

THESIS

DETERMINANTS OF PRIMARY TIMBER PROCESSING FACILITY CLOSURES IN
COLORADO: A SURVIVAL ANALYSIS

Submitted by

Faith Elizabeth Glaze

Department of Forest and Rangeland Stewardship

In partial fulfilment of the requirements

For the Degree of Master of Science

Colorado State University

Fort Collins, Colorado

Summer 2026

Master's Committee:

Advisor: Srijana Baral

Anita Alves Pena
Wilfred Previant

Copyright by Faith E. Glaze 2026

All Rights Reserved

ABSTRACT

DETERMINANTS OF PRIMARY TIMBER PROCESSING FACILITY CLOSURES IN COLORADO: A SURVIVAL ANALYSIS

The forest products industry (FPI) in the United States (US) plays a vital role in sustaining rural economies, providing employment opportunities, and supporting healthy forests. Over the past several decades, the FPI has undergone significant changes as the number of timber processing facilities has declined across the US. While this trend of closures is evident, little research has examined patterns of forest plant closure or the factors influencing such patterns. Using a Complementary Log-Log discrete-time survival model, we identify the external and internal factors driving the closure of primary forest product manufacturers in Colorado between 2002 and 2020. Internal factors, such as plant size and plant type, and external factors, such as the volume of timber removed from federal lands, had a significant impact on the survival probability. Compared with larger mills, small mills (<250 MCF) exhibited an 82% higher risk of closure. Sawmills and log home manufacturers were less likely to exit the industry than log furniture manufacturers. In addition, an increase in the average annual volume of timber cut from federal forests was associated with a 1% reduction in the closure hazard. Similarly, an increase in industry employment of 100 employees was associated with a 13% decrease in closure hazard. Findings from this study highlight the importance of federal timber availability, skilled labor availability, and targeted policies for local FPI, depending on product type and input capacity. This study offers one of the first applications of survival modeling to the FPI in the

western US, providing insights into policy implications that support federal timber programs and investment in workforce development as effective instruments for improving industry viability.

ACKNOWLEDGEMENTS

This study would not have been possible without the contributions of several people. I would like to first acknowledge my advisor Dr. Srijana Baral for offering me this opportunity and providing me with support and guidance along the way. Thank you to my advisory committee members, Dr. Anita Pena and Dr. Wilfred Previant, for taking on this project. I am incredibly grateful to Dr. Mahesha Kuluppuarachchi for the amount of time and energy she devoted to assisting me at all stages of this process.

Thank you to the University of Montana Bureau of Business and Economic Research for allowing us to use their data for our analysis. Many thanks to the USDA National Institute of Food and Agriculture for financial support.

As with everything I have and will ever accomplish, the credit goes to my family. To my parents, for their hard work and sacrifice to provide me with every opportunity. To my brother and sister-in-law, my two most favorite people, for never failing to brighten my day. Last but not least, to Erik, my rock. Your support and encouragement carried me through this program; I owe it all to you.

TABLE OF CONTENTS

ABSTRACT	ii
ACKNOWLEDGEMENTS	iv
LIST OF TABLES	vi
LIST OF FIGURES	vii
1.0 Introduction.....	1
1.1 Colorado Forest Products Industry	3
1.2 Study Contributions and Objectives	7
2.0 Literature Review.....	9
2.1 Colorado Forest Products Industry Trends	9
2.2 Survival Analysis	14
2.3 Drivers of Mill Closure.....	16
2.4 Use of Complementary Log-Log Model in Survival Analysis	23
3.0 Methods.....	24
3.1 Study Area	24
3.2 Data	26
3.3 Survival Analysis	30
3.3.1 Kaplan Meier and Log Rank Test	31
3.3.2 Complementary Log-Log Model.....	32
3.4 Variable Descriptions.....	35
4.0 Results.....	39
4.1 Results of the Kaplan Meier and Log Rank Test.....	40
4.2 Results of the Complementary Log-Log Model	44
5.0 Discussion.....	51
6.0 Conclusion	61
References.....	64
Appendices.....	73
A-1 Data Dictionary for Figures 2 and 3	73

LIST OF TABLES

Table 1: Variable definitions and sources with summary statistics for continuous variables	35
Table 2: Number of original 2002 primary timber processing facilities remaining operational by type for each BBER survey year	39
Table 3: Results of the Complementary Log-Log model with cluster-robust standard errors	46

LIST OF FIGURES

Figure 1: Colorado timber harvest volumes by ownership class, 1982, 2002, 2007, 2012, 2016, 2020	10
Figure 2: Figure 2: Volume of timber cut from federal forests and federal grasslands in Colorado, 1980-2020	11
Figure 3: Finished product sales by sector each survey year from all ownership classes, deflated to 2002 USD.....	14
Figure 4: Left and right censoring of events in survival analysis	15
Figure 5: Distribution of forest cover types across Colorado	25
Figure 6: Map of mill locations by survey year in the state of Colorado	27
Figure 7: Number of original 2002 timber processing facilities remaining active per survey year by size	40
Figure 8: Kaplan-Meier estimate of survival function for all primary timber processing facilities, including 95% confidence bands.....	41
Figure 9: Kaplan-Meier estimate for BBER survey mills by size.....	42
Figure 10: Kaplan-Meier estimate for BBER survey mills by type	43
Figure 11: Observed vs predicted hazards for base model	49
Figure 12: Observed vs predicted hazards for full model	49
Figure 13: Observed vs predicted hazards for reduced model	50

1. INTRODUCTION

The Forest Products Industry (FPI) has a long history of supporting rural economic development and environmental stewardship in the United States (US) (Dahal et al., 2015; Sorenson et al., 2016). As one of the leading forest product producing countries worldwide, the US provided about 30% of the global roundwood supply at the start of the 21st century (Wear et al., 2015). Nationwide, FPI supported nearly 2 million jobs in the early 2000s (Poudel and Dahal, 2025). In addition to economic contribution, FPI are critical for active forest management. Thriving forest products markets provide essential infrastructure to manage forests for long-term health and public support. However, over the past few decades, multiple events including industry restructuring, changing workforce dynamics, economic conditions, changing environmental policies, and natural disturbances have impacted FPI, increasing concerns about the long-term viability of the forestry sector in the US (Wear et al., 2015).

During the late 1900s, production of industrial roundwood declined due to policies limiting timber harvesting on federal lands (Wear et al., 2015). Federal policies, such as the National Environmental Policy Act (NEPA) of 1969, the Endangered Species Act of 1973, and the National Forest Management Act (NFMA) of 1976, required federal forests to consider ecosystem management in addition to timber production (Wear and Murray, 2004; Loomis, 2017). This decline in federal timber availability increased domestic prices, demand for industrial roundwood imports, and reliance on timber from private forestlands in the US south, while consumption continued to expand until 2005 (Wear et al., 2015). The collapse of the housing market and economic recession lasting from December 2007 until June of 2009 (National Bureau of Economic Research, 2010) created poor market conditions for the FPI

(Woodall et al., 2012). The wood products sectors in US and Canada experienced greater impacts of the Recession than other top roundwood producing countries (Wear et al., 2015), with the US losing over 1 million jobs in the forestry and forest products sectors alone (Woodall et al., 2012). More recently, the COVID-19 pandemic created an economy wide disruption, impacting the workforce, supply chains, and economic activities in the FPI. Other shocks, including wildfires, hurricanes, trade policies, and tariff agreements also increased market uncertainty for FPI in some regions.

As a consequence, many forest products manufacturers remained idle or permanently closed, reducing the timber processing capacity in many states. Many of these closures were concentrated in the US west, leaving FPI in this region with limited wood producing capacity (Spelter, 2004; Woodall et al., 2012). These closures also affected employment, labor income, and household consumption across county and state boundaries (Lamsal et al., 2025). Specifically, individual contractors and companies operating in the forestry sector struggled due to workforce consolidation, employment reduction, decreased profitability, increased mechanization of operations, and an aging population of business owners (Conrad et al., 2018). While increased mechanization in the FPI can replace some labor, there is still a need for skilled and technical workers. Difficulty finding and retaining qualified workers for these skilled positions is commonly cited as one of the largest issues faced by firms in the logging and forestry industries (Allen et al., 2008; Vaughan and Mackes, 2015).

The loss of processing facilities also disturbed market extent for forest management actions (Pokharel et al., 2020). In other words, insufficient access to milling infrastructure severely limited merchantability of timber and reduced the economic feasibility of many forest management activities that are critical for forested landscapes across the US. This has

contributed to overstocked forests with a higher probability of widespread wildfire, disease, and insect outbreaks (Pokharel, 2020). Addressing the loss of timber processing capacity and reduced distribution of milling facilities is crucial to tackle these threats to forest health and support the long-term viability of FPI and its economic contributions.

1.1 Colorado Forest Products Industry

The FPI in the state of Colorado contends with many of the same challenges faced in the forestry sector across the US due to policy changes, industry restructuring, slow recovery following the Great Recession, and COVID-19. While Colorado's FPI may not contribute to the state's economy to the same extent as those in the US south (Wear et al., 2015), they provide important economic and ecological benefits to local communities (Chung et al., 2024). Active management of Colorado's forests creates jobs, supports local economies, protects valuable water resources, provides opportunities for clean energy through biomass, increases forest resilience to insect and disease outbreaks, allows for recreational opportunities, and reduces the risk of wildfires. While FPI in Colorado contributes only about 0.59% of total state economic output (Chung et al., 2024), forest management supported by FPI is crucial for major industries like recreation and tourism.

In addition to federal policy changes, Colorado also had a unique shift in forest management goals from focusing primarily on timber harvesting to expanding to include recreation, aesthetics, and watershed protection in response to an influx of new residents following the end of the second World War (Vaughan and Mackes, 2015). Federal policies in the following decades restricting the volume of timber that could be harvested on federal lands fueled this trend (Keegan et al., 2012). As the majority of forestland in the state falls under federal ownership, these policies posed challenges for the local FPI, significantly reducing state's

milling capacity (Keegan et al., 2012). During and post Great Recession, similar to national patterns, the FPI in Colorado experienced reductions in both production (about 50%) and consumption of roundwood and employment (about 23%) in the forest products and forestry sectors (Keegan et al., 2012).

Over the past several decades, a pattern of mill closures has been observed in Colorado, increasing concerns about the future of FPI in the state (Morgan et al., 2006). Individual mill owners and forestry contractors in Colorado struggle with similar issues as those faced across the US, such as difficulty finding and retaining skilled labor (He et al., 2021). In addition, Colorado's timber mills face other challenges, such as reduced tree health and timber availability due to frequent extensive wildfires and insect outbreaks (Vaughan and Mackes, 2015). In response to these forest health threats, recognition of recreational value, and the substantial percentage of forestlands under federal ownership, the forestry industry in the state has shifted to focus on service projects as opposed to traditional timber sales (Vaughan and Mackes, 2015). Here traditional timber sale is used to refer to projects where work is carried out with a main goal of harvesting timber to produce forest products. Service based projects are typically thinning projects carried out with the main goal being improving forest health, fire resistance, restoration of beetle-killed or fire-burned areas, and trail maintenance (Vaughan and Mackes, 2015; Daniels et al., 2018) often with the production of timber products as a secondary objective of the project to help offset costs of the main service work. The removals from fire mitigation projects tend to be of smaller diameter and lower quality than the wood that would be recovered from commercial timber harvests. Trees removed due to insect activity are often larger in diameter, but insect infestation results in checking, or cracking, of the tree and may introduce blue stain fungus, degrading the quality of the timber (Richardson, 2016).

As the number of mills throughout the state declines, the trucking distance from the harvest site to processing facility increases, making it challenging to economically carry out salvage or harvest activities, particularly in areas with difficult terrain. Reduced accessibility and timber processing capacity combined with the industry focus on service type projects (Vaughan and Mackes, 2015) leaves Colorado's FPI with a dispersed network of small timber processing facilities struggling to offset high harvesting and transportation costs with revenue generated from the sale of low-value end products. As a result, many mill owners and forestry contractors find themselves relying on grants and subsidies.

Several programs and grants are offered by federal or state agencies, non-governmental organizations (NGO), or often through private and public partnerships to businesses and landowners in Colorado. These programs support Colorado's FPI in different ways, either by allowing state and local governmental agencies to expand forest management activities, incentivizing private landowners to carry out risk mitigation actions, or by financially supporting timber processing facilities in the use of small diameter wood removed from forest management activities. For instance, the Good Neighbor Authority, first authorized in 2001, allows the USFS and the BLM to authorize state, local, and recognized tribal governments to carry out forest management projects on federal land (Congressional Research Service, 2009). Healthy Forests and Vibrant Communities, House Bill 09-1199 passed in 2009, provides funding from the Colorado severance tax revenue fund to enhance the capacity of the Colorado State Forest Service (CSFS) to address growing forest management and wildfire mitigation needs (Colorado State Forest Service, 2016). In addition, the Wildfire Risk Reduction Grant Program administered by the Colorado Department of Natural Resources and the Colorado Forest Restoration Grant Program administered by the CSFS (Colorado State Forest Service, 2016)

were joined under the Healthy Forests and Vibrant Communities. Together, these programs provide grant and loan funding to community-level actions across the state that reduce risk of wildfire in the Wildland-Urban Interface (WUI), promote forest health and restoration, and encourage the use of woody material both for traditional forest products and for biomass. The program aids forestry businesses through loans that allow for increased efficiency and the purchase of new equipment as well as through employee training to improve retention of current employees and facilitate the creation of new jobs (Colorado State Forest Service, 2016). The programs also fund outreach and education through workshops and presentations, distribution of educational materials through various outlets, and support volunteer outreach programs (Colorado State Forest Service, 2016). Additionally, the Colorado Forest Restoration Institute (CFRI) supports Colorado's timber industry by improving collaboration between researchers, managers, and stakeholders as well as by reducing conflict, streamlining the planning process, and enhancing the effectiveness of forest management activities to improve wildfire resilience (Colorado Forest Restoration Institute, n.d.).

Several other programs specifically focus on supporting forestry businesses. For instance, the Timber, Forest Health & Wildfire Mitigation Industries Workforce Development Program established in 2023 provides grants to businesses and organizations to help hire and train employees across the timber, forest health, and wildfire mitigation industries. The Wildfire Risk Mitigation Loan Fund, established in 2022, provides funding for wildfire mitigation contractors and forest products businesses to invest in new equipment and working capital to address Colorado's increasing wildfire challenges. The Wood to Energy program helps communities evaluate and adopt biomass energy systems. The CSFS also maintains the Colorado State Forest Products Database that promotes local businesses and strives to reduce reliance on imports.

Another effort to support businesses at the state level is a state sales tax exemption on wood products made from trees infested or killed by bark beetles in effect July 1, 2008 through June 20, 2026 (Colorado Department of Revenue, 2021). In addition to these state programs, businesses in Colorado are also eligible for federal grants and loan programs. The Wood Innovations grant programs from the USFS awarded \$9.2 million to Colorado businesses between 2020-2024 from a total of 33 projects (Colorado State Forest Service, 2025). These grants invest in projects that expand traditional wood utilization. Another USFS program that assists qualified Colorado businesses are the Hazardous Fuels Transportation Assistance Grants (U.S. Forest Service, n.d.). This program supports projects that remove hazardous fuels from federal lands and move them to wood processing facilities.

1.2 Study Contributions and Objectives

Research on FPI in Colorado is limited and fragmented. A small number of forestry contractor studies have been conducted to explore logging capacity changes over time and issues faced by business owners (Vaughan and Mackes, 2015; Vaughan et al., 2022). The Bureau of Business and Economic Research (BBER) at the University of Montana, in partnership with the USFS and the Forest Inventory Analysis (FIA) Timber Products Output (TPO) Program, conducts periodic surveys of timber processing facilities in the western US (Alaska, Arizona, California, Colorado, Idaho, Montana, Nevada, New Mexico, Oregon, Utah, Washington, and Wyoming) to report on changes in number and capacity of mills over time. These surveys are conducted every four to five years and target the entire primary timber processing industry in each state. Published survey results provide information on the number of mills operational in the state during the year the survey was given, the geographic distribution of milling infrastructure throughout the state, and the proportion of mills by size and product type. These

surveys are useful for examining the change in mill numbers, distribution, and industry composition over time, but they do not provide any empirical analysis of mill closures or challenges faced by mill owners.

Only a handful of studies focused on other regions have examined the dynamics of timber mill closures (Sun et al., 2006; Sasatani and Zhang, 2015; Panti, 2020). While the decline of Colorado's FPI is widely documented, no such studies have been conducted in Colorado or the surrounding states. The overall goal of this study is to improve understanding of the pattern of forest products manufacturing facility closures observed in the state of Colorado over the past several decades. The specific objective is to identify factors that contribute to the failure of primary manufacturers in the state. As the programs established to support businesses and landowners participating in Colorado's FPI suggest that the long-term resilience of the industry is of great importance to Colorado's forests and of interest to many parties, the findings of this research will inform future decision making of how best to support forest products manufacturing in the state. The results will also inform policy decisions on how to build a resilient network of milling infrastructure, which will support a robust FPI, and in turn healthy forests and strong local economies.

2. LITERATURE REVIEW

2.1 Colorado Forest Products Industry Trends

The FPI in Colorado has faced several challenges since the late 20th century, resulting in noteworthy trends and deviations from historical patterns. As about 70% of forestland in Colorado is under federal ownership (Irey et al., 2025), timber harvested from those forestlands historically supplied the majority of the state's annual harvest volume (McLain, 1985). However, federal policies passed during the last third of the 20th century restricted timber harvest on federal lands (Binkley and Duncan, 2009), with removal volumes following a downward trend from the 1990s through around 2012 (McLain, 1985; Sorenson et al., 2016; U.S. Department of Agriculture, Forest Service, n.d.). Logging rates in Colorado declined by 90% from the 1980s through the first decade of the 21st century, largely as a response to reduction in the reliability of timber supplied from the national forests. Timber harvested from federal lands accounted for 90% of the state's total harvest volume in 1974 (Setzer and Shupe, 1977) and 80% of total harvest volume in 1982 (McLain, 1985). By 1999, federal share of total timber harvest volume had decreased to 47% (Lynch and Mackes, 2001) and decreased further to 38% in 2002 (Morgan et al., 2006). This decline in annual harvest volumes occurred despite a trend of increasing salvage of dead wood. In 1982, salvage accounted for only 8% of timber harvest volume (McLain, 1985). Contribution of salvaged wood to timber harvest volume climbed to 26% in 2002 (Morgan et al., 2006) and further to 56% in 2016 (Hayes et al., 2021). In recent years, Colorado's harvest volume trend has changed. In 2016, the annual harvest volume was similar to that of 1999 (Lynch and Mackes, 2001; Hayes et al., 2021), whereas in 2020, harvest volume was about 40% greater than the 1999 volume (Lynch and Mackes, 2001; Irey et al., 2025). The

decades long decline in contribution of timber harvested from federal forestland also saw a reversal in recent years, though not to levels seen in the 1980s. Federal timber contributed 65% and 53% of the 2016 and 2020 annual harvest volumes, respectively (Hayes et al., 2021; Irej et al., 2025). Figure 1 offers a visual representation of changes in overall timber harvest volume in Colorado as well as changes in harvest volume by ownership class.

