FUNDAMENTAL RESEARCH

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economics

# Structural Changes on Pulpwood Market in the US South: Wood Pellets Investments and Price Dynamics

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We investigated the impact of wood pellet mills on pulpwood price structure in the US South. Rather than focusing exclusively on price elasticities, we progress by examining how wood pellet production has affected the spatial transmission of pulpwood prices. Pairwise price ratios were modeled using smooth transition regression to identify changes in the cointegration (linkage) between markets over time. A logistic model was fitted to estimate market linkages as a function of market distances, industry concentration, and capacity of pellet wood production. Results show that the US South is not composed of market clusters, but each market pair has a particular relation. Distance and wood pellet production capacity are the only factors driving market linkages; the pulp and paper industries did not affect market structure changes. Our research suggests spatial price transmission varies over time, and pellet mills have caused a structural change in the pulpwood prices in the US South.

**Keywords:** price transmission, STAR models, pulpwood market, southern US

In recent years, investments in wood pellet plants have gained attention among forestry groups in the US South. This attention is related to the current renewable energy policies from European countries, which have increased incentives for investments in pellet mills in the US South (Forest2Market 2015). Consumer and producers of pulpwood are concerned about the size of the impact of the pellet mills, since they compete for residuals, pulpwood, and low-quality logs (US Industrial Pellet Association 2019). Forest landowners now have a new possible timber buyer in their portfolio, and more incentives to convert their timberland to shorter management regimes. The entry of new competitors in the US South has had significant consequences, including increased competition for raw material and changes in pulpwood price patterns. We investigate if the consumption of wood fibers by pellet mills impacts the relation between pulpwood prices of different regions. Since timber prices are a key component of timberland investment returns, having a deeper understanding of how a large market consumer such as wood pellets can affect spatial timber price transmission is essential to forest management and its profitability.

European policymakers have offered fiscal incentives to convert energy production from nonrenewable to low-carbon sources over the past decade. Their goal is to expand the share of renewable energy from the current 12.5 percent to 20 percent by 2020 (Sturc 2012). According to the US Census Bureau (2017), wood pellet exports from the US to Europe increased by 56 percent (from US$267 to US$607 million per year) between 2012 and 2016. A total of 16 pellet mills started their operation during the same period in the US South. Adding their capacity to the mills under construction, they can achieve a production of 7.4 million metric tons of pellets or consume 17.12 million tons of wood fiber (Forest2Market 2015). The total economic benefit originating from operating costs of US$13.8 million can range from US$20.7 million to US$25 million depending upon the state in the US South (Henderson et al. 2017).

One of the consequences of the entry of pellet mills in the US South is the increase in competition for raw material with pulp and paper industries (PPIs) and composite panels since their markets overlap (Forest2Market 2015) (Figure 1). Although there are not yet any signs of price changes (Conrad and Bolding 2011), it is likely that raw material will have higher costs in the future (Benjamin et al. 2009, Galik et al. 2009, Conrad et al. 2011, Abt et al. 2014). Another effect that is less explored is the possible changes in the relation between pulpwood prices of different regions, hereafter referred to market linkage or cointegration.

There is a massive literature on spatial price transmission in agriculture with several econometric approaches to test for market efficiency and cointegration. In the forest sectors, economists have examined spatial patterns on the US exports of pulp and paper

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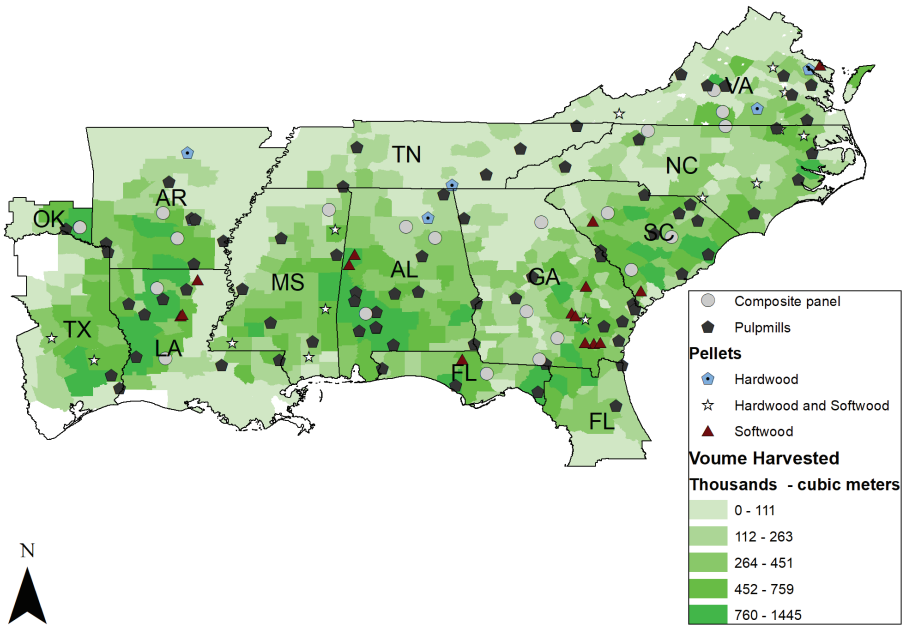


**Figure 1. Distribution of pulpwood consumers by 39 micromarket. Sources: (i) pellet mills: Southern Environmental Law Center and Biomass Magazine, (ii) composite panel and pulpmills: USDA Forest Service, (iii) pulpwood consumption: Forest Inventory and Analysis (FIA)—Timber Products Output (TPO)—2015, (iv) micromarkets: Forest2Market.**

(Buongiorno and Uusivuori 1992), Canadian market for wood pulp (Alavalapati et al. 1997), newsprint trade between Canada and the US (Tang and Laaksonen-Craig 2007), sawnwood imports in United Kingdom (Hanninen 1998), lumber markets (Mehrotra and Kant 2009, Sun and Ning 2014), roundwood markets in New Zeeland (Niquidet and Manley 2011), and Oriented Strand Board in the United States (Goodwin et al. 2011). Less research has focused on spatial price transmission in the US South.

Previous studies have shown that timber prices are linked across different markets in the US South. Yin et al. (2002) analyzed 11 regions in the US South and found that there are at least three large markets where pine sawtimber and pulpwood prices behave similarly. Pulpwood and sawtimber stumpage prices in South Carolina also respond to price movements in other markets (Prestemon and Holmes 2000). Hood and Dorfman (2015) reviewed a dynamic market linkage with market clusters forming and disappearing over time in the US South. This relation between timber prices in different markets can be explained by distance, volume, and market power (Bingham et al. 2003). Bingham et al. investigated sawtimber markets; it not clear if a particular industry such as pellet mills can affect this linkage in the pulpwood stumpage prices. If so, prices in regions not linked before could become linked and vice versa.

We complement the current literature in spatial price transmission in several respects. First, our dataset is more detailed and disaggregated than in Hood and Dorfman (2015) and Yin et al. (2002) or any other paper using stumpage prices in the United States. Although they studied 11 and 21 micromarkets in the US South, respectively, we investigated 39 micromarkets. Since distance has played an essential role in defining cointegration across markets (Bingham et al. 2003), we believe data aggregation might mask some regional particularities. Second, little attention has been given to pulpwood markets, and the last paper published on pulpwood market was more than 15 years ago (Yin et al. 2002). Since then, the timber market has been through several changes—e.g., the housing crisis in 2008 and the rise of a strong bioenergy market. Last, we tested if pellet mill capacity has affected the cointegration process over time similarly to Bingham et al. (2003), but this paper estimated it as in panel data instead of a cross-section.

### Pulpwood Market in the US South

The pulpwood market in the US South is composed of three main types of buyers, PPIs, composite panels, and pellet mills, as well as multiple landowners. These industries are capital-intensive, have a relatively constant demand for raw material, and tend to be more concentrated than sawmills (Mei and Sun 2008b, 2008a, Murray 1995). In 2013, the South accounted for 79.5 percent of the pulpwood production in the United States (169.12 million cubic meters), whereas the West's share was 4.8 percent (10.21 million cubic meters), and the North's share was 15.7 percent (33.37 million cubic meters) (Howard and Kwameka 2016). Softwood

### Management and Policy Implications

Over the last decade, the timber market in the US South has attracted international investments on wood pellets. The growing demand for biomass has driven pellet mills to consume pulpwood in order to complement the shortage on wood residuals. This demand can change not only pulpwood prices but also how markets are linked spatially. Understanding how different market players and external shocks can change price behavior is an essential tool for forest landowners and timberland investors. We show that external shocks can change the market equilibrium for long periods, giving opportunities to rent seekers. In addition, timberland investors should expect that, in some cases, pulpwood markets are linked by economic forces other than geographical distance. Having this information or acknowledging this possibility can reduce risks related to price fluctuations and promote better allocation of resources.



