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Impacts of the European renewable energy policy on forest resource markets in the Southern United States: A case of the wood pellet industry

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ABSTRACT

Exports of wood pellet from the southern United States (US) have surged significantly in the last decade to meet renewable energy requirements set by the Renewable Energy Directives in European Union nations. Several export-oriented industrial wood pellet production facilities have been established across the southern US, which utilize a significant amount of woody feedstock including roundwood stumpage. We employ quasi-experimental causal inference approaches to assess the impacts of the growing wood pellet production on pine and hardwood pulpwood feedstock markets in 39 wood basins across 11 southern states in the US. The findings suggest that the booming wood pellet industry has minimal impacts on the pulpwood feedstock markets in the micro-markets that host wood pellet mills. Findings shed light on how the expanding industrial wood pellet production has influenced the forest resource harvests and product prices in the largest wood basket region of the world.

1. Introduction

The International Energy Agency (2021) projects that global renewable energy capacity will grow by over 60 % from 2020 levels to more than 4800 gigawatts by 2026, which equates to the current global power capacity of fossils fuels and nuclear. International policies, both existing and future, with explicit goals and deadlines will play a critical role in removing barriers to increasing energy production from renewable sources (Sen and Ganguly, 2017). Existing European policies such as the Renewable Energy Directive (RED) I and II, enacted in 2009 and 2018, respectively, have already proven to be effective in expanding renewable energy consumption (Aguilar et al., 2020; Bersalli et al., 2020; Ciucci, 2022). For example, RED I required at least 20 % of energy consumption by European Union (EU) member nations to be powered by renewable energy sources by 2020. Meanwhile, RED II increased the renewable energy quota for EU member nations to at least 32 % of energy consumption by 2030 (Ciucci, 2022). In July 2021, EU legislators proposed an amendment to RED II as a part of the European Green Deal package to further increase the amount of energy supplied by renewables to 40 % of total EU energy consumption by 2030 (Ciucci, 2022). This most recent amendment is necessary for achieving Europe's goal of reducing net greenhouse gas emissions by 55 % by 2030 and becoming the first "climate-neutral" continent by 2050 (European Commission, 2021; Eurostat, 2023).

The current version of RED in force, RED II, also introduced an expanded scope of the EU sustainability criteria for bioenergy, specifically biomass and biogas for heating, cooling, and electricity generation, which are derived from organic compounds such as wood products (Aguilar et al. 2020; Ciucci, 2022). One of the bioenergy sustainability provisions prohibits the use of woody biomass from primary and highly biodiverse forests and roundwood (European Commission, 2021; Mai-Moulin et al., 2021). Despite the restrictions, 60 % of the renewable energy produced in the EU came from bioenergy in 2021 (European Commission, 2021). Pelletized wood, derived from forestry products and byproducts, mill residues, and urban and yard wastes, is a plant-based fuel that is in high demand as a bioenergy technology due to its low moisture content and relatively high energy density (Sgarbossa et al., 2020; European Pellet Commission, 2022). Exports of wood pellets from the United States (US), primarily from the southern states, to other countries such as the EU member nations and the United Kingdom as well as Asian nations has increased from over 1.9 million metric tons (MMT) or $338 million in 2012 to approximately 7.4 MMT or $1.6 billion in 2022 in 2022 US dollars (USDA Foreign Agricultural Service, 2023), largely due to renewable energy policies (Masum et al., 2019; Aguilar et al., 2020).

Forisk, a US forestry consulting firm, estimates that global demand

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for industrial wood pellets will reach 31 million metric tons in 2025 (Mendell, 2021). To meet the growing demand, the wood pellets market in the US South has responded by increasing industrial grade pellet production capacity from just over 1.8 million metric tons in 2009 to over 10 million metric tons in 2019 (Mendell, 2019). Currently, there are at least five pellet plants under construction and four others proposed in the US South, which are expected to increase capacity by 5.2 million metric tons per year (Biomass Magazine, 2023). The US South, the largest wood basket in the world, may attract processing mills due to the region's supply of feedstock for wood pellet production and multiple ports to ship products to customers (Visser et al., 2022), two key drivers in site selection of biorefineries (Martinkus et al., 2017). While the initial expectation was for the expanding wood pellet industry to utilize mainly low-valued hardwood feedstock, according to a survey of 17 pellet mills in the southern US, pine roundwood pulpwood has been the principal fiber feedstock for wood pellet production (Kittler et al., 2020; ENVIVA, 2023).

Several studies have examined feedstock availability, timber market dynamics, land use dynamics, and socioeconomic impacts of the industrial wood pellet industry in the US South. Early studies, based on scenario simulations, projected that wood pellet production would influence roundwood production and prices substantially (Abt et al., 2010; Abt and Abt, 2013; Rafal et al., 2013; Abt et al., 2014; Nepal et al., 2019). Hoefnagels et al. (2014) analyzed the availability of low-valued woody feedstock in the US South and reported a higher potential for wood pellet production from unmerchantable forest residues in terms of availability and cost-effectiveness. Similarly, Duden et al. (2017) projected that higher wood pellet demand would lead to 5–11 % additional pine plantation acres in the US South by 2030. In terms of major feedstock types consumed by wood pellet producers, Kittler et al. (2020) revealed that most of the larger capacity wood pellet mills utilize roundwood pulpwood which is also the major feedstock for traditional pulp and paper mills, and Parajuli (2021) investigated the price competition between wood pellet and pulp and paper mills. Visser et al. (2022) also revealed that by 2030, the share of pulpwood consumption by the wood pellet industry might rise by 37 % from the 2020 level. On the other hand, Aguilar et al. (2022) reported that the wood pellet industry in the US Southeast contributed to net incremental effects on carbon pools within live trees.

