From Forest Waste to Resource: A Biomass Utilization Strategy for Boulder County

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Glossary

Acronym	Full Term
ACB	Air Curtain Burner
ABP	Avoided Burn Probability
AWE	Avoided Wildfire Emissions
EPA	Environmental Protection Agency
BC	Black Carbon
BCPOS	Boulder County Parks and Open Space
BRD	Boulder Ranger District
BVLCD	Boulder Valley and Longmont Conservation Districts
BWC	The Boulder Watershed Collective
CFSY	Community Forestry Sort Yard
CH_4	Methane
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CO_2e	Carbon Dioxide Equivalent
CSFS	Colorado State Forest Service
CWPP	Community Wildfire Protection Plan
EPA	Environmental Protection Agency
FVS	Fores Vegetation Simulator
FPD	Fire Protection District
GHG	Greenhouse Gas
GWP	Global Warming Potential
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
Mg	Megagram (metric ton)
NMOC	Non-Methane Organic Compounds
OSMP	Open Space and Mountain Parks
PM2.5	Fine Particulate Matter (≤2.5 microns)
REM	Reduce Emissions from Megafires
TRL	Technology Readiness Level
TWC	The Watershed Center
USFS	United States Forest Service

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Executive Summary

The challenge: wildfire mitigation efforts generate lots of waste wood

Boulder County and its regional partners face growing challenges at the wildland-urban interface, where increased wildfire risk, dense forest fuels, and climate pressures converge. In response, this report provides a comprehensive strategy for managing and utilizing woody biomass generated from forest restoration and wildfire mitigation treatments.

This report estimates that organizations within Boulder County currently produce approximately 55,000 green tons of woody biomass annually from treatment activities. With full implementation of priority projects under the 2024 Community Wildfire Protection Plan (Boulder County CWPP, 2024), annual production could reach up to an estimated 135,000 green tons.

This report assesses twelve biomass utilization pathways, considering environmental impact, economic feasibility, technical maturity, co-benefits, and local infrastructure. The top-ranked pathways - biochar, compost, and firewood - received the highest combined scores and offer strong potential for scalable implementation. Other evaluated options include small sawmills, biomass heat, animal bedding, mass timber, bio-oil and more. Each utilization pathway was assessed in detail, with additional life cycle analysis completed for the top three to quantify greenhouse gas benefits.

With respect to the results of the life cycle assessment, the climate impacts across the three biomass utilization pathways - composting, biochar production, and firewood use - were similar. Biochar and firewood pathways each achieve about 1.2 metric tons of CO_2-equivalent (Mg CO_2e) reduction per metric ton of dry liability biomass processed, while the composting pathway achieves slightly less, at about 1.0 Mg CO_2e per metric ton processed. In all cases, the baseline assumption - pile burning of biomass - had the largest influence on the overall climate benefit. For example, processing 10,000 dry metric tons of liability biomass annually would yield approximately 9,550 Mg CO_2e (10,527 US tons) in annual benefits through composting, 11,200 Mg CO_2e (12,346 US tons) through biochar production, and 11,000 Mg CO_2e (12,125 US tons) through firewood use – with each pathway providing an equivalent of removing ~ 3,950 passenger vehicles from roadways annually. This similarity in climate benefit led to additional emphasis on other considerations, such as the scale of landscape improvement (e.g., biochar supports wider landscape application benefits), presence of existing infrastructure (e.g., compost facilities), and air quality regulations (notably affecting firewood usage).

For biomass managers, this effort developed detail profiles for each biomass utilization pathway – including information on feedstock, economic, infrastructure, technology, environmental, and other considerations. The report cataloged over 40 wood products facilities within a 50-mile radius of the City of Boulder, gathered from state and local databases and verified through public records and direct outreach. These facilities span 13 categories of wood use - including firewood, compost, mulch, lumber, and other specialty products - and are further classified by size (small, medium, or large) based on workforce and operational capacity. For each facility, the types of accepted feedstock were also identified. The report also includes a detailed breakdown of transportation and processing costs, offering a framework for estimating delivered biomass costs based on travel distance and facility logistics. Two key infrastructure assets, Nederland and Meeker Park Sort Yards, are noted as community-operated sites critical for aggregating and processing woody biomass from fire mitigation and forest restoration efforts.

Improved management of woody biomass is also a climate solution

Modeled findings from a co-benefits assessment demonstrated that the large-scale implementation of fuels reduction treatments - especially those proposed under the Boulder County CWPP (2024) - yield forest health and climate benefits, including over 200,000 metric tons of avoided greenhouse gas emissions over 40 years if the annual burn probability is 2.7% or higher. Modeled treatments also indicated reductions in particulate matter and nitrogen oxide emissions by 17% and 52% respectively, indicating a likely benefit to public health if populations were exposed. At this scale, forest health metrics evaluated improved: treated areas exhibited 43% tree mortality (in terms of basal area) by 2047 compared to 75% tree mortality in untreated areas, and lower stand density index values indicated healthier forest structure with reduced competition and greater resilience. Canopy cover reductions in treated areas lowered the risk of high-severity crown fires while aligning with historical forest conditions.

Key considerations for decision-makers include:

- **Scale and Feasibility**: While large-scale biomass production is technically possible, near-term efforts should prioritize pathways that align with existing infrastructure and offer flexible deployment. Small and medium-scale solutions - such as on-site chipping for compost, or mobile firewood or biochar units - may offer the best return on investment given logistical constraints.
- **Infrastructure Gaps**: Existing facilities like the Nederland and Meeker Park Sort Yards play a vital role in processing biomass. However, scaling utilization will require investment in processing, drying, and transport capacity, along with public-private partnerships and incentive mechanisms to attract market participants.
- **Co-Benefits**: Biomass utilization provides important ancillary benefits, including avoided wildfire emissions, improved forest and soil health, and support for the circular economy. These co-benefits strengthen the case for public investment and regional collaboration on forest fuels reduction actions.
- **Policy and Programmatic Support**: Success hinges on leveraging state and federal funding, streamlining permitting for small-scale processing, and aligning with broader sustainability goals. Proposed actions include subsidizing transportation, enabling project-site processing permits, and exploring carbon finance mechanisms.

Key recommendations from the report include:

- **Enhance community sort yards** by expanding hours, staffing, and equipment to improve biomass throughput.
- **Develop supply agreements** with utilizers for pre-processed biomass, improving value and market certainty.
- **Explore partnerships** for new regional biomass processing facilities, particularly those that integrate composting.
- **Subsidize transportation** to improve material flow from forest sites to processing facilities.
- **Encourage small-scale and on-site processing** to improve cost-efficiency and utilization rates.
- **Leverage carbon financing** by investing in biomass pathways that generate marketable carbon credits (e.g., biochar, bio-oil).
- **Support post-fire recovery and community resilience** by linking biomass utilization to wildfire risk mitigation, health, and economic strategies.

Report Introduction

Boulder County, within county partners – such as the City of Boulder, and neighboring Larimer County are increasingly motivated to develop a comprehensive woody biomass utilization strategy in response to converging threats from wildfire, climate change, and growing sustainability commitments. Located within the wildland-urban interface, both counties face heightened wildfire risks driven by dense forest fuels, rugged topography, and a warming, drying climate. Recent destructive events such as the 2020 Cameron Peak Fire and the 2021 Marshall Fire have underscored the urgency of proactive vegetation management. Forest thinning and hazardous fuel reduction are now recognized as critical tools not only for public safety but also for landscape resilience. However, these treatments generate large volumes of woody biomass, much of which historically has been piled and burned, chipped, and scattered, or left onsite - representing a missed opportunity to convert forest 'waste' into value.

Recognizing this challenge, Boulder County has taken notable steps in the past to develop biomass management infrastructure and explore beneficial uses of woody materials. Community-operated forestry sort yards in Nederland and Meeker Park, along with urban green waste collection through Western Disposal, have supported local material aggregation and redistribution. The county has piloted biochar kilns, installed biomass boilers at government facilities, and partnered with local businesses to divert urban wood waste into products like firewood, mulch, and compost. These efforts laid an important foundation for more integrated biomass utilization planning.

Building on this history, the current initiative aims to scale up biomass utilization in ways that deliver co-benefits for climate mitigation, forest health, rural economic development, and the circular economy. This plan is supported by a favorable policy landscape, including Colorado Senate Bill 22-007, the Healthy Forests and Vibrant Communities Act, and federal investments from the Infrastructure Investment and Jobs Act. Locally, Boulder County's Climate Action Plan and Wildfire Mitigation Strategy emphasize innovation in carbon management and sustainable materials use. Together, these drivers highlight a timely opportunity for Boulder County to align its forest management and climate goals by transforming woody biomass from a liability into a strategic resource.

The Report is structured into four main chapters, supported by an executive summary, glossary, and multiple appendices. Each chapter addresses a distinct aspect of biomass utilization, moving from resource availability to pathway analysis, environmental co-benefits, and final recommendations.