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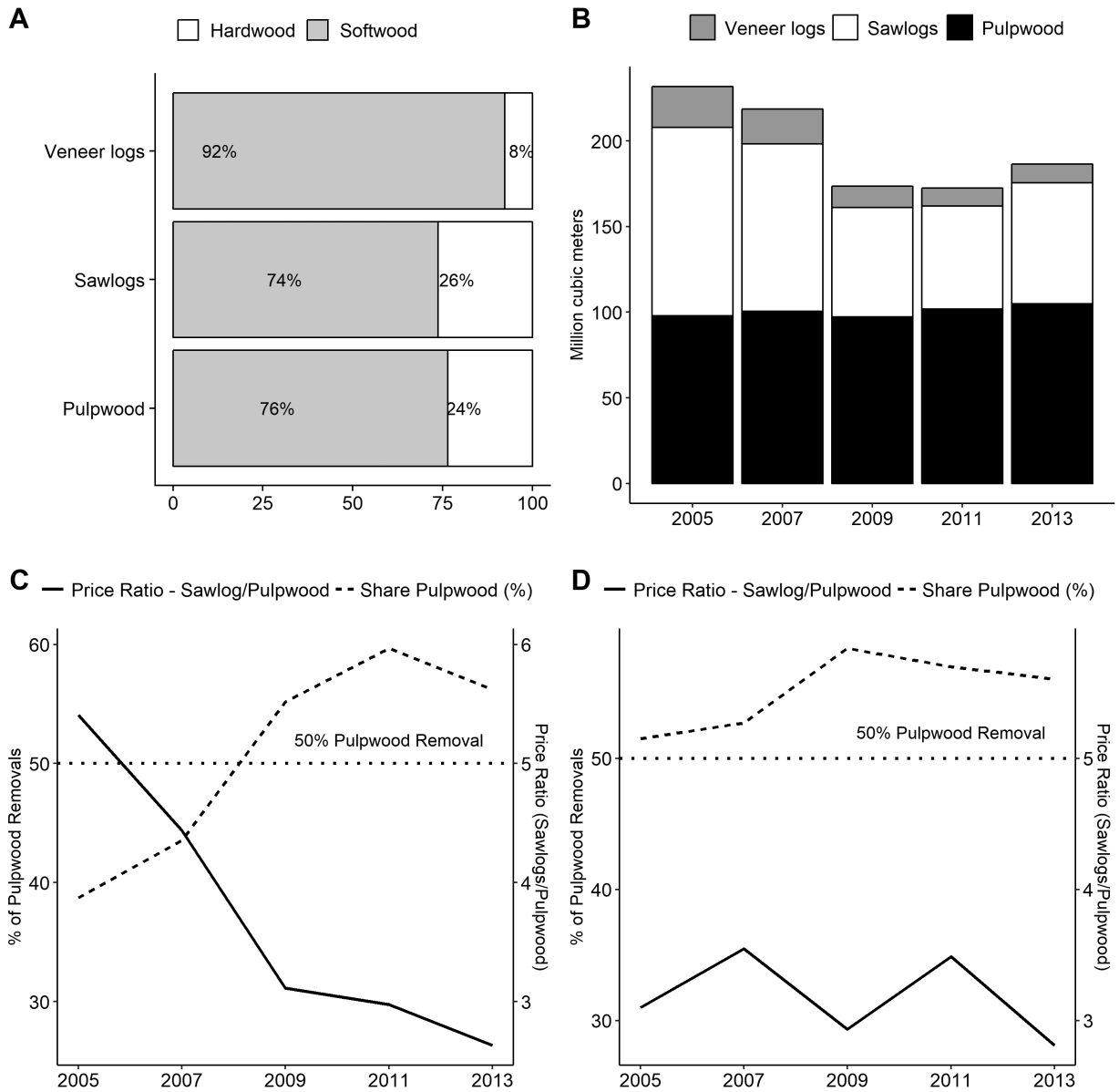


**Figure 2. (A) Share of hardwood and softwood harvested in the US South by product—2013. (B) Total volume harvested in the US South by product between 2005 and 2013. (C) Softwood—percentage of pulpwood removed and price ratio of sawlog and pulpwood. (D) Hardwood–percentage of pulpwood removed and price ratio of sawlog and pulpwood. Sources: (i) timber removals: Timber Products Output Studies (TPO)—USDA Forest Service. (ii) Timber prices: Timber2Market.**

species account for 76 percent of the total harvest in 2013 (142 million of 186 million cubic meters) (Figure 2A).

In the last decade, the volume of all timber removed decreased by 19.5 percent (from 231.8 to 186.5 million cubic meters) (Figure 2B). The supply of sawlogs and veneer had the most severe contraction with 54 percent and 35.6 percent respectively. Pulpwood supply, on the other hand, increased by 7.1 percent during the same period.

The economic recession in 2008 partially explains the increase in pulpwood supply; prices of sawtimber were severely affected by the collapse of the housing market (Ince and Nepal 2012). The ratio between sawtimber and pulpwood (softwood) prices has decreased from 5.3 to 2.6 between 2005 and 2013 (Figure 2C). Consequently, producers often have opted to intensify thinning or postpone harvesting until sawlog prices recover. The hardwood market also showed a decrease in the price ratio; the management system, however, is different than the one used in softwood of softwood (Figure 2D). Whereas softwood supply comes mostly from productive planted forests, hardwood is slow-growing natural forests. Also, hardwood pulpwood demand declined in the US South by 8 million tons (20 percent) between 2007 and 2017; three facilities have converted from hardwood to softwood pulp, two International Paper Company mills, in Franklin, VA and Riegelwood, NC and one Domtar Inc. mill in Ashdown, AR (Forest2Market 2018). Even though there is an interesting question regarding the hardwood market, such as how this shift in demand has affected market linkage, hardwood market is not the scope of this paper; we focus only on softwood.

## Economic Theory

The definition of price linkage (cointegration) here is based on Fackler and Goodwin (2001)'s definition: "a measure of the degree to which demand and supply shocks arising in one region are transmitted to another region." According to the authors, given a



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hypothetical shock in region A, $\varepsilon_A$, the price transmission ratio between region A and B is defined as:

$$R_{AB} = \frac{dp_B / d\varepsilon_A}{dp_A / d\varepsilon_A} \quad (1)$$

where $p_{A(B)}$ is the price of a good in market A (B), and $R_{AB}$ is the price transmission ratio between regions A and B, which equals 1 if markets A and B are perfectly integrated and 0 if there is no integration between them. Market linkage therefore does not necessarily require any trade of goods; these regions could be linked, and these regions could be linked by a third or fourth market. Also, prices of in situ commodities, like stumpage, might be spatially linked by market forces over an "information space" in which economic indicators (supply, demand, employment, stock, industries concentration, etc.) behave similarly in different regions (Prestemon and Holmes 2000, Bingham et al. 2003). These definitions are essential to this study, since we analyze stumpage prices, and it is not physically possible to trade standing trees, so spatial arbitrage does not really apply.

## Data

The dataset used is composed of a bimonthly of softwood prices from 2005 to 2015 of 39 microregions in the US South provided by Forest2Market (Figure 3A). Pellet mill capacity and location data were collected from *Biomass Magazine* (http://biomassmagazine.com/) and the Southern Environmental Law Center (2018) (Figure 3B); we also called or emailed wood pellet plants lacking complete information. Data containing the location and status of PPI, and composite panels are from Forest2Market (2015).

For every price series in each market, we calculated the log-linear price ratio ($\ln(p_{it}/p_{jt})$), and used a smooth transition model (STAR) with two regimes to analyze their cointegration dynamics.

## Empirical Methods

Forest economists have recently begun to employ regime shifting techniques to estimate price transmission (Goodwin et al. 2011, Niquidet and Manley 2011, Sun and Ning 2014, Hood and Dorfman 2015). These models assume that prices would follow a nonlinear adjustment to market equilibrium after external shocks (Serra et al. 2011), which is more realistic for products with high transaction costs like timber. Since the US South is composed of heterogeneous consumers and producers, it is expected that the price adjustments to a new equilibrium occur by different speeds. Therefore, here we used the STAR model to capture either an abrupt or smooth changes in the market structure, which is not possible with either the linear or threshold models.

Our model uses similar components from the previous literature on price transmission (Connell and Wei 2002, Goodwin et al. 2011). We used the log of the ratio between the pulpwood prices of region $i$ and $j$ as in $y_t = \ln(p_{it}/p_{jt})$[1]. For a pair of prices, the error correction model of $p$th order is then

$$\Delta y_t = \varphi_0 + \varphi' x_t + \theta_1 y_{t-1} + \varepsilon_t \quad (2)$$

where $\varphi = (\varphi_p, \ldots, \varphi_{p-1})$, $x_t = (\Delta y_{t-1}, \ldots, \Delta y_{t-p})$, and $\varepsilon_t$ is a white noise. The STAR model (Terasvirta 1994) for a univariate time series with a transition function is defined as

$$\Delta y_t = \underbrace{\tilde{\phi}_1 \tilde{x}_t \left[1 - G(s_t; \gamma, c)\right]}_{\text{Regime 1}} + \underbrace{\tilde{\phi}_2 \tilde{x}_t \left[G(s_t; \gamma, c)\right]}_{\text{Regime 2}} + \varepsilon_t \quad (3)$$

where $\tilde{x}_t = (1, x_t, y_{t-1})$. The first section of Equation 3 (Regime 1) is a unit root process, $p_{it}$ and $p_{jt}$ are not cointegrated, or price changes in one region do not impact the other. The coefficients are restricted to $\tilde{\phi}_1 = (0, \phi_1, 0)'$. In the second part (Regime 2) $p_{it}$ and $p_{jt}$ are cointegrated, or changes in price in one region will cause changes in the other. Its coefficients are then $\tilde{\phi}_2 = (\phi_{2,0}, \phi_2, \theta_2)'$, and $\theta_2 < 0$ is required. $G(s_t; \gamma, c)$ is a continuous function that ranges from 0 to 1 as the transition variable $s_t$ increases. Micromarkets $i$ and $j$ are considered completely integrated when $G(s_t; \gamma, c) = 1$ and not integrated when $G(s_t; \gamma, c) = 0$. Finally, $\gamma$ is the smoothness coefficient, and $c$ is the threshold coefficient.