The main purpose of this study is to evaluate the impacts of the growing export-oriented wood pellet industry driven by European renewable energy policies on forest resource markets in the southern US. We employ quasi-experimental causal inference approaches to assess the impacts of the growing export-oriented wood pellet production capacity on the US South's roundwood markets. First, this study evaluates the wood pellet market using a difference-in-difference (DID) approach. However, the traditional difference-in-difference approach does not account for treatment intensity such as the impact of mill capacity, for spatial effects such as spillover effects, where treated units influence control units, or for self-selection of mill facilities in specific locations. For these reasons, we expand the difference-in-difference methodology to account for treatment heterogeneity in terms of timing as well as intensity and spatial effects. Amidst the conflicting debates on the wood pellet industry impacts on southern forest resource markets, it is imperative to conduct an empirical data-based assessment on causal inference offering scientific evidence on the impacts of the wood pellet industry in the southern US forest resource harvests and markets. The findings of this study shed light on how the rapidly rising wood pellet production to meet the growing overseas demand has influenced the forest resource uses and corresponding markets in the largest wood basket region of the world.

2. Methods

2.1. Study area and data

The US mill capacity to produce industrial quality wood pellets concentrates primarily in the country's southeastern coastal region (Fig. 1a). For our study, we use 39 timber micro-markets (MMs) areas as delineated by Forest2Market, a private US subscription-based price reporting company (F2M, 2023). These MM areas represent local woodsheds, covering forestlands from Virginia to East Texas (Fig. 1a), with several of these MMs hosting one or more industrial, export-oriented wood pellet production facilities. These pellet facilities compete with traditional wood-based manufacturing firms for similar woody biomass feedstock (Kittler et al., 2020: Parajuli, 2021).

We assess effects of export-oriented industrial wood pellet mills on pulpwood markets in these MMs based on two outcome measures- prices of standing roundwood pulpwood (stumpage) and the volume of pulpwood production (or pulpwood harvest), where pulpwood production refers to roundwood, whole or chipped, used to produce wood pulp. To evaluate the effect on prices, we use annual average pulpwood prices computed from Forest2Market historical MM-specific bi-monthly data, covering the period from January 2005 through December 2020. To explore potential effects on pulpwood production, we use annual data (2005–2020) on aggregated pulpwood production available from the USDA Forest Service Forest Inventory and Analysis Timber Product Output program (USDA Forest Service, 2023).

To evaluate the impact of export-oriented wood pellet production on roundwood pulpwood markets, we start by creating a binary treatment variable at the MM level, which has a varying treatment period in line with the year the first industrial wood pellet mill came into operation in a particular MM. However, effects are likely different for MMs that host multiple pellet mills with varying capacities (Fig. 1b). Therefore, we also evaluate treatment effects of wood pellet production using total capacity of export-oriented wood pellet facilities. For capacity as a treatment, we facilitate our estimation approach by categorizing the capacity values into five groups, based on active production capacity in a micro-market; 0: no pellet production, 1: the pellet production capacity of 200,000 tons per year or less, 2: the production capacity of 200,001–600,000 tons per year, 3: the production capacity of 600,001–1million tons per year, 4: the production capacity of over 1 million tons per year. Further, since hardwood and softwood have distinct end-use markets (Polyakov et al. 2005; Parajuli 2021), the models are estimated separately for hardwood and softwood pulpwood, resulting in four models.

Table 1 presents details for all variables used and their respective data sources. All the stumpage price series are purchased from Forest2Market, currently renamed as ResourceWise, pulpwood production was obtained from the USDA Forest Service, and wood pellet export-capacity information was sourced from various industry news blogs and websites. We deflate all the price series to real 2017 dollars using the US producer price index for all commodities (US Bureau of Labor Statistics, 2020). Moreover, rainfall data and the wood pulp price index are obtained from the National Centers for Environmental Information, National Oceanic and Atmospheric Administration (NOAA, 2020) and the Bureau of Labor Statistics (US Bureau of Labor Statistics, 2020), respectively. All the continuous variables are log-transformed before estimating empirical models.

Wood processing mills draw wood from wide procurement areas, likely impacting pricing and resource conditions of neighboring counties and possibly neighboring MMs. This potential interaction among MM units would violate the stable unit treatment value assumption (Rubin, 1980). Further, an assignment to treatment is not random, but rather guided by characteristics of the selected location. As such, locations with desired characteristics will be more likely to be treated (i.e., more likely to house industrial wood pellet mills). Spatial dependence might be, therefore, present in our analysis (Kolak and Anselin, 2020), as MM's characteristics such as historical prices, raw material availability,