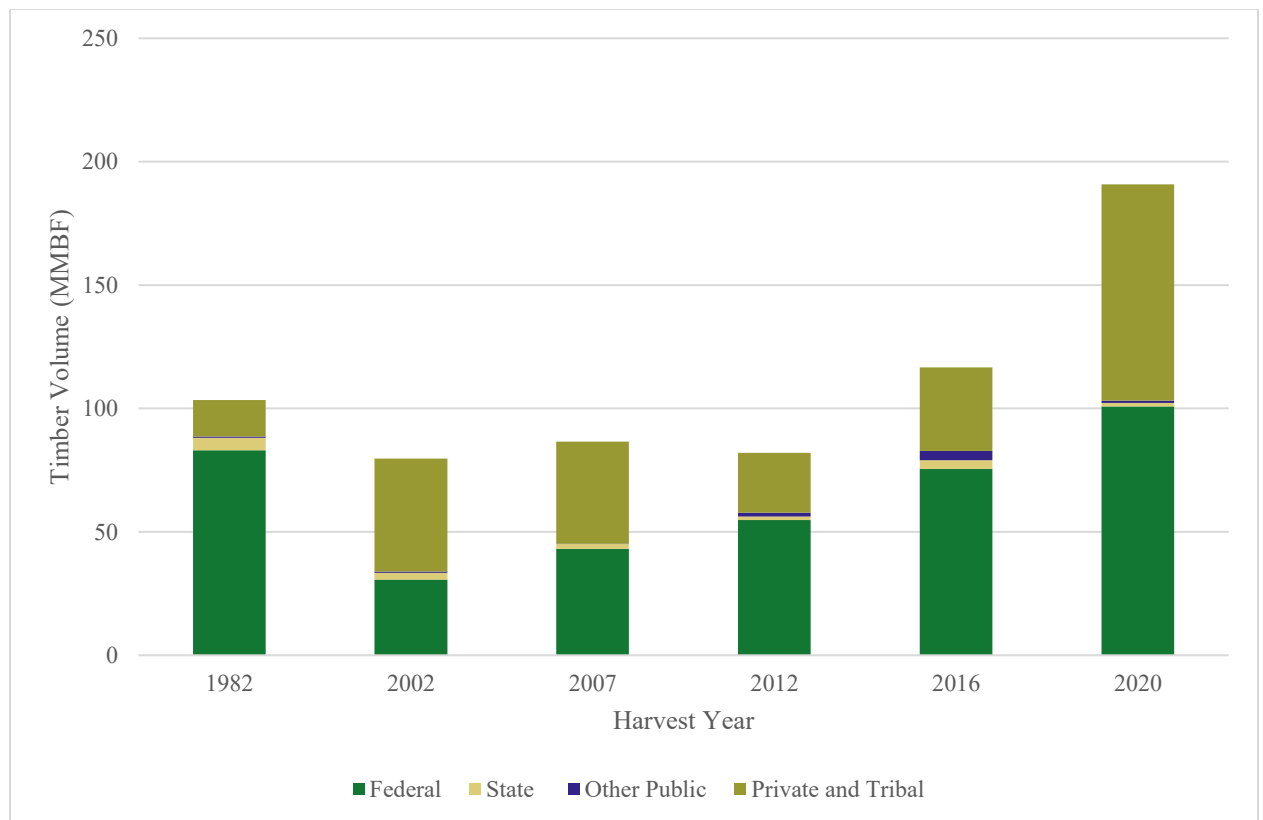


Figure 1: Colorado timber harvest volumes by ownership class, 1982, 2002, 2007, 2012, 2016, 2020. Sources: McLain, 1985; Morgan et al., 2006; Hayes et al., 20012; Sorensen et al., 2016; Hayes et al., 2021; Irej et al., 2025.

Figure 2 shows the changes in federal timber harvest volumes in Colorado from 1980 through 2020 as reported in U.S. Forest Service Cut and Sold reports (U.S. Department of Agriculture, Forest Service, n.d.).

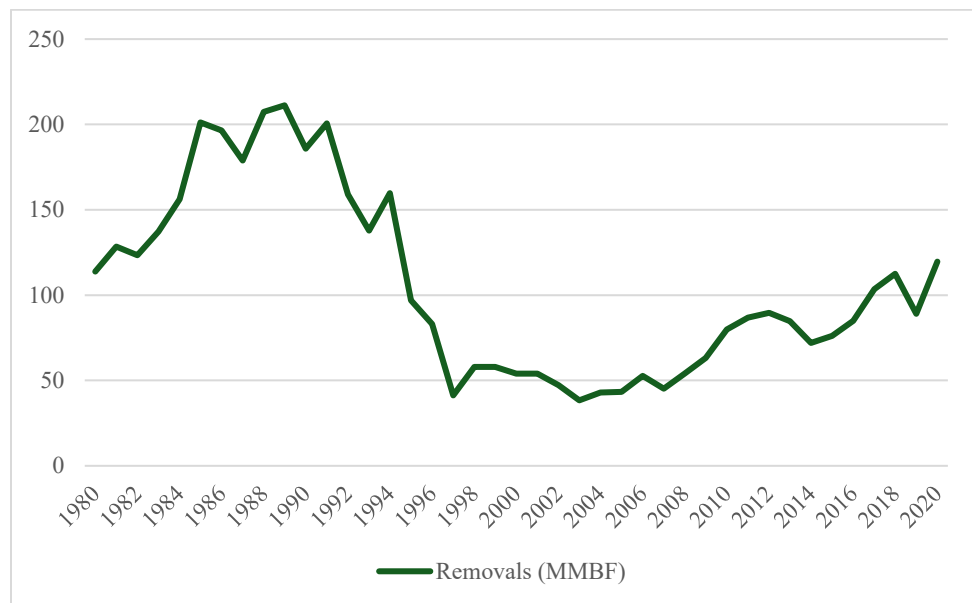


Figure 2: Volume of timber cut from federal forests and federal grasslands in Colorado, 1980-2020. Source: U.S. Department of Agriculture, Forest Service, n.d.

Fire suppression activities in Colorado combined with population expansion into the WUI, an increase in the frequency and severity of wildfires, and warmer, dryer climactic conditions have contributed to unhealthy forests that are more susceptible to catastrophic wildfire, disease, and insect outbreaks (Vaughan and Mackes, 2015; Negrón and Cain, 2019; Wright and Sen Roy, 2022). Mountain Pine Beetle (MPB) are native to Colorado, and they can provide an ecological service by removing diseased or dying trees to make more room for young, healthy trees (Leatherman et al., 2011). Historically, they are the most damaging insect to Colorado's pine forests as observed between 1996 and 2013 (Colorado Forestry Advisory Board, 2002). While the impacts of this outbreak on the health of Colorado's forests and forest products industry are ongoing, Colorado is now experiencing a resurgence of epidemic-level infestation

(Colorado State Forest Service, 2024). Insect infestation and wildfire can influence each other in Colorado's forests. Trees that have suffered nonlethal fire injury may be more susceptible to future insect infestations (Negrón and Cain, 2019). The conversion of live fuels following beetle caused tree mortality can increase the severity and difficulty of containment for future wildfires as pine needles become more flammable as they dry out following mortality and downed trees can act as ladder fuels (Negrón and Cain, 2019). Population growth along the WUI also places a strain on Colorado's forests. Colorado's population was estimated at 5.5 million in 2014 and is projected to increase by 41%-70%, as much as an additional 4 million people, by 2050 (Colorado Department of Local Affairs, 2017). This increases housing starts along the WUI fragments forest landscapes and adds complexity to forest management activities (Loomis, 2017). These threats to Colorado's forests are heightened by a changing climate (Soucy et al., 2022). Colorado has seen increasing average annual temperatures, more frequent drought conditions, and below average snowpack since 2000 and climate projections suggest continued declines to snowpack as well as increased frequency and severity of heat waves, wildfire, and droughts (Gordon and Ojima, 2015). Current changes coupled with future uncertainties create a need for adaptive forest management (Holmes et al., 2014).

In terms of sales, annual sales of timber products have been steadily trending down (Figure 3). Sales of finished products decreased from \$96 million in 2002, with sales from sawmills alone accounting for \$41 million, to about \$71 million in 2012, all in 2002 dollars (Morgan et al., 2006; Sorenson et al., 2016). It is important to note that 2012 deviated from previous years as sales from other manufacturers (post/pole/piling, log furniture, excelsior, and firewood) made up the largest percentage of total sales, exceeding sales from the sawmill sector. The percentage of sales from the house log sector fell noticeably due to the housing market crash

and the slow recovery (Keegan et al., 2012). In 2016 and 2020, sales from sawmills rose to account for the majority of total sales of \$74 million and \$77 million, respectively (Hayes et al., 2021). Though sales from other manufacturers made up a less significant portion of total sales than they did in 2012, the percentage of sales allocated to the other products sector remained elevated compared to 2002 and 2007. Employment in the forest industry in Colorado has also seen a steady decline over the years. The number of FPI jobs decreased from 9,250 in 2007 to 5,618 in 2020 (Sorenson et al., 2016; Hayes et al., 2021; Ireys et al., 2025).

Decrease in sales and employment can be attributed to the loss of a significant portion of timber milling capacity. The number of primary wood processing facilities in Colorado increased from 1982 through the end of the 20th century, peaking in 2002, and then following a downward trend from 2002 through 2020 (McLain, 1985; Morgan et al., 2006; Hayes et al., 2012; Sorenson et al., 2016; Hayes et al., 2021; Ireys et al., 2025). In addition to an overall reduction in primary manufacturer numbers, there has been a trend of contraction in the sawmill sector and diversification of the overall industry to include more timber processing facilities in other sectors. While the overall number of primary wood processing facilities increased from 1982 to 2002 the number of sawmills declined (McLain, 1985; Morgan et al., 2006). Between 1982 and 2020 the number of sawmills in Colorado declined by over 50% (McLain, 1985; Ireys et al., 2025), but it still remains the largest sector operating in the state. As mill numbers decline, trucking distances, a significant contributor to the overall cost of harvest activities, tend to become greater, increasing costs across the FPI (Vaughan and Mackes, 2015; Pokharel and Latta, 2020). As the state continues to tackle the long-standing issues such as fluctuation in overall timber harvest volumes, decline revenue from sales of forest products, and reduction in FPI employment, perhaps the most concerning trend for the future of Colorado's FPI is the steady

decline in timber processing infrastructure. This decline has lead to increased timber harvesting and processing costs and challenges to carry out necessary forest management activities economically.

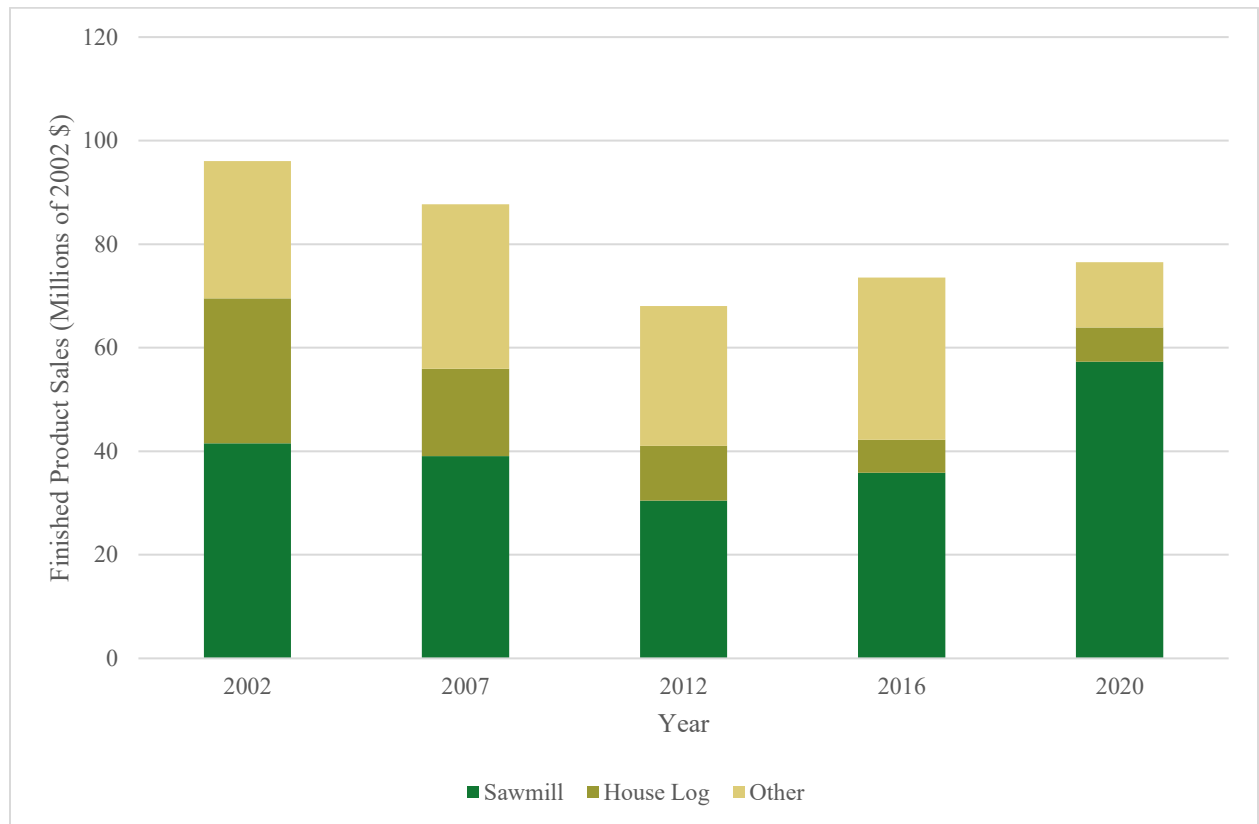


Figure 3: Finished product sales by sector each survey year from all ownership classes, deflated to 2002 USD. Other sectors includes post/pole/piling, log furniture, excelsior, and firewood. Sources: Morgan et al, 2006 ; Hayes et al, 2012 ; Sorenson et al, 2016 ; Hayes et al, 2021 ; Irej et al, 2025.

2.2 Survival Analysis

Survival analysis, also referred to as time-to-event analysis or duration analysis, is a statistical method used to estimate the time it takes an event to occur given a specified starting point. Historically, survival analysis has been prevalently used in medical and biological research to estimate time until events such as recovery, death, or relapse (Clark et al., 2003). In more recent years, survival analysis has been applied to a diversity of disciplines, including economics

to analyze firm performance (Jiang, 2012; Macdonald, 2012). In a few notable cases, survival analysis has been specifically applied to the wood products industry (Sasatani and Zhang, 2015; Panti, 2020). Survival analysis is preferred over conventional statistical models because it is able to handle two common issues in longitudinal data: censoring and time-dependent covariates (Allison, 2010). There are many methods for survival analysis, all of which can handle censoring and some of which are able to handle time-dependent covariates. There are multiple kinds of censoring, the most common being right censoring and left censoring (Figure 4). Right censoring exists when a subject does not experience the event of interest by the end of the observation period. Left censoring occurs when a subject experiences the event of interest prior to the start of the observation period (Allison, 2010).

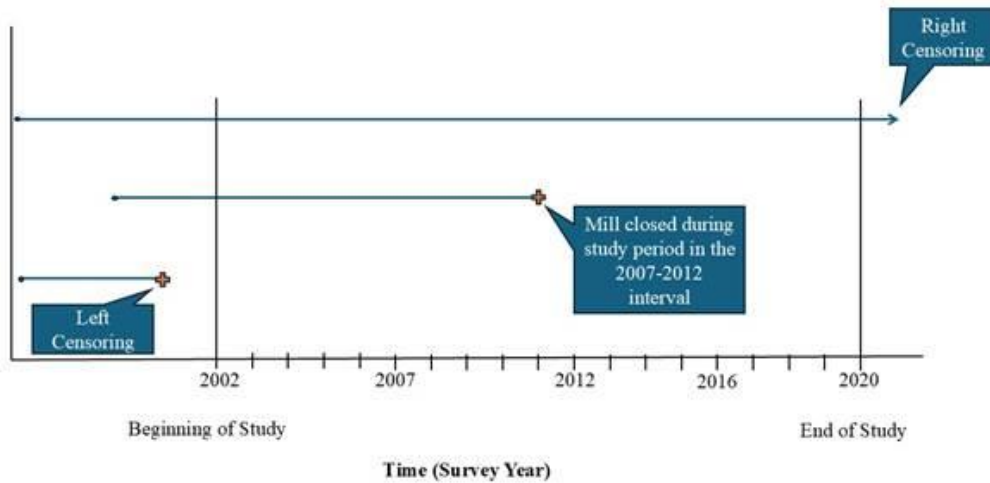


Figure 4: Left and right censoring of events in survival analysis

In general, all methods of survival analysis rely on two key functions: the survivor function and the hazard function. The survivor function, $S(t)$, gives the probability (Pr) of a subject surviving beyond a specified time (t). In other words, the probability that the survival time (T) for a subject is greater than the specified time (t). Given that the output of the survivor

function is a probability, its value is bound between 0 and 1 (Allison, 2010). The survivor function relates to nonoccurrence of the event of interest. A general formula for the survivor function can be written as (Emmert-Streid and Dehmer, 2019):

$$S(t) = Pr(T > t) \quad (1)$$

The hazard function, $h(t)$, aims to quantify the instantaneous risk of the event of interest occurring at time t , conditional on the subject surviving until time t . In other words, the risk that the survival time (T) falls in the small interval between t and Δt . The function gives the probability that the event of interest will occur in a small interval between t and Δt because time is continuous, so the hazard of closure at exactly time t will always be 0 (Allison, 2010). As opposed to the survivor function, the hazard function relies on a conditional probability. It gives only the hazard of closure for subjects that have survived to time t (Allison, 2010). The hazard function relates to occurrence of the event of interest. A general formula for the hazard function can be written as:

$$h(t) = \lim_{\Delta t \rightarrow 0} \frac{Pr(t \leq T < t + \Delta t | T \geq t)}{\Delta t} \quad (2)$$

2.3 Drivers of Mill Closure

The closure of a business is an unambiguous indicator of its performance and as such business closures are commonly used as the event of interest when studying the performance of an industry (Sasatani and Zhang, 2015). There is an extensive body of literature that has tangentially addressed timber mill closures in the US, though not necessarily as the main focus of the analysis. Spelter (2004) utilized data from periodic surveys (1996 and 2003) profiling softwood sawmills in the US and Canada and assessed the impacts of permanent mill closures, new mills opening, and net capacity changes on the size of the softwood lumber industry. Sun

(2021) conducted a performance analysis of sawmills in Oregon between 2003 and 2017. Crandall et al. (2017) used an Input-Output model to estimate direct, indirect, and induced economic effects of forest product mill closures in Maine. Lamsal et al. (2025) identified the economic consequences of sawmill entry and exit in Michigan between 2019 and 2023.