### Transition Variable

There are many candidates to represent the transition variables. In the finance literature, a typical candidate is the lag of the dependent

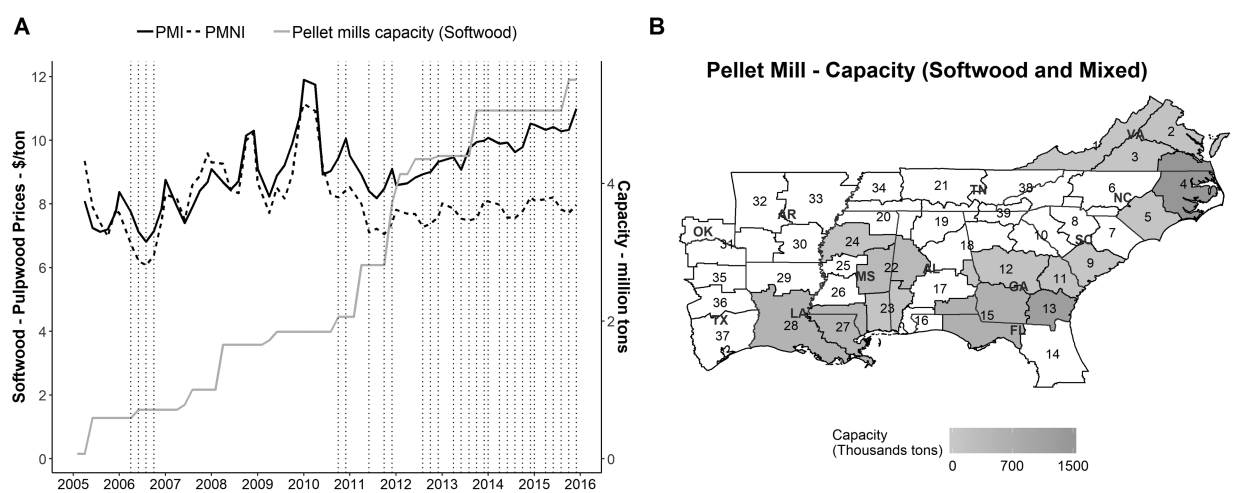


**Figure 3. (A, B) Real softwood pulpwood stumpage prices (average on micromarkets with [PMI] and without pellet mills [PMNI] installed—02/2015 to 12/2015). Vertical dotted lines indicate the period in which the average prices in PMI and PMNI were statistically different at 10 percent of significance level. Source: (i) Forest2Market, (ii) Pellet Mills: Southern Environmental Law Center and Biomass Magazine.**



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variable ($\Delta y_{t-t}$). Goodwin et al. (2011) proposed that $s_t$ should be represented by a moving average of the lags in $y_t$ defined as:

$$s_t = \left(\frac{1}{D_{\max}}\right) \sum_{d=1}^{D_{\max}} y_{t-d} \tag{4}$$

where $D_{\max}$ is the prespecified lag limit. This specification agrees with the economic concept that the profit opportunities occur when there is a large discrepancy in relative prices compared to a given average. After a cautious analysis of the different model criteria (log-likelihood, Aikaike Information Criterion [AIC] and Bayesian Information Criterion) and the fact that in many cases timber market information (demand and supply) is available only annually or longer periods, $D_{\max}$ adopted was 6 (or 12 months).

### Transition Function

The transition function, $G(s_t; \gamma, c)$, might assume various forms. In this paper, we use two: (1) logistic (LSTAR) (Equation 5) and (2) exponential (ESTAR) (Equation 6).

$$G(s_t; \gamma, c) = [1 + \exp(-\gamma(s_t - c)]^{-1} \tag{5}$$

$$G(s_t; \gamma, c) = 1 - \exp\left[-\gamma(s_t - c)^2\right] \tag{6}$$

where $\gamma > 0$ is required. To facilitate the optimization process, we modified Equations 5 and 6 by: (1) substituting $\gamma$ by $exp(-\eta)$, which ensures a positive value of $\gamma$ without imposing any constraint, and (2) dividing $exp(-\eta)$ by the standard deviation of the transition variable $s_t$; thus, $exp(-\eta)$ is transformed into a scale-free parameter (Goodwin et al. 2011).

The LSTAR models embed linear and threshold regime shifting model in one function. When $\gamma \to \infty$, Equation 5 has a rapid change between 0 and 1, as in a threshold model, whereas when $\gamma \to 0$, the LSTAR model decreases to a linear model. The ESTAR model, Equation 6, on the other hand, becomes linear as $\gamma \to \infty$ or $\gamma \to 0$. We compared and selected Equations 5 and 6 for every pair price using statistical criteria (AIC and log likelihood).

### Model Estimation

Equation 3 was estimated using conditional nonlinear least squares. A critical step to reach the best solution is to select the initial values as close as possible to the global optimum. We adopted an approached proposed initially by Terasvirta (1994) and also applied by Hood and Dorfman (2015). We ran the sum of square function conditioned on $\eta$ to a range predetermined value (from-6 to 6) multiple times and selected the coefficients with the minimal residual sum of squares. Once the optimal value was found, we used these coefficients as initial values and ran the model without any restriction.

We estimated the coefficients on the STAR model using the Broyden–Fletcher–Goldfarb–Shannon algorithm. Because of the large quantity of pairwise equations (1,482 for logistic and exponential—741 each), high-performance computing hardware was used through the software R, reducing the estimation time to less than a fiftieth of the time of that required for a typical PC.

### Generalized Impulse Response Function (GIRF)

We used the GIRF (Koop et al. 1996) to explain how an external shock affects the equilibrium conditions in the price-pair model in Equation 3. The GIRF is defined as:

$$\begin{aligned} \text{GIRF}(h, \delta, \Omega_{t-1}) = {} & E\left[\Delta y_{t+h} \mid (\varepsilon_t = \delta_j, \Omega_{t-1})\right] \\ & - E(\Delta y_{t+h} \mid \Omega_{t-1}) \end{aligned} \tag{7}$$

where $h$ is the forecast time horizon, $\delta_j$ is the external shock at period $j$, and $\Omega_{t-1}$ is the historical variable $(\Delta y_{t-1}, \ldots, \Delta y_{t-p})$. The positive and negative shocks were analyzed to the time horizon ($h$) of 48 months, and their intensities at $j = 1$ were $\pm 1$ and 3 standard deviations from the residual. To estimate the expected values on Equation 7, we built $\Delta y_{t+(1,\ldots,h)}$ from Equation 3 by bootstrapping $\varepsilon_{t+(1,\ldots,h)}$ 999 times.

### Meta-Analysis

To analyze the effects of the pellet mills and other economic variables on the cointegration of pulpwood markets over time, we estimated a logit regression using the results of $G(.)_{ijt}$ as the dependent variable. We defined the binary function $\widehat{Z(.)}_{ijt}$ as $Z(.)_{ijt} = 1$ if $\widehat{G(.)}_{ijt} \geq W$ and $Z(.)_{ijt} = 0$ if $\widehat{G(.)}_{ijt} < W$, where $W$ is a proxy for the $p$-value adopted in the standard cointegration test; we initially assumed that W is 0.90, or 0.10 of significance, and progressed to 0.95 and 0.99, 1 and using only $\widehat{G(.)}_{ijt}$ to check the model robustness (Appendix A1).

The independent variables tested are the distance between market $i$ and $j$ ($D_{ij}$), the absolute difference between the wood pellet production capacity in the two markets ($DWP_{ijt}$), the total wood pellet production capacity of both pairs ($TWP_{ijt}$), the absolute difference of the volume of pulpwood consumed in the two markets ($DVol_{ijt}$), and the total volume consumed of both markets ($VolT_{ijt}$). The variables $DWP_{ijt}$ and $DVol_{ijt}$ are proxies to market distribution; the higher their value, the greater the volume or capacity concentrated in one region.

We expect a negative sign on distance given the concept of spatial arbitrage and transportation costs. However, it has also shown no specific trend in previous literature (Prestemon and Holmes 2000, Yin et al. 2002). Market concentration ($DWP_{ijt}$ and $DVol_{ijt}$) can have mixed results; a positive effect on cointegration implies that these regions have some level of price leading, which is expected on the basing-point pricing system (Faminow and Benson 1990). A negative sign would indicate that one of these locations has a thinner market with fewer transactions and is less sensitive to external shock, whereas the other market is more mature, and the volume of timber is constantly supplied. It is also uncertain how total volume or total wood pellet capacity would affect cointegration; they depend directly on the distribution between the two locations. Therefore, we added to our model the interaction between the total and absolute difference between the two markets and distance.