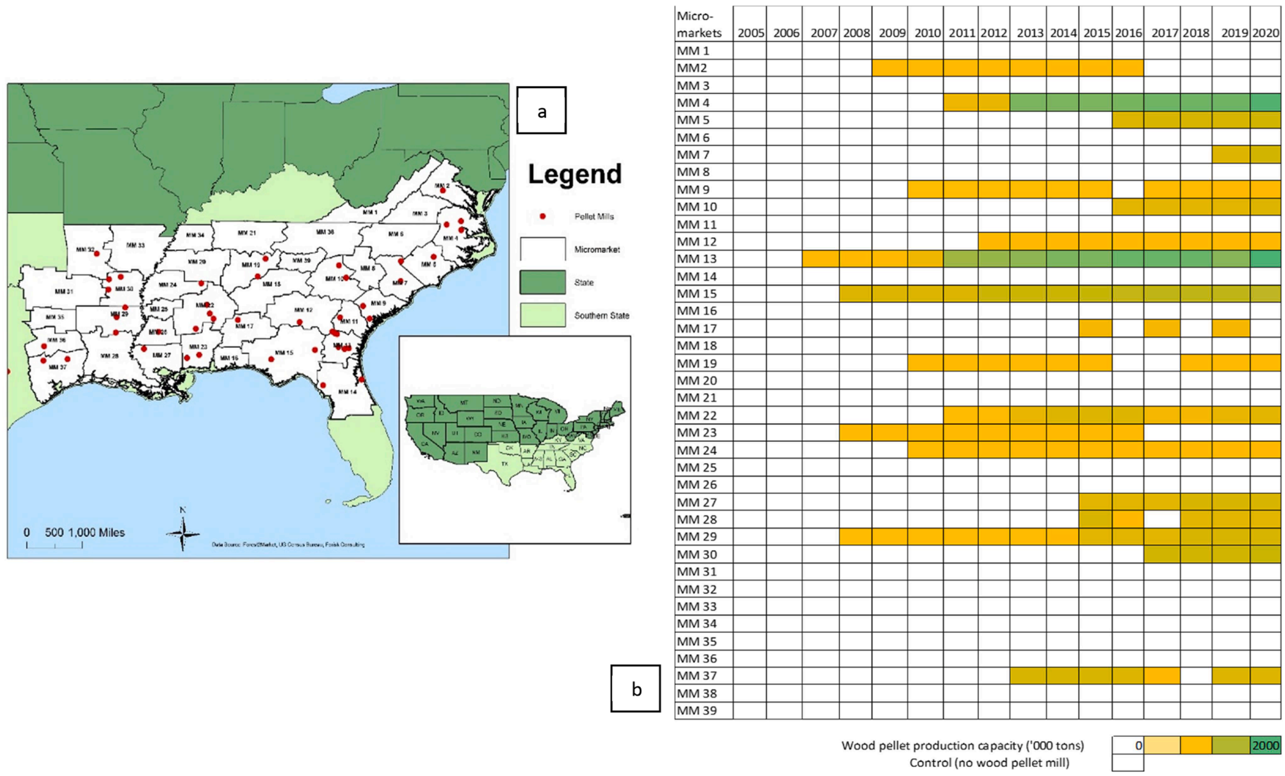

Fig. 1a. A map showing the location of export-oriented wood pellet mills in 39 micro-markets in the southern United States. Fig. 1b. A heat chart representing wood pellet production capacities by year, for each of the 39 micro-markets in the southern United States, 2005–2020. Cell coloring indicates a micro-market's wood pellet capacity (or treatment level) in thousand metric tons, from white (blank) cells indicating zero capacity (untreated) to darker green showing higher capacity (higher treatment).

proximity to ports, existing competing markets, among others, likely influence the location of export-oriented pellet mills in a particular MM.

We perform a preliminary analysis to evaluate these potential spatial specification issues using the Moran-I index, a measure of spatial autocorrelation (Anselin and Bao, 1996). We include our four outcome measures: pulpwood stumpage prices and pulpwood production for softwood and hardwood species groups under both binary and categorical treatment setups. The spatial structure was represented using a contiguity matrix, with normalized weights. Results for our preliminary analysis of spatial dependence indicate the need to include spatial components in our specifications, suggesting prices as highly spatially dependent (Appendix, Table A1) for both species groups, all with positive Moran's I index values indicating spatial clustering. Conversely, our treatment variables show signals of spatial correlation only for the continuous case in 2012 (Appendix, Table A2) with a P-value = 0.049. A closer look at spatial autocorrelation for pellet mill capacity (continuous variable) in 2012 reveal MMs 13, 14, and 15 as statistically significant (Appendix, Table A3).

In addition to a spatial component for the treatment variables, we include two covariates to help capture wood pellet mill location decision: Average density of pulpmill capacity ($\text{HPULPD}_{\text{it}}$ and $\text{SPULPD}_{\text{it}}$ for hardwood and softwood, respectively) and total volume of standing timber (HWD_{it} and SWD_{it} for hardwood and softwood, respectively), estimated as follows:

$$PULPD_{i,t} = \frac{1}{J_i}\sum_{j=1}^{J_i}\left(\frac{1}{K_t - 1}\sum_{k=1}^{K_t}\frac{vol_{k,t}}{Dist_{j,k}}\right)$$

Where j represents the number of counties in MM i, K_t is the number of active pulpmills at time t, $vol_{k,t}$ is corresponding softwood or hardwood capacity of mill k at time t in green tons, and $Dist_{j,k}$ the Euclidian distance between county j and mill k.

$$WD_{it} = \sum_{j=1}^{J_i} Stock_{jt}$$

Where $Stock_{jt}$ represents the volume of standing timber in county j at time t.

2.2. Empirical strategy

To test the effects of the wood pellet industry on roundwood pulpwood markets, we use the difference-in-differences (DID) approach as a quasi-experimental empirical strategy. We look at MMs as the evaluating units and assess effects by considering treatment as binary as well as categorical. For the binary treatment case, we consider a MM treated when there is at least one active export-oriented wood pellet mill located within it. For the categorical treatment case, we use the total capacity of active export-oriented wood pellet mills at each MM at time t, as stated in Table 1. The empirical specification that estimates the average post-treatment effect in a traditional two-way fixed effect (TWFE) setting for the roundwood pulpwood stumpage markets is:

$$y_{it} = \alpha_0 + \beta^{DD}D_{it} + \delta_i X_{it} + \alpha_i + \alpha_t + \varepsilon_{it},$$

Where, y_{it} represents log prices of pine and hardwood roundwood pulpwood stumpage in MM i and period t; D_{it} represents the treatment periods with differential timing; X_{it} denotes the vector of covariates; α_i and α_t represent MM specific fixed effects and time period effect, respectively; and ε_{it} is the error term. The same TWFE model can be used for both binary and continuous treatment variables.

The standard DID approach is not applicable in our situation (Roth et al., 2023; de Chaisemartin and D'Haultfoeuille, 2020), as we have varying treatment periods and export capacities (Fig. 3) consistent with openings, expansions, closings, and idling of wood pellet mills at different times throughout the study period. For instance, the first

Table 1
Variables, their explanations, and sources.

Variable	Explanation	Unit	Data source or details
PPW_{it}	Pine pulpwood stumpage price in micro-market *i* at time *t*	2017$/ton	Forest2Market (2020)
HPW_{it}	Hardwood pulpwood stumpage price in micro-market *i* at time *t*	2017$/ton	Forest2Market (2020)
QPW_{it}	Pine pulpwood production in micro-market *i* at time *t*	Green tons	USDA, Forest Service (2023b)
QHW_{it}	Hardwood pulpwood production in micro-market *i* at time *t*	Green tons	USDA, Forest Service (2023b)
TREAT1	Binary variable representing the existence of an export-oriented wood pellet mill in micro-market *i* at time *t*	0 or 1	Variable dates consistent with the starting period of wood pellet mills
TREAT2	Total export-oriented wood pellet capacity in micro-market *i* at time *t*	1000 tons	Various sources
	Covariates		
$WPULP_{it}$	US producer price index for wood pulp (WPU0911)	Index (1982 = 100)	US Bureau of Labor Statistics (2020)
PST_{it}	Pine sawtimber stumpage price in micro-market *i* at time *t*	2017$/ton	Forest2Market (2020)
HST_{it}	Hardwood sawtimber stumpage price in micro-market *i* at time *t*	2017$/ton	Forest2Market (2020)
$RAIN_{it}$	Aggregate rainfall in micro-market *i* at time *t*	Inches[a]	NOAA (2020)
HWD_{it}	Hardwood volume of standing timber in micro-market *i* at time *t*	Thousand cubic feet[b]	USDA, Forest Service (2023a)
SWD_{it}	Softwood volume of standing timber in micro-market *i* at time *t*	Thousand cubic feet	USDA, Forest Service (2023a)
$HPULPD_{it}$	Density of hardwood pulpmill capacity in micro-market *i* at time *t*	Tons/mile[c]	USDA, Forest Service (2023b)
$SPULPD_{it}$	Density of softwood pulpmill capacity in micro-market *i* at time *t*	Tons/mile	USDA, Forest Service (2023b)