Existing literature on the application of survival analysis methods to the FPI is limited. Sasatani and Zhang (2015) conducted a survival analysis of softwood sawmills in 13 southeastern US states. This analysis examined the influence of various internal and external covariates on the sawmill survival probability of 433 softwood sawmills from 1995 to 2013. While survival analysis commonly considers time to closure from firm initiation, the method used by Sasatani and Zhang (2015) allows for the inclusion of firms with unknown initiation dates, which is a common study limitation. Panti (2020) expanded on this analysis by including multiple mill types and additional socioeconomic variables, such as employment and population density. This analysis explored the survival probabilities of 1584 primary timber processing facilities in the same 13 states as Sasatani and Zhang (2015) between 2005 and 2017. A less directly applicable but nonetheless relevant duration analysis of 662 paper mills was conducted by Sun (2006) between 1970 and 2000.

Notably, none of the previous research surrounding timber mill closure has focused on Colorado or the southwestern US. Only a handful of studies have examined FPI in the southwestern US in general, and even fewer have focused on timber processing facilities. Richardson (2016) conducted a spatial analysis of Colorado's forestry contractors, timber processing facilities, and timber resources as a decision-support tool to maximize the affordability and efficiency of future forest management activities. Simmons et al. (2020) provided information on local timber processing facilities to advise the planners of timber

harvest treatments on the capacity of small-diameter timber that FPI in the USDA Forest Service Rocky Mountain Region 2 could affordably process. Chung et al. (2024) used an Input-Output model to quantify the economic impacts of the forest sector in Colorado. A small number of forestry contractor surveys also exist in the US Southwest (Mackes, 2004; Vaughan and Mackes, 2015; Vaughan et al., 2022).

Regarding the factors driving primary mill closure, mill type was found to have a significant influence on mill survival probability across all previous studies (Sun, 2006; Sasatani and Zhang, 2015; Panti, 2020). Key primary mill types in Colorado are sawmills, house logs, log furniture, utility poles, and a small number of other manufacturers such as excelsior, fuel pellets, and firewood (BBER, 2024). These mills use different feedstocks because they require logs of varying diameters and log quality (Simmons et al., 2020). Sawlogs are sourced from trees with a diameter at breast-height (DBH) greater than or equal to 9 inches for softwoods (ponderosa and lodgepole pine, spruce, Doug-fir) and greater than or equal to 11 inches for hardwoods (aspen, cottonwood) (U.S. Department of Agriculture Forest Service, 2023). Logs used to produce utility poles are sourced from softwood trees with a DBH between 5 and 8.9 inches and hardwood trees with a DBH between 5 and 10.9 inches (U.S. Department of Agriculture Forest Service, 2023). Additionally, the sale of different end products generates different revenue. Sawlogs are the highest priced as they are used to make lumber, veneer, and plywood (Pokharel et al., 2020). In Colorado, timber harvest and transport costs are high due to challenging terrain and long trucking distances. The revenue from product sales must exceed these harvest and transport costs (Pokharel et al., 2020). Because the capacity to use larger-diameter roundwood is consolidated in sawmills and house log producers, these mills have an opportunity to generate greater revenue

from the sale of their end products and offset the cost of harvesting and transporting logs, thereby increasing their survival probability (Simmons et al., 2020).

Another important factor is mill capacity. Sasatani and Zhang (2015) found that larger mills had greater survival probability than smaller mills. Panti (2020) similarly found higher survival probabilities for larger mills than for smaller mills. In agreement with Sasatani and Zhang (2015) and Panti (2020), Sun (2006) also found that paper mills of larger size were expected to have greater life expectancy than smaller ones. Larger mills may outperform smaller mills due to economies of scale (Sasatani and Zhang, 2015), as mills with greater production volumes are likely to see lower per-unit production costs (Conrad et al., 2010). Additionally, larger mills may be better positioned to negotiate with forestry contractors and landowners to secure more consistent timber supplies and control prices (Sasatani and Zhang, 2015).

Competition between neighboring mills may also influence survival probability. Sasatani and Zhang (2015) incorporated a non-weighted localized density, summing the distance between each operational sawmill and all neighboring sawmills, and a weighted localized density with the distance weighted by the capacity of neighboring mills. Panti (2020) adopted a more straightforward methodology, counting the number of active mills within 10- and 30-mile straight-line radii of each mill. Richardson (2016) considered the effects of competition on sawmill production capacity in northern Colorado by counting how many other active sawmills fell within a 50-mile radius of each sawmill. Businesses in the same industry located near each other may benefit from economies of scale. Multiple timber mills in the same area may share infrastructure, labor pools, and suppliers so labor and other inputs may be available at a lower average cost (Sasatani and Zhang, 2015). However, timber processing facilities compete for

roundwood inputs (Sasatani and Zhang, 2015), and mills with the same end products compete for market share.

In Colorado, years of fire suppression activities combined with the pressures of a growing population and changing climate have contributed to overstocked forests and declining forest health (Vaughan and Mackes, 2015). In overly dense forests, trees compete for resources, making them less healthy and therefore more susceptible to mortality from fire, insects, and disease. (Chung et al., 2024). These stressed forests have higher volumes of deadwood, both standing and on the ground. Deadwood provides fuel for wildfires, increasing the risk for larger, more severe burns (Chung et al., 2024). Wildfires in Colorado's forests are often compounded by interactions with another agent of mortality: insect outbreaks. Colorado experienced severe drought conditions from 2001 to 2003, which stressed trees, making them more susceptible to insects, including MPB (Negrón and Cain, 2019). The MPB is extremely damaging to Colorado's pine forests (Colorado Forestry Advisory Board, 2002), greatly reducing the availability of timber for harvest (Colorado State Forest Service, 2023). The number of live lodgepole pine trees in Colorado greater than 5 inches in diameter declined by over 50% between 2002 and 2012 (Negrón and Cain, 2019). Lodgepole pine is significant to Colorado's timber industry, covering 1.6 million acres of the state (Thompson et al., 2017) and making up 16% to 55% of total annual harvest volumes across the study period (Morgan et al., 2006; Hayes et al., 2012; Sorenson et al., 2016; Hayes et al., 2021; Irey et al., 2025). Overall, large wildfires, coupled with widespread insect and disease outbreaks, have contributed to a steep decline in both the quality and availability of timber for Colorado's timber processing facilities (Colorado State Forest Service, 2023), making them likely drivers of mill closures.

The FPI in Colorado is unique among other regions that have been more widely studied, such as the US South, because of the substantial contribution of federal forestlands (Binkley and Duncan, 2009). Nearly 70% of forested land in Colorado is under federal ownership (Richardson, 2016) and over 80% of merchantable timber volume is in federal forestlands (U.S. Department of Agriculture, 2020). In Colorado, service-focused harvesting activities to reduce hazards, including fire, disease, and insect outbreaks (Binkley and Duncan, 2009) and to preserve valuable ecosystem services provided by forests (Vaughan and Mackes, 2015) have largely replaced traditional timber harvests that were carried out with a primary goal of generating revenue from harvesting timber (Vaughan and Mackes, 2015). However, generating revenue is still a component of these service-based projects. An important mechanism for conducting service projects is stewardship contracting from the United States Forest Service (USFS) and the Bureau of Land Management (BLM). Stewardship contracts allow land management activities to take place despite challenges such as reduced milling infrastructure and capacity, long haul distances, and low value material (Daniels et al., 2018). Service-type projects can impose constraints on nearby mills. The woody material recovered from these projects is often small diameter and may have defect introduced by insects, disease, or fire. The high cost of timber removal and transport, coupled with the large proportion of material extracted from treatments that consists of small-diameter, low-grade, and low-value timber, poses a financial barrier for local processing facilities (Herbert et al., 2026). However, service projects facilitate the harvest of high volumes of merchantable timber on federal lands, increasing timber flow to mills and allowing them to operate at higher capacity. In Colorado, just under half of timber processing capacity tends to go unused (Simmons et al., 2020), meaning that local mills could process more timber if it were available. If service projects can balance the need to remove

small-diameter and dead trees with the local industry's ability to process that material at a profit (Simmons et al., 2020), then it is likely that a greater available volume of timber from service contracts will translate to a greater survival probability for local timber mills.

Demand for softwood sawtimber, the primary timber product of the western US (Keegan et al., 2012), is largely driven by new housing construction (Haynes, 2003). In their profile of softwood sawmills in the US and Canada, Spelter (2004) found that more mill closures occurred when demand for new housing construction was reduced. In general, the number of housing starts is likely to be positively correlated with mill survival. Spelter (2004) also found that more mill closures occur during recession periods. The housing market crash during the Great Recession posed significant challenges for timber processing facilities worldwide, including those in Colorado. In the 50 years preceding the housing collapse, the western US (Alaska, California, Colorado, Hawaii, Idaho, Montana, Nevada, New Mexico, Oregon, Utah, Washington, and Wyoming) was the major producer of softwood lumber in the US (Keegan et al., 2012). During the recession, US consumption of softwood lumber fell by half, 30 large mills and countless small mills closed in the western US, and employment in the forest products industry in the Interior West (Arizona, Colorado, Idaho, Montana, Nevada, New Mexico, Utah, and Wyoming) dropped by 32% (Keegan et al., 2012). In 2009 the US became a net exporter of forest products, a variation of an almost century long trend of net import that began in 2013 (Zhang et al., 2017). The decline in US imports of softwood lumber was largely related to the crash of the housing market and economic recession (Woodall et al., 2012). Due to these considerations, the risk of timber mill closure in Colorado was likely higher during the Great Recession than during the rest of the study period.

Finding and retaining skilled labor has been reported as one of the greatest barriers to success for businesses in Colorado's FPI in previous surveys of forestry contractors (Vaughan and Mackes, 2015; Vaughan et al., 2022). This claim is supported by Pelki and Sherman (2020), who found that the quantity of rural labor is the most important predictor of the contribution of the FPI to local economies. Existing literature on the effect of wages on business performance suggests heterogeneous relationships between wage levels and business closure. Wolf (1977) found that higher wages are associated with lower worker turnover in wood processing facilities. As training new employees is costly and time-consuming, businesses that can avoid worker turnover are less likely to exit the industry (Wolf, 1977). Conversely, He et al. (2021) found that wages were negatively correlated with profitability. Higher wages are suggested to increase labor supply and reduce worker turnover (Wolf, 1977), but wage increases have also been found to decrease firm profitability (He et al., 2021), suggesting a complex relationship between wages and mill closure in the FPI.

2.4 Use of Complementary Log-Log Model in Survival Analysis

In firm-level survival analysis for FPI, a key requirement is the time of entry and exit for each individual observation. Other firm-level characteristics, including size, location, ownership structure, changes in ownership, and specific equipment used, are commonly used covariates (Sun, 2006; Sasatani and Zhang, 2015; Panit, 2020). Sourcing such firm-specific data is challenging and not always readily available to the public. Previous studies have sourced raw mill data from industry reports (Sun, 2006; Sasatani and Zhang, 2015) and industry surveys (Panti, 2020). These sources each present their own modeling difficulties, such as data censoring or agglomeration to protect the privacy of individual firms, nonresponse bias, and intermittent data availability due to the publication schedules of surveys and reports. Previous studies using

surveys and reports consisted of annual or biannual data, allowing for the use of continuous time survival models. However, BBER survey data for Colorado FPI is available every four to five years (BBER, 2024), presenting unique challenges and unsuitability of a continuous time model. A Complementary Log-Log (clog-log) model is utilized in this study to overcome these challenges. While this model has not often been applied for firm level analysis, it has been utilized for survival analysis in other fields where discrete data with intervals of several years and uneven interval lengths are common.

Siipilehto and Lee (2025) used a clog-log model to predict tree mortality in planted silver birch, accounting for a series of tree-level, plot-level, and site-level characteristics. This accommodated interval-censored data, which is common in the forestry industry (Siipilehto and Lee, 2025). Variation in interval length was accounted for through the inclusion of an offset variable: $\ln(L/5)$, where $\ln$ is the natural logarithm and L is the interval length in years. Southey et al. (2003) employed the clog-log model to examine lamb survival probability estimated across three time periods: birth to weaning, birth to 365 days of age, and weaning to 365 days of age. As determining the exact time of mortality was challenging, the clog-log link was deemed appropriate for the discrete-time analysis. This study argues that although some information can be lost when data is grouped into discrete intervals, it tends to have minimal effect on the efficiency of estimation, and that the clog-log approach yields results similar to those obtained when the exact time of mortality is known.

3. METHODOLOGY

3.1 Study Area

The state of Colorado is covered by approximately 23 million acres of forestland (U.S. Department of Agriculture Forest Service, 2025). Of this, about 70% is under federal ownership with the USFS and BLM owning over 11 and 4 million acres, respectively (Richardson, 2016; Vaughan and Mackes, 2015). Over 7 million acres, or just under 30% is under private ownership (Vaughan and Mackes, 2015). The small remaining percentage is managed by state, tribal, and local governments, non-governmental agencies, and land trusts (Colorado State Forest Service, 2023). The fragmented ownership structure of forestlands means that such small parcels are often dispersed throughout larger tracts of federal lands (Vaughan and Mackes, 2015). Colorado's forestland is diverse, ranging from the plains cottonwoods of the Arkansas River riparian forests at 3,350 feet, to high elevation spruce-fir forests at 12,000 feet (Colorado State Forest Service, 2023). There are ten major forest types: conifer-hardwood, conifer, mixed conifer, hardwood, lodgepole pine, oak shrubland, pinon-juniper, ponderosa pine, riparian, and spruce fir (Figure 5; Colorado Forest Atlas, 2022).

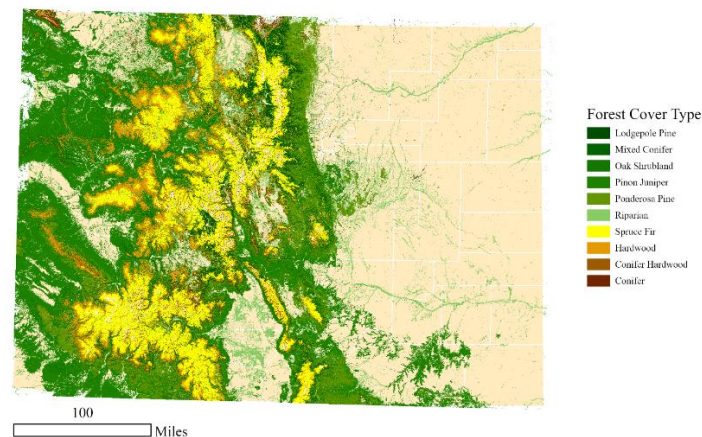


Figure 5: Distribution of forest cover types across Colorado. Derived from 2022 Colorado Wildfire Risk Assessment (CO-WRA). See Appendix A-1 for data sources.

3.2 Data

Mill-level data were obtained from a periodic mill survey conducted by the BBER, in cooperation with the USDA Forest Service and the FIA TPO Program (BBER, 2024). This survey targets the entire population of primary timber processing facilities in Colorado. Survey responses include mill name, approximate location via GPS coordinates, mill type, mill size as estimated by input capacity in thousand cubic feet (MCF), and status in each survey year determined by response or nonresponse. Surveys were conducted in 2002, 2007, 2012, 2016, and 2020. After some raw data cleaning, we found 130 active primary timber processing facilities in 2002. Of these, 55 were sawmills, 42 house log facilities, 23 log furniture facilities, 9 post and pole firms, and one excelsior producer.

Figure 6 shows the locations of 2002 survey respondents and the number of original respondents that remain active in each of the following survey years. To identify open and closure times when the exact date of closure is unknown, a mill that responded to the 2002 survey but did not respond to the 2007 survey is assumed to have closed at some time between 2002 and 2007. Survey data on interval of closure and firm location were confirmed by searching for firms in the Colorado Secretary of State Business Search tool (Colorado Secretary of State, n.d.) and less formally through an internet search for local news articles, blog posts, and web maps. If a reliable address was found, this was then searched in the respective county tax roll data to confirm dates of sale and ownership. For a small number of mills, no information was available in the Colorado Secretary of State Business Search, the county tax roll, or through an informal internet search. For these mills, response or nonresponse to the BBER survey was assumed to be an accurate representation of years of operation.

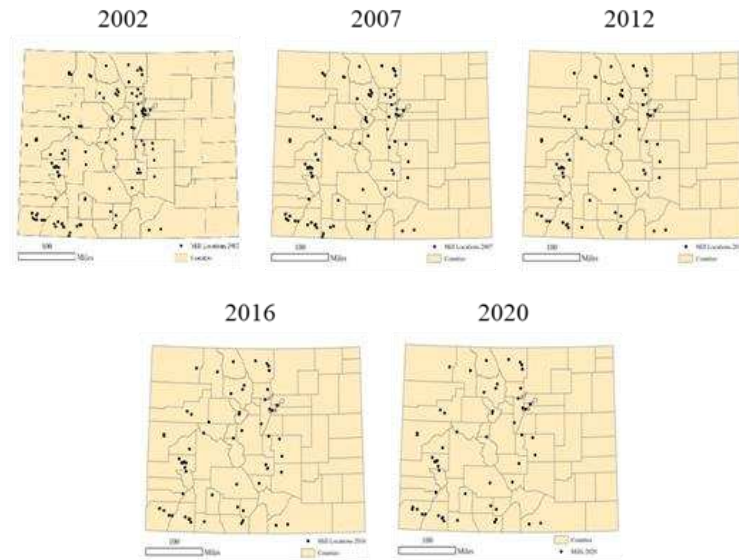


Figure 6: Locations of active BBER survey mills by survey year in Colorado. See Appendix A-1 for data sources.

To consider the interactions of density, location, and competition on mill closure, data on mill location were sourced from GPS coordinates included in BBER survey results (BBER, 2024). Addresses approximated from GPS coordinates were checked against addresses listed on business licenses and articles of incorporation, mill websites, and web maps. For mills for which location data could not be cross-referenced, GPS coordinates from the BBER survey were assumed to be correct. Once a location was determined for each mill, mills were plotted in ArcGIS Pro version 3.3.0 (Esri, 2023) using the geocode addresses tool and then projected in the Universal Transverse Mercator (UTM) coordinate system in the 1983 North American Datum (NAD), Zone 13 using the Project tool.