- **Executive Summary and Introduction** – These sections frame the purpose and urgency of the plan, citing wildfire risk, climate mitigation goals, and state and federal policy support as key motivators. They establish Boulder County's intention to utilize woody biomass as both a climate strategy and wildfire mitigation tool.
- **Chapter 1: Estimates of Woody Feedstock Availability** – This chapter quantifies current and future woody biomass supply using a combination of reported data and modeled projections. It evaluates historical removals from public agencies and land managers and uses tools like TreeMap and the Forest Vegetation Simulator (FVS) to model potential production under different thinning prescriptions. Supply estimates range from 55,000 to 135,000 green tons annually, depending on treatment extent and implementation feasibility.
- **Chapter 2: Biomass Utilization Pathways and Infrastructure Assessment** – This chapter inventories more than 40 wood product facilities within 50 miles of Boulder County and evaluates 12 selected biomass utilization pathways using a multi-criteria matrix. Pathways are ranked based on factors like climate benefits, economic viability, scalability, and technical readiness. Biochar, compost/mulch, and firewood rank highest. The chapter includes detailed profiles of each pathway, a life cycle assessment (LCA) of three key pathways, and transportation cost estimates for biomass delivery.

- **Chapter 3: Evaluation of Co-Benefits of Fuels Reduction Projects –** This section analyzes ecological and social benefits of biomass removal and fuels reduction projects. It includes modeling of avoided wildfire emissions, forest health indicators (e.g., canopy cover, stand density index), biodiversity, invasive species control, and impacts on recreation, tourism, and watershed protection.
- **Chapter 4: Conclusions and Recommendations –** The report concludes with practical recommendations for enhancing biomass utilization in Boulder County. Suggestions include expanding sort yard capabilities, developing site-based processing permits, investing in transportation subsidies, exploring carbon financing, and leveraging public-private partnerships.
- **Appendices –** These provide supporting data, facility listings, model assumptions, biomass evaluation tables, and modeling methodologies used for avoided wildfire emissions.

Overall, the report is structured to support data-informed decision-making by combining quantitative feedstock analysis, infrastructure assessment, pathway feasibility evaluation, and co-benefit modeling - all aligned with Boulder County’s climate and resilience goals.

Chapter 1. Estimates of Woody Feedstock Availability for Biomass Utilization

Chapter 1 Summary

The chapter evaluates woody biomass availability in Boulder County, Colorado, between 2017 and 2024, combining reported biomass removal data with modeled projections and future estimates from the 2024 Boulder County Community Wildfire Protection Plan (Boulder County CWPP, 2024). Reported removals came from sources such as Boulder County Parks and Open Space, the City of Boulder's Urban Forestry and Open Space and Mountain Parks programs, the Longmont and Boulder Valley Conservation Districts, and the U.S. Forest Service. Modeled estimates were used to supplement gaps where data were incomplete or biomass was not removed, employing spatial datasets and forest simulation tools like TreeMap and the Forest Vegetation Simulator (FVS). Across reported and modeled sources, the county currently produces approximately 55,000 green tons of biomass annually. Future potential biomass production could increase significantly - up to 135,000 green tons per year - if planned treatments outlined in the CWPP are fully implemented, although this is an optimistic scenario based on full treatment of identified priority areas.

In terms of decision-making, several considerations are highlighted: existing infrastructure capacity for processing biomass, treatment feasibility in difficult terrains (especially in areas far from roads or with steep slopes), and the differences between accessible and inaccessible biomass. The scale of opportunity is substantial, but practical biomass removals are constrained by site accessibility, agency resources, and funding availability. Furthermore, distinguishing between biomass that is technically produced (but often left in place) versus biomass that is actually removed and available for utilization is critical. These insights emphasize the importance of strategic planning and prioritization to scale up biomass utilization initiatives in Boulder County while balancing ecological, operational, and economic realities.

Chapter 1 Introduction

This chapter assesses woody biomass supply in Boulder County, Colorado, from 2017 to 2024. It combines data on biomass removals from different jurisdictions, modeled projections using spatial datasets of fuel treatment areas, and future projections from the 2024 Boulder County Community Wildfire Protection Plan (Boulder County CWPP, 2024). Biomass removals were compiled from public agencies and forestry partners, while tree inventory tools, and a vegetation growth simulator, based on different treatment scenarios, accounted for unreported or inaccessible data. These sources provide a comprehensive view of woody biomass availability for potential utilization efforts in the region.

Reported Woody Biomass Removals from Completed Projects

The following sources of reported data were used to calculate removed biomass in Boulder County and summarized in Table 1.1 below. Where biomass was reported by weight, it was converted to green tons. Where biomass was reported as volume (cubic yards or cubic feet), it was converted to green tons[1] using a multiplier of 50 pounds per cubic foot (Winn et al., 2020). Calculations and totals are shown in "*Boulder Biomass Reported V4.1.xlsx*" spreadsheet and listed in Appendix 1.A.

Boulder County Parks and Open Space - This source provided information regarding biomass removed from Boulder County Parks and Open Space (BCPOS) properties and delivered from the Community Forestry Sort Yard (CFSY) to Boulder County processing facilities, such as the biomass boilers installed at the Boulder County Open Space and Transportation Complex and the Boulder County Jail. Both types of data were included in the total biomass supply estimates but can be

[1] 2,000 pounds not adjusted for moisture content.

separately detailed and summarized. Additionally, data from two significant projects completed in 2024 were provided, where the biomass was not removed (see Table 1.1 below). Source data is listed in Appendix 1.A and contained in the "*Biomass Deliveries – Boulder County Parks Open Space.xlsx*".

Boulder County Community Forestry Sort Yards - The biomass processing data from the Nederland and Meeker Park sort yards, evaluated from 2008 to June 29, 2024, were not included in the analysis due to potential redundancy with BCPOS data and overlap with other spatial data. However, these datasets provided valuable insights into the processing capacity and types of woody biomass handled at the two facilities. Source data is listed in Appendix 1.A and contained in the "*CFSY DATA from 2008 till 2024.xlsx*" spreadsheet.

City of Boulder - Urban Forestry Program - Kathleen Alexander, the City of Boulder Forester, provided a spreadsheet via email detailing biomass removed from urban forests from 2014 to 2024. Cambium Carbon's (2022) report estimated woody biomass at 10,000 green tons per year, slightly exceeding the City's reported amount. Source data is listed in Appendix 1.A and contained in the "*City of Boulder – Urban Biomass Estimates.xlsx*" spreadsheet.

Table 1.1. Reported woody biomass (in green tons) produced and removed from wildfire mitigation projects by entity, 2019-2024. Annual average row only counts years for which data was provided.

Year	Boulder County (BCPOS)	City of Boulder (Urban Forestry Program)	City of Boulder (OSMP)	Longmont & Boulder Valley Conservation District	US Forest Service[b]	Total
2019	1,368	5,985	915	-	-	**8,268**
2020	668	-	315	-	-	**983**
2021	11,163	11,198	708	-	2,768	**25,837**
2022	1,380	4,705	864	-	-	**6,949**
2023	2,161	5,927	762	4,298	-	**13,148**
2024	5,375[a]	4,674	1,121	7,380	184	**18,734**
6-year Total (2019-2024)	**22,115**	**32,489**	**4,685**	**11,678**	**2,952**	**73,919**
Annual Average	**3,686**	**6,498**	**781**	**5,839**	**1,476**	**12,320**

[a] Biomass reported as produced but was not removed from project areas.
[b] Information reported but not used in final assessment. Modeled values for biomass production were ultimately used in final assessment.

City of Boulder - Open Space and Mountain Parks - Open Space and Mountain Parks (OSMP) reported acres treated, residual basal areas, and log loads removed from 2019 to 2024. Each log load weighed 6,000 pounds (3 tons). For years with reported log loads, green tons removed were calculated directly; for other years, average tons per acre were extrapolated. Logs included trees 6" – 14" in diameter at breast height (DBH); smaller trees and slash (<6" DBH) were chipped and scattered on site. Source data is listed in Appendix 1.A and contained in the "*City of Boulder OSMP forest biomass.xlsx*" spreadsheet.

Longmont and Boulder Valley Conservation Districts - These districts provided data on project acreage, target basal areas, and trees per acre as "*Desired Future Conditions*." They also supplied biomass volumes for the 2024 Eagle Ridge project. Initially, biomass removal estimates from Eagle Ridge were used for other projects but were deemed too high by the Biomass Utilization Plan Core Team. After feedback, removal estimates were revised to 20 green tons per acre for most projects and 40 green tons per acre for Eagle Ridge, based on BCPOS staff judgment. Data was available for 2023 and 2024 only. Source data is listed in Appendix 1.A and contained in the "*Conservation District_Boulder_Biomass_Assessment_Completed_Projects_2024.xlsx*" spreadsheet.