[a] 1 inch = 25.4 mm.
[b] 1 cubic foot = 0.0283 m^3.
[c] 1 mile = 1.61 km.

export-oriented wood pellet mill came into operation in MM 13 in 2007, but several wood pellet mills started their production in 2010 and 2011, and MM 6 has a relatively newer wood pellet mill which came into operation in 2019. As a result, our dataset consists of 19 MMs that have experienced some level of treatment and 20 MMs that, to date, have not received treatment, indicating that these MMs have yet to host at least one industrial wood pellet mill inside their boundaries. We can also observe that MMs are not only first treated at different times in the study period, but treatment status (for the binary treatment case) and treatment intensity (for the continuous categorized treatment case) vary between and within MMs (Fig. 3). This treatment heterogeneity creates difficulties for isolating the effects, biasing results when using the typical TWFE approach (Cunningham, 2021; de Chaisemartin and D'Haultfoeuille, 2020).

Recent DID literature (Goodman-Bacon, 2021; Callaway and Sant'Anna, 2021; Sun and Abraham, 2021) proposed new and advanced DID designs that consider variation in treatment timing that produce unbiased treatment estimates compared to the traditional TWFE approach. However, their approaches specifically, Goodman-Bacon (2021) and Callaway and Sant'Anna (2021) are applicable to cases with staggered treatment timing, meaning for units that are treated at different times and remain treated after their first treatment, which as seen in Fig. 3, is not the case for our analysis, even for the binary treatment assignment. Recent work by de Chaisemartin and D'Haultfoeuille (2022) (henceforth DID_L) offer an approach more suitable to our study design, allowing for treatment level that can vary in time and intensity, defining the event as the time where a group *g* changes for the first time. Rather than using as a control those never treated or yet to be treated, the DID_L approach proposes using as controls those that have not yet switched (changed in treatment) and that have the same level of treatment as those that switched at the start of the period. Following de Chaisemartin and D'Haultfoeuille (2022) nomenclature, a DID estimator ($DID_{g,l}$) compares the outcome evolution of $F_g - 1$ to $F_g + l$ between group *g* and groups that have not yet switched at time $F_g + l$ and have the same treatment level at period one, where F_g represents the first period at which treatment for group *g* changes. The $DID_{g,l}$ estimators are then aggregated across groups, generating an estimator of the effect from a weakly higher amount of treatment for l and $l + 1$ periods (see de Chaisemartin and D'Haultfoeuille 2022 for specifics).

All the DID approaches rely on the strong assumption of parallel trends, which indicates that in absence of the treatment effect, outcome for both treated and untreated units would follow the same pattern. The $DID_{g,l}$ estimators are reported to be unbiased under parallel trends, and the DID_L approach offers a test for the assumption consisting of placebo estimators that compare outcomes of those that switch to those that do not, prior to the switch (de Chaisemartin and D'Haultfoeuille, 2022). Evidence of parallel trends is reported when placebo effects are zero. Further, the DID_L method allows us to estimate the effects of not only the presence of a wood pellet mill in a MM but also the categorical production capacity of those mills on pulpwood markets. We estimate the DID_L model (did_multiplegt in STATA) assuming a dynamic effect (i.e., past levels of treatment likely influence current treatment), including covariates, and using the placebo option. While spatial dependency on the outcome variable is likely, we do not include a spatially weighted outcome variable, as this would violate the strong exogeneity assumption required by DID_L (de Chaisemartin and D'Haultfoeuille, 2022). Estimated errors are generated through bootstrap using 100 repetitions.

3. Results

Table 2 presents the average treatment effects from the DID_L method for both hardwood and softwood pulpwood prices and production volume under the binary and categorical treatment setups. We controlled for both time and MM specific fixed effects in estimating the models. The results suggest that the estimated treatment effects are not statistically significantly different from zero across all outcomes at the 95 % confidence level. The joint placebo test for parallel trends assumption (De Chaisemartin and D'Haultfoeuille, 2020) suggests that parallel trends

Table 2
Average effects of wood pellet production on pulpwood markets in the southern United States estimated using the DID_L approach.

	Average effects (Binary treatment)			
	LN (pulpwood prices)		LN (pulpwood harvests)	
	Pine	Hardwood	Pine	Hardwood
Average treatment effect ($\widehat{\beta^{DD}}$)	0.086 (0.06)	−0.092 (0.06)	0.122 (0.10)	0.028 (0.17)
Parallel trends [P-value]	Yes [0.51]	Yes [0.08]	Yes [0.86]	No [0.03]
	Average effects (Categorical treatment)			
	LN (pulpwood prices)		LN (pulpwood harvests)	
	Pine	Hardwood	Pine	Hardwood
Average treatment effect ($\widehat{\beta^{DD}}$)	0.049 (0.03)	−0.050 (0.03)	0.070 (0.05)	0.019 (0.10)
Parallel trends [*P*-value]	Yes [0.51]	Yes [0.07]	Yes [0.85]	No [0.05]

Values in parentheses are micro-market clustered robust standard errors. Values in brackets are *p*-values.

hold well for pine pulpwood prices and quantities, but it is barely the case for hardwood pulpwood prices and quantities as the P-values range between 0.05 and 0.10. The estimated coefficient of 0.086 for the pine pulpwood price denotes that the pine pulpwood price would be about 9 % higher in the micromarkets that host a wood pellet mill, but this estimate coefficient is not statistically significant at the 5 % level of significance.