To capture the importance of MPB infestation, wildfire, federal forestlands, and service contracts on mill closure, data on annual acres of active MPB infestation from 2002-2020 were sourced from multiple sources (U.S. Department of Agriculture, Forest Service, Forest Health Protection, 2007; Chase, 2008; Leatherman, 2009; Ciesla, 2010; Ciesla, 2011; Ciesla, 2012;

Duda et al., 2013; Duda et al., 2014; Barry et al., 2015; Duda et al., 2016; Duda et al., 2017; Barry et al., 2018; Aspelin et al., 2019; Colorado State Forest Service et al., 2019; Colorado State Forest Service et al., 2020). The average area of active infestation in thousands of acres was calculated for each interval by summing the acreage for each individual year and dividing by the number of years in the interval. The wildfire occurrence data used in this analysis were extracted from the Forest Service Research Data Archive (Short, 2022). The data includes a spatial database of wildfires in the United States from 1992 to 2020. Annual acres burned by wildfire in each county were recorded for 2002-2020. To convert annual data to interval data, the acres burned for each year of the interval were summed to find total acres burned per interval at the county level.

To capture the significance of timber supply and the significant contributions of federally owned timber (USDA, 2020), the volume of timber removed from federal lands was included as a covariate. The Forest Service provides Cut and Sold Reports containing forest management actions on National Forest System and National Grasslands for each fiscal year (U.S. Department of Agriculture, Forest Service, n.d.). These reports include the value and volume of timber both cut and sold on Federal lands in the state each year. We converted the volume for 2002-2020 from thousand cubic feet (MCF) to 100 MCF. The average annual volume of convertible timber cut for each interval was calculated by summing volume cut in 100 MCF for each year in the interval and dividing by the number of years per interval.

To identify the influence of macroeconomic shocks on mill closure, specifically those occurring in the housing market, we used the number of Census Building Permits issued annually in each county and the 2008 recession (Colorado Department of Local Affairs, State Demography Office, n.d.). The Permits Survey provides statistics on new privately owned

residential construction (U.S. Census Bureau, n.d.). Yearly data was converted to interval data by summing the number of Census Building Permits issued within each year of the interval and then dividing by the number of years in the interval. In the US, new housing construction accounts for a significant volume of annual consumption of wood products (Howard and Liang, 2019). In Colorado, as in the rest of the country, the 2008 Great Recession led to the permanent closure of many timber mills (Vaughan and Mackes, 2015) as both the price and demand of wood products plummeted (Keegan et al., 2011).

To capture the effect of the workforce on mill survival, industry-specific wage and employment values were considered. Relevant North American Industry Classification System (NAICS) 3-digit codes for Colorado's primary FPI were determined to be 113: Forestry and Logging, 115: Support Activities for Agriculture and Forestry, and 321: Wood Product Manufacturing. County-level data on beginning-of-quarter employment counts and full-quarter employee average monthly earnings from 2002 to 2020 were sourced from the US Census Bureau's Quarterly Workforce Indicators (QWI) (U.S. Census Bureau, Longitudinal Employer-Household Dynamics Program, n.d.). In some counties, for some or all quarters, data were unavailable for one of two reasons: not all counties in Colorado had active timber processing facilities or forestry contractors during the study period, or some counties lacked enough active firms to publish data without providing identifying information for businesses or employees. These quarters were assigned a value of 0 in the data set, which may lead to an underestimation of wages or employee numbers in these counties. The data were first transformed from quarterly to yearly for each NAICS code. Quarterly data for each year was summed and divided by the number of quarters for which data were available to find yearly averages. This resulted in the average beginning-of-quarter employee counts and the average monthly earnings for full-quarter

employees for each year. Yearly averages for each NAICS code were summed together to get industry-level averages. This was then converted from annual to interval data by summing the yearly industry-level averages within each interval and dividing by the number of years per interval. Wage was deflated to 2002 USD using CPI data from the US Bureau of Labor Statistics (U.S. Bureau of Labor Statistics, 2017; U.S. Bureau of Labor Statistics, n.d.). To facilitate easier interpretation, the average beginning-of-quarter employee counts per interval were transformed from units of single employees to units of 100 employees by dividing by 100 and the average monthly earnings for full quarter employees were transformed from units of single dollars to units of thousands of dollars by dividing by 1000.

3.3 Survival Analysis

In this analysis, the event of interest is mill closure, indicated with a binary response variable. Mills are assigned a value of 0 for intervals in which they remain operational and a value of 1 for the interval in which they close. Once an observation experiences closure, it is excluded from subsequent intervals. Mills that do not close before the end of the study period are said to be right censored (Figure 4). These observations are included in the analysis because their removal would bias results towards observations that experienced closure. Right censored mills were considered to be at risk until the end of the final interval in 2020. Mills that close before the start of the study period are said to be left censored (Figure 2). As only mills that responded to the 2002 survey are included in the analysis, all observations were operational in 2002 by the nature of the data collected. As a result, left censoring is not present. Data were organized by mill and by interval. All mills were considered to enter the study in 2002, and their status at the end of each interval was recorded to determine the interval in which the closure occurred. The dependent variable is the time to closure since 2002. Survival analysis often considers time to

closure since plant birth, however the intention of this study is to identify greater industry patterns in the region, not the survival duration of individual mills (Sasatani and Zhang, 2015).

3.3.1 Kaplan-Meier and Log-Rank Test

The Kaplan-Meier (KM) estimator is commonly used for survival analysis of categorical variables (Kaplan and Meier, 1958). Comparing the KM curves for different conditions of a categorical variable visually communicates whether survival times differ across conditions (Panti, 2020). The KM estimator is nonparametric and univariate. It communicates the relationship between duration and time. The general KM formula can be written as:

$$\hat{S}(t_i) = \hat{S}(t_{i-1}) \times \widehat{Pr}(T > t_i | T \geq t_i) \dots\dots\dots (3)$$

where, the KM estimator ($\hat{S}(t_i)$) gives the survival probability at time t_i by multiplying the probability of surviving to the previous failure time (t_{i-1}) with the conditional probability of surviving past t_i given survival to at least t_i (Kleinbaum and Klein, 2012).

The log-rank test is used to test the null hypothesis that the KM curves for two or more independent groups are identical (Panti, 2020). In large samples, the log-rank test approximately follows a chi-square distribution (Kleinbaum and Klein, 2012). The formula for the log-rank statistic can be approximated as:

$$\chi^2 \sim \sum \frac{(O_i - E_i)^2}{E_i} \dots\dots\dots (4)$$

where O_i is the number of observed events in group i and E_i is the number of expected events in group i (Kleinbaum and Klein, 2020) with $k-1$ degrees of freedom, where k =the number of independent groups being compared (Panti, 2020).

3.3.2 Complementary Log-Log Model

Previous studies performing similar analyses used the Cox-Proportional Hazards (Cox PH) model (Sasatani and Zhang, 2015; Panti, 2020). The Cox PH model is a commonly used statistical tool for survival analysis and is most appropriate for continuous-time data (Cox, 1972). Due to the discrete nature of our data, the complementary log-log (clog-log) model was used in place of the Cox PH model for analysis. The clog-log model is also referred to as the grouped proportional hazards model as it can be considered a version of the Cox PH model that is appropriate for discrete data (Tutz and Schmid, 2016). The clog-log model is estimated by first specifying a continuous model, such as the Cox PH and then applying the clog-log transformation to the continuous-time model (Allison, 2010).

The Cox PH model works by first estimating a hazard function that measures the probability of firm closures for surviving firms at time t . The hazard function can be written as:

$$h(t|x) = P(\text{closure at } t, x | \text{survival to } t, x) = h_0(t)e^{\beta_i x_i} \dots\dots\dots (5)$$

where $e^{\beta_i x_i}$ describes the change in the hazard function that results from a change in x_i , β_i is the vector of coefficients estimated by the model, and $h_0(t)$ is the baseline hazard function that does not need to be estimated in practice (Sasatani and Zhang, 2015). From the hazard function, the hazard ratio (HR) can be calculated by dividing the hazard function for one individual by the hazard function for another individual:

$$HR(t, x_i, x_j) = \frac{h(t, x_i)}{h(t, x_j)} = e^{\beta_i(x_i - x_j)} \dots\dots\dots (6)$$

It is important to note that it is possible to calculate the hazard ratio without estimating the baseline hazard function, as the value of the hazard ratio between individuals x_i and x_j depends only on $e^{\beta_i(x_i - x_j)}$. The Cox model uses a maximum likelihood (ML) procedure to estimate

coefficients. The ML procedure used in the Cox model is known as a partial likelihood estimator (Allison, 2010):

$$L_p(\beta) = \prod_{i=1}^n \left[\frac{e^{\beta_i x_i}}{\sum_{k \in R_i} e^{\beta_j x_j}} \right]^{\delta_i} \dots\dots\dots (7)$$

where R_i is the risk set at time t , β_i is the vector of unknown coefficients to be estimated, δ_i indicates if an individual experiences an event (1=event, 0=no event), and $e^{\beta_i x_i}$ communicates the change in the hazard function that results from a change in the x_i covariate (Panti, 2020).

After estimating the continuous-time Cox PH model, the clog-log transformation can be applied to its hazard function to analyze discrete-time data. Considering equation (5) for the hazard function in the Cox PH model, the clog-log model can be written as:

$$\log(-\log(1-P_{it}(x_i))) = \alpha_t + \beta_i x_i \dots\dots\dots (8)$$

where the left-hand side of the equation is referred to as the clog-log function (Allison, 2010). P_{it} is the probability that individual i experiences an event at some point in interval t . The clog-log function takes the probability, a value between 0 and 1, and transforms it to a value between negative infinity and positive infinity. Note that the logarithm of $(1-P_{it}(x_i))$ will always be a negative number. The clog-log function is asymmetrical. This means the model must be set up to predict the probability of the event rather than the probability of the non-event. The distribution function corresponding to the clog-log model is known as the Gumbel distribution. The coefficients of the clog-log model can be interpreted as in a proportional-hazards model. Importantly, this means that exponentiating the coefficients gives associated hazard ratios. Unequal intervals must be handled because, all else being equal, the probability of an event will increase with the length of the interval. For a model with only two distinct interval lengths, as in this study, a single variable to adjust for exposure time is considered sufficient (Allison, 2010).

In this analysis, an offset variable is used, following the procedure described by Siipilheho and Lee (2025).

A generalized linear model with a clog-log link function and offset for unequal interval lengths was constructed (Austin, 2017; Siipilehto and Lee, 2025). A benefit of the use of the clog-log link for discrete time analysis as opposed to the logit or the probit link function is that the coefficients estimated with the use of the clog-log link function are identical to the underlying proportional hazards model (Austin, 2017). Given that the data was structured by mill and by interval, there were repeated observations for mills across intervals. Cluster-robust standard errors were calculated at the mill level to account for heteroskedasticity and serial correlation that may have been introduced by including repeated observations for the same mills. First, a full model was estimated including all covariates (discussed in the section below) that were hypothesized to influence the survival probability of primary processing facilities. Second, a series of reduced models were tested and compared to the full model. The Akaike Information Criterion (AIC) (Akaike, 1973), Bayesian Information Criterion (BIC) (Schwarz, 1978), and a Wald test with clustered standard errors, along with visualization of the predicted hazards to observed hazards, were used to determine the best reduced model. When comparing alternative models, the model with the lower AIC and BIC is considered to better fit the data. The results of the best fit reduced model are reported alongside the results of the full model. The best model was then compared to a base model containing only the time offset variable using a Likelihood Ratio Test (LRT) to test the null hypothesis that the additional covariates in the best reduced model do not improve the explanatory power of the model. If the null hypothesis is rejected, at least one covariate included in the best reduced model improves the model and this model should be used over the base model.

3.4 Variable Description

Table 1 shows variable definitions and summary statistics for all continuous variables included in the full model (equation 8). Each mill contributes a unique observation per interval until closure or censoring, resulting in 354 observations (N) from 130 mills across 4 discrete intervals.

Table 1: Variable definitions and sources with summary statistics for continuous variables

Variable	Definition	Mean
Size ¹	Dummy variable with a value of 1 for mills with production capacity greater than or equal to 250 MCF, 0 otherwise	---
Mill Type ¹	House Log Sawmill Log Furniture Other	---
Competition at 5 Miles ¹	Number of total active mills within a 5-mile straight line radius of each individual active mill. Calculated at the beginning of each interval period.	0.80
Competition at 20 Miles ¹	Number of total mills within a 20-mile straight line radius	3.42
Direct Competition at 50 Miles ¹	Number of active mills of the same type that fall within a 50-mile straight line radius of each individual active mill. Calculated at the beginning of each interval period.	3.39
Acres of Active MPB Infestation ²	Mean annual area of active Mountain Pine Beetle (MPB) infestation at the state level for each interval period, in millions of acres.	0.38
Fire Acres burned per Interval ³	Sum of acres burned by wildfire at the county level for each survey period, in 10,000 acres	4.81 1.47
Timber Cut from National Forest/Grassland ⁴	Mean annual volume of timber removed from National Forests and National Grasslands for each interval period at the state level in hundreds of thousand cubic feet (MCF).	98.30
Census Building Permits ⁵	Mean of yearly permits issued for new residential construction at the county level for each interval period.	806.87 5.45

Recession ⁶	Dummy variable with a value of 1 for active mills in the interval 2007-2012, 0 for other intervals	---
Wage ⁷	Mean of annual average monthly earnings of full quarter employees working in the forest product sectors (NAICS 113, 115, 321) at the county level for each interval period, in thousands of 2002 USD.	4.73
Employment ⁷	Mean of annual average of beginning of quarter employee counts in the forest products sectors (113, 115, 321) at the county level for each interval period, in hundreds of employees.	1.50

Note: ¹Data obtained from BBER (BBER, 2024); ²Short, 2022; 2025; ³USDA Forest Service, Colorado State Forest Service; ³Short, 2022; ⁴USDA Forest Service Cut and Sold Reports; ⁵US Census Bureau; ⁶NBER; ⁷US Census Bureau QWI Explorer.

The internal independent variables included mill type and mill size (BBER, 2024). The mill type is a categorical variable, with log furniture producers set as the base category, to control for structural differences and for different market conditions across facilities. For this analysis, post/pole/piling and excelsior manufacturers were grouped into a single category, “other,” for a total of 10 “other” manufacturers. Mill size in the BBER survey was estimated using five categories for input capacity volume: less than 250 MCF, 250 to 499 MCF, 500 to 999 MCF, 1000 to 4999 MCF, and 5000 MCF or greater. As Colorado’s forest products industry is primarily composed of small businesses (Colorado State Forest Service, 2023), the majority of mills in the data had an annual input capacity of less than 250 MCF. For this analysis, mills have been divided into two input capacity categories: less than 250 MCF (small) and 250 MCF or more (large). A dummy variable (small = 0, large = 1) was used to include mill size in the analysis. Mill type and mill size were considered to be time invariant in this analysis.

The external independent variables included density, location, and competition on mill closure. General competition was calculated using two search distance radii. General competition is used to refer to competition between a mill and any other active mill, regardless of mill type. Appropriate search radii were determined using the Average Nearest Neighbor tool in ArcGIS

Pro version 3.3.0 (Esri, 2023). The output units (meters) of the Average Nearest Neighbor tool are the same as the units of the map, for Universal Transverse Mercator. The observed mean distance between mills at the start of the study period (2002) was 8,714 meters, or approximately 5 miles. Competition was calculated using the pairwise buffer tool with two different search radii: 5 miles and 20 miles. The spatial join tool was used to calculate how many points fell within the search radius of each individual mill. Competition is a time-varying covariate as its value decreases when nearby mills close. General competition was calculated at the beginning of each interval (2002, 2007, 2012, 2016). Direct competition was considered using a single search radius. Direct competition is used to refer to competition between mills of the same type. A search radius of 50 miles was chosen based on a spatial analysis of sawmills in Colorado completed by Richardson (2016), which found that the number of other sawmills within 50 miles was a significant predictor for annual product volume. As mills of the same product type are likely competing for timber of the same size and quality and mills in CO report an average working distance of about 75 miles along roads (Richardson 2016), in the absence of harvest and logging road data, a 50 mile competition buffer serves as an approximation of the local market in which mills are most likely competing for timber procurement. In their analysis, annual product volume was used as an indicator of mill performance. Here, we hypothesize that the relationship between sawmills in competition at 50 miles and annual product volume will hold between other mill types in direct competition at 50 miles and our indicator of performance: mill closure. To calculate direct competition, mill points were subset by mill type in ArcGIS Pro version 3.3.0 (Esri, 2023). Then, the Pairwise Buffer Tool was used with a search radius of 50 miles. Finally, a spatial join was performed to count how many mills of the same type fell within 50 miles of each

active mill. As with general competition, direct competition was considered time-varying and calculated at the beginning of each interval.

Several other external independent variables included MPB infestation, building permits, recession, wildfire, and federal contracts. Due to evidence of nonlinearity, a log transformation was applied to MPB and Census Building Permits. MPB infestation and timber cut on Federal lands were included as time-varying state-level covariates. Wildfire, wage, and employment were included as time-varying covariates at the county level. A dummy variable was created to capture the impacts of the Great Recession, which is considered to have begun in December 2007 and ended in June 2009 (National Bureau of Economic Research, 2010). Mills were assigned an independent value for the Recession dummy variable in each interval in which they were active. Mills that were active during the interval from 2007-2012 received a value of 1 for the Recession dummy. At all other intervals, active mills received a value of 0.

A non-weighted localized density (NWLD) indicator was constructed to explore if mills in high-concentration areas had different survival probabilities than those in low-concentration areas. The NWLD for mill i at time t is given by the equation:

$$NWLD_{it} = \sum_j \frac{1}{1+d_{ij}} \dots\dots\dots (9)$$

where j is the vector of all operational mills at time t other than mill i , and d is the distance between mill i and mill j (Sasatani and Zhang, 2015). In words, NWLD is calculated for each mill by summing the inverse distances from the mill of interest to all active mills at time t . The inverse distance is used because it accounts for nearby mills exerting greater competitive pressure than far away mills. NWLD was calculated in ArcGIS Pro version 3.3.0 (Esri, 2023) first using the Generate Near Table tool, then calculating a field for inverse distance within the

near table, and finally using the summary statistics tool to sum the inverse distances for each mill. NWLD was calculated at the beginning of each interval.

4. RESULTS

Table 2 shows the change in total mill numbers and change in mill numbers by type across survey periods. During the study period (2002-2020) a total of 130 primary mills operated in Colorado. Of the original 130 primary timber processing facilities operational in 2002, 71 (54.6%) had closed by 2020 while 59 (45.4%) remained active at the end of the observation period and were treated as right censored. Of the initial 55 sawmills operational in Colorado in 2002, 45.5% had closed by 2020. By 2020, 54.8% of the 42 house log producers operational in 2002 had closed. Over the course of the study, 73.9% of the 23 log furniture producers operational in 2002 and 40% of the 10 “other” manufacturers operational in 2002 closed.