Mathematically, the binary regression is defined as:

$$\begin{aligned} \Pr\left[Z(.)_{ijt} = 1 \mid \mathbf{X}\right] = {} & \beta_0 + \beta_1 D_{ij} + \beta_2 TWP_{ijt} + \beta_3 DWP_{ijt} \\ & + \beta_4 WPT_{ijt} * DWP_{ijt} + \beta_5 TVol_{ijt} \\ & + \beta_6 DVol_{ijt} + \beta_7 TVol_{ijt} * DVol_{ijt} \\ & + \beta_8 D_{ij} * DVol_{ijt} + \beta_9 D_{ij} * TVol_{ijt} \\ & + \beta_{10} D_{ij} * DWP_{ijt} + \beta_{11} D_{ij} * TWP_{ijt} \\ & + \delta_i + \delta_j + \delta_t + \eta_{ijt} \end{aligned} \tag{8}$$

where: $\Pr[Z(.)_{ijt} = 1|\mathbf{X}]$ is the probability $Z(.)_{ijt}$ equals 1, $F(.)$ is the *cdf* of the logit distribution, and $\delta_i$, $\delta_j$, and $\delta_t$ are the fixed



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effects of region $i$ and $j$ and period $t$. The other variables were already described.

## Results and Discussion

We examined how wood pellet production has affected pulpwood price dynamics in the US South. We used a log–price ratio of pulpwood between two different locations to investigate their linkage in a two-regime STAR model. Our analyses of pellet mill effects, timber price dynamics, effects of external price shocks, and regional market linkages are discussed next.

### Pulpwood Prices and Pellet Mills

As of December 2015, the softwood pulpwood price was on average US$7.00 per ton (±US$2.90) in markets where there was no pellet mill installed (21 micromarkets), and US$9.65 (±3.65) in markets where pellet mills were operating (18 micromarkets) (Figure 3A and B). These two regions have had different trends since 2010. The pulpwood price in pellet mill regions has increased by 33 percent since its previous lowest value in 2011; it almost reached the historical high at US$10.24 per ton in 2010. On the other hand, prices in other micromarkets have kept steady, increasing by only 9 percent since 2011.

To start exploring the impact of pellet mills on pulpwood prices, we pursued a simple comparison between averages. Figure 3A shows an average $t$-test between the micromarkets with the presence of pellet mills (PMI) and without it (PMNI) for every period investigated. The vertical dotted line indicates when there is a statistical difference. The result shows that between 02/2005 and 10/2011 their average prices presented a significant difference only in 10/2011 (Figure 3A). After 10/2011, they became more likely to diverge and followed different trends. Also, as expected, regions with pellet mills seem to have a stronger correlation with the total wood pellet capacity, whereas the others have no noticeable trend during this period.

Many other factors might have affected pulpwood prices over the last few years. Our initial regression analysis did not show a significant impact of capacity on prices directly. However, it is evident that regions where pellet mills are installed have higher prices. Next, we explore the pulpwood market dynamics and its behavior after external shocks.

### Price Dynamics

To examine relations of prices among regimes, we investigated the pulpwood price ratio between 39 microregions. For every 741 pairwise combinations, we ran a Logistic STAR (LSTAR) and the Exponential STAR (ESTAR) model. After comparing their performance using the AIC statistic, 157 pairs were better represented by LSTAR and 584 by ESTAR. As explained below, results reinforce that the US South is composed of different market clusters, and their composition varies across time.

Each price pair has a different behavior as its transition variable ($s_t$) changes. The transition function ($G[.]$) shifts smoothly between regimes as in the pairs (4)/(34) and (13)/(14) (Figures 3, 4). The sudden change from one regime to another indicates the presence of a large smoothness coefficient ($\gamma$) and a sharp movement from one regime to another. In the exponential form, it translates into a fast change to another regime and back to the original one such as in pairs (4)/(13), and (13)/(32), which $\gamma$ equals 365.1 and 81.5 respectively (Table 1). On the other hand, in the logistic form,

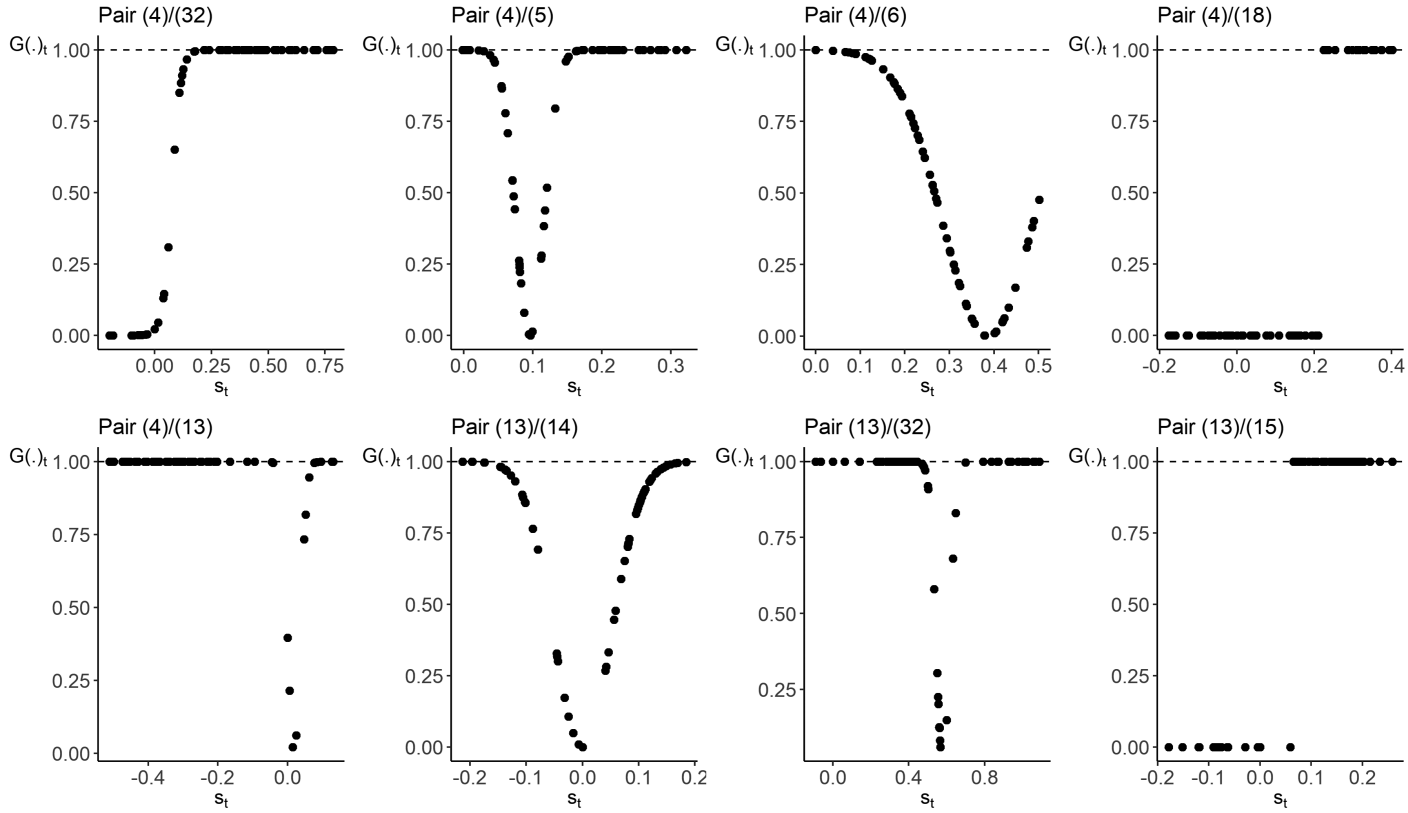


**Figure 4. Transition function versus the respective transition variable of select price pairs,** $s_t = \left(\frac{1}{6}\right)\sum_{d=1}^{6} y_{t-6}$.