US Forest Service, Boulder Ranger District – The US Forest Service (Colin Hutten, pers. comm.) provided an estimate of biomass removals for 2021 and 2024 via an email correspondence. This information is reported in Table 1.1 but was not ultimately used in the final biomass production estimates for completed projects since the vast majority of biomass produced from USFS treatments was not removed from treatment locations. Instead, US Forest Service biomass production was estimated via modeling as described in the following "Modeled Biomass Supply" section.

Other Potential Urban Woody Biomass Supply Sources – A data request was made of municipalities within Boulder County, and a response was received from Louisville, Erie, and Longmont. Other municipalities (beyond the City of Boulder) were surveyed to get an estimate of potential urban woody biomass sources that were not included in the biomass supply estimation scope of the biomass assessment were surveyed. In aggregate, an additional 11,400 green tons of biomass was reported. About half of this material is retained for municipal landscaping or provided free to residents for their use, while the other half is composted.

Other Potential Urban Woody Biomass Supply Sources – A data request to other municipalities in Boulder County, including Louisville, Erie, and Longmont, revealed an additional 11,400 green tons of biomass annually (Table 1.2). About half is used for municipal landscaping or provided to residents, while the rest is composted. Although identified and enumerated, this biomass supply is reported here but was not included in this analysis.

Table 1.2. Reported annual biomass supply and utilization for Louisville, Erie, and Longmont communities.

Municipality	Cubic Yards	Green Tons	End Use and Notes
Louisville	6,500	4,388	In-house landscaping and free pile.
Erie	1,000	675	
Longmont (Logs)	500	338	In-house landscaping.
Longmont (Chips)		6,000	To A1 for compost via Longmont Waste Services.
TOTAL		**11,400**	

Modeled Biomass Production

A spatial modeling technique was used to estimate biomass production rates for fuel reduction treatment areas where biomass removals were not directly measured and reported. It is important to note that this analysis does not evaluate the accessibility of the biomass for removal, its suitability for processing, or the financial feasibility of such activities. Spatial datasets containing project areas were supplied by project partners, including details of treatment areas and treatment years (Figure 1.1). Ultimately, three datasets were utilized, encompassing the most recent treatments with clearly defined boundaries and treatment years, including.

US Forest Service (USFS) spatial data from the Boulder Ranger District, and publicly available online enterprise data.

- USFS Hazardous Fuel Enterprise Layer
- Boulder Ranger District fuel treatment layer

Colorado State Forest Service (CSFS) aggregated data for private and non-federal lands

- Colorado Forest Tracker – primary dataset
- GeoTracks – recent projects not yet incorporated into Forest Tracker

Open Space and Mountain Parks (OSMP), City of Boulder

- 10-year completed thinning treatments

Other datasets, such as those from the Colorado Forest Restoration Institute, Watershed Center, and Boulder Watershed Collective, were reviewed but not used because they were included in the Colorado Forest Tracker dataset. BCPOS spatial data were also excluded due to available reported removal data.

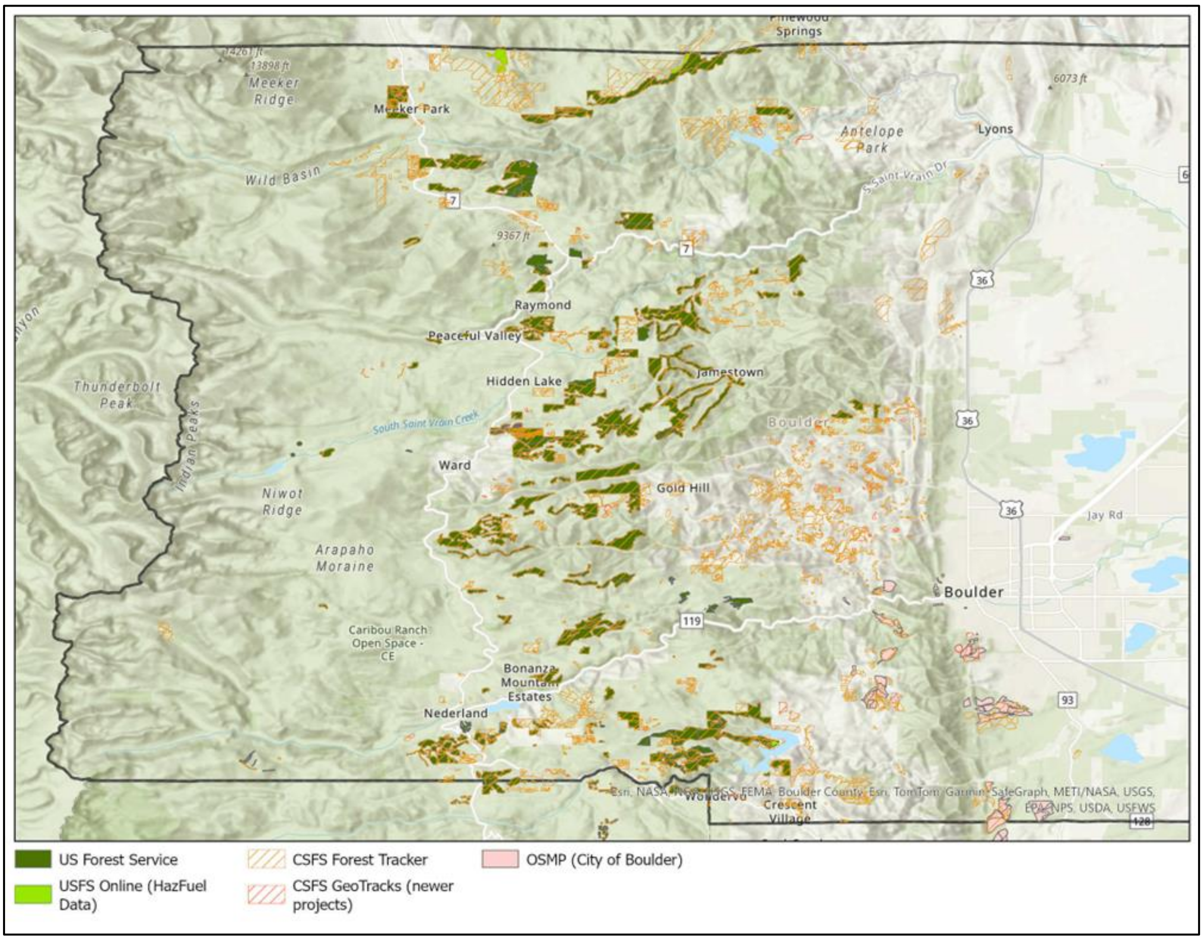


Figure 1.1. Map showing spatial datasets used to model biomass production in Boulder County. Note: The black outline is the County boundary; project areas outside of the county were not included in this analysis.

Modeling Approach

Spatial overlap was removed in the datasets used in the model to avoid double-counting, with the CSFS Forest Tracker dataset being used as the primary dataset where there was overlap. TreeMap, a tree-level model of the forests of the conterminous United States (Riley et al., 2021), was then used to develop an imputed tree inventory for the treatment areas. Several treatment prescriptions were applied to the tree-level data in the Forest Vegetation Simulator (FVS; Dixon, 2025).[2] The treatment prescriptions are:

Two model runs were created for ponderosa-pine dominant stands

1. Thin from below prescription with a residual basal area of 30 ft^2/acre – this prescription would leave approximately 30 of the largest trees/acre within a ponderosa pine forest type assuming average basal area/tree was 1ft^2.

[2] Forest Vegetation Simulator is a forest growth simulator model that simulates forest vegetation change over time in response to natural succession, disturbances and management. https://www.fs.usda.gov/managing-land/forest-management/fvs

2. Thin from below prescription with a residual basal area of 60 ft^2/acre - this prescription would leave approximately 60 of the largest trees/acre within a ponderosa pine forest type assuming average basal area/tree was 1ft^2.

In both model runs, all lodgepole pine was removed in lodgepole forest type stands. Non-lodgepole species were left as standing residual. For the OSMP dataset specifically, the residual stand basal area was set to 70 ft^2 based on the average of the prescriptions provided in the reported data.

FVS was used to model tree growth and treatments in five-year timesteps. TreeMap is based on 2016 data, and therefore 2016 was used as the initial inventory year. The first treatment year modeled in FVS was 2017. The 2017 treatment timestamp represents treatments in the first five years (2017-2021). The 2022 timestamp represents treatments in 2022 and beyond 2023/2024.

FVS outputs include total biomass produced, merchantable biomass produced,[3] slash (i.e. the difference between total and merchantable), and salvage (dead) biomass produced. A summary of biomass totals by ownership and biomass type is provided in Table 1.3 and Table 1.4. All units were reported in green tons.

Table 1.3. Modeled biomass production in Boulder County with the 30 ft^2 residual basal area (BA) prescription for ponderosa-dominant mixed conifer, 70 ft^2 residual basal area (BA) prescription for OSMP lands, and lodgepole removal for lodgepole-type stands as described above. Units in green tons of biomass.