Table 2: Number of original 2002 primary timber processing facilities remaining operational by type for each BBER survey year.

Survey Year	Sawmill	House Log	Log Furniture	Other ¹	Total Mill Number
2002	55	42	23	10	130
2007	43	28	12	7	90
2012	35	22	7	6	70
2016	33	19	6	6	64
2020	30	17	6	6	59

Note: ¹Other includes post, pole, piling, and excelsior.

Figure 7 offers a visualization of the change in number of active mills by size over the observation period (2002-2020). Small mills accounted for a larger proportion of closures than large mills. Out of the original 115 small mills operational in 2002, 60% (69) had closed by 2020. In contrast, only 13.3% (2) of large mills closed.

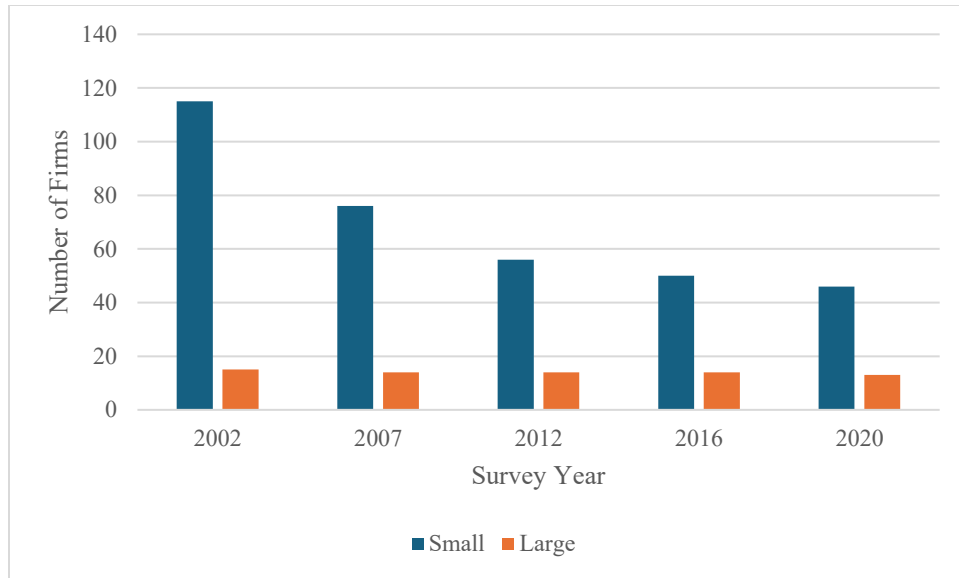


Figure 7: Number of original 2002 timber processing facilities remaining active per survey year by size. Small mills have input capacity <250 thousand cubic feet, large mills have input capacity $\geq$ 250 thousand cubic feet.

4.1 Results of Kaplan-Meier and Log-Rank Test

The Kaplan-Meier survival curve for all mills in the study (Figure 8) shows the survival probability at a given point in time. Given the methods of the BBER surveys that the data is sourced from (BBER, 2024), time is communicated in years since 2002. Events occur 5, 10, 14, and 18 years after 2002 corresponding to the years the BBER survey was conducted. The plus sign at the final step indicates the mills that are surviving at the end of the survey period, referred to as right-censoring. The median survival time is approximately 14 years, that is 50% of primary timber mills in Colorado will survive to at least 14 years. Note that the steepest drop occurs after the first interval, indicating that for the study population the risk of failure is highest at the beginning of the study period and most mill closures occurred early on.

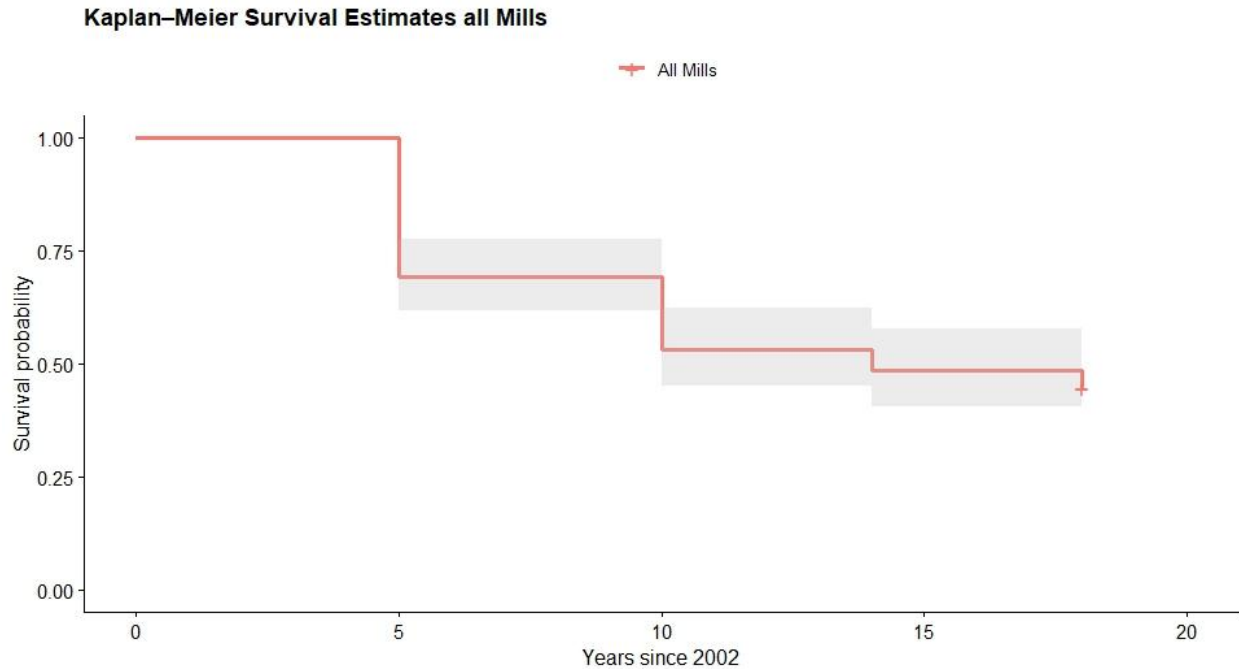


Figure 8: Kaplan-Meier estimate of survival function for all primary timber processing facilities, including 95% confidence bands.

The Kaplan-Meier estimator was used to compare the survival probabilities of different conditions for the categorical variables mill size, mill type, and mill region. The log-rank test was used to test the null hypothesis that the survival curves between groups were equivalent. If the null hypothesis is rejected, it suggests the variable has a statistically significant influence on survival time.

Figure 9 compares the KM curves for small mills (input capacity less than 250 MCF) and large mills (input capacity greater than or equal to 250 MCF). The survival probabilities for both sizes of mills are the same, logically, until the end of the first interval as this is when the occurrence of events is first observable. The survival curve for small mills declines steeply, while the curve for large mills remains relatively flat. The curves do not overlap at any point. The median survival time for small mills is approximately 10 years. The median survival time for

large mills cannot be estimated, as more than 50% of large mills are surviving at the end of the interval period. The log-rank test ($\chi^2=10.1$, $p=0.0015$, $df=1$) suggests that the survival curves for small and large mills are statistically significantly different from each other. The results of the KM estimator and the log-rank test suggest that mill size is a useful predictor of mill survival.

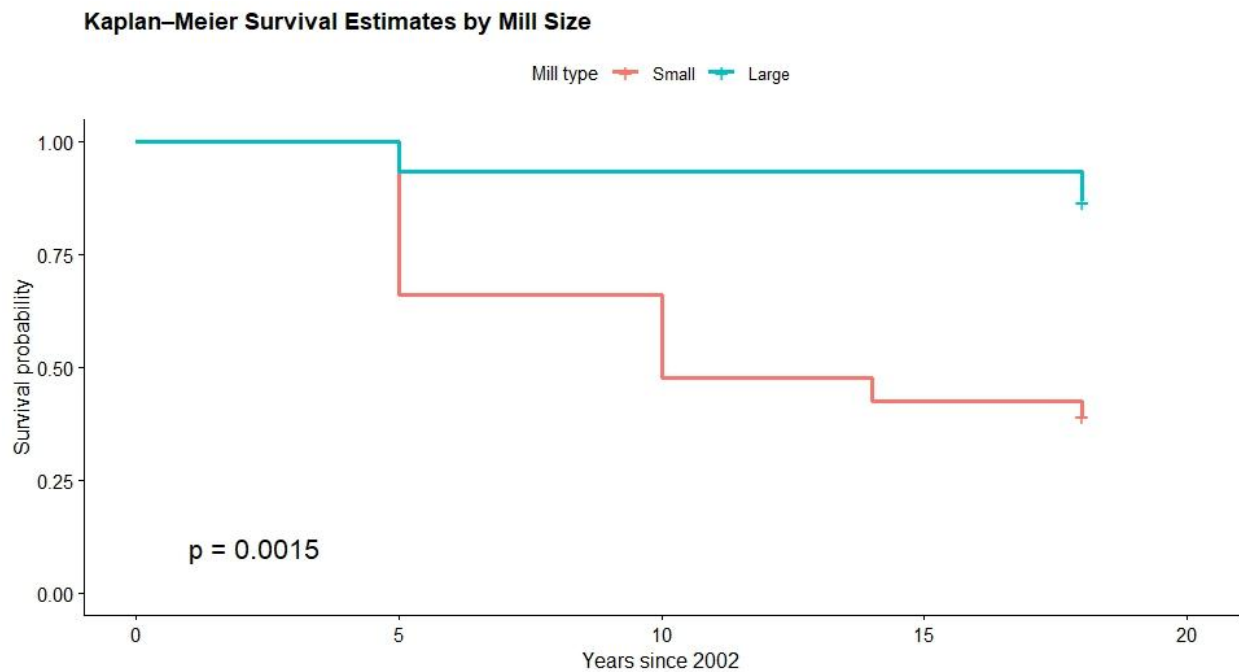


Figure 9: Kaplan-Meier estimate for BBER survey mills by size

Figure 10 compares the KM survival curves for different mill types. The survival curves for sawmills and other manufacturers cross at approximately 14 years after 2002. The median survival time for house log facilities is approximately 14 years. The median survival time for log furniture facilities is approximately 10 years. The median survival times for sawmills and post/pole/piling/other mills cannot be estimated as greater than 50% of mills belonging to these categories remain active at the end of the study period. However, the 25th percentile can be estimated for all four mill types. Visually, the 25th percentile corresponds with a survival

probability of 0.75 in Figure 10. House log facilities, log furniture facilities, and post/pole/piling/other manufacturers share the same 25th percentile for survival probability of 5 years. That is, 75% of mills belonging to each of these mill type categories survived past 5 years. The 25th percentile for sawmills is 10 years. That is, 75% of sawmills survived past 10 years. The results of the log-rank test ($\chi^2=7.2$, $p=0.067$, $df=3$) suggest that the survival curve of at least one mill type is marginally different from the others. The KM estimator and log-rank test suggest that mill type may be an important predictor of mill survival.

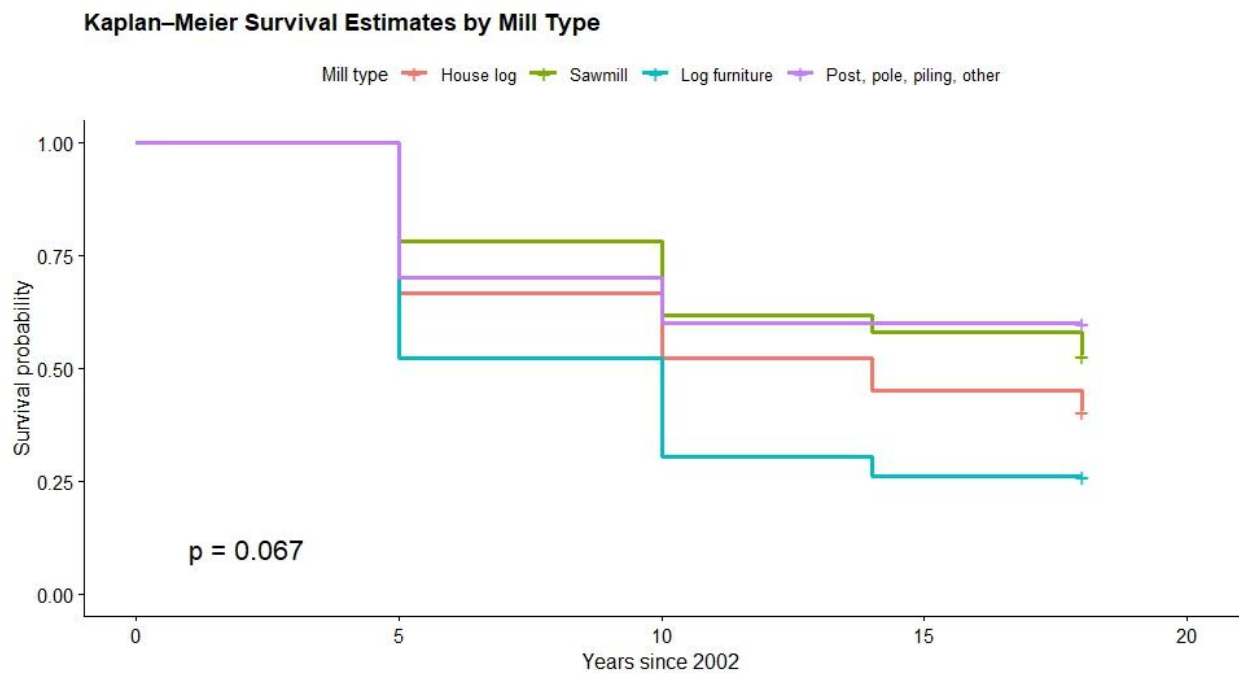


Figure 10: Kaplan-Meier estimate for BBER survey mills by type

4.2 Results of Complementary Log-Log Model

Table 3 reports the full model and best fit reduced model estimated using the clog-log function. Coefficient estimates, cluster-robust standard errors, and hazard ratios are reported. Alternate models were compared to the full model based on a combination of information criterion, theory, and graphical hazard diagnostics. While several models were tested, only the results of the best fit model are shown. Holding all variables in the model constant, the variables for size and type had a statistically significant impact on the survival probability of primary timber processing facilities in the study. This is consistent with the results of the KM estimates reported in the previous section. The volume of timber removed from National Forests and National Grasslands had a statistically significant influence on mill survival probability and was retained in the best fit reduced model. The other variables specific to Colorado (“Acres of Active MPB Infestation” and “Fire Acres Burned per Interval”) did not have a statistically significant effect on mill survival. While the variable capturing acres of active infestation by MPB was not a statistically significant predictor and its inclusion in the model did not improve information criterion, its exclusion resulted in a deviation between observed and predicted hazards, so it was retained in the model. A Wald test with clustered standard errors comparing the best fit reduced model against the reduced model without MPB strongly rejected the null hypothesis that the model without MPB was sufficient ($F=149.93$, $p=2.2e-16$). The variable NWLD was included to capture the effects of mill density on the hazard of closure. This variable was not statistically significant and was not included in the best fit reduced model. The variables used to capture the effects of general competition were number of mills within 5 and 20 miles. Competition at either search radius was not statistically significant and these variables were removed from the final reduced model. While the variable for direct competition at 50 miles was not statistically

significant, it was retained in the model for theoretical relevance to approximate working distance (Richardson 2016). The variables included to capture workforce availability were “Wage” and “Employment.” The mean wage deflated to 2002 USD was not a significant predictor of mill survival probability and as such was removed from the final reduced model. However, following the removal of irrelevant variables as explained in the previous paragraph, the mean number of employees did have a statistically significant influence on the hazard of closure of primary timber processing facilities in the study and is included in the final reduced model. The variable included to capture changes in the housing market (“Census Building Permits”) did not have a statistically significant influence on mill survival time and was not included in the final reduced model. The reduced model includes the dummy variable created to capture the impact of the Great Recession. The coefficient estimate for this variable was not significant, but its inclusion improved the fit of the predicted hazards, so it is included in the final reduced model.

The full model considered a total of 13 covariates. Of the original 13 covariates, 6 were dropped and 7 were retained in the reduced model. The reduced model was selected over the full model based on lower AIC and BIC values and the results of a cluster-robust Wald test. The AIC of the full model was 342.1. Removal of the 6 covariates lowered AIC by 9.1 points resulting in a value of 333.0 in the reduced model. The removal of the 6 covariates lowered BIC from 403.9 in the full model to 371.6 in the reduced model, a difference of 32.3 points. A Wald test with clustered standard errors failed to reject the null hypothesis that the reduced model was sufficient ($F=0.481$, $p=0.822$). This test confirms that the removal of the 6 covariates did not cause any meaningful loss of fit to the reduced model.

Variable	Full Model			Reduced Model (best)		
	Coeff.	SE	HR	Coeff.	SE	HR
Intercept	-0.936	1.535	0.392	-0.615	1.300	0.541
Size (Large)	-1.818*	0.774	0.162	-1.695**	0.757	0.184
Recession	0.515	0.478	1.674	0.450	0.463	1.568
<i>Type</i>						
House Log	-0.676**	0.340	0.508	-0.611*	0.324	0.543
Sawmill	-0.751**	0.334	0.472	-0.749**	0.313	0.473
Log Furniture (reference)	0.000	---	1.000	0.000	---	1.000
Other	-0.453	0.567	0.635	-0.501	0.590	0.606
Federal Timber Cut	-0.011*	0.006	0.989	-0.012**	0.006	0.988
Acres of Active MPB ¹ Infestation	-0.080	0.144	0.957	-0.053	0.127	0.910
Fire Acres Burned	0.043	0.040	1.044			
Competition at 5 Miles	0.119	0.127	1.126			
Competition at 20 Miles	-0.006	0.063	0.994			
Direct ² Competition at 50 Miles	0.056	0.065	1.058	0.057	0.059	1.059
NWLD ³	0.041	0.167	1.042			
Wage	0.014	0.068	1.014			
Employment	-0.131	0.092	0.878	-0.136*	0.076	0.873
Census Building Permits	-0.032	0.110	0.968			
AIC		342.1			333.0	
BIC		403.9			371.6	

Table 3: Results of the Complementary Log-Log model with cluster-robust standard errors.

****** $p < 0.05$

***** $p < 0.10$

Note: ¹Mountain Pine Beetle. ²Direct competition refers to competition between mills of the same type. ³Non-Weighted Localized Density.