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**Table 1. Core results of smooth transition autoregressive model (STAR)—selected region pairs.**

| | Selected region pairs | | | | | |
|---|---|---|---|---|---|---|
| | (4)/(13) | (4)/(18) | (4)/(34) | (13)/(14) | (13)/(32) | (13)/(15) |
| $c$ | 0.018** | 0.220*** | 0.415*** | 0.000 | 0.061 | 0.580 |
| | (0.010) | (0.003) | (0.037) | (0.011) | (0.053) | (0.020) |
| $\phi_{11}$ | –0.237 | –0.485** | –0.342 | 0.744** | 0.084 | 0.891 |
| | (0.802) | (0.123) | (4.665) | (0.303) | (0.145) | (3.148) |
| $\phi_{12}$ | – | 0.273** | –0.207 | 0.008 | –0.141 | 0.192 |
| | – | (0.100) | (0.099) | (0.100) | (0.122) | (2.250) |
| $\phi_{13}$ | – | – | –1.967 | – | – | –1.278 |
| | – | – | (13.434) | – | – | (1.98) |
| $\phi_{14}$ | – | – | –4.309 | – | – | –0.699 |
| | – | – | (8.874) | – | – | (1.399) |
| $\phi_{15}$ | – | – | – | – | – | 0.042 |
| | – | – | – | – | – | (1.128) |
| $\phi_{20}$ | –0.175*** | 0.218** | 0.072*** | 0.041** | 0.189*** | 0.131** |
| | (0.036) | (0.086) | (0.024) | (0.019) | (0.038) | (0.052) |
| $\phi_{21}$ | –0.098 | –0.160 | –0.206** | 0.744 | 0.627 | –0.388** |
| | (0.091) | (0.252) | (4.665) | (0.303) | (0.002) | (0.109) |
| $\phi_{22}$ | – | –0.195 | –0.282*** | – | 0.682*** | –0.503*** |
| | – | (0.224) | (0.103) | – | (0.152) | (0.103) |
| $\phi_{23}$ | – | – | –0.159* | – | – | –0.329*** |
| | – | – | (0.093) | – | – | (0.105) |
| $\phi_{24}$ | – | – | –2.74* | – | – | 2.66*** |
| | – | – | (0.09) | – | – | (0.092) |
| $\phi_{25}$ | – | – | – | – | – | –0.235*** |
| | – | – | – | – | – | (0.091) |
| $\theta_2$ | –0.541*** | –0.580*** | –0.090* | 0.726*** | –1.335*** | –0.137* |
| | (0.098) | (0.254) | (0.050) | (0.110) | (0.205) | (0.083) |
| $\gamma$ | 2.460 | 81.451 | 33.115 | 54.598 | 365.037 | 24.533 |
| | – | – | – | – | – | – |
| Model | ESTAR | LSTAR | ESTAR | ESTAR | LSTAR | ESTAR |
| $R^2$ | 0.310 | 0.260 | 0.330 | 0.340 | 0.440 | 0.470 |
| Akaike information criterion | 8.730 | –51.896 | –34.731 | –54.275 | 25.804 | –7.186 |

*Note:* Other region pairs are available in the supplementary material. ESTAR, exponential smooth autoregressive model; LSTAR, logistic smooth autoregressive model. $\phi_{ij}$, the autoregressive coefficients where $i$ represent the regime and $j$ the autoregressive order; $c$, threshold coefficient; $\gamma$, smoothness coefficient; $\theta_2$, error correction of the second regime. $\theta_1$ and $\phi_{10}$ equal 0 by the random walking assumption in the first regime.
$^{*}p < .1$; $^{**}p < .05$; $^{***}p < .01$.

$y_t$ moves abruptly from one regime to another like in threshold models, pairs (4)/(18) and (13)/(15).

The threshold coefficients ($c$) also vary according to the pair analyzed; the price ratios of micromarkets (13)/ (14), (13)/(15), and (4)/(13) were near 1, whereas (13)/(32), (4)/(18), and (4)/(34) were 1.78, 1.24, and 1.51 respectively. As observed, there is no relation between smoothness speed ($\gamma$) and the threshold coefficient; the pairs have different behaviors according to their particularities.

This distinction between the smooth transition function reveals that the market agents represented by different price pairs can be heterogeneous (smooth transition) or homogeneous (sharp transition). It highlights the complexity of the market relation of each pair analyzed and shows the advantages of using a nonlinear approach to price transmission of stumpage timber to capture these movements.

## Price-Shock Simulations

After estimating and selecting the best model for every pair, we simulated an external shock in their error term and calculated the GIRF. The significant advantage of using GIRF is its flexibility regarding a shock's sign and size, and histories preceding the shocks. In contrast with the linear counterparts, the nonlinear models are not restricted to symmetric reactions caused by different shock types. These features are desirable when studying pairwise prices because they make it possible to detect shifts from equilibrium when external shocks affect different markets. In a price ratio study as in this paper, a positive shock means an increase/decrease in the nominator/denominator prices, whereas a negative shock indicates an increase/decrease in the denominator/nominator prices. After shocking the price ratio by one and three times the residual standard deviation, prices are expected to return to equilibrium, which is represented by the straight line in the GIRF plots in Figure 5. If prices do not return to equilibrium, the markets are inefficient, and agents can practice arbitrage.

The results of the GIRF suggest a range of adjustment speeds and symmetry of the pulpwood price ratio. In the first row, (4)/(13) and (13)/(14) return to equilibrium between 12 and 24 months after external shocks of one standard deviation on pulpwood price ratio. Although the price ratios (13)/(32) and (13)/(15) tend to an equilibrium, they do not reach the horizontal line within the 48 months. These types of behavior provide opportunities for higher profit. There was also a mixed reaction of price ratio analyzed over the different direction and magnitude.

The reaction after external shocks was asymmetric in most price pairs. In all cases selected, positive shocks showed a higher impact on price equilibriums. The positive shock in pair (4)/(13)



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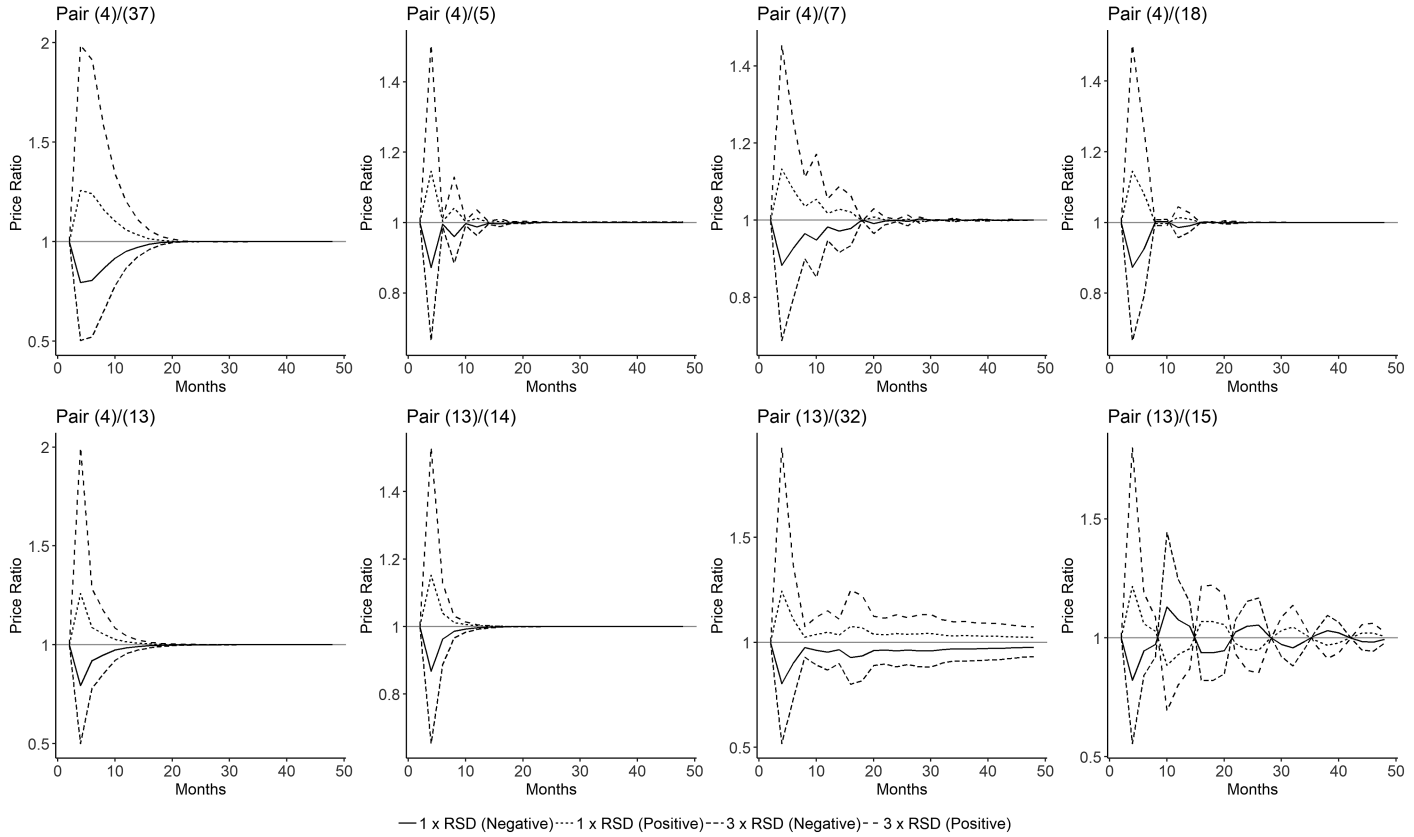


**Figure 5. Generalized impulse response functions (GIRFs) of pulpwood price ratio of selected micromarkets. The shocks are positive or negative, one or two times the residual standard deviation (RSD).**

was four times as large as the negative shock. In the following periods, they have a similar shape and tend to adjust to equilibrium in similar speed, except for pairs (13)/(14) and (4)/(18) where negative shocks take a longer adjustment. Price ratio (13)/(15) changes from positive to negative, converging to zero in the long-run equilibrium.

Surprisingly, the convergence to equilibrium presented a similar speed when different shock sizes were applied. Except for the last two plots in the second row in Figure 5, the adjustment to equilibrium was very similar between the sizes of different shocks. It demonstrated a higher competitiveness within these market pairs, where few opportunities for rent profits were available even after stronger external shocks.

