in the following month. It seems that the adjustment of arrival is more important than that of price. The price of sawlogs affected profitability, but sustainability in operation seems more important than current profitability. Michinaka (2022) estimated that the adjustment coefficients for these two models were 0.824 and 0.114, respectively. This implied a negative change in the arrival model but a positive change in the price model in this research. For the arrival model, this may be because of the substitution of LS for sawlog consumption. For the price model, this may be because of the two dummy variables—tax increase and lumber shortage—being added.

Consumption tax increase and lumber shortage were not shown in the arrival model, but they were shown in the price model. This indicates that both factors affected prices but not arrivals from the view of model fitting. However, the coefficients of tax increase and lumber shortage in the price model were small, despite being statistically significant at the 1% level. Therefore, we cannot confirm whether a tax increase or lumber shortage caused structural changes. Rather, we found that no obvious structural changes were detected.

We also compared the results in this study with those in Michinaka (2022). Instead of using sawlog consumption as in Michinaka (2022), this study explored LS as a factor affecting arrival. LS seems "more external" than sawlog consumption to arrival. Sawlog consumption was directly connected with the production volume of lumber, which is decided mainly by sawmills. However, concerning LS, volume relies more on the orders from lumber consumers. Michinaka (2022) estimated the long-term multiplier of sawlog consumption on sawlog arrival as 1.020 at a 1% level, and this study estimated that of LS as 1.274. Both estimates support the strong association, but the latter shows that arrival was more strongly affected by LS when adding the lumber shortage period.

Michinaka (2022) estimated the long-term multiplier of LP on sawlog price as 1.292 at 1% level. Conversely, this study estimated it as 1.332, just a minor positive change. In one-way, we added the lumber shortage period from January 2021 to April 2022 to the study. A sharp increase in both prices of sawlogs and lumber may show their strong association by a higher coefficient. Essentially, the values of 1.292 and 1.332 are rather close. This may imply that even if a lumber shortage occurred, the long-term relationship between sawlog price and LP did not change.

As indicated in the model diagnostics, series correlation in the residuals was not detected in the estimated ARDL models. Additionally, the arrival and price of sawlogs had an endogenous relationship. However, the diagnosis of the regression model residuals verified the independence of the explanatory variables and residuals. This indicates that the ARDL model could solve the endogeneity problem (Pesaran & Shin 1995). Unit root tests showed that no spurious regression relationships in the specified ARDL models occurred.

Structural changes in the supply and demand balance for lumber were not considered in the model of this study. The self-sufficiency rate for timber has increased since 2002. Moreover, the supply and demand relationship is changing because of the construction of large sawmills. However, as the period covered is not too long (13 years), we did not consider structural changes. To account for seasonality, we added a monthly dummy variable.

Conclusions

This study clarified the long-term and short-term factors affecting arrival quantity and sawlog price. This empirical study found that both supply and value chains are important in the long-term relationships. One of the policy implications of this study is that we confirmed the association between the price of sawlogs (sugi, medium diameter size of 24 cm - 28 cm) and the price of lumber (sugi nuki, special grade). We found that even if a lumber shortage occurred, the long-term relationship between sawlog price and LP did not change. However, the association between the prices of lumber (nuki) and that of sugi sawlogs of medium (14 cm - 22 cm) and large (30 cm - 36 cm) sizes showed a different trend from that of a medium size at 24 cm - 28 cm and was not detected (details were omitted in this paper). This shows that the increase in price of sawlogs preferred in the industry is strongly associated with an increase in LP. The issue of utilizing sugi of other sizes efficiently remains unsolved.

For sawmills, securing arrivals is important because the sawlog need for consumption must be met. Moreover, adequate inventory levels are necessary for sustainable operations. In the long term, the effects of price and inventory on the arrival quantity were not significant. LS had a statistically significant and elastic effect on arrival.

In the short term, previous arrivals and inventories negatively affected current arrivals. However, the inventory in the current month positively affected arrival. Conversely, in the short term, sawlog price was not affected by LP but it was positively affected by arrival quantity, sawlog price in the previous month, and precipitation. All of these impacts were significant, but they were inelastic.

The speed of error correction or adjustment of deviations from the long-term equilibrium relationship in the arrival model was faster than that in the price model. This reflected the importance of sustainable operation in the sawmill management for their supply chain. Conversely, regarding the slower adjustment speed in the price model, this may be because changing sawlogs' purchasing price would complicate the paperwork. Prices also do not change frequently because of the agreed prices between sawmills and logging companies.

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