Table 3 reports the hazard ratios for covariates in the best fit reduced model. A hazard ratio equal to 1 indicates a variable with no significant effect on survival time. A hazard ratio greater than 1 indicates a variable that increases the risk of closure. A hazard ratio of less than 1 indicates a variable that decreases the risk of failure and thereby increases the probability of survival (Panti 2020). Holding all other variables constant, large mills with an input capacity greater than or equal to 250 MCF on average had an 82% lower hazard of closure compared to small mills with an input capacity less than 250 MCF. In terms of mill type, controlling for all other factors house log manufacturers and sawmills had a lesser hazard as compared to log furniture producers (reference category) by 46% and 53%, respectively. An increase of 100 MCF in the mean volume of timber removed per interval period corresponds to a decrease in the hazard of closure at time t by approximately 1.2%. There was a change in significance between the full model and the best fit model. Removal of the covariate “Census Building Permits” resulted in a slight reduction of standard errors for the coefficients remaining in the model. The standard error for the coefficient estimate of the covariate “Employment” was near the threshold for 10% significance and removal of the insignificant covariate “Census Building Permits” reduced the standard error enough for this variable to cross the significance threshold. An increase in the mean number of employees in the forest products industry by 100 employees at the county level was associated with a 13% reduction in hazard for mills in that respective county.

The goodness of fit of the final reduced model was confirmed by comparing it to a baseline hazard model including only the time offset variable. An LRT comparing the reduced model against the base model strongly rejected the null hypothesis that the additional covariates in the reduced model did not improve the explanatory power of the model ($\chi^2=36.54$, $p=3.172e-$

05). AIC prefers the final reduced model (351.5 base, 333.0 reduced). BIC, however, favors the baseline model (355.4 base, 371.6 reduced). Model dispersion was assessed using the ratio of residual deviance to residual degrees of freedom. The resulting value of 0.9 indicated no evidence of overdispersion in the reduced model.

Figure 13 compares the observed hazards against those predicted by the reduced model. Figure 12 compares observed vs predicted hazards for the full model, and Figure 11 compares observed vs predicted hazards for the baseline model. From Figure 11, the hazards predicted by the baseline model deviate substantially from the observed hazards. Hazards are underestimated in the early intervals and overestimated in the late intervals with a brief period of agreement. The addition of internal, external, and socioeconomic covariates, seen in Figure 12, improved hazard predictions to more accurately align with the observed hazards. However, there is still an observable overestimation in the earlier periods and underestimation in the later periods. The reduced model, shown in Figure 13, exhibits a modest improvement in calibration between predicted and observed hazards as compared to the full model, indicating the reduced model is the best fit model.

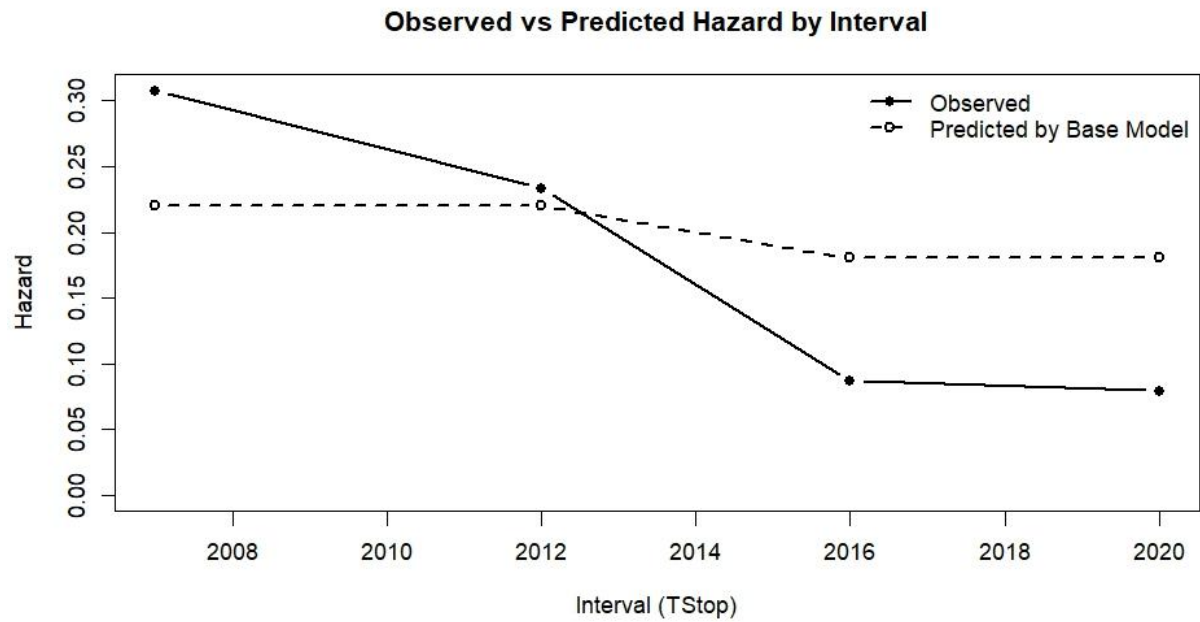


Figure 11: Observed vs predicted hazards for base model

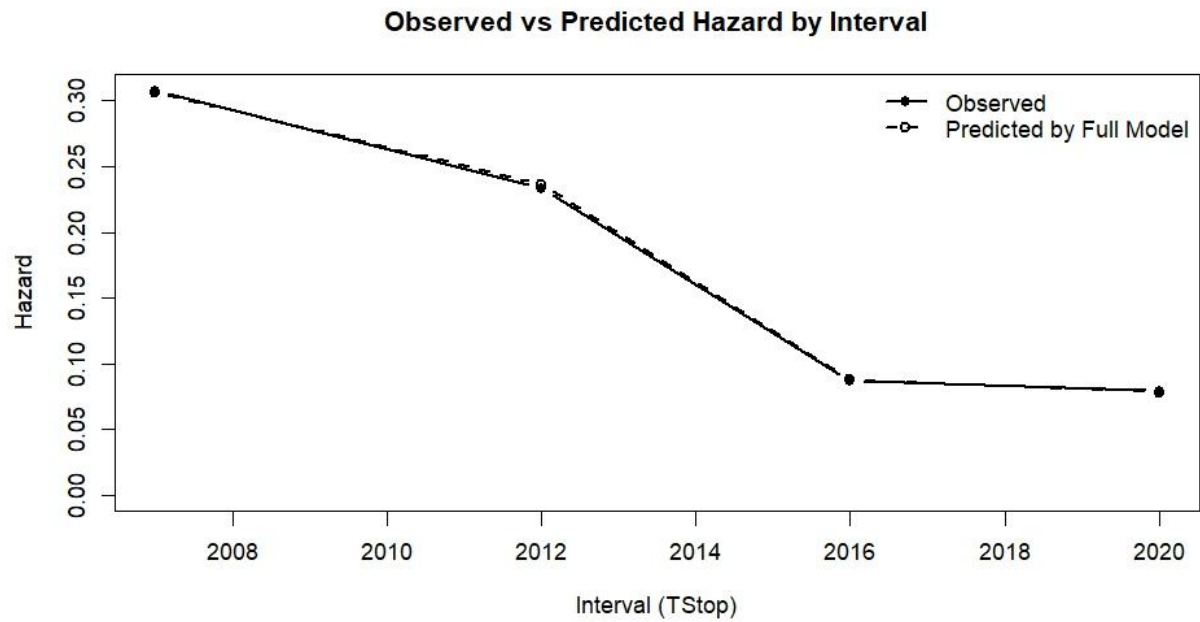


Figure 12: Observed vs predicted hazards for full model

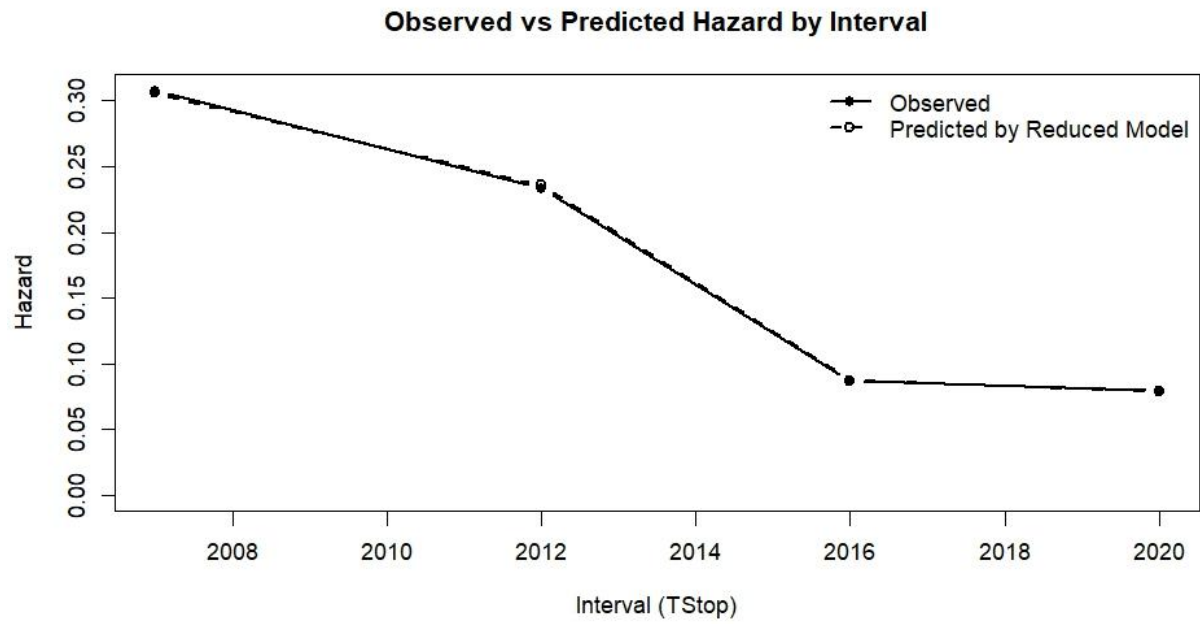


Figure 13: Observed vs predicted hazards for reduced model

5. DISCUSSION

The FPI in Colorado has been in a state of decline since the end of the 20th century (Vaughan and Mackes, 2015). There was a reduction in mill numbers in the state of Colorado by 55% between 2002 and 2020. The greatest number of closures (56%) occurred between 2002 and 2007. Over the same period of time, Colorado has seen an increase in forest health threats including larger and more frequent wildfire, insect infestation, and disease outbreaks, all of which threaten crucial ecosystem services such as water quality and quantity from forested watersheds, public safety, recreation, and aesthetics (Colorado State Forest Service, 2023). Factors such as reduced wood quality, changing federal policies, and economic downturn (Keegan et al., 2012; Wear et al., 2015) have contributed to a loss of milling and forestry contractor capacity across Colorado, increasing the challenges of meeting forest management needs economically (Vaughan and Mackes, 2015). While infrastructure has been lost at all stages of the forest product manufacturing process (Binkley and Duncan, 2009), primary timber processing facilities hold a vital position in the middle of the supply chain (Lamsal et al., 2025). There is a need for greater understanding of the determinants of mill closures in the state, as any loss of primary processing capacity could have far reaching social, economic, and environmental consequences throughout the FPI and to other industries through indirect effects (Lamsal et al., 2025).

Previous research on the FPI in the state of Colorado has focused on forestry contractors (Vaughan and Mackes 2015; Vaughan et al., 2022), forest health, and overall industry trends (Colorado State Forest Service, 2023). While reduction in mill numbers and loss of milling capacity is acknowledged, mill level analysis has rarely been performed. Previous research on

timber mill closure that has been performed in other regions has often focused on the economic impacts of mill closures (Candall et al., 2017; Lamsal et al., 2025), the impact of mill closures on the size of the industry (Spelter, 2004), and rarely on factors affecting the survival duration of timber processing facilities (Sun, 2006; Sasatani and Zhang, 2015; Panti, 2020). Findings address the need for empirical analysis of Colorado's FPI.

The results of this study indicate that mill level characteristics are important determinants of mill closure. Previous firm-level survival analysis in the FPI suggests that size is an important determinant of mill survival time (Sun, 2006; Sasatani and Zhang, 2015; Panti, 2020). The findings of this analysis agree with those of previous studies. Compared to small mills, large mills had an 82% lower hazard of closure. Sasatani and Zhang (2015) argued that larger mills may have greater bargaining power in timber procurement and that economies of scale and greater capital give larger mills more flexibility in responding to changing market conditions and may offer them the ability to purchase newer equipment, improving their efficiency and giving them a competitive edge over smaller mills. In addition to size, mill type also had a significant influence on survival probability. The results of this study suggest that sawmills and log home manufacturers are less likely to exit the industry than log furniture manufacturers, with a reduction in risk by 53% and 46%, respectively. While previous studies incorporated a variety of mill type categories, making direct comparison of results challenging, Panti (2020) found that sawmills were less likely to exit the industry as compared to other categories of mills in their analysis. Sasatani and Zhang (2015) argued that the influence of mill type on survival time was a result of differences in profitability across market sectors. Mills producing different product types input different sizes of round wood (Simmons et al., 2020). House log manufacturers and sawmills are able to process larger diameter wood than the other primary timber facilities

considered in this analysis. House logs and saw logs are also used to produce higher value end products than posts, poles, or excelsior (Vaughan and Mackes, 2015). The greater revenue generated by the sale of these end-products offsets the high costs of timber harvest and transport that are typical in the region, improving profit margins for these mills and reducing their hazard of closure.

A series of covariates were included in the analysis to capture how competition influences risk of closure. The methodologies used to develop these covariates were suggested by previous literature and include general competition at 5 and 20 miles (Panti, 2020), direct competition at 50 miles (Richardson, 2016), and NWLD (Sasatani and Zhang, 2015). The results for general competition are consistent with the findings by Panti (2020) as both studies found that the number of mills within an appropriately chosen radius of each active mill did not have a significant influence on mill survival. The results for direct competition differ from the previous study. Richardson (2016) found that for sawmills in Colorado, the number of other sawmills within a 50-mile radius was a significant predictor of mill performance as measured by annual product volume. The results of this study did not find the number of other mills of the same type within 50 miles to have a significant influence on mill survival. The difference in findings could be explained by the use of different indicators of mill performance and the inclusion of additional mill types in this study. The results for NWLD coincide with the results of the previous study. Neither this analysis nor that conducted by Sastani and Zhang (2015) found NWLD to have a significant effect on mill closure.

Extensive forest disturbances distinguish FPI in Colorado from FPI in other regions. Wildfire and MPB serve as key agents of mortality for important timber species in Colorado (Colorado State Forest Service, 2023). It was hypothesized that the greater acres of active MPB

infestation and the greater the acres burned by wildfire, the greater the hazard of closure that mills would face. Despite substantial theoretical justification, the relationships between these important forest disturbances and the likelihood of mill closures were insignificant in this analysis. Wildfire and MPB activity result in short-run increases in timber supply from salvage logging. However, these disturbances have lasting impacts on forest health, resulting in long-run decreases in timber supply. Depending on the severity of disturbance it can take as long as centuries for forests to produce timber again (Cyphers et al., 2019). Averaging the area affected by wildfire and MPB across 4- and 5-year intervals likely smoothed the short-run and long-run impacts, resulting in insignificance. The effects of these disturbances may be dependent on market conditions. For example, the 1996-2013 MPB epidemic in Colorado reached its greatest volume of active infestation in 2008, coinciding with the Great Recession and a steep decline in demand for wood products. Overall, it is possible that the extent to which forest disturbances contribute to mill closures is dependent on the market for wood products at the time of increased salvage harvest. Despite its insignificance, MPB was retained in the final reduced model as it improved the fit of the predicted hazards. A lack of statistical significance does not necessarily equate to a variable not contributing to the explanatory power of the model. The results of the cluster-robust Wald test and hazard predictions comparing the best fit reduced model against the reduced model without MPB both suggest that the inclusion of improves the explanatory power of the model.

The majority of forested land in the state of Colorado is federally owned and about 83% of merchantable timber in the state is in federally owned forestlands (Colorado State Forest Service, 2022). The volume of timber cut from federal land (National Forest and National Grassland) had a significant influence on mill closure risk. An increase in the average annual

volume of timber removed from federal forests of 100 MCF during an interval period was associated with a 1.2% decrease in the hazard of closure. In recent years, the FPI in the state of Colorado has experienced a shift towards service-type projects (Vaughan and Mackes, 2015) offered by federal landowners (U.S. Department of Agriculture, Forest Service, n.d.). The results of this analysis support the continued use of stewardship contracts and other policies that promote access to federal timber. Such mechanisms may help stabilize timber flow to local processing facilities, increasing the predictability of access to affordable roundwood inputs, and reducing uncertainty in operating costs.

As wood used for new housing construction accounts for a significant volume of annual consumption of wood products in the US (Howard and Liang, 2019), demand for new housing can be used as a proxy for demand for softwood sawtimber (Keegan et al., 2012). The number of permits issued for new residential construction was included as a covariate. The results of the analysis found that the number of new residential constructions was not a significant driver of mill closure. It is possible that averaging the cycles of the housing market across four- and five-year intervals diluted some of this covariate's explanatory power. As there was a decline in import of softwood lumber related to the decrease in demand for new housing following the housing market crash and Great Recession (Woodall et al., 2012; Zhang et al., 2017) this lack of significant relationship cannot be explained by a shift to imported lumber over domestic lumber. The housing market crash in 2006 and the Great Recession in 2008 contributed to the closure of many timber mills across the country (Woodall et al., 2012). There was not a significant change in the hazard of closure during the Recession interval. However, the inclusion of a dummy variable absorbing the impacts of the Great Recession did improve the accuracy of hazard predictions made by the models. This contrasts with previous research by Spelter (2004) which

found that there was an increase in mill closures during periods of economic downturn. The necessity of grouping the data into intervals of four to five years resulted in the impact of the recession, which is considered to have lasted 18 months or 1.5 years, being dispersed across a period of 5 years. This means that the variable explores changes in survival probability during the recession and post-recession periods.

The KM curve for all mills (figure 8) indicated that closure risk was most significant in the first interval of the study from 2002 to 2007 rather than the second interval from 2007 to 2012 even though this is the interval in which the Great Recession occurred. The Recession dummy variable did not successfully capture the interval of highest closure risk in the study. By the start of the Recession, the FPI in Colorado had already experienced years of compounding supply-side shocks. As a result of pressures including reduction in the availability of federal timber for harvest in the last third of the 20th century, the onset of epidemic levels of MPB infestation in 1996, historic drought from 2001-2003, and large wildfires such as the Hayman fire of 2002, both the value and the quantity of timber available to Colorado's primary processing facilities were already reduced. For example, the quantity of insect-killed lodgepole increased from 331 thousand dry tons in 2002 to 926 thousand tons in 2006 (Thompson et al., 2010). As such, the most vulnerable timber mills in Colorado had likely already exited the industry by the onset of the recession in 2007. This may explain in part why the Recession dummy variable was insignificant as well as why the hazard of closure was highest in the first interval.