	Total (Merchantable + Slash)	**Merchantable**	**Slash**	**Salvage (dead)**
CSFS Aggregated	**83,011**	**67,025**	**15,986**	**12,114**
2017	50,841	41,490	9,351	8,644
2022	32,170	25,536	6,635	3,470
OSMP	**11,332**	**6,644**	**4,688**	**1,288**
2017	4,352	2,081	2,271	534
2022	6,980	4,563	2,418	754
USFS	**140,401**	**112,308**	**28,093**	**19,959**
2017	92,543	74,271	18,272	12,614
2022	47,858	38,037	9,821	7,345
Grand Total	**234,744**	**185,977**	**48,767**	**33,361**
Annual avg (7 yrs)	**33,535**	**26,568**	**6,967**	**4,766**

[3] Merchantable biomass is defined as logs greater than 5” in a diameter from the 1-foot high stump to a 4” top. The rest (limbs, tops, small trees) is part of the slash biomass pool.

Table 1.4. Modeled biomass production in Boulder County with the 60 ft² residual BA prescription and 70 ft² residual basal area (BA) prescription for OSMP lands, and lodgepole removal for lodgepole-type stands. Units in green tons.

	Total (Merchantable + Slash)	Merchantable	Slash	Salvage (dead)
CFCS Aggregated	**56,533**	**44,053**	**12,480**	**12,114**
2017	33,729	26,597	7,132	8,644
2022	22,804	17,456	5,348	3,470
OSMP	**11,332**	**6,644**	**4,688**	**1,288**
2017	4,352	2,081	2,271	534
2022	6,980	4,563	2,418	754
USFS	**89,524**	**68,645**	**20,879**	**19,959**
2017	57,138	43,906	13,232	12,614
2022	32,386	24,739	7,647	7,345
Grand Total	**157,389**	**119,342**	**38,047**	**33,361**
Annual avg (7 yrs)	*22,484*	*17,049*	*5,435*	*4,766*

Combined Reported and Modeled Biomass Production Results

The modeled and reported biomass removals were combined to estimate the overall biomass supply in Boulder County using the 'Rx:30 BA Residual' model run (Table 1.5). The reported biomass estimates were included for *Boulder County*, *Urban*, and *Conservation District*. Modeled biomass production was estimated for *CSFS Aggregated*, *OSMP*, and *USFS* (Table 1.5).

Modeled results were used for OSMP and USFS, as most USFS treatments use mastication or pile burning rather than biomass removal. Modeled outcomes better reflected total woody biomass produced for these ownerships. For OSMP projects, trees under 6 inches in diameter are chipped and spread on site and excluded from removed data. These smaller trees were considered in the OSMP modeled results as a potential biomass source for utilization.

Table 1.5. Combined reported and modeled biomass production in Boulder County. Modeled database year was 2017, and the reported data was for 2019 - 2024. Note that the 2024 Boulder County value in the table was reported but not removed biomass.

Year	REPORTED				MODELED (30 BA Residual)				Total Biomass
	Boulder County (P&OS)	Urban (City of Boulder)	Conservation District	Reported Subtotal	CSFS Aggregated	OSMP (City of Boulder)	USFS	Modeled Subtotal	
2019	1,368	5,985		7,353					
2020	668			668	50,841	4,352	92,543	147,736	
2021	11,163	11,198		22,361					
2022	1,380	4,705		6,085					
2023	2,161	5,927	4,298	12,386	32,170	6,980	47,858	87,008	
2024	5,375	4,674	7,380	17,429					
Total	**22,115**	**32,489**	**11,678**	**66,282**	**83,011**	**11,332**	**140,401**	**234,744**	**301,026**
Annual Average	**3,686**	**6,498**	**5,839**	**16,023**	**13,835**	**1,889**	**23,400**	**39,124**	**55,147**

Notably, blue highlighted columns in Table 1.5 represent woody biomass that was removed from project sites while the green highlighted columns represent biomass that was produced but not necessarily removed. The project areas for green and blue highlighted columns in Table 1.5 are not overlapping. Most of the biomass produced in areas modeled are currently burned or spread on-site. Note that in Table 1.1, the US Forest Service only removed around 3,000 green tons over six years, while Table 1.3 and Table 1.5 show an estimated biomass production of around 140,400 green tons over that time period.

Estimates of Future Biomass Availability

2024 Boulder County Community Wildfire Protection Plan Estimates

Future potential biomass removals were estimated from the Boulder County CWPP (2024) using the anticipated wildfire mitigation projects delineated in Appendix J of that document, as well as the *Priority Areas of Action* and *Fireshed Focus Areas* as delineated in Figures 4.4 and 4.5 of the CWPP. Appendix J of the Boulder County CWPP (2024) detailed expected wildfire mitigation projects and acreages by entity within Boulder County, including municipalities, agencies, NGOs, and Fire Protection Districts (FPD). Using the total biomass volume produced from the 30 ft^2 residual basal area (BA) model run, an average production rate of 35.2 green tons per acre was determined based on aggregated data from the Colorado State Forest Service (CSFS; Colorado Forest Tracker and GeoTrack). Biomass production estimates were calculated for each anticipated project and then aggregated across organizations, as detailed in Table 1.6. See *Boulder Bio Estimates – Appendix J 2024.12.16.xlsx* for specifics.

Table 1.6. Biomass production estimates for the planned treatments in Appendix J of the 2024 Boulder County Community Wildfire Protection Plan. Biomass units are in green tons. Biomass calculated using 35.2 green tons per acre based on the average for the CSFS aggregated data, total volume removed, residual basal area 30 ft^2 run.

Organization	Approximate Total Acreage	Biomass Production Estimate
USFS BRD	19,750	695,200
BWC	6,000	211,200
Longmont (Button Rock)	3,000	105,600
BVLCD	2,849	100,285
BCPOS	1,767	62,205
CSFS	820	28,864
Nederland FPD	785	27,632
TWC	640	22,528
Lefthand FPD	534	18,797
Sugarloaf FPD	345	12,144
Boulder Mountain FDP	327	11,510
Timberline FPD	300	10,560
Fourmile FPD	249	8,765
Boulder Rural FPD	141	4,963
TOTAL	**40,307**	**1,320,253**

CWPP Priority Areas and Planned Treatment Biomass Estimates

In addition to biomass availability estimates derived from the Appendix J (from Boulder County CWPP, 2024) planned projects, additional modeling was completed to assess biomass production under different treatment scenarios for Boulder County CWPP (2024) priority areas and OSMP planned treatment areas. The priority areas are defined in Figures 4.4 and 4.5 of the Boulder County CWPP (2024) in the *Countywide Priority Treatment Areas for Action* and *Fireshed Focus Areas* sections. OSMP planned treatment areas were provided by OSMP staff.

One treatment scenario was applied to OSMP planned treatments, and two different treatment scenarios were used for CWPP priority areas – a 30 ft^2 residual BA treatment scenario and 60 ft^2 residual BA treatment scenario. To model treatment scenarios, CWPP priority areas were first filtered for treatment accessibility by excluding areas over half a mile from roads and those with slopes above 40%. Previously completed treatments were also excluded. The model treated 65,386 acres under the 30 ft^2 residual BA treatment and 57,837 acres under the 60 ft^2 residual BA treatment. 738 acres of City of Boulder OSMP planned treatments were modeled without filtering, using a 70 ft^2 residual basal area treatment prescription. Table 1.7 provides a summary of the modeling results for biomass availability for each scenario modeled.

Table 1.7. Potential biomass production from the CWPP Priority Areas and OSMP planned projects. Units in green tons.

	Total (Merchantable + Slash)	Merchantable	Slash	Salvage (dead)
CWPP Priority Areas				
BA 30 Residual	2,760,741	2,160,394	600,348	272,785
BA 60 Residual	1,724,045	1,280,325	443,721	262,283
OSMP Planned	22,949	17,359	5,590	3,559

Range of Woody Biomass Availability Estimates

The annual *potential* biomass production was estimated at 139,185 green tons a year, assuming the entire CWPP priority area could be treated over twenty years. This was estimated by combining the 'CWPP Priority Areas/BA 30 Residual' (2,760,741green tons) and 'OSMP Planned' (22,949 green tons) total biomass volumes from Table 1.7 above for a total production of 2,783,690 green tons divided by 20 years.

Under the assumption that Appendix J (Boulder County CWPP, 2024) projects are near-term priorities and could be completed within ten years, a similar rate of 132,000 green tons per year was estimates.

To summarize, based on this evaluation, Boulder County's annual biomass supply is estimated to be between 55,000 (Table 1.5) and 135,000 green tons/year (Tables 1.6 and 1.7). Currently, woody biomass production is about 55,000 green tons per year. This estimate is well-parametrized based on removal data and project information. The potential maximum production in an ideal scenario is around 135,000 green tons, but, based on past biomass removals, near-term production is likely to remain at about 55,000 green tons per year.