The graphs in Figs. 2 and 3 display estimated treatment effects to the right of −1, and estimated placebos to the left, along with their respective 95 % confidence intervals. The overall average treatment effect on pine pulpwood prices is not statistically significant under both binary and categorized treatment scenarios. However, as shown in event-study plots (Figs. 2a and 3a), the treatment effect of wood pellet on pine pulpwood prices is positive and statistically significant in the second and third treatment switching periods. Hardwood pulpwood prices show a statistically significant treatment effect at the fourth switching period, under both treatment specifications, however with a negative estimate effect (Figs. 2b and 3b). Estimates for pulpwood production for both species groups are found to be not significantly affected by the presence of at least one pellet mill in MMs. While there are somewhat positive post-treatment effects in pulpwood harvest models after an opening of the mill specifically in the case of pine pulpwood harvests, the overall average impact is found to be statistically insignificant.

We also estimated the traditional DID (TWFE) models just to compare the results with DID_L models. Table 3 summarizes results from the naïve TWFE models for both pine and hardwood pulpwood prices and harvest volumes under both treatments. While the TWFE estimates are biased under the heterogeneous treatment timing setting (Goodman-Bacon, 2021; Callaway and Sant'Anna, 2021), results match the pattern of the DID_L method for the pulpwood harvest outcome across the binary treatment and species, failing to reject the null of no effect at the 5 % significance level (Table 3). A different result emerged for the categorical treatment, with signs of statistical significance for larger capacities on both pine and hardwood pulpwood prices. Signs of coefficients also mirror, to some extent, those found through the DID_L estimations. For the pulpwood pine price model, the top three pellet capacity categories show a positive sign, while hardwoods show a significant effect with a negative sign. Results suggest that, compared to a MM without any pellet production capacity, MMs having over one million tons per year of production capacity are found to have about 51 % higher pine pulpwood prices. Similarly, the average treatment effect of pellet production in a MM with an annual capacity between 600,000 and 1 million is estimated to be around 14 %, compared to a MM not hosting any pellet mill. However, contrary to the expectation but similar to DID_L results, average effects of having larger pellet mills with over 600,000 annual production capacity are found to be statistically significant with a negative sign, indicating that having a wood pellet mill in a MM leads to a decrease in hardwood pulpwood prices by 17–28 %, compared to MMs without wood pellet production. Readers are cautioned that significant results for the categorical treatment are likely biased due to the misspecification of the treatment considered by the TWFE models in the presence of treatment heterogeneity.

4. Discussion

The EU's RED I and II have fostered demand for renewable energy including bioenergy (Aguilar et al., 2020; Bersalli et al., 2020; Ciucci, 2022), which constituted 60 % of the renewable energy produced in the EU in 2021 (European Commission, 2021). Exports of industrial wood pellets, largely from the US South to other countries including EU member nations and the United Kingdom, has increased in response to renewable energy policies in Europe (Aguilar et al., 2020). To illuminate the potential effects of increased demand and consumption of industrial

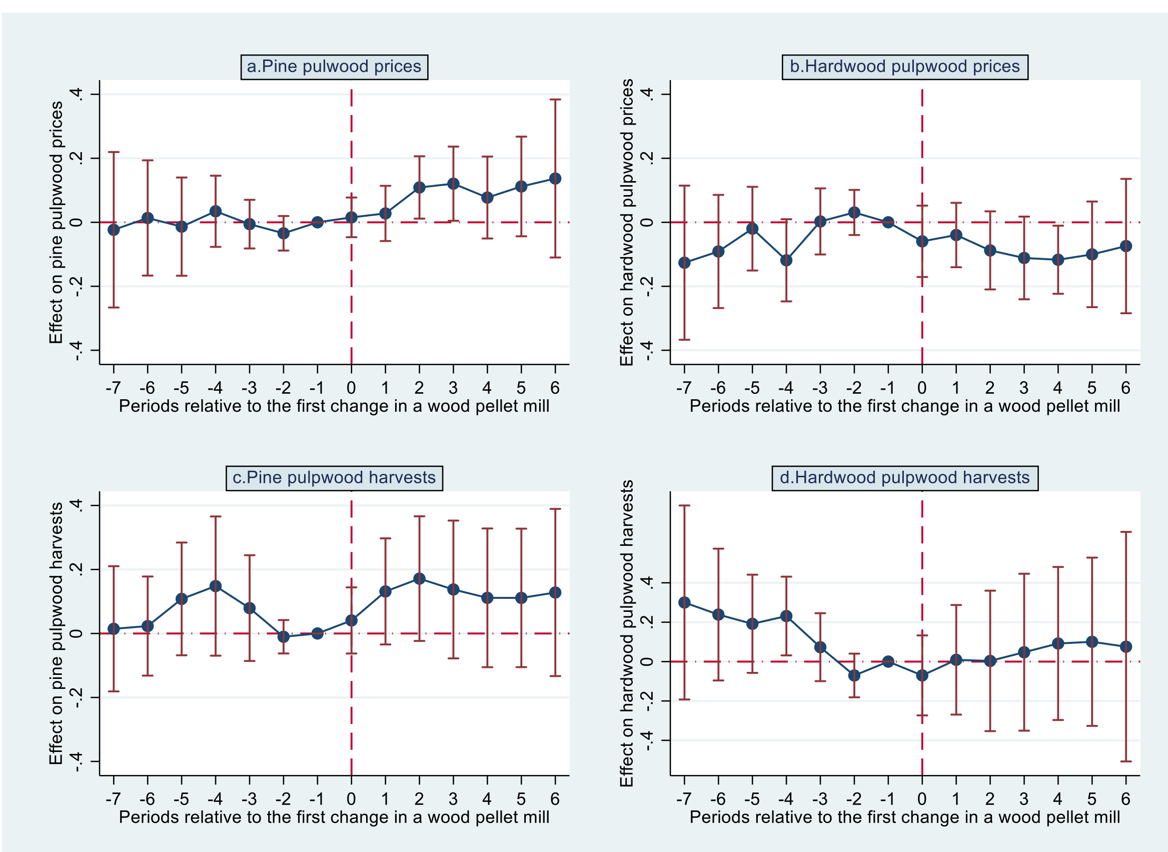

Fig. 2. Average effects of a wood pellet mill on pine and hardwood prices and quantities under a binary treatment setup.