Businesses in the FPI in Colorado have often referenced shortage of skilled labor (Vaughan and Mackes, 2015; Colorado State Forest Service et al., 2020) as among their greatest operational challenges. The number of employees working in the forest products industry in each Colorado county and the wages of these employees were included as covariates in the analysis as

a metric for labor market conditions. Results suggest that the number of employees in the FPI has a significant influence on mill survival. An increase in industry employment of 100 employees was associated with a 13% decrease in hazard. Wage was not found to be a significant predictor of mill survival, despite theoretical justification from previous research. It is possible that employee wages have offsetting interactions with mill closure risk. Existing research suggests that high wages increase labor availability and decrease worker turnover, decreasing closure risk (Wolf, 1977). Conversely, higher wages also increase operating costs, decreasing profitability (He et al., 2021). Wages are an indirect driver of mill closure as wage increases act directly on labor availability and operating costs. These offsetting interactions and the indirect relationship between wages and mill closures likely contribute to the non-significant findings in this analysis.

Previous examples of survival analysis in the FPI have focused on regions like the US south (Sasatani and Zhang, 2014; Panti 2020). In the south, timberlands are predominantly under private ownership and local processing facilities have abundant access to timber inputs so mill closure is largely a result of demand-side shocks. Colorado's industry is structured differently, and mill closure is primarily supply-side. The majority of timber in Colorado is under federal ownership and timber availability is constrained by disturbance driven supply shocks such as wildfire, insect outbreaks, and drought. Demand-side drivers of mill closure such as the Great Recession, housing demand, and competition were found to be insignificant in this analysis. These findings are consistent with the FPI in Colorado being supply limited as opposed to demand driven but should be interpreted with caution as additional demand-side drivers, such as timber product imports, could not be controlled for in the model due to data limitations.

The findings of this study have important implications for mill owners, future policy, and forest management strategies in Colorado. The significance of mill-level structural characteristics such as product type and mill size suggests that policies and programs intended to support mills need to be targeted. It is important to maintain the diversity of mill types in Colorado. While sawmills and house log producers are important, they cannot be relied on to process the high volumes of small diameter and low-quality timber removed from service focused forest management actions and post-disturbance salvage. Results suggest that mills producing posts and poles, log furniture, or other products will need additional attention to prevent further loss of small diameter processing capacity. Additionally, while Colorado's FPI is dominated by small mills, these mills had a significantly greater risk of closure than large mills. Consolidation or collaboration between multiple small mills could allow them to benefit from economies of scale in the same way that larger mills do. The negative relationship between the volume of timber harvested from federal forestlands and the risk of mill closure supports the continued harvest of federal timber in Colorado. Additionally, a reliable supply of federal timber may reduce closure risk and any interruption in timber supply may result in mill closures. If policymakers are interested in reducing the risk of future mill closures, they should consider implementing policies that support consistent federal harvest levels and be cautious of policies that may restrict access to federal timber. Finally, the significance of a skilled local workforce in reducing hazards has crucial implications for how to best support and rebuild milling capacity in Colorado. Grants and programs targeted at workforce development through training programs, public education on forestry careers, or funding for job creation could be effective mechanisms for reducing closure risk.

It is important to acknowledge several limitations in this study. The sample size was only 130 mills. Sasatani and Zhang (2015) conducted their analysis on a sample size of 433 mills and Panti (2020) used a sample size of 1584 mills. Mills were also not evenly distributed across size and type categories, with larger contributions from small mills and sawmills. The lack of annual mill data and exact closure dates prevented the use of a continuous time survival analysis approach. While this research proposes a novel methodology for firm-level survival analysis in the FPI when only discrete data is available, it is likely that more significant relationships between covariates and time to closure could be determined if exact failure dates were known. The clog-log model used in this analysis required grouping continuous data into intervals of several years. Inevitably there will be some loss of information with this approach. Specifically, short-term dynamics may be obscured by averaging covariate interactions across periods of several years. The intervals alternated between four and five years and longer intervals will naturally have a higher hazard. This limitation was addressed with the inclusion of a time offset variable as suggested by Siipilehto and Lee (2025). In addition to exact failure dates, exact processing capacities as opposed to ranges would have provided more insight into how mill size influences mill survival.

There is great potential for future research expanding on this study. Finding consistent, accurate, and relevant data for Colorado's forest products industry proved to be the most challenging aspect of the study. In the future, interested parties may want to conduct a more robust mill survey of their own with greater frequency. This suggests the possibility of a future project to create a database to collect and store data on timber processors in the region. Expanding this study to include states such as Arizona, New Mexico, and Utah that have similar FPI conditions would at least partially address the limitations of sample size and under

representation of large mills and mill types other than sawmills. Additionally, there are many current and recent events that are likely to influence mill closures in Colorado that would be beneficial to examine in future studies. As more BBER (BBER, 2024) reports are published, the time frame of this analysis can be expanded to consider the effects of the Covid-19 pandemic and recent tariffs on timber imports. There are many government incentives and grant programs from the USDA Forest Service and Colorado State Forest Service to assist businesses and landowners in the forest products industry. These programs include the Wood Innovations Program launched by the USDA Forest Service in 2015, the Forest Restoration and Wildfire Risk Mitigation Grant Program initiated by the Colorado State Forest Service in 2017, the Wildfire Mitigation Industries Workforce Development Program through the Colorado State Forest Service effective since 2023, and many others, all instated too recently for this research to truly consider their impacts. Future research is needed to evaluate the efficacy of these programs and inform future initiatives. Additionally, future research expanding the study period can explore the influence of recent political changes affecting timber markets including the March 1, 2025, executive order for Immediate Expansion of American Timber Production (The White House, 2025).

This study provides a comprehensive examination of the determinants of primary timber processing facility closure in the state of Colorado. Mill structure, market conditions, timber supply, policy mechanisms, and labor markets play important roles in shaping closure risk. Findings suggest that the FPI in Colorado is dependent on stable timber supply, supportive policy, and reliable labor pools. Although subject to certain data and modeling limitations, this study contributes to a need for further understanding of mill closure dynamics and specifically provides new knowledge of FPI in Colorado and the southwestern US.

6. CONCLUSIONS

In this study, we investigated the determinants of primary timber processing facility closure in the state of Colorado using a discrete time survival analysis approach. We considered a range of internal, external, and socioeconomic variables. A generalized linear model with a clog-log link function and time-offset variable was used to accommodate survey data grouped into intervals varying between four and five years. As many mills were observed across two or more intervals, cluster-robust standard errors were used to address heteroskedasticity and serial correlation associated with repeated observations.

The findings indicate that mill closure in Colorado is driven by a combination of structural, institutional, and market factors. Smaller mills experienced a greater hazard of closure than their larger counterparts. Larger mills tended to have greater advantages over small mills in obtaining raw materials, and, in general, may have had more options at their disposal before a plant shutdown (Sasatani and Zhang, 2015). Without intervention to support small mills, this trend of consolidation may continue. As the industry transitions to fewer larger mills, the cost of transporting and processing timber can increase even further. Conversely, a wider network of small mills means greater geographic dispersion of processing capacity and therefore lower transportation costs which would likely allow for more projects to be completed resulting in more acres being treated for reduced wildfire risk and improved forest health. Additionally, subsidizing small mills will support the communities that rely on them, as FPI plays a major role in rural economies (Dahal et al., 2015; Sorenson et al., 2016). Mills that had the capacity to process large-diameter, high-quality wood into high-revenue end products faced a lower risk of closure than mills processing smaller diameter wood into lower value end products. The greater

revenue generated from the sale of these end products helps offset the rising operating costs across Colorado's FPI, including transporting timber and labor costs (Irey et al., 2025). Increased availability of timber from federal lands was associated with a decreased hazard of mill closure. Policy mechanisms from the USFS and BLM help to stabilize timber flow throughout the region and reduce uncertainty for mill owners. Any future forest management plans or policies that result in a loss of access to federal timber could contribute to further timber mill closures. Conversely, plans and policies that promote a stable federal timber harvest could reduce the risk of operational timber facilities closing, allowing existing operations to expand and even encouraging the birth of new timber processing facilities by eliminating uncertainty. A larger local labor pool reduced mills' risk of closure. These findings suggest that the long-term resilience of the FPI in Colorado depends on interactions between mill-level structural characteristics, labor markets, and state and federal policies.

This study contributes to the existing knowledge on mill closures by building on previous mill-survival analyses in other regions and is novel in several ways. First, while similar analyses exist in other regions, the pattern of mill closure in Colorado is influenced by the unique challenges in the state, including wildfire, insect and disease outbreaks, an expanding population along the WUI, and substantial federal forestlands. Second, this study provides a needed contribution to the gap in previous research on Colorado's FPI as a whole, and specifically in research focusing on Colorado's primary timber mills. Finally, this study is among the first to utilize the clog-log model for firm-level survival analysis in the FPI to accommodate discrete-time data with uneven intervals, as data in this form are common in the FPI. Maintaining a resilient forest products industry is essential to addressing these threats, promoting healthy forests, and supporting rural economies. The results of this analysis will inform decision-making

of mills, landowners, and lawmakers in the state of Colorado to support primary timber processing, which will translate to improved resilience of the FPI as a whole.

REFERENCES

- Akaike, H. (1973). Information theory and an extension of the maximum likelihood principle. In Second International Symposium on Information Theory, ed. B. N. Petrov, and F. Csaki, 267-281. Budapest: Akailseoniai–Kiudo
- Allen, T.T., H.S. Han, and S.R. Shook. (2008). A structural assessment of the contract logging sector in the Inland Northwest. *For. Prod. J.* 58:27–33.
- Allison, P. (2010). *Survival Analysis Using SAS®: A Practical Guide Second Edition*. Cary, NC: SAS Publishing.
- Austin, P. C. (2017). *A tutorial on multilevel survival analysis: Methods, models, and applications*. *International Statistical Review*, 85(2), 185–203.
<https://doi.org/10.1111/insr.12214>Digital Object Identifier (DOI)
- Aspelin, C., Barry, P., Duda, J. A., Garrison, K., Lockwood, R., Matthews, S., Previant, W., Underhill, J., West, A., & West, D. (2019). *2018 report on the health of Colorado's forests* (Colorado State Forest Service). <https://hdl.handle.net/10217/194394>
- Battaglia, M. A., Gannon, B., Brown, P. M., Fornwalt, P. J., Cheng, A. S., & Huckaby, L. S. (2018). Changes in forest structure since 1860 in ponderosa pine dominated forests in the Colorado and Wyoming Front Range, USA. *Forest Ecology and Management*, 422, 147–160. <https://doi.org/10.1016/j.foreco.2018.04.010>
- Barry, P., Duda, J. A., Lockwood, R., Mason, L., Matthews, S., Mueller, K., & Ciesla, W. M. (2015). *2014 report on the health of Colorado's forests: Urban and community forests: An investment in Colorado* (Colorado State Forest Service).
<https://hdl.handle.net/10217/186518>
- Barry, P., Duda, J. A., Garrison, K., Lockwood, R., Mason, L., Matthews, S., Mueller, K., Reader, T., & West, D. (2018). *2017 report on the health of Colorado's forests: Meeting the challenge of dead and at-risk trees* (Colorado State Forest Service).
<https://hdl.handle.net/10217/186521>
- BBER. (2024). Bureau of Business and Economic Research. Forest Industries Data Collection System (FIDACS). Missoula, MT: Bureau of Business and Economic Research, Forest Industry Research Program. Unpublished dataset. Data obtained October 2024
- Binkley, D., Duncan, S.L. 2009. The Past and Future of Colorado's Forests: Connecting People and Ecology. *Ecology and Society*. 14(2). <https://www.jstor.org/stable/26268297>
- Bousfield, C.G., Lindenmayer, D.B. & Edwards, D.P. (2023). Substantial and increasing global losses of timber-producing forest due to wildfires. *Nat. Geosci.* 16, 1145–1150.
<https://doi.org/10.1038/s41561-023-01323-y>
- Chase, J. (2008). *Special issue: Forest challenges today and tomorrow — 2007 report on the health of Colorado's forests*. Colorado State Forest Service.
<https://spl.cde.state.co.us/artemis/nrserials/nr1311internet/nr13112007internet.pdf>

- Chung, N., Lowstuter, D., Reader, T., & Alves Pena, A. (2024). *Economic and community contribution analysis of the forest product industry in Colorado*. Regional Economic Development Institute (REDI), Colorado State University.
- Ciesla, W. M. (2010). *The health of Colorado's forests: Threats to Colorado's current and future forest resources: 2009 report* (Special issue). Colorado State Forest Service.
<https://spl.cde.state.co.us/artemis/nrserials/nr1311internet/nr13112009internet.pdf>
- Ciesla, W. M. (2011). *2010 report on the health of Colorado's forests: Continuing challenges for Colorado's forests: Recurring & emerging threats: 10th anniversary report*. Colorado State Forest Service.
<https://spl.cde.state.co.us/artemis/nrserials/nr1311internet/nr13112010internet.pdf>
- Ciesla, W. M. (2012). *2011 report on the health of Colorado's forests* (Colorado State Forest Service).
<https://spl.cde.state.co.us/artemis/nrserials/nr1311internet/nr13112011internet.pdf>
- Clark, T. G., Bradburn, M. J., Love, S. B., & Altman, D. G. (2003). Survival analysis part I: basic concepts and first analyses. *British journal of cancer*, 89(2), 232-238.
- Conrad, J.L., W.D. Greene, and P. Hiesl. (2018). A review of changes in US logging businesses 1980s-present. *J. For.* 116:291–303.
- Colorado Department of Local Affairs. (2017). *Colorado population data*.
<https://demography.dola.colorado.gov/population>
- Colorado Department of Local Affairs, State Demography Office. (n.d.). *County population and housing data lookup*.
https://demography.dola.colorado.gov/assets/lookups/county_pop_lookup.html
- Colorado Department of Revenue. (2021, August). Sales & use tax topics: Beetle wood products. https://tax.colorado.gov/sites/tax/files/documents/SUTT_Beetle_Wood_Products_Aug_2021.pdf
- Colorado Division of Fire Prevention & Control. (n.d.). *Historical wildfire information*. Colorado Department of Public Safety. <https://dfpc.colorado.gov/sections/wildfire-information-center/historical-wildfire-information>
- Colorado Forest Atlas. (2022). *Forest Cover Type* [GIS dataset]. Colorado State Forest Service, Colorado Wildfire Risk Assessment (CO-WRA). Retrieved from <https://data-csfs.hub.arcgis.com/maps/cf68f35d64b745c1ac614b8007727e72/about>
- Colorado Forestry Advisory Board. (2002). *Report on the condition of Colorado's forests* (Annual forest report). Colorado State Forest Service.
<https://api.mountainscholar.org/server/api/core/bitstreams/bae315e9-c491-40f3-be94-e8a972aa54ae/content>
- Colorado Forest Restoration Institute. (n.d.). *Colorado Forest Restoration Institute*. Colorado State University. <https://cfri.colostate.edu/>
- Colorado Secretary of State. (n.d.). *Business database search*.
<https://www.sos.state.co.us/biz/BusinessEntityCriteriaExt.do>

- Colorado State Forest Service. (2016). Healthy forests & vibrant communities: HB-1199 accomplishment report (2009–2016). <https://csfs.colostate.edu/wp-content/uploads/2017/01/HB1199-Report.pdf>
- Colorado State Forest Service. (2022). Accessible timber volume in Colorado, 2010–2019. Colorado State Forest Service. <https://csfs.colostate.edu/2022/05/16/accessible-timber-volume-2010-2019>
- Colorado State Forest Service. (2023). 2020 Colorado Forest Action Plan (Annual forest action plan). Colorado State Forest Service. <https://csfs.colostate.edu/forest-action-plan/>
- Colorado State Forest Service. (2024). 2024 forest health report: Insects and diseases. Colorado State University. <https://csfs.colostate.edu/forest-management/forest-health-report-2024/>
- Colorado State Forest Service. (2025). Forest Action Plan: Five-year review – Forest products section. Colorado State University. <https://csfs.colostate.edu/forest-action-plan/five-year-review/forest-products/>
- Colorado State Forest Service, Colorado Division of Forestry, & Colorado State University, Warner College of Natural Resources. (2019). *2019 report on the health of Colorado's forests: Celebrating the diverse regions of our state*. Colorado State Forest Service. <https://hdl.handle.net/10217/233630>
- Colorado State Forest Service, Colorado Division of Forestry, & Colorado State University, Warner College of Natural Resources. (2020). *2020 report on the health of Colorado's forests: Protecting our future after a historic wildfire year*. Colorado State Forest Service. <https://hdl.handle.net/10217/233631>
- Congressional Research Service. (2020). Forest Service: Good Neighbor Authority (IF11658). https://www.congress.gov/crs_external_products/IF/PDF/IF11658/IF11658.1.pdf
- Conrad IV, J. L., Bolding, M. C., Aust, W. M., & Smith, R. L. (2010). Wood-to-energy expansion, forest ownership changes, and mill closure: Consequences for US South's wood supply chain. *Forest Policy and Economics*, 12(6), 399-406.
- Conrad IV, J. L., & Dwivedi, P. (2025). Timber procurement practices and mill-logger relationships in the US South. *Forest Products Journal*, 75(1), 71-81.
- Cox, D.R. (1972). Regression models and life tables (with discussion). *J R Statist Soc. B* 34: 187– 220
- Crandall, M. S., Anderson, J. L., & Rubin, J. (2017). Impacts of recent mill closures and potential biofuels development on Maine's forest products industry. *Maine Policy Review*, 26(1), 15-22.
- Cyphers, L., Mackes, K., & Duda, K. (2019). *Timber losses from West Fork Complex fire in southwest Colorado*. *Forest Products Journal*, 69(4), 272–277. <https://doi.org/10.13073/FPJ-D-17-00062>
- Dahal, R. P., Henderson, J. E., & Munn, I. A. (2015). Forest products industry size and economic multipliers in the US South. *Forest Products Journal*, 65(7–8), 372–380. <https://doi.org/10.13073/FPJ-D-14-00083>

- Daniels, J. M., Nielsen-Pincus, M., Paruszkiewicz, M., Poage, N. (2018). The economic contribution of stewardship contracting: Two case studies from the Mount Hood National Forest. *Journal of Forestry*.
- Duda, J., Halford, M., Lockwood, R., Marcus, N., Pfohl, B., Rogers, K., Rossiter, G., Tansey, M., & Ciesla, W. M. (2013). *2012 report on the health of Colorado's forests: Forest stewardship through active management*. Colorado State Forest Service. <https://hdl.handle.net/10217/186516>
- Duda, J. A., Barry, P., Lockwood, R., Mason, L., Schaubert, K. T., & Ciesla, W. M. (2014). *2013 report on the health of Colorado's forests: Caring for Colorado's forests: Today's challenges, tomorrow's opportunities* (Colorado State Forest Service). <https://hdl.handle.net/10217/186517>
- Duda, J., Lockwood, R., Mason, L., Matthews, S., Mueller, K., West, D., & Ciesla, W. M. (2016). *2015 report on the health of Colorado's forests: 15 years of change*. Colorado State Forest Service. <https://hdl.handle.net/10217/186519>
- Duda, J. A., Lockwood, R., Mason, L., Matthews, S., Mueller, K., Peterson, C., & West, D. (2017). *2016 report on the health of Colorado's forests: Fire and water* (Colorado State Forest Service). <https://hdl.handle.net/10217/186520>
- Emmert-Streib, F., & Dehmer, M. (2019). Introduction to Survival Analysis in Practice. *Machine Learning and Knowledge Extraction*, 1(3), 1013-1038. <https://doi.org/10.3390/make1030058>
- Esri. (2023). *ArcGIS Pro* (Version 3.3.0) [Computer software]. Environmental Systems Research Institute. <https://www.esri.com>
- Federal Reserve Bank of Dallas. (n.d.). *Nominal* (Data Basics). <https://www.dallasfed.org/research/basics/nominal>
- Gordon, E., & Ojima, D. (Eds.). (2015). *Colorado climate change vulnerability study: A report submitted to the Colorado Energy Office*. University of Colorado Boulder and Colorado State University. <https://www.colorado.edu/sites/default/files/2021-08/GordonOjima2015.pdf>
- Hayes, S.W., Bingham, C.A., Morgan, T.A., Simmons, E.A., Marcille, K.C. (2021). The Four Corners Timber Harvest and Forest Products Industry, 2016. *Resour. Bull. RMRS-RB-34*. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 72 p.
- Hayes, S.W., Morgan, T.A., Berg, E.C., Daniels, J.M., Thompson, M.T. (2012). The Four Corners timber harvest and forest products industry, 2007. *Resour. Bull. RMRS-RB-13*. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 61 p.
- He, M., Smidt, M., Li, W., & Zhang, Y. (2021). Logging industry in the United States: Employment and profitability. *Forests*, 12(12), 1720. <https://doi.org/10.3390/f12121720>
- Holmes, T. P., McNulty, S., Vose, J. M., Prestemon, J. P., & Li, H. (2014). A conceptual framework for adaptive forest management under climate change. In J. M. Vose & K. D.