Discussion

The analysis of woody biomass availability in Boulder County provides details of current and future feedstock supplies for biomass utilization planning purposes. Between 2019 and 2024, an average of approximately 12,320 green tons of woody biomass per year was removed from completed wildfire mitigation projects, largely sourced from Boulder County Parks and Open Space, the City of Boulder, and other conservation entities. Other municipalities in Boulder County reported an annual estimate of 11,400 green tons of urban biomass removed and utilized. Additional biomass was generated from U.S. Forest Service projects, although much of it remained on-site, and thus required modeled projections rather than reported removals. Spatial modeling efforts estimated even greater biomass availability when accounting for areas where biomass was produced but not removed, yielding an overall combined estimate of about 55,000 green tons of woody biomass produced annually under existing treatment programs.

Future projections suggest that Boulder County could increase its biomass supply if planned mitigation projects from the 2024 Community Wildfire Protection Plan (Boulder County CWPP, 2024) are implemented. If the full scope of identified priority areas is treated over a 20-year timeframe, annual biomass production could reach approximately 139,000 green tons. Shorter-term projects outlined in Boulder County CWPP (2024) Appendix J are projected to generate a similar annual volume of roughly 132,000 green tons over the next decade. However, while higher biomass production estimates highlight significant potential, they reflect idealized assumptions about treatment implementation, accessibility for utilization, and project completion rates.

In practice, near-term biomass availability is expected to remain closer to the current level of around 55,000 green tons annually. This estimate reflects actual past removals and considers realistic constraints such as logistical, operational, and economic factors. Overall, while Boulder County has a robust baseline biomass supply to support utilization efforts today, additional gains are possible with expanded treatment activities and transportation/infrastructure investments, particularly if challenges related to biomass removal and processing can be addressed.

Chapter 2. Biomass Utilization Pathways and Infrastructure Assessment

Chapter 2 Summary

Chapter 2 provides a comprehensive assessment of biomass utilization infrastructure and pathway opportunities for Boulder County, Colorado. It begins by cataloging over 40 wood products facilities within a 50-mile radius of Boulder, gathered from state and local databases and verified through public records and direct outreach. These facilities span 13 categories of wood use - including firewood, compost, mulch, lumber, and specialty products - and are further classified by size (small, medium, or large) based on workforce and operational capacity. Two key infrastructure assets, Nederland and Meeker Park Sort Yards, are noted as community-operated sites critical for aggregating and processing woody biomass from fire mitigation and forest restoration efforts.

The report identifies, scores, and ranks twelve biomass utilization pathways using a multi-criteria matrix approach that considers environmental, economic, and technical factors. These pathways were selected through stakeholder input and further evaluated across attributes such as technology readiness, operational costs, feedstock requirements, market potential, and permitting complexity. Each pathway received a score out of 210 possible points. Top-ranked pathways included biochar (169 points), compost/mulch (168 points), and firewood (164 points), reflecting their strong climate mitigation potential, product value, and relative technical feasibility. Other pathways evaluated include small sawmill operations, animal bedding, biomass heating, mass timber, air curtain burners, pellets, bio-oil, post and pole production, and fungal decomposition.

In comparing climate impacts, the analysis found GHG benefits to be broadly similar across the highest-ranked pathways (i.e., biochar, compost, and firewood). This led to emphasis on other considerations, such as the scale of landscape improvement (e.g., biochar supports wider acreage benefits), presence of existing infrastructure (e.g., compost facilities), and air quality regulations (notably affecting firewood usage). The report also includes a detailed breakdown of transportation and processing costs, offering a framework for estimating delivered biomass costs based on travel distance and facility logistics. Overall, the analysis supports a diversified biomass utilization strategy for Boulder County, where different pathways may be optimal depending on site-specific factors such as feedstock availability, facility access, permitting environment, and desired co-benefits like wildfire risk reduction and circular economy advancement.

Chapter 2 Introduction

This chapter provides a comprehensive evaluation of woody biomass management infrastructure, utilization capacity, and environmental performance in the Boulder County region. It begins with an infrastructure inventory that maps and classifies more than 40 operational facilities within a 50-mile radius that process forest-derived biomass into products such as firewood, compost, mulch, animal bedding, lumber, and other biomass utilization pathways. Utilization pathways are analyzed by scale, proximity to Boulder County's sort yards, and compatibility with current and projected feedstock availability. The chapter then introduces a multi-criteria decision framework used to evaluate and rank 12 biomass utilization pathways, incorporating stakeholder input across economic, environmental, logistical, and social factors. In parallel, a life cycle assessment (LCA) is conducted to quantify the greenhouse gas (GHG) impacts of three selected utilization pathways - composting, biochar production, and firewood for heat - relative to a baseline of open pile burning. Together, the infrastructure mapping, pathway scoring, and LCA provide decision-makers and managers with an integrated planning tool to align biomass utilization with forest health, wildfire mitigation, and Boulder County's broader climate and sustainability goals.

Biomass Management Infrastructure and Utilization Capacity

This section identifies existing biomass management facilities and their potential for liability biomass utilization. To assist Boulder County decision-makers and project managers, detailed lists of facilities within a 50-mile radius of Boulder, including drive distances and loading/unloading costs, were compiled.

Wood Products Facilities in the Boulder Region

Information for the list of facilities in Table 2.1 and the Tables in Appendix 2.A were acquired from various databases, such as the Colorado State Forest Service (CSFS) Wood Utilization and Marketing Program, the CSFS Forest Products Database, the CSFS GIS Open Data Portal, lists from local organizations, and the City of Boulder forestry department. Information and data from these sources were merged in an electronic database that lists wood products facilities in a 50-mile radius of the City of Boulder. The types of facilities that were incorporated into this project facilities database were the following general categories:

- Firewood
- Compost
- Mulch
- Wood chips
- Animal bedding
- Lumber products
- Beams
- Pellets
- Post & Pole
- Shavings
- Log Homes
- Wood Furniture
- Specialty Products

The merged information and data sources resulted in over 40 facilities within a 50-mile radius of the City of Boulder that offered some type of wood utilization in the 13 categories. Next, an extensive investigation of the identified companies was undertaken. Each company was called to verify their continued operation and the categories of products they produce or utilize. Further, the Colorado Secretary of State online records were searched to ascertain their status as an operating business in the agency's 'Good Standing' certification program.

As part of the continued efforts to verify the previously identified businesses, an additional online search was conducted to assess key indicators such as the presence of an active website and current ratings on community platforms (e.g., Yelp, Facebook, and the Better Business Bureau). This evaluation process aimed at determining both the operational status and the capacity of each listed business.

Given that many local businesses are small-scale operations, often relying solely on personal phone contact without a dedicated website, this verification process ensured that such businesses were not inadvertently excluded, provided they remained active and open to new business opportunities. Businesses falling within this category were classified as Small (S) enterprises. For more established entities - those employing three or more individuals and maintaining a physical business location, and possibly a website - are categorized as Medium (M) businesses. These companies typically possess the capacity to manage multiple projects simultaneously. Finally, organizations characterized by high operational throughput, a workforce of ten or more employees, and large or multiple physical locations were classified as Large (L) businesses. This classification system allowed for a clearer understanding of each business's scale and operational capability, ensuring a comprehensive and accurate assessment. It should be noted that the listings presented in Table 2.1 below are not necessarily an exhaustive compilation of all wood products facilities in the Boulder Region.

Accompanying the listing for the thirteen categories are detailed maps in Appendix 2.A, which show the location of the respective wood products category facilities listing preceding the figure. It was the location of these facilities and their location to relative to roads and highways from the geographic center of the City of Boulder that determined the actual distances in the facility tables. This resulted in road miles in some cases exceeding 50 miles, even though facilities are with the 50-mile radius.

Boulder County currently operates two Community Forestry Sort Yards (CFSY) that facilitate the collection and processing of woody biomass to mitigate wildfire risks and promote forest health. These facilities are:

- Nederland Sort Yard – located at 291 Ridge Road, Nederland (approximately 17 road miles west of the city of Boulder)
- Meeker Park Sort Yard – located at 8200 Highway 7, Allenspark (approximately 35 miles northwest of city of Boulder).

The following requirements apply for biomass received at CFSYs:

- Logs
    - All species are accepted.
    - Trim the branches, flush to the trunk.
    - End of logs must be cut square.
    - Burned logs are accepted.
- Slash and Branches
    - Separate conifers and broad leaf trees.
    - Chunk and decayed wood.
    - All wood must be free of nails, wire, and metal.

- Remove root ball.

Although materials other than liability biomass can be accepted at the County's sort yards, such as noxious weeds, nearly all materials (>95%) brought to these facilities have been woody biomass removals from fire mitigation activities (Wayne Harrington, pers. comm.).