## Market Linkages

Two or more markets are considered linked or cointegrated if price changes in a region affect the other. Mapping this relation is tricky. There are many possible combinations, and choosing a definitive one is often not possible. For instance, market A might be integrated with market B and C, but B and C are not necessarily linked. The complexity increases with the number of markets analyzed. If A is linked to {B, C, D}, B is linked to {A, C, D}, and C is only linked to {A, B}, a reasonable market cluster would be {A, B, C}. However, choosing C over D might be an arbitrary decision if market D is also linked to {A, B}.

To overcome this issue, we presented a pairwise cointegration map using micromarkets (4) and (13) as a reference for the softwood pulpwood market. Micromarkets (4) and (13) have the most significant share of wood pellet capacity and are considered part of the "fuelsheds" that supply wood-based pellets to Europe (Dale et al. 2017). Further results are available in the supplementary material for different pairwise comparisons.

We show the cointegration map (where the $G(.)$function equals 1) of micromarkets (4) and (13) in four specific periods: (1) the initial period analyzed (04/2005); (2) the period when a pellet mill started operating in the micromarket; (3) the period when the market reached the maximum historical production capacity of wood pellet; and (4) the final period of our data (12/2015).

We use micromarkets (13) and (4) as examples for discussion, since they are two of the most dynamic timber markets in the South. There is a substantial variation in composition and number of markets cointegrated with (13) and (4) over time (Figures 6 and 7). On average, 27 and 17 micromarkets were cointegrated with (13) and (4) between 2005 and 2015 respectively, 30 and 22 at the highest peak (10/2006 and 10/2005), and 22 and 12 at the lowest peak (6/2012 and 12/2008). For comparison, the other micromarkets studied are linked to 19 micromarkets on average.

The location of the market (13) (Southeast Georgia) is known as the "wood basket," where the stock of wood, removals, and growth are higher than in any other place in the United States. Even though the share of pulpwood removals exclusively in the market (13) is equivalent to only 1 percent of the US South, when aggregated to micromarkets (12) and (15), they are responsible for 9 percent of the pulpwood removals in the US South (TPO 2015). There are 13 pulp and paper, and composite mills operating in the micromarkets, the highest number in our sample. This concentration of pulpwood consumers makes the local market dynamic and



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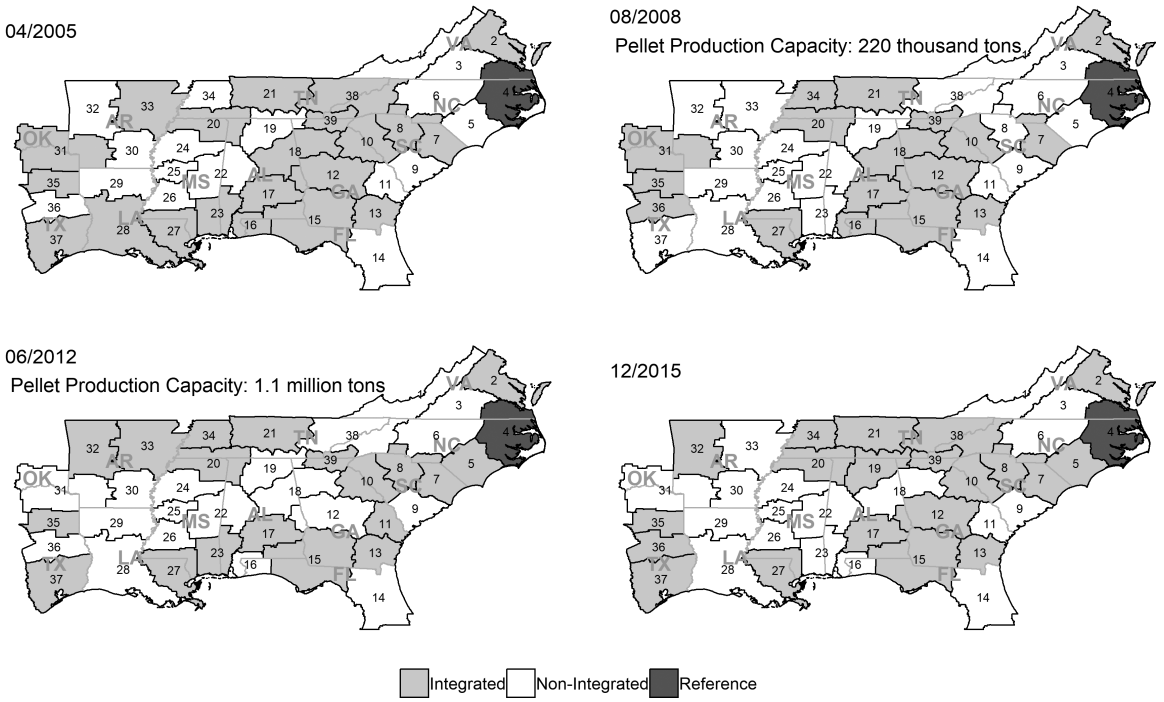


**Figure 6. Spatial-Temporal market linkage of softwood pulpwood - Market (13).**

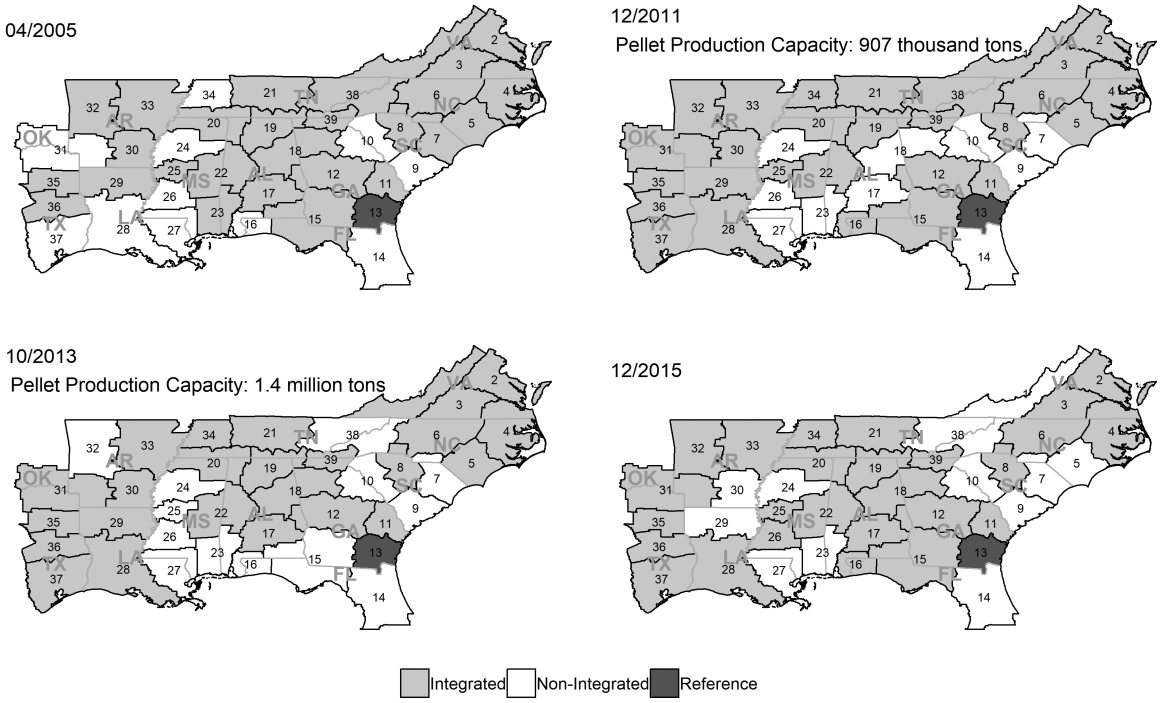


**Figure 7. Spatial-Temporal market linkage of softwood pulpwood - Market (4).**

competitive. Also, these micromarkets are dominant players in the long-run equilibrium in the sawtimber market (Mei et al. 2010a). Therefore, it might not be an exaggeration to claim that Southeast Georgia dominates or, at least, has a strong influence on the pulpwood market in the US South as well.

Micromarket (4)—the North Carolina/Virginia border—is surrounded by a dynamic market too, and it is a strong market itself. Micromarket (4) had 4 percent of the US South removals of the hardwood and softwood in 2015. It is home to four PPI and composite panel and three pellet mills. Its internal market seems to be strong enough to protect it against the movement in prices in another market, since there are few micromarkets integrated with them. Another region in a similar situation is micromarket (15)—between Florida, Georgia, and Alabama—which has the highest pulpwood removals (5 percent) and among the lowest number of micromarkets cointegrated—18 on average, 24 and 13 on its highest and lowest peak respectively.



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The linkage of the market (13) and (4) seems to overcome geographical barriers, since they are integrated to distant micromarkets in the west. This outcome corroborates with previous studies. Prestemon and Holmes (2000) showed the coastal plain of South Carolina (Micromarkets 9 and 7) is also cointegrated with distant markets. According to their results, they are cointegrated with pulpwood markets in Texas (Micromarkets 36 and 37), Louisiana (Micromarkets 29) and Mississippi (Micromarkets 20 (partially), 23, 24, 26). Yin et al. (2002) found similar evidence in Southeast Georgia, which was linked with all the 11 micromarkets in the US South studied by them, except, ironically, by its nearest neighbor North Georgia.