- Klepzig (Eds.), *Climate change adaptation and mitigation management options: A guide for natural resource managers in southern forest ecosystems* (pp. 45–60). CRC Press.
- Howard, J. L., & Liang, S. (2019). *U.S. timber production, trade, consumption, and price statistics, 1965–2017* (Research Paper FPL-RP-701). U.S. Department of Agriculture, Forest Service, Forest Products Laboratory.
https://www.fpl.fs.usda.gov/documnts/fplrp/fpl_rp701.pdf
- Ince, P. J., Li, X., Buonogiorno, J., Reuter, M. R. (2001). United States paper, paperboard, and market pulp capacity trends by process and location, 1970-2000. U.S. Department of Agriculture, Forest Service, Forest Products Laboratory, Madison, WI. 39 p.
- Irey, B. T., Townsend, L., Dillion, T., Scott, S. G., Simmon, E. A., Morgan, T. A., Shaw, J. D. (2025). Colorado's timber harvest and forest products industry, 2020. Resour. Bull. RMRS-RB-41. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 30 p.
- Jessup, E., Magagnotti, N., Soucy, M., & Spinelli, R. (2017). Perspectives and challenges of logging enterprises in the Italian Alps. *Forest Policies and Economics*, Vol 80: 44-51.
<https://doi.org/10.1016/j.forpol.2017.03.006>.
- Jiang, S. (2012). Survival in the US petroleum refining industry. *Journal of Applied Statistics*, 39(7), 1505-1530
- Kaplan, E.L., & Meier, P. (1958). Nonparametric estimation from incomplete observations. *Journal of the American statistical association*, 53(282), 457-481.
- Keegan, C. E., III, Morgan, T. A., Blatner, K. A., & Daniels, J. M. (2010). *Trends in lumber processing in the western United States. Part I: Board foot Scribner volume per cubic foot of timber*. Forest Products Journal, 60(2), 133–139. <https://doi.org/10.13073/0015-7473-60.2.133>
- Keegan, C.E., Sorenson, C.B., Morgan, T.A., Hayes, S.W., & Daniels, J.M. (2012). *Impact of the Great Recession and housing collapse on the forest products industry in the Western United States*. University of Montana, Bureau of Business and Economic Research & U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station.
- Kleinbaum, D.G., & Klein, M. (2012). *Survival analysis: A self-learning text, Third edition*. Springer Science+Business Media, LLC.
- Lamsal, B., Poudel, J., & Pokharel, R. (2025). Regional economic and employment impacts of industrial decline in the forest sector: Evidence from sawmill closures in Michigan. *Forest Policy and Economics*, 178, 103601. <https://doi.org/10.1016/j.forpol.2025.103601>
- Leatherman, D.A., Aguayo, I., & Mehall, T.M. (2011). *Mountain Pine Beetle* [Fact Sheet]. Colorado State Forest Service. <https://csfs.colostate.edu/wp-content/uploads/2024/01/Mountain-Pine-Beetle-Fact-Sheet-5.528.pdf>
- Leatherman, D. A. (Ed.). (2009). *2008 report on the health of Colorado's forests: Special issue* (Colorado State Forest Service). Colorado State Forest Service, Colorado State University. Retrieved from https://static.colostate.edu/client-files/csfs/pdfs/894651_08FrstHlth_www.pdf

- Loomis, E. (2017). Forests and logging in the United States. In Oxford Research Encyclopedia of American History. Oxford University Press.
<https://doi.org/10.1093/acrefore/9780199329175.013.310>
- Macdonald, R. (2012). *Firm dynamics: The death of new Canadian firms: A survival analysis of the 2002 cohort of entrants to the business sector*. Statistics Canada.
- Mackes, K. 2004. Results of Stefan Reinold contractor survey. In: 2004 Smallwood Conference Proceedings, May 18–21, 2004, Sacramento, California.
- McLain, W. H. (1985). *Colorado's industrial roundwood production and mill residues, 1982* (Resource Bulletin INT-35). U.S. Department of Agriculture, Forest Service, Intermountain Research Station.
- Morgan, T.A., Dillon, T., Keegan, C.E.III, Chase, A.L., & Thompson, M.T. 2006. The Four Corners timber harvest and forest products industry, 2002. Resour. Bull. RMRS-RB-7. Fort Collins, CO: United States Department of Agriculture, Forest Service, Rocky Mountain Research Station. 64 p.
- National Bureau of Economic Research. (2010). Business Cycle Dating Committee announcement: June 2009 business cycle trough/end of last recession.
<https://www.nber.org/news/business-cycle-dating-committee-announcement-september-20-2010>
- Negrón, J. F., & Cain, B. (2019). *Mountain pine beetle in Colorado: A story of changing forests*. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. General Technical Report RMRS-GTR-402. <https://doi.org/10.2737/RMRS-GTR-402>
- Panti, N. C. 2020. Mill dynamics: Exploring factors that influence closure patterns of primary forest product mills in the Southern U.S. Master's Thesis, University of Tennessee.
https://trace.tennessee.edu/utk_gradthes/5613
- Pelkki, M., & Sherman, G. (2020). Forestry's economic contribution in the United States, 2016. *Forest Products Journal*, 70(1), 28–38. <https://doi.org/10.13073/FPJ-D-19-00037>
- Pokharel, R., & Latta, G. S. (2020). A network analysis to identify forest merchantability limitations across the United States. *Forest Policy and Economics*, 116, 102181.
<https://doi.org/10.1016/j.forpol.2020.102181>
- Poudel, J., & Dahal, R. (2025). A comprehensive look at the forest products industry's economic contribution to the United States: Pre- and post-COVID analysis. *Forest Policy and Economics*, 172, 103440. <https://doi.org/10.1016/j.forpol.2025.103440>
- Posit Software, PBC. (2024). *RStudio: Integrated development environment for R* (Version 4.4.1) [Computer software]. <https://posit.co/products/open-source/rstudio/>
- R Core Team. (2024). *R: A language and environment for statistical computing*. R Foundation for Statistical Computing. <https://www.R-project.org/>
- Riddle, A. A. (2022). Stewardship End Result Contracting: Forest Service and Bureau of Land Management. <https://www.congress.gov/crs-product/IF11179>

- Richardson, E.A. 2016. Spatial Component for the Decision Support Systems of Colorado's Forest Products Industry: Industry Cluster Analysis on Sawmills in Northern Colorado. Master's Thesis, Colorado State University.
- Sasatani, D., & Zhang, D. 2015. The Pattern of Softwood Sawmill Closures in the US South: A Survival Analysis Approach. *Forest Science*. 61(4):635-643.
- Schwarz, G. (1978). Estimating the dimension of a model. *The annals of statistics*, 461-464.
- Short, K.C (2022). Spatial wildfire occurrence data for the United States, 1992-2020 [FPA_FOD_20221014]. 6th Edition. Fort Collins, CO: Forest Service Research Data Archive. <https://doi.org/10.2737/RDS-2013-0009.6>
- Siipilehto, J., & Lee, D. (2025). *Comparison of marginal and mixed-effects complementary log-log regression models for predicting planted silver birch mortality*. Ecological Modelling, 510, Article 111349. <https://doi.org/10.1016/j.ecolmodel.2025.111349>
- Simmons, E.A., Morgan, T.A., Hayes, S.W., Ng, K., & Berg, E.C. (2020). Timber Use, Processing Capacity, and Capability within the USDA Forest Service, Rocky Mountain Region Timber-Processing Area. *Journal of Forestry*. 118(3):233-243. <https://academic.oup.com/jof/article/118/3/233/5811313>
- Sorenson, Colin B.; Hayes, Steven W.; Morgan, Todd A.; Simmons, Eric A.; Scudder, Micah G.; McIver, Chelsea P.; & Thompson, Mike T. (2016). The Four Corners timber harvest and forest products industry, 2012. Resour. Bull. RMRS-RB-21. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 62 p.
- Soucy, A., Rahimzadeh-Bajgirani, P., & De Urioste-Stone, S. (2022). *A Comprehensive and Spatially Explicit Regional Vulnerability Assessment of the Forest Industry to Climate Change*. *Journal of Forestry*, 120(2), 170–185.
- Southey, B. R., Rodriguez-Zas, S. L., & Leymaster, K. A. (2001). Survival analysis of lamb mortality in a terminal sire composite population. *J. Anim Sci*. 79:2298-1665.
- Southey, B. R., Rodriguez-Zas, S. L., & Leymaster, K. A. (2003). Discrete time survival analysis of lamb mortality in a terminal sire population. *J. Anim Sci*. 81:1399-1405.
- Spelter, H. (2004). Sawmill closures, openings, and net capacity changes in the United States and Canada. U.S. Forest Service.
- Sun, C. (2006). Lifetimes of US paper and allied products mills: Insights from a duration analysis. *Southern Journal of Applied Forestry*. 30(1):5–12. <https://doi.org/10.1093/sjaf/30.1.5>
- Sun, C., Marcille, K.C., Daniels, & J.M. (2021). A Performance Analysis of Sawmills in Oregon from 2003 to 2017, *Forest Science*, Volume 67, Issue 4, August 2021, Pages 398–411, <https://doi.org/10.1093/forsci/fxab007>
- The White House. (2025). "Immediate Expansion of American Timber Production." March 1, 2025. <https://www.whitehouse.gov/presidential-actions/2025/03/immediate-expansion-of-american-timber-production/>.
- Thompson, M. T., Duda, J. A., DeBlander, L. T., Shaw, J. D., Witt, C., Morgan, T. A., & Amacher, M. C. (2010). *Colorado's forest resources, 2002–2006* (Resource Bulletin

- RMRS-RB-11). U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. <https://doi.org/10.2737/RMRS-RB-11>
- Thompson, M. T., Shaw, J. D., Witt, C., Werstak, C. E., Jr., Amacher, M. C., Goeking, S. A., DeRose, R. J., Morgan, T. A., Sorenson, C. B., Hayes, S. W., & Menlove, J. (2017). *Colorado's forest resources, 2004–2013* (Resource Bulletin RMRS-RB-23). U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. <https://doi.org/10.2737/RMRS-RB-23>
- Tutz, G., & Schmid, M. (2016). *Modeling Discrete Time-to-Event Data*. Springer International Publishing.
- U.S. Bureau of Labor Statistics. (2017). *Historical Consumer Price Index for All Urban Consumers (CPI-U)* (Oct. 2017) [PDF]. <https://www.bls.gov/cpi/tables/historical-cpi-u-201710.pdf> (bls.gov)
- U.S. Bureau of Labor Statistics. (2021). Business employment dynamics by wage class. Monthly Labor Review. <https://www.bls.gov/opub/mlr/2021/article/business-employment-dynamics-by-wage-class.htm>
- U.S. Bureau of Labor Statistics. (n.d.). *Consumer Price Index historical tables for U.S. city average*. U.S. Department of Labor. Retrieved January 14, 2026, from https://www.bls.gov/regions/mid-atlantic/data/consumerpriceindexhistorical_us_table.htm
- U.S. Census Bureau. (n.d.). *Building Permits Survey (BPS)*. U.S. Department of Commerce. Retrieved January 14, 2026, from <https://www.census.gov/construction/bps/index.html>
- U.S. Census Bureau, Longitudinal Employer-Household Dynamics Program. (n.d.). *QWI Explorer* [Data tool]. Retrieved January 14, 2026, from <https://qwiexplorer.ces.census.gov/>
- U.S. Department of Agriculture, Forest Service. (2020). Forest Service, Forest Inventory EVALIDator web-application Version 1.8.0.01, St. Paul, MN: U.S. Department of Agriculture, Forest Service, Northern Research Station. <https://apps.fs.usda.gov/Evalidator/evalidator.jsp>
- U.S. Department of Agriculture, Forest Service. (n.d.). *Forest products cut and sold from the national forests and grasslands*. U.S. Forest Service. <https://www.fs.usda.gov/managing-land/forest-management/products/cut-sold/>
- U.S. Department of Agriculture, Forest Service. (2009). *Major forest insect and disease conditions in the United States: 2008 update* (FS-933). Forest Health Protection. https://www.fs.usda.gov/foresthealth/publications/ConditionsReport_2008.pdf US Forest Service
- U.S. Department of Agriculture, Forest Service. (n.d.). *Stewardship contracting overview*. U.S. Forest Service.
- U.S. Department of Agriculture Forest Service. (2023). *Forest Inventory and Analysis glossary: Standard terminology* (Revision 12.11.2023). Forest Inventory and Analysis Program. <https://research.fs.usda.gov/sites/default/files/2024-01/wo->

- [fia_glossary_standardterms20231211.pdfhttps://www.fs.usda.gov/restoration/Stewardship/Contracting/overview.shtml](https://www.fs.usda.gov/restoration/Stewardship/Contracting/overview.shtml)
- U.S. Department of Agriculture, Forest Service, Forest Health Protection. (2007). *Forest Insect and Disease Conditions in the United States 2006* (Report). U.S. Department of Agriculture.
https://www.fs.usda.gov/foresthealth/publications/ConditionsReport_2006.pdf
- U.S. Department of Agriculture, Forest Service. 2025. Forests of Colorado, 2023: FIA annual snapshot. Resource Update FS-808. Washington, DC: U.S. Department of Agriculture, Forest Service. 4 p. <https://doi.org/10.2737/FS-RU-808>.
- U.S. Forest Service. (n.d.). Hazardous fuels transportation assistance grants. U.S. Department of Agriculture. <https://www.fs.usda.gov/managing-land/forest-management/products/hazardous-fuels-transport-assist-grants>
- Vaughan, D., & Mackes, K. (2015). Characteristics of Colorado forestry contractors and their role in current forest health issues. *Forest Products Journal*, 65(5-6), 217-225.
- Vaughan, D., Edgeley, C., & Han, H. S. (2022). Forest contracting businesses in the US southwest: current profile and workforce training needs. *Journal of Forestry*, 120(2), 186-197. <https://doi.org/10.1093/jofore/fvab060>
- Venable, N. B. H., Lockwood, R., DiMaria, J., Duda, J., Rhoades, C., & Mason, L. (2017). *Forest management to protect Colorado's water resources: A synthesis report to support House Bill 16-1255*. Colorado State Forest Service.
- Wear, D. N., & Murray, B. C. (2004). Federal timber restrictions, interregional spillovers, and the impact on US softwood markets. *Journal of Environmental Economics and Management*, 47(2), 307-330.
- Wear, D. N., Prestemon, J. P., & Foster, M. O. (2015). US forest products in the global economy. *Journal of Forestry*. <https://doi.org/10.5849/jof.15-091>
- Wolf, C. H. (1977). Wage differentials among Appalachian sawmills. (Research Paper NE-237). U.S. Forest Service, Northeastern Forest Experiment Station.
- Woodall, C. W., Ince, P. J., Skog, K. E., Aguilar, F. X., Keegan, C. E., Sorenson, C. B., Hodges, D. G., & Smith, W. B. (2012). *An overview of the forest products sector downturn in the United States*. *Forest Products Journal*, 61(8), 595–603. <https://doi.org/10.13073/0015-7473-61.8.595>
- Wright, J. L., & Sen Roy, S. (2022). *Geospatial characteristics of Colorado wildfire occurrences from 2001 to 2020. Remote Sensing Applications: Society and Environment*, 28, 100872. <https://doi.org/10.1016/j.rsase.2022.100872>
- Zhang, D., Lin, Y., & Prestemon, J. P. (2017). *From deficit to surplus: An econometric analysis of U.S. trade balance in forest products*. *Forest Science*, 63(2), 209–217. <https://doi.org/10.5849/FS-2016-018>

APPENDICES

A-1: Data Dictionary for Figures 2 and 3

Layer Name	Definition	Source
Counties	Polygon layer showing Colorado state and county boundaries	CDPHE https://data-cdphe.opendata.arcgis.com/datasets/colorado-county-boundaries/explore
Mill Location 2002	Point layer showing locations of primary processing facilities active in the state of Colorado in 2002	BBER 2024
Mill Location 2007	Point layer showing locations of primary processing facilities active in the state of Colorado in 2007	BBER 2024
Mill Location 2012	Point layer showing locations of primary processing facilities active in the state of Colorado in 2012	BBER 2024
Mill Location 2016	Point layer showing locations of primary processing facilities active in the state of Colorado in 2016	BBER 2024
Mill Location 2020	Point layer showing locations of primary processing facilities active in the state of Colorado in 2020	BBER 2024
Land Cover Type	Raster layer showing forest cover classes in the state of Colorado in 2022.	CO-WRA and Colorado Forest Atlas, 2022 https://data-csfs.hub.arcgis.com/maps/cf68f35d64b745c1ac614b8007727e72/about In accordance with the data use policy, the raw datasets are not redistributed or hosted elsewhere. Proper attribution is provided in this work, and additional information about the datasets can be found at https://coloradoforestatlas.org