In addition to the two Boulder County facilities, a significant local/regional waste management company, Western Disposal Services, also accepts and processes wood and woody yard waste at its Material Management Center (2052 63rd Street, Boulder) from both residential and commercial sources (primarily landscaping and tree trimming companies). The woody portion of the waste is ground at the facility and then repurposed for local composting. Unlike the County sort yards, the Western facility charges a tipping fee for acceptance of the wood waste. These fees are currently $2.97 per 100 pounds for residential yard/wood waste generators, and $99.20 for commercial yard/wood waste generators. The City and County of Boulder offer a 40% subsidy of this rate for City/County residents.

Most of the liability biomass generation in the Boulder County Region (discussed in Chapter 1), has historically been either piled and burned at the site of the biomass reduction activities, or in some instances chipped and spread onto the forest floor. Whole logs have also been removed during these activities and utilized by local and regional firms for various wood products such as lumber. Lumber is currently the least utilized market for logs sourced from Boulder County forests.

Woody Biomass Materials Accepted by Facilities

Although the identified and verified facilities accept a wide variety of woody biomass waste, each category has specific requirements for the type of woody biomass. Users of the category lists should be aware of these requirements during their project planning and when engaging with specific facilities. Table 2.2 below outlines the types and forms of woody biomass by wood product category.

As there are no mass timber production facilities identified to date within the 50-mile radius, it was not included in the above table. However, if liability biomass was to be utilized for mass timber production, primarily whole logs are needed for long, uniform, and structurally sound boards necessary for engineered wood products.

Table 2.1. Boulder region wood product facilities.

Facility Number	Facility name	Distance	Firewood/fuel wood	Compost	Wood Mulch	Wood Chips	Animal Bedding	Lumber Products	Beams	Pellets	Post, Poles & Fencing	Shavings	Log Homes	Furniture	Speciality products
1	J.C. Custom Design Works	56.3						X							
2	JCK Corp.	30.5	X	X											
3	Jeremiah Johnson Log Homes Inc.	50						X					X		
4	JKC Woods LLC	13.4						X	X					X	X
5	A1 Organics - Eaton	70.6		X	X										
6	Blue Pine Woodworks	28.2												X	X
7	Clear Creek Service Company LLC	34.4	X		X	X		X							
8	Cleveland Creek Log & Lodge Furniture	26.9												X	X
9	Crown Hill Landscaping LLC	27.6	X												
10	Deerwood Forest Products Co.	43.7	X								X				
11	Denver Wood Slabs	24.6						X	X					X	X
12	Frameworks Timber	63.7							X						
13	Golden West Pine Mills LLC	65						X	X		X				X
14	Hard Up Lumber	86.4	X					X	X		X		X	X	
15	LumberJacks Logging & Firewood	22.8	X			X		X							
16	Meier Skis	32.5													X
17	Moose Haven Milling Ltd.	29.7	X					X	X					X	
18	Morgan Forest Agriculture	7.2	X												
19	Nature's Casket	15.1													X
20	Reclaimed West	11.2						X	X		X			X	X
21	A1 Organics - Keenesburg	54		X	X										
22	TimberScapes	47.3	X					X			X				X
23	TJ's Wood Products	57.4						X	X		X		X		
24	Rocky Mountain Log & Saw Co. LLC	69.6	X								X				
25	Ryan Schlaefer Fine Furniture Inc.	32.5												X	
26	Sears Trostel Lumber CO	63.3						X							X
27	Shreiner Enterprises	71.9	X	X	X	X	X	X		X	X	X	X	X	
28	Timberline Log Exteriors	49						X					X		X
29	TM Grand County Inc.	97.3	X			X					X				
30	Western Log Creations	49						X							X
31	Mountain Woodworks	31.5												X	X
32	Mourning Reclaimed Wood	34.8	X					X	X	X				X	
33	Naked Aspen Designs	82.5												X	X
34	Andersons Adirondacks	35.9												X	
35	GreenWay Building Products LLC	31.6						X	X		X		X	X	
36	Morgan Timber Products	69.8	X		X	X	X	X	X		X	X	X		X
37	Summerhill Tree Farm	46.1	X								X				
38	T & G Hardwood Flooring Specialists	23.4						X							
39	TC Woods, Tree Recycling Center	7.9	X					X						X	
40	United Wood Products Inc.	11.8	X			X	X								X
41	Where Wood Meets Steel	24.6						X						X	X
42	Wood Butcher Ltd.	40.8	X				X	X	X		X		X	X	X
43	Wood Source	24.8						X	X		X				X

Table 2.2. Acceptable liability biomass per wood products category.

Facility Category	Acceptable Woody Biomass
Firewood	Logs and large limbs greater than 3 inches in diameter.
Compost	Any forest liability biomass, especially slash composed of smaller branches, twigs, bark, needles and leaves. Preference is chipped or ground material, however some composters have shredders and grinders and some could accept logs.
Mulch	Any forest liability biomass, especially slash composed of smaller branches, twigs, bark, needles and leaves. Preference is chipped or ground material, however some composters have shredders and grinders and some could accept logs.
Wood Chips	Branches and larger twigs; bark (used for high-quality decorative purposes); small-diameter logs – (logs that are not suitable for lumber but can be chipped for landscaping purposes; treetops (upper portions of trees, which are typically less useful for lumber, can be chipped); small trees.
Animal Bedding	Bark-Free Logs – Debarked softwood logs (like pine or aspen) are processed into shavings or sawdust for clean, dust-free bedding. Branches and Small-Diameter Trees – Whole small trees can be chipped and processed into fine bedding material.
Lumber Products	Logs of the main bole or a tree used in CO.
Beams	Logs of the main bole or a tree used in CO.
Pellets	Bark-Free Small-Diameter Logs – Whole small trees that are not suitable for lumber can be chipped and processed into pellets; Tree Tops and Branches –, can be chipped and used; Wood chips – can be processed into finer particles for pellets.
Pole & Pole	Straight, small to medium-diameter trees – The tree bole of the tree is the primary source for poles and posts. Trees with minimal taper and few knots are preferred. Whole Small-Diameter Trees – entire young trees are used for fence posts, utility poles, and construction poles.
Shavings	Debarked Logs – The main trunk (bole) is the primary source of high-quality shavings, especially for animal bedding and packaging materials; small-diameter trees.
Log Homes	Main trunk (bole) – The straight, thick, and knot-free portion of the trunk is the primary source of logs for building construction; Full-Length Logs – In traditional log home construction, long logs are used to minimize joints and maintain structural stability.
Furniture	Main trunk (bole) – The straight, defect-free section of the trunk is the primary source for high-quality furniture wood and slabs; Large branches – Thick, strong branches are used for rustic furniture, artistic designs, or specialty pieces; Tree butt (Base of the Trunk) – Can contain unique grain patterns and burls, making it valuable for decorative furniture and veneers.
Specialty Products	Whole logs, branches and limbs expect relatively low volumes needed.

Estimated Delivery Cost Assumptions

In the Tables in Appendix 2.A, distances from the center of the City of Boulder to the 44 wood utilization facilities within a 50-mile radius were calculated. These calculations included the following:

1. Real Distance
Formula: Real Distance = Total Distance × 2

Total Distance: One-way distance (in miles).
Assumption: Accounts for round-trip travel (to and from the destination).

2. Total Drive Time
Formula: Total Drive Time (hours) = Real Distance x Average Speed

Average Speed: Fixed at 30 mph.

3. Drive Cost Subtotal
Formula: Drive Cost Subtotal =Total Drive Time × $/hr Trucking Cost

$/hr Trucking Cost: Fixed at $160/hr.

4. Unload Time Cost
Formula: Unload Time Cost = Unload Time × $/hr Load/Unload

Unload Time: Fixed at 1 hour.
$/hr Load/Unload Cost: Fixed at $250/hr.

5. Estimate Delivery Cost
Formula: Estimate Delivery Cost = Drive Cost Subtotal + Unload Time

6. Per Ton Delivered Cost
Formula: Per Ton Delivered Cost = Estimate Delivery Cost /Tons per load

20 total tons of feedstock transported in one trip.
Assumption: The truck operates at full capacity, carrying 20 tons per trip.
Delivery costs are evenly distributed across all tons.

Example Calculation

Given: Total Distance = 50 miles (one-way)

1. Real Distance: 50 miles × 2 (roundtrip) = 100 miles
2. Total Drive Time: 100 miles/30 mph = 3.33 hours
3. Drive Cost Subtotal: 3.33 hours × $160.00 ≈ $533.00
4. Unload Time Cost: 1 hour × $250 per hour =$250
5. Estimate Delivery Cost: $533.33 + 250 = $783.33
6. Per Ton Delivered Cost: $783.33/20 tons ≈ $39.17 per ton

As the mileage and transport costs calculated for the various facilities was determined using the City of Boulder as the starting destination, additional miles will need to be added for any liability biomass removal activity. The above assumptions and step-by-step example calculation will allow for extra distances and therefore costs of delivered liability biomass to be further estimated for fire mitigation project management costs. For example, if liability biomass was to be transported from the Boulder County Nederland Sort Yard, which is approximately 16 miles for the center of Boulder, an additional $21.03 per ton is estimated (32 miles round trip/30 mph X $160 + $250 = $420.66/20 = $21.03).