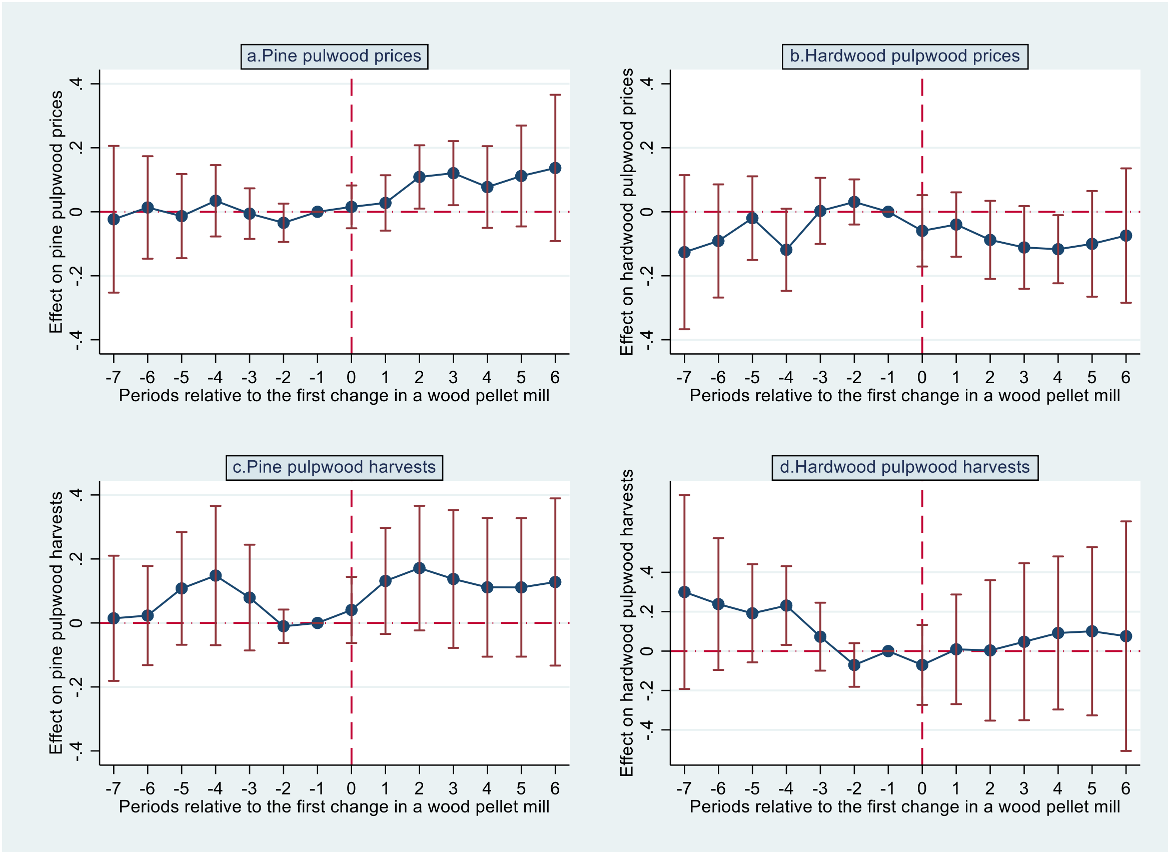

Fig. 3. Average effects of a wood pellet mill on pine and hardwood prices and quantities under a categorical treatment setup.

Table 3
Estimated average effects of the wood pellet industry on pulpwood roundwood markets in the US South, using the TWFE approach.

	Average effects (Binary treatment)			
	LN (pulpwood prices)		LN (pulpwood harvests)	
	Pine	Hardwood	Pine	Hardwood
Average treatment effect: TWFE ($\widehat{\beta^{DD}}$)	0.062 (0.06)	−0.071 (0.05)	0.009 (0.05)	−0.064 (0.10)
	Average effects (Categorical treatment)			
	LN (pulpwood prices)		LN (pulpwood harvests)	
	Pine	Hardwood	Pine	Hardwood
Pellet capacity 200,000 M tons or less	−0.020 (0.08)	−0.050 (0.05)	−0.024 (0.07)	0.020 (0.09)
Pellet capacity 200,001–599,000 M tons	0.106** (0.05)	−0.038 (0.06)	0.035 (0.04)	−0.158 (0.13)
Pellet capacity 600,000–1 million M tons	0.144* (0.08)	−0.177* (0.10)	0.061 (0.07)	−0.027 (0.28)
Pellet capacity over 1 million M tons	0.510*** (0.05)	−0.282** (0.11)	0.038 (0.11)	−0.587 (0.44)
Controlled MMs	20	20	20	20
Treated MMs	19	19	19	19
N	624	624	624	624
Micro-Market FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes

Values in parentheses are micro-market clustered robust standard errors. *** significant at 1 % ** significant at 5 % level, * significant at 10 % level. For the categorical treatment, the controlled group represents the micro-markets with no pellet production capacity. Both micro-market and year fixed effects were controlled.

wood pellets on forest resource uses and corresponding markets, this study evaluates the impacts of the industrial wood pellet industry on pulpwood markets in the US South utilizing causal inference techniques. This is the first study to our knowledge to assess the causal impact of the wood pellet industry on stumpage markets in the US South, the largest wood basket in the world and a major supplier of wood pellets for global consumption.

We complemented the naive DID or TWFE approach with the novel DID_L approach, as the standard DID model approach can produce biased estimates in the presence of treatment heterogeneity (Cunningham, 2021; de Chaisemartin and D'Haultfoeuille, 2020). More specifically, the DID_L approach allows for the evaluation of treatment effects when there is variation in timing and intensity of treatment and treated units can go in and out of treatment, to account for varying starting times and capacities of export-oriented wood pellet plants in various southern US MMs.