The geographical discontinuity of pulpwood markets seems to relate to the market power exercised by the PPI. Market (13) and (4) is often linked to micromarkets with traditional pulpwood markets (15, 30, 4, 29, and 38) or their closest neighbors. Also, there are few opportunities to reduce costs in a pulp and paper mill because of the substantial investment in capital. Since the raw material account for 30 percent of the total costs (FisherSolve 2018), it is expected that mill managers use information in different micromarkets to negotiate the final price, thereby creating links with other pulpwood markets.

On the other hand, the period with the lowest number of markets integrated was when the pellet production at micromarkets (13) and (4) reached the highest capacity. One explanation is that pellet mills might create stronger internal demand, which protects the local market against shocks from the market (13) and (4). Alternatively, the increase in price expectation was too low to impact their surrounding micromarkets. Also, the most recent pellet mills are installed in micromarkets where there is less competition, where pulp and paper or composite panels recently closed their operations (Forest2Market 2015). These micromarkets probably have few transactions, and the pulpwood market was stagnating.

### Market Linkage (Cointegration) Drivers

To re-examine the determinants of the spatial linkage between pulpwood markets, we ran a series of regression analyses and evaluated the role of distance, pellet mill capacity, and pulpwood volume harvested. Table 2 shows descriptive statistics.

We accounted for spatial and temporal heterogeneity by adding micromarket and temporal fixed effects. The models were robust over the different cointegration thresholds, 0.90, 0.95, 0.99, and 1 or when estimating $G(.)_{ijt}$ (Table A1). Table 3 presents the marginal effects (MEs) at percentile 25 percent and 75 percent of the logit model in Equation 8 using the cointegration threshold of 0.90[2]. The marginal effect is measured at a selected percentile of the variables in the rows plus the interaction terms (if any) for every variable. For instance, reading the first row in the Table (3) from left to right, the marginal effect of distance at percentile 25 percent ($D_{ij}[25\%]$) is 0.0274 plus the effect on the interactions with $DWP_{ijt}$ (–0.0003), $TWP_{ijt}$ (0.0002), $DVol_{ijt}$ (–0.0057), and $TVol_{ijt}$(–0.0253).

**Table 2. Descriptive statistic—meta analyses.**

| | Unit | Mean | SD | Min | Max |
|---|---|---|---|---|---|
| $Distance_{ij}$ | Miles | 692.15 | 374.92 | 108.9 | 1,828.93 |
| Wood pellet capacity$_{i(j)}$ | Thousand tons | 457.76 | 447.73 | 45.35 | 1,417.00 |
| Total wood pellets$_{ij}$ ($TWP_{ij}$) | | 802.47 | 564.93 | 0.00 | 2,603.08 |
| Diff. wood pellet$_{ij}$ ($DWP_{ij}$) | | 491.63 | 405.96 | 0.00 | 1,417.00 |
| Pulpwood volume$_{i(j)}$ | Million green tons | 2.18 | 1.54 | 0.10 | 7.13 |
| Total pulpwood volume$_{ij}$ ($TVol_{ij}$) | | 4.36 | 2.16 | 0.31 | 13.35 |
| Diff. pulpwood volume$_{ij}$ ($DWP_{ij}$) | | 1.70 | 1.39 | 0.00 | 7.13 |

*Note: Distanceij*, distance between the centroids of micromarkets *i* and *j*; wood pellet capacity$_{i(j)}$, total wood pellet capacity (thousand tons) in market *i* (*j*); total wood pellets*ij*, sum of wood pellet capacity between the market pairs *i* and *j*; diff. wood pellet*ij*, absolute difference between wood pellet capacity in market *i* and *j*; pulpwood volume$_{ij}$, total pulpwood volume (million green tons); total pulpwood volume$_{ij}$, sum of pulpwood volume between the market pairs *i* and *j*; diff. pulpwood volume$_{ij}$, absolute difference between pulpwood volume in market *i* and *j*.

**Table 3. Meta-analysis: marginal effects (ME) at percentile 25 percent and 75 percent.**

| | $Z = I[G(.) \geq 0.90]$ | | | | |
|---|---|---|---|---|---|
| | *D*ij | *DWP*ijt | *TWP*ijt | $DVol_{ijt}$ | $TVol_{ijt}$ |
| $D_{ij}$ (25%) | 0.0274 | –0.0003*** [0.000] | 0.0002*** [0.000] | –0.0057*** [0.003] | –0.0253*** [0.0097] |
| $D_{ij}$ (75%) | 0.0280 | –0.0002*** [0.000] | 0.0001*** [0.000] | –0.0203*** [0.003] | 0.0108*** [0.0104] |
| $DWP_{ijt}$ (25%) | 0.0186*** [0.0061] | –0.0002 | 0.0001*** [0.000] | –0.0134*** [0.0016] | –0.0057 [0.086] |
| $DWP_{ijt}$ (75%) | 0.0187*** [0.0052] | –0.0002 | 0.0001*** [0.000] | –0.0134*** [0.0036] | –0.0057 [0.052] |
| $TWP_{ijt}$ (25%) | 0.0158** [0.0062] | –0.0002*** [0.000] | 0.0001 | –0.0132*** [0.0034] | –0.0055*** [0.0080] |
| $TWP_{ijt}$ (75%) | 0.0758*** [0.0080] | –0.0001*** [0.000] | 0.0001 | –0.0119*** [0.0027] | 0.0034*** [0.0091] |
| $DVol_{ijt}$ (25%) | 0.0431*** [0.0063] | –0.0002*** [0.000] | 0.0001*** [0.0040] | –0.0135 | –0.0155*** [0.0061] |
| $DVol_{ijt}$ (75%) | 0.0196*** [0.0047] | –0.0002*** [0.000] | 0.0001*** [0.0030] | –0.0131 | 0.0006 [0.0095] |
| $TVol_{ijt}$ (25%) | –0.0236*** [0.0069] | –0.0002*** [0.000] | 0.001*** [0.0000] | –0.0276*** [0.0025] | –0.0276 |
| $TVol_{ijt}$ (75%) | 0.0720*** [0.0058] | –0.0002*** [0.000] | 0.0001*** [0.0000] | –0.0014*** [0.0018] | –0.0014 |

*Note:* The percentiles are shown in parentheses. The standard errors, in brackets, were measured by the bootstrap method with 999 repetitions. $Z = I[G(.) \geq 0.90]$, Estimated transition function $G(.)$ greater or equal than 0.90; *Dij*, distance between the centroids of micromarkets *i* and *j*; *TWPijt*, sum of wood pellet capacity between the market pairs *i* and *j*; *DWPijt*, absolute difference between wood pellet capacity in market *i* and *j*; $TVol_{ijt}$, sum of pulpwood volume between the market pairs *i* and *j*; $DVol_{ijt}$, absolute difference between pulpwood volume in market *i* and *j*.
*$P < .1$; **$P < .05$; ***$P < .01$.



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The distance between the micromarket pairs has a positive effect on market linkage in almost every variable. Column $D_{ij}$, from top to bottom, shows that distance has a negative effect only in markets with smaller pulpwood demand, $TVol_{ijt}$ (25%). In addition, its marginal effect increases in either micromarkets with large wood pellet capacity ($TPW_{ijt}$) or large pulpwood demand ($TVol_{ijt}$), and it reduces when the absolute difference goes from the 25th to 75th percentile ($DVol_{ijt}$). The interaction of distance with the absolute difference and the total pulpwood volume in two locations reviews that market size can overcome the distance effects (first two rows from left to right). Neighbor markets ($D_{ij}$ [25%]) tend to be less integrated when there is an expansion in demand for pulpwood, and the distribution of volume is asymmetric ($TVol_{ijt}$ and $DVol_{ijt}$ respectively). In distant markets ($D_{ij}$[75%]) the impact of volume asymmetry is even more significant (–0.0203), but it is diminished by the weaker but positive effect of volume (0.0108). Therefore, distant markets are less likely to be cointegrated if the increase in volume demanded is totally concentrated in one micromarket.

The combination of the market size (total quantity of pulpwood volume) and distance seems to define market cointegration more than wood pellet capacity. Large markets, where there is an intense harvesting activity, tend to be more mature, and the supply and demand follow expected behavior. These micromarkets are likely to be a price reference to smaller markets (Mei et al. 2010). On the other hand, the price in weak markets tends to be more sensitive to external shocks, missing the link with other areas if they are not located near strong pulpwood markets. Two interactions in Table 3 indicate this behavior in the US South: (1) the marginal effect of the absolute difference ($DVol_{ijt}$) in a small ($TVol_{ijt}$ [25 percent]) and large ($TVol_{ijt}$ [75 percent]) markets, and (2) the marginal effect of total volume in market $i$ and $j$ ($TVol_{ijt}$) in a more symmetric ($DVol_{ijt}$[25%]) and less symmetric ($DVol_{ijt}$[75%]) volume distribution.

The first interaction shows that an increase in the absolute difference between markets has a greater negative effect on pairs with smaller total volume (–0.0276) than in large ones (–0.0014). So, a sudden change in demand or supply micromarkets would reduce the linkage between prices in weaker markets, although the second indicated that when the volume is highly concentrated in one micromarket ($DVol_{ijt}$ [75%]), the increase in volume would not change market linkage. In less concentrated markets ($DVol_{ijt}$ [25%]), a total increase in volume would reduce the cointegration probability by –0.0155.