Liability Biomass Utilization Pathways Selection and Analysis

This section describes the liability biomass utilization pathways selection and analyses process that was conducted. This process used the following protocols, previously used for several other similar projects in the Western United States:

- Listing and categorization of potential biomass utilization pathways currently in use.
- Selecting technologies in coordination with stakeholders.
- Subjecting the stakeholder selections to a matrix-based scoring and ranking.
- Conducting follow-on detailed analyses of the top-ranking technologies.

Listing and Categorization of Pathways

Currently established and emerging biomass utilization pathways were listed each with a summary of the required woody biomass feedstock specifications, main equipment to produce their respective bioproducts, market potential, and general comments about the pathway and its applicability. These pathways and attributes were placed in tabular form for ease of review. The full table is included in Appendix 2.B.

A matrix of various biomass utilization technologies and pathways (27 in total), along with facilitating discussion, was presented to the Biomass Management and Utilization Core Team (for full matrix, see Appendix 2.B). To facilitate the selection of 10 pathways for further review and analysis, support, mixed support, and non-support of the pathways was requested by the Core Team representatives at a meeting on August 26, 2024, at the Boulder County Parks and Open Space offices. Table 2.3 below displays the results on that selection interaction.

Table 2.3 - Initial biomass utilization pathways examined

Selected - Highly Supported	Selected -Supported	Mixed – Not Selected	Not Supported – Not Selected
Biochar	Biomass Heat	Biomass Burial	Electricity Generated
Bio-Oil	Compost/Mulch	Composites	Biofuel
Firewood	Fungal Decomposition		Hog Fuel
	Small Sawmill		Chips for Pulp
	Post & Pole		Landfill
	Mass Timber		
	Animal Bedding		
	Air Curtain Burner		
	Pellets/Fuel Bricks		

Twelve technology pathways were supported by the Core Team and then subjected to the next step in the selection protocol.

Scoring and Ranking Methodology

The scoring and ranking methodology used for this project has been utilized on several other biomass utilization pathway projects to assist in a more systematic approach to further refining information and selecting technology pathways that are most beneficial to a region's biomass utilization needs. The methodology compares attributes common to forest woody biomass utilization needs. Some of these included:

- Nevada County Biomass Feasibility Assessment (https://tssconsultants.com/wp-content/uploads/2015/10/FSCNC-Final-Report-20141201.pdf)

- Wood Waste Utilization Assessment for the Greater Taos New Mexico Region (https://tssconsultants.com/wp-content/uploads/2017/01/TNC-Report-Final-20170112.pdf)
- Feasibility Assessment for a Commercial Sacle Woody Biomass Conversion Facility in Central Arizona (https://tssconsultants.com/wp-content/uploads/2018/11/UVRWPC-Com-Facility-Assess-Report-Final-20181017.pdf)
- Biomass Utilization Solutions for Forest Fuels Reduction Activities for the Eastern Sierra (https://tssconsultants.com/wp-content/uploads/2023/12/Biomass-Utilization-Solutions-for-Forest-Fuels-Reduction-Activities-for-the-East-Sierra-FINAL-20221017.pdf)
- Bioenergy Solutions for Forest Fuels Reduction Activities for the Eastern Sierra (https://tssconsultants.com/wp-content/uploads/2023/12/Biomass-Utilization-Solutions-for-Forest-Fuels-Reduction-Activities-for-the-East-Sierra-FINAL-20221017.pdf)
- Feasibility Study for a Value-Added Wood Products Campus within the Central Sierra Region of California (https://tssconsultants.com/wp-content/uploads/2024/07/Feasibility-Study-for-a-Value-Added-Wood-Products-Campus-Within-the-Central-Sierra-Region-of-California.pdf)
- Woody Biomass Energy Technology Evaluation (https://tssconsultants.com/wp-content/uploads/2024/10/YWA-Bioenergy-Technology-Evaluation-October-2023.pdf)

Biomass Utilization Attributes and Descriptions

In the scoring and ranking methodology, several attributes are considered. These attributes were used as evaluation criteria to aid in identifying viable utilization pathways and were presented to the Boulder County Biomass Management and Utilization Core Team for their input and suggested changes. The following are the final attributes along with a description used for semi-quantitatively scoring each of the 12 selected pathways:

Primary Products - What are the marketable products produced via these pathways? Are there multiple products? What waste materials might require post-production handling or disposal? Identifying marketable byproducts, in addition to the primary products, is crucial since these byproducts can significantly enhance revenue generation.

Feedstock Matches - Can the pathway utilize all components of liability biomass—such as wood, bark, needles, and cones—or is it limited to clean bole wood only?

Technology Considerations and Maturity - Is the pathway technology commercially available with established equipment vendors in the United States, or is it only available outside the U.S.? The federal Technology Readiness Level (TRL) should be considered, with a minimum of TRL 7. A TRL of 9 is preferred for immediate commercial operations. See Table 2.4 below for details.

Scalability - Can the pathways and associated technology and equipment be easily scaled if the availability of woody biomass feedstock increases over time?

Transportation of Feedstock - Can the processing activity be located closer to the source of the woody biomass? Transportation capacity and distances are the highest costs in wood utilization pathways and is a critical factor in the financial viability of any biomass utilization project.

Capital Expenditure (CAPEX) - Does the producing of woody biomass-based products facility require significant investments in infrastructure, including building construction, site preparation, and the purchase of specialized machinery?

Operational Expenditure (OPEX) – Does the woody biomass-based industry heavily depend on a consistent supply of feedstock materials (e.g., timber, logs, wood chips, slash)? Feedstock costs are typically a major component of OPEX. Labor costs, including salaries, wages, benefits, and training programs, usually rank second in OPEX considerations after feedstock expenses.

Feedstock Specifications – Can local and regional wood feedstock types be processed meet the specification needs for efficient, high-quality production? Meeting specific feedstock standards, such as sizing and dimensions ensures better processing, higher quality/value end products, and optimized production costs.

Current Use of Technology in the Region – Can expanding or enhancing existing facilities, with the possible use of new biomass utilization processes and equipment, be accomplished in the region? This approach can help reduce capital expenditures, simplify site issues, and alleviate personnel acquisition challenges by leveraging existing infrastructure.

Potential Co-benefits Importance - How important are the co-benefits of biomass utilization pathways to the Greater Boulder Region? Consider aspects such as greenhouse gas emission reduction, carbon sequestration, waste reduction, circular economy contributions, enhanced resource efficiency, sustainable forest management, and reduced wildfire risk by creating value for liability biomass.

Market Potential - Is there a demand in local and regional markets for products derived from biomass utilization? Is the market sufficiently large to absorb additional woody biomass-based products if production is expanded with new or upgraded facilities?

Environmental and Permitting Issues – How difficult are the biomass utilization facilities environmental and permitting challenges, particularly regarding the handling of organic materials, emissions, and sustainability considerations?

Table 2.4. Summary of technology readiness levels.

DEPLOYMENT	9	ACTUAL SYSTEM PROVEN IN OPERATIONAL ENVIRONMENT
	8	SYSTEM COMPLETE AND QUALIFIED
	7	SYSTEM PROTOTYPE DEMONSTRATION IN OPERATIONAL ENVIRONMENT
DEVELOPMENT	6	TECHNOLOGY DEMONSTRATED IN RELEVANT ENVIRONMENT
	5	TECHNOLOGY VALIDATED IN RELEVANT ENVIRONMENT
	4	TECHNOLOGY VALIDATED IN LAB
RESEARCH	3	EXPERIMENTAL PROOF OF CONCEPT
	2	TECHNOLOGY CONCEPT FORMULATED
	1	BASIC PRINCIPLES OBSERVED

Scoring and Ranking Matrix

The scoring and ranking matrix (matric) is the heart of the pathway selection process. It compares and scores for each pathway by the attributes (evaluation criteria) listed above. For each attribute under the pathways shown in Table 2.5, a score of 1 to 5 was assigned, with 5 being the most favorable for that combination of attribute and utilization pathway. For example, lower cost for capital or operational expenditures would be assigned a high score within the range of 1 to 5. Conversely, if a pathway has potentially significant environmental effects and/or permitting challenges a lower score would be assigned. In addition to the evaluation of the candidate technologies and the attributes considered below, an importance factor was applied to each attribute. This importance level of each attribute is a qualitative value based in part on the Boulder Biomass Core Team's knowledge, experience and consideration of the needs for the Boulder Region. An importance ranking of 1 to 5, 5 being of highest importance, is presented in Table 2.5 below. It acts as a multiplier of the 1 to 5 attribute scores, 5 being the best obtainable score per the attribute under consideration. Thus, a pathway could obtain a maximum numerical score of 25 for a given attribute.