Results from our DID_L specifications fail to provide evidence to reject the null of zero average effect from our two treatment variables at the 5 % significance level for either softwood or hardwood markets. Overall, both binary and categorical treatments appear to not significantly affect pulpwood prices or volume of production. However, results indicate significant effects from the categorical treatment at a couple of points during the observation period. Namely, the second and third switching periods for pine prices, and the fourth switching period for hardwood prices. In those instances, the categorical treatment shows a positive effect on pine prices and a negative effect on hardwood prices. Those results indicate a sensitivity to specification, with potential for significant effects under given conditions. While in the average over the period studied effects are not statistically significant, perhaps when analyzing individual MMs and/or narrower periods, results might differ. Nonetheless, comparing results from the DID_L and TWFE specifications highlight the need to account for the complexity of our treatment variable in the treatment effect specification, as not doing so could lead to erroneous conclusions.

Our findings also suggest that hardwood pulpwood price impacts from the wood pellet industry are not statistically significant, which is consistent with Parajuli (2021), but it directly contrasts the various projected scenarios showing an increase in pulpwood harvest and prices over the coming years (Abt et al. 2014; Nepal et al. 2019; Visser et al. 2022). Low demand for hardwood resources for wood pellet production in the southern US, except for pellet production in Virginia which uses hardwood feedstock as a primary input in pellet production (Abt et al., 2022), may explain the result. Hardwood pulpwood constitutes a small portion of the feedstock utilized by operating and announced wood pellet mills in the US South (Brandeis et al., 2021; Kitter et al. 2020). According to the Timber Products Output survey (US Forest Service, 2023), hardwood resources constitute only about 25 % of the roundwood bioenergy/fuelwood feedstock in 13 southern states in 2022, while softwood and mixed resources comprise the remaining 75 %. Furthermore, the low utilization rate of hardwood roundwood resources for bioenergy is reflected in Enviva's aggregate consumption of various feedstock types (Enviva, 2023), as only approximately 4.3 % of their feedstock comes from hardwood forests. Hardwood pulpwood prices are found to be driven primarily by traditional pulp and paper industries. For instance, hardwood pulpwood prices were down 43 % when the International Paper mill in Riegelwood, North Carolina converted its production from market pulp to pine-based fluff and specialty pulp products (International Paper, 2020; Parajuli, 2021).

Overall, the findings from this analysis suggest that the wood pellet industry in the US South, on average, has not driven the pulpwood feedstock market significantly. It is worth noting that the estimated DID coefficients are the average treatment effects which are the mean values across the MMs over the period between 2005 and 2020. The overall insignificant impacts do not necessarily mean that the wood pellet industry has not influenced the timber markets in local wood basins. For example, Parajuli (2021) reported that the positive impact of the wood pellet industry on pine pulpwood prices varied across the southeast Atlantic coastal MMs with a range of 5–12 %. Hence, it can be expected that some MMs might have realized significant impacts of the wood pellet mills in certain pulpwood markets.

While the findings suggest minimal impacts based on the historical data, this could change soon with rapidly expanding wood pellet production across the coastal regions in the southern US. The wood pellet exports from the US continue to be in an upward trend for the last several years, which did not slow down even during the COVID-19 pandemic (Parajuli, 2021; USDA FAS 2023). To illustrate, Mendell (2021) projects that demand for industrial wood pellets to increase 19 % by 2025. Overseas markets for US wood pellets are expanding rapidly with favorable policy support and trade environments. Johnston et al. (2022) estimated the global wood pellet consumption to increase under each Shared Socioeconomic Pathway (SSP), except SSP3, and to continue to rise through 2070 and wood pellet production in the US South to continue to increase under SSP2 ("Middle of the Road" scenario through 2070. To meet this demand, wood pellet production capacity in the US South is expected to continue to increase with the construction of at least five new facilities and the expansion of at least four operational facilities (Lang, 2022). Therefore, more impacts of the wood pellet industry on the consumption and prices of woody feedstock might be forthcoming.

5. Conclusion

Our results suggest that the expansion of the industrial wood pellet industry has not had a statistically significant impact on pulpwood markets, in terms of average treatment effects or impacts averaged over the entire treatment period. However, we did find that (1) the treatment effect of wood pellet on pine pulpwood prices is positive and statistically significant in the second and third treatment switching periods, (2) the wood pellet treatment effect on hardwood pulpwood prices is negative and statistically significant in the fourth switching period, and (3) failing to account for the complexity of the event or heterogeneous treatment i.e. changing export-oriented wood pellet mill capacity over the periods pattern across the area of interest can lead to misleading results, as shown in Table 3.

Our DID_L results are not without potential error, however. Our preliminary analysis provide evidence for spatial correlation on prices, therefore, future work exploring specifications that relax the strict exogeneity assumption would strengthen results. Our results reject the parallel trends assumption for hardwood harvest indicating a need to explore alternative approaches to evaluate effects of pellet mills on hardwood pulpwood harvest. Lastly, analyzing treatment effects with treatment applied at a smaller geographical scale (such as county) could also prove an informative approach to evaluate the effects.

Despite projections in the literature that growing demand for wood pellets would likely alter roundwood and timber markets (Abt et al. 2014; Nepal et al. 2019), our findings suggest the alternative: the expanding wood pellet industry has had minimal significant impacts on pulpwood harvests and prices in the southern US. Nonetheless, the uncertain future of wood pellet demand and the effects of which hinge on global trade trends in addition to renewable energy policies. For instance, the EU and United Kingdom consume more wood pellets than their domestic production, thus these countries must import wood pellets in order to meet their demand (Franco, 2022). The relatively low cost of sea transportation, compared to land transportation, in addition to the availability of feedstock and high production capacity make the US South an ideal producer and exporter of wood pellets (Franco, 2022). The region's competitive advantage may become even more crucial in the near future due to the ongoing war in Ukraine, which is disrupting energy markets in Europe (European Commission, 2022) and outside the scope of this analysis. As such, since July 2022, sanctions in the EU have been imposed, effectively ceasing Russian wood pellet exports (Lesprom, 2022). The EU has also announced that it is planning to ban imports of Russian oil and coal by the end of 2022 (European Commission, 2022). As a result, the European Commission (2022) developed the REPowerEU Plan, which outlines the EU's pathway to reducing dependence on Russian fossil fuels and expediting a transition to a cleaner, more resilient energy system. This study could provide a timely baseline for comparison to evaluate future economic shocks resulting from policy change and trade relations, particularly as demand for wood pellets continues to grow in countries in Europe, Asia, and beyond.