The capacity of wood pellet production might affect pulpwood market cointegration but on a smaller scale when compared to the market volume. In all specifications and interactions, we observed the higher the capacity of wood pellet production, the more likely it is that two micromarkets will be integrated. However, if this capacity is unevenly distributed between micromarkets, there will be a negative effect on cointegration. Here, we do not find any evidence of wood pellet mills causing any price increases or decreases. We speculate that markets are still adapting to pellet mills, and even though the mills are expanding their capacity, the impact on pulpwood prices dissipates between species and other sources like residuals. However, the structure of pellet production might rapidly affect prices, since only seven companies dominate the wood pellet market. They have in total 70 percent of US wood pellet production capacity. One firm has eight mills and 40 percent of southern wood pellet capacity (Forisk 2018). Pellet mills also have some degree of market power, which would lead to similar movements in pulpwood prices in facilities located in different micromarkets.

## Conclusion

This paper investigated the impact of wood pellet mills in the pulpwood prices dynamics in the US South. We adopted a STAR model with regimes shifting between cointegrated and nonintegrated markets. This study expanded previous research on forest products by adding a powerful tool such as the STAR models.

We first examined the response of micromarket to external shocks and the length of time for the market to return to equilibrium. In general, it took less than 48 months for markets to go back to equilibrium, although in a few cases, prices remained at a higher level. The cases with longer adjustments are characterized by weaker market linkage, mostly related to market distance, volume, and pellet mill capacity. Although not the focus of this paper, this also might have implications for responses to shocks such as hurricanes.

In the detailed analysis of the effect of pellet mills, our results suggest that there are no specific market clusters in the US South, but every pair of micromarkets has some relation. Markets are connected in many configurations; practitioners should consider not only proximity but also similar market structures in terms of the mix of pulp, solid wood, and pellet mill manufacturing plants. The GIRF combined with nonlinear models revealed a complex relation between timber prices. Investors should be aware of the market behavior of regions with similar characteristics, regardless of the distance between them.

An aspect less explored in this paper is the role of the timber suppliers. Even though we assumed the supply side is composed of many landowners, there is a substantial landownership concentration in areas near pulp and paper mills. This supplier market power might weaken market linkage, since prices will be determined by local supply influences. Future research could include these variables to capture the entire market dynamics, but it would be extremely difficult to obtain useful data on timber supply concentration of even large timberland landowners.

Finally, the answer to whether the pellet mills have impacted pulpwood price dynamics is "Yes." Wood pellet mills have shown a mixed impact depending on the market structure and depth of surrounding markets.

### Endnotes

1. The Argument Dickey Fuller test in the log-relative prices is equivalent to testing $\beta = 1$ in the log-linear price relation $\ln(p_{it}) - \beta_0 - \beta_1 \ln(p_{jt})$ (Goodwin et al. 2011).
2. Appendix A2 checks for robustness the model in Equation 8 by adding and reducing the number of variables.

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# Appendix A

**Table A1. Meta-analysis regression results: softwood pulpwood—robust analysis.**

| | $Z = I[G(.) \geq 0.90]$ | $Z = I[G(.) \geq 0.95]$ | $Z = I[G(.) \geq 0.99]$ | $Z = I[G(.) \geq 1]$ | $Z = G(.)$ |
|---|---|---|---|---|---|
| | (1) | (2) | (3) | (4) | (5) |
| $\beta_0$ | 0.023 | 0.009 | –0.109 | –1.222*** | 0.598*** |
| | (0.167) | (0.167) | (0.168) | (0.187) | (0.034) |
| $D_{ij}$ | 0.090*** | 0.105*** | 0.160*** | 0.198*** | 0.013** |
| | (0.028) | (0.028) | (0.028) | (0.031) | (0.006) |
| $DWP_{ijt}$ | –0.001*** | –0.001*** | –0.001*** | –0.001*** | –0.0002*** |
| | (0.0002) | (0.0002) | (0.0002) | (0.0002) | (0.00003) |
| $TWP_{ijt}$ | 0.0004*** | 0.001*** | 0.001*** | 0.001*** | 0.0001** |
| | (0.0002) | (0.0002) | (0.0002) | (0.0002) | (0.00003) |
| $DVol_{ijt}$ | –0.232*** | –0.210*** | –0.172*** | –0.139*** | –0.066*** |
| | (0.034) | (0.034) | (0.035) | (0.038) | (0.007) |
| $TVol_{ijt}$ | –0.100** | –0.104** | –0.120*** | –0.054 | –0.021** |
| | (0.044) | (0.044) | (0.044) | (0.049) | (0.009) |
| $TWP_{ijt} * DWP_{ijt}$ | 0.00000** | 0.00000 | 0.00000** | 0.00000** | 0.00000** |
| | (0.00000) | (0.00000) | (0.00000) | (0.00000) | (0.00000) |
| $TVol_{ijt} * DVol_{ijt}$ | 0.040*** | 0.038*** | 0.032*** | 0.029*** | 0.010*** |
| | (0.006) | (0.006) | (0.006) | (0.007) | (0.001) |
| $N$ | 40,755 | | | | |
| Log likelihood | –28,082.620 | –28,101.150 | –27,944.400 | –24,278.500 | –24,136.75 |
| Akaike information criterion | 56,181.250 | 56,218.310 | 55,904.810 | 48,573.010 | 48,291.51 |

*Note:* $Z = I[G(.) \geq W]$, estimated transition function $G[.]$ greater or equal than 0.90, 0.95, 0.99 or 1; $D_{ij}$, distance between centroid in market $i$ and $j$; $TWP_{ijt}$, sum of wood pellet capacity between the market pairs $i$ and $j$; $DWP_{ijt}$, absolute difference between wood pellet capacity in market $i$ and $j$; $TVol_{ijt}$, sum of pulpwood volume between the market pairs $i$ and $j$; $DVol_{ijt}$, absolute difference between pulpwood volume in market $i$ and $j$.
$^{*}p < .1$; $^{**}p < .05$; $^{***}p < .01$.

**Table A2. Meta-analysis regression results: softwood pulpwood.**

| | $Z = I[G(.) \geq 0.90]$ | | | |
|---|---|---|---|---|
| | (1) | (2) | (3) | (4) |
| $\beta_0$ | 0.023 | 0.648*** | 0.031 | 0.687*** |
| | (0.167) | (0.173) | (0.167) | (0.173) |
| $D_{ij}$ | 0.090*** | –0.373*** | 0.064** | –0.392*** |
| | (0.028) | (0.041) | (0.028) | (0.042) |
| $DWP_{ijt}$ | –0.001*** | –0.001*** | –0.001*** | –0.002*** |
| | (0.0002) | (0.0002) | (0.0004) | (0.0004) |
| $TWP_{ijt}$ | 0.0004*** | 0.0004** | 0.0004 | 0.001*** |
| | (0.0002) | (0.0002) | (0.0003) | (0.0003) |
| $DVol_{ijt}$ | –0.232*** | –0.162*** | –0.236*** | –0.156*** |
| | (0.034) | (0.038) | (0.034) | (0.038) |
| $TVol_{ijt}$ | –0.100** | –0.284*** | –0.091** | –0.300*** |
| | (0.044) | (0.046) | (0.044) | (0.046) |
| $D_{ij} * TVol_{ijt}$ | – | 0.138*** | – | 0.147*** |
| | – | (0.009) | – | (0.009) |
| $D_{ij} * DVol_{ijt}$ | – | –0.059*** | – | –0.060*** |
| | – | (0.013) | – | (0.013) |
| $D_{ij} * TWP_{ijt}$ | – | – | 0.0002 | 0.0004** |
| | – | – | (0.0002) | (0.0002) |
| $D_{ij} * DWP_{ijt}$ | – | – | 0.00001 | –0.0005*** |
| | – | – | (0.0002) | (0.0002) |
| $TWP_{ijt} * DWP_{ijt}$ | 0.00000** | 0.00000** | 0.00000* | 0.00000** |
| | (0.00000) | (0.00000) | (0.00000) | (0.00000) |
| $TVol_{ijt} * DVol_{ijt}$ | 0.040*** | 0.040*** | 0.040*** | 0.041*** |
| | (0.006) | (0.006) | (0.006) | (0.006) |
| $N$ | 40,755 | | | |
| Log likelihood | –26,282.440 | –26,150.540 | –26,274.480 | –26,145.640 |
| Akaike information criterion | 52,836.870 | 52,577.090 | 52,824.960 | 52,571.280 |

*Note:* $Z = I[G(.) \geq 0.90]$, estimated transition function $G(.)$ greater or equal than 0.90; $D_{ij}$, distance between the centroids of micromarkets $i$ and $j$; $TWP_{ijt}$, Sum of wood pellet capacity between the market pairs $i$ and $j$; $DWP_{ijt}$, absolute difference between wood pellet capacity in market $i$ and $j$; $TVol_{ijt}$, sum of pulpwood volume between the market pairs $i$ and $j$; $DVol_{ijt}$, absolute difference between pulpwood volume in market $i$ and $j$.
$^{*}p < .1$; $^{**}p < .05$; $^{***}p < .01$.

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