CRediT authorship contribution statement

Rajan Parajuli: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Consuelo Brandeis:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Methodology, Investigation, Formal analysis, Conceptualization. **Stephanie Chizmar:** Writing – review & editing, Writing – original draft, Validation, Software, Methodology, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A

Table A1
Moran's I index for outcome variables, 2005–2020 (2-tail test results).

	Pulpwood price						Pulpwood harvest					
	Softwood			Hardwood			Softwood			Hardwood		
Year	*I*	*Z*	*P*-value	*I*	*Z*	*P*-value	*I*	*Z*	*P*-value	*I*	*Z*	*P*-value
2005	0.155	1.805	0.071	0.565	5.818	0.000	0.374	3.901	0.000	0.032	0.581	0.561
2006	0.203	2.264	0.024	0.456	4.719	0.000	0.341	3.597	0.000	0.027	0.539	0.590
2007	0.403	4.326	0.000	0.308	3.318	0.001	0.378	3.949	0.000	0.008	0.342	0.732
2008	0.465	4.844	0.000	0.347	3.682	0.000	0.360	3.757	0.000	−0.016	0.108	0.914
2009	0.442	4.585	0.000	0.438	4.520	0.000	0.380	3.943	0.000	−0.076	−0.497	0.620
2010	0.525	5.413	0.000	0.540	5.542	0.000	0.380	3.957	0.000	−0.052	−0.262	0.794
2011	0.580	5.974	0.000	0.396	4.134	0.000	0.425	4.423	0.000	−0.046	−0.200	0.841
2012	0.609	6.254	0.000	0.418	4.350	0.000	0.376	3.941	0.000	−0.023	0.033	0.974
2013	0.622	6.360	0.000	0.502	5.182	0.000	0.373	3.918	0.000	0.001	0.284	0.776
2014	0.649	6.640	0.000	0.543	5.546	0.000	0.359	3.758	0.000	−0.010	0.175	0.861
2015	0.621	6.391	0.000	0.544	5.568	0.000	0.394	4.120	0.000	−0.043	−0.175	0.861
2016	0.632	6.507	0.000	0.525	5.357	0.000	0.294	3.144	0.002	−0.027	−0.010	0.992
2017	0.632	6.500	0.000	0.429	4.439	0.000	0.312	3.306	0.001	−0.007	0.192	0.848
2018	0.652	6.716	0.000	0.481	5.008	0.000	0.349	3.649	0.000	−0.028	−0.015	0.988
2019	0.599	6.250	0.000	0.471	4.891	0.000	0.317	3.340	0.001	−0.018	0.082	0.935
2020	0.591	6.336	0.000	0.448	4.670	0.000	0.329	3.476	0.001	0.019	0.477	0.634

Table A2
Moran's I index for treatment variables, 2005–2020 (2-tail test results).

	Binary			Continuous		
Year	*I*	*Z*	*P*-value	*I*	*Z*	*P*-value
2005	.	.	.	.	.	.
2006	.	.	.	.	.	.
2007	−0.0294	−0.3659	0.7144	−0.0294	−0.3659	0.7144
2008	−0.0239	0.0255	0.9797	0.0309	1.2191	0.2228
2009	−0.0725	−0.4775	0.6330	0.0127	0.7327	0.4638
2010	−0.2124	−1.8426	0.0654	0.0640	1.1896	0.2342
2011	−0.123	−0.9455	0.3444	0.0663	1.3351	0.1819
2012	−0.0952	−0.671	0.5022	**0.1209**	**1.9682**	**0.0490**
2013	−0.1456	−1.1574	0.2471	−0.0180	0.0948	0.9245
2014	−0.1456	−1.1574	0.2471	−0.0226	0.0418	0.9666
2015	0.0059	0.31	0.7565	−0.0158	0.1132	0.9098
2016	0.0102	0.3522	0.7247	−0.0202	0.0670	0.9466
2017	−0.1002	−0.7132	0.4757	−0.0296	−0.0354	0.9717
2018	−0.1147	−0.8528	0.3938	−0.0333	−0.0750	0.9402
2019	−0.0624	−0.347	0.7286	−0.0543	−0.2935	0.7691
2020	−0.0664	−0.3863	0.6993	−0.0560	−0.3183	0.7502

Table A3
Index for continuous treatment by micro-market, 2012.

Micro-market	Ii	*Z*	*P*-value
1	0.0771	0.2837	0.7766
2	0.0406	0.1586	0.8740
3	−0.0777	−0.1408	0.8880
4	−0.3122	−0.7841	0.4330
5	−0.0837	−0.1361	0.8917
6	0.0342	0.2209	0.8252
7	0.115	0.3878	0.6982
8	0.1166	0.439	0.6606

(*continued on next page*)

Table A3 (*continued*)

Micro-market	Ii	*Z*	*P*-value
9	0.0923	0.3253	0.7449
10	0.0884	0.4187	0.6755
11	−0.4118	−1.0576	0.2903
12	0.2653	0.9837	0.3253
13	**2.9203**	**8.083**	**0.0000**
14	**−1.3704**	**−2.5971**	**0.0094**
15	**2.3526**	**7.3102**	**0.0000**
16	−0.3012	−0.6518	0.5145
17	−0.1444	−0.3983	0.6904
18	0.0382	0.2175	0.8278
19	−0.0446	−0.0616	0.9509
20	0.0425	0.232	0.8166
21	0.0786	0.2879	0.7734
22	0.0006	0.1051	0.9163
23	−0.0489	−0.0694	0.9447
24	−0.0489	−0.0694	0.9447
25	0.0434	0.2143	0.8303
26	0.0566	0.2797	0.7797
27	0.0614	0.2081	0.8352
28	0.1044	0.4017	0.6879
29	0.0316	0.2114	0.8326
30	0.0769	0.348	0.7279
31	0.0999	0.3461	0.7292
32	0.1226	0.3532	0.7240
33	0.0859	0.3449	0.7302
34	0.1226	0.3532	0.7240
35	0.0923	0.2812	0.7786
36	0.0999	0.3461	0.7292
37	0.1226	0.2878	0.7735
38	0.0975	0.4519	0.6513
39	0.0786	0.2879	0.7734

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