The results of the biomass utilization pathways scoring are presented in Table 2.6. Each attribute is further addressed for pathways in Appendix 2.C (Tables 1, 2, and 3). These matrices contain important summaries of how the attributes are addressed. The evaluation of woody biomass utilization pathways ranked twelve options based on a maximum possible score of 210 points, reflecting considerations such as environmental benefits, technical feasibility, market potential, and scalability. Biochar emerged as the highest-ranked pathway, scoring 169 points (80.5%), followed closely by compost/mulch production at 168 points (80.0%) and firewood production using kilns at 164 points (78.1%). Other strong performers included small sawmill operations (157 points, 74.8%) and animal bedding production (152 points, 72.4%). Biomass heat and mass timber pathways also performed moderately well, each scoring just above 69%. Lower-ranked options included air curtain burners and pellets/fuel bricks (both at 68.1%), bio-oil (65.7%), post and pole production (64.3%), and fungal decomposition (63.8%). The relatively close clustering of top scores indicates that multiple pathways could offer viable opportunities for biomass utilization, though pathways like biochar, composting, and firewood present the most immediately promising options based on their combined environmental, economic, and operational benefits.

Table 2.5. Biomass utilization pathways scoring matrix (part 1).

Biomass Utilization Pathways →	Importance*	Biochar		Bio-Oil		Firewood/Kiln		Biomass Heat		Compost/Mulch		Fungal Decomposition	
Biomass Utiliation Attributes ↓		*Score*	*Weighted Score*	*Score*	*Weighted Score*	*Score*	*Weighted Score*	*Score*	*Weighted Score*	*Score*	*Weighted Score*	*Score*	*Weighted Score*
Primary products	4	4	16	2	8	4	16	4	16	5	20	3	12
Feedstock matches	2	5	10	4	8	4	8	5	10	3	6	3	6
Technology considerations and maturity	3	4	12	4	12	5	15	5	15	5	15	3	9
Scalability	5	4	20	2	10	5	25	3	15	5	25	4	20
Transportation of feedstock	5	4	20	4	20	3	15	2	10	3	15	5	25
Capital Expenditure	4	4	16	4	16	5	20	3	12	3	12	0	0
Operational Expenditure	3	3	9	3	9	1	3	3	9	3	9	3	9
Feedstock specifications	2	4	8	4	8	4	8	4	8	5	10	3	6
Current use of technology in region	2	4	8	3	6	5	10	4	8	5	10	4	8
Potential co-benefits importance	5	5	25	4	20	3	15	4	20	4	20	3	15
Martket potential	4	4	16	3	12	5	20	4	16	5	20	3	12
Environmental & permitting issues	3	3	9	3	9	3	9	3	9	2	6	4	12
TOTAL WEIGHTED SCORE POSSIBLE	**210**	--	**169**	--	**138**	--	**164**	--	**148**	--	**168**	--	**134**
	Score Percentage of Total		80.5%		65.7%		78.1%		70.5%		80.0%		63.8%

Table 2.5. Biomass utilization pathways scoring matrix (part 2).

Biomass Utilization Pathways →	Importance*	Animal Bedding		Pellets/Fuel Bricks		Small Sawmill		Mass Timber		Post&Pole		Air Curtain Burner	
Biomass Utiliation Attributes ↓		*Score*	*Weighted Score*	*Score*	*Weighted Score*	*Score*	*Weighted Score*	*Score*	*Weighted Score*	*Score*	*Weighted Score*	*Score*	*Weighted Score*
Primary products	4	4	16	4	16	5	20	5	20	4	16	2	8
Feedstock matches	2	4	8	4	8	3	6	3	6	3	6	3	6
Technology considerations and maturity	3	5	15	4	12	5	15	5	15	5	15	5	15
Scalability	5	4	20	4	20	4	20	4	20	5	25	3	15
Transportation of feedstock	5	3	15	3	15	3	15	2	10	0	0	3	15
Capital Expenditure	4	3	12	2	8	3	12	2	8	3	12	5	20
Operational Expenditure	3	3	9	2	6	3	9	3	9	2	6	3	9
Feedstock specifications	2	3	6	3	6	3	6	3	6	3	6	3	6
Current use of technology in region	2	4	8	2	4	3	6	2	4	3	6	3	6
Potential co-benefits importance	5	3	15	4	20	4	20	4	20	3	15	3	15
Martket potential	4	4	16	4	16	4	16	4	16	4	16	4	16
Environmental & permitting issues	3	4	12	4	12	4	12	4	12	4	12	4	12
TOTAL WEIGHTED SCORE POSSIBLE	**210**	--	**152**	--	**143**	--	**157**	--	**146**	--	**135**	--	**143**
	Score Percentage of Total		72.4%		68.1%		74.8%		69.5%		64.3%		68.1%

Table 2.6. Biomass utilization pathways ranking summary.

Rank	Pathway	Score (out of 210 points)	Score (Percent)
1	Biochar	169	80.5%
2	Compost/Mulch	168	80.0%
3	Firewood/Kiln	164	78.1%
4	Small Sawmill	157	74.8%
5	Animal Bedding	152	72.4%
6	Biomass Heat	148	70.5%
7	Mass Timber	146	69.5%
8	Air Curtain Burner	143	68.1%
9	Pellets/Fuel Bricks	143	68.1%
10	Bio-Oil	138	65.7%
11	Post & Pole	135	64.3%
12	Fungal Decomposition	134	63.8%

Profiles of High-Ranking Woody Biomass Utilization Pathways

The following provides a review of the top three biomass utilization pathways: biochar, compost, and firewood, as identified in Table 2.6 (above). It also describes nine other pathways to offer a range of options for decision-makers and project managers.

Biochar Pathway

Overview

Biochar is a carbon-rich material produced through the pyrolysis of biomass under oxygen-limited conditions, offering benefits in soil enhancement, carbon sequestration, and renewable energy production. Typically derived from forest residues such as logging and thinning waste, branches, and underbrush, biochar is created through slow or fast pyrolysis, with the former maximizing yield and the latter favoring bio-oil production. Various reactor types, including batch kilns, retort systems, and continuous reactors, facilitate biochar production at temperatures between 300 and 700°C. The process consists of drying, devolatilization, and carbonization phases, followed by cooling in an inert atmosphere to prevent oxidation. Post-processing steps such as particle size adjustment, activation, and nutrient enrichment further enhance biochar's effectiveness. Its applications include improving soil health, stabilizing carbon in soil to mitigate climate change, filtering contaminants from wastewater, and supporting renewable energy initiatives (Cambium Carbon, 2022). As an efficient and sustainable solution for forestry residue utilization, biochar is gaining recognition as a key contributor to circular bio-economies and climate resilience strategies.

The production of biochar from woody biomass through pyrolysis involves a series of critical steps, from sourcing the feedstock to delivering the final product to the market. In the pyrolysis process, biomass feedstock is introduced into the pyrolysis system using automated feed mechanisms, which may function in either batch or continuous mode. Thermal decomposition occurs in the absence of oxygen, typically at temperatures between 300-600°C, with slow pyrolysis maximizing biochar yield at approximately 30-50% of the original mass. Precise control over temperature, heating rate, and residence time ensures optimal product quality. After thermal decomposition, the separation of pyrolysis products takes place, where biochar is extracted and cooled to prevent combustion. Additionally, bio-oil and syngas are collected as valuable energy sources or co-products, enhancing the sustainability of the process.

Post-processing steps are crucial for stabilizing biochar and ensuring its safe storage and usability. Cooling and stabilization involve mechanisms such as water sprays, air quenching, or inert gas purging to prevent re-ignition. A curing process follows, allowing the release of volatile organic compounds (VOCs) and ensuring chemical stability. If necessary, biochar undergoes sieving and grinding to optimize its properties for applications such as soil amendment, filtration, or energy use. Pelletization or briquetting is employed to enhance handling and transport efficiency. The packaging phase involves bulk storage in silos or covered piles, with smaller retail packages available for ease of distribution. A structured pyrolysis process ensures sustainable biomass utilization while maximizing resource efficiency and environmental benefits.

In addition to the stationary type of biochar production system, there is growing use of “place-based” biochar production systems which can have value in directly converting liability biomass where it is generated. This alleviates the need to transport the biomass to an off-site centralized facility which can lower the overall cost of the biochar production pathway. The U.S. Forest Service and other researchers, through considerable experimentation, currently recommend eight different methods and equipment that could be used for in-forest biochar production from liability biomass. These are: Air curtain burners (CharBoss®, BurnBoss®, or Tigercat 6050 – described in more detail in the Air Curtain Burner section below), pile burning (hand-made or machine-made), and kilns of various sizes (e.g., Ring of Fire®, Oregon Kiln, or Big Box kiln) (USFS, 2024). These mobile systems employ flame carbonization to produce biochar (and essentially remove the waste wood from the environment). Flame carbonization operates on the principle of top-lit, oxygen limited combustion, where the flame front moves downward through stacked layers of biomass, partially combusting the upper material while pyrolyzing the lower layers. As the top layers combust, they produce a flame and release pyrolysis gases, which in turn create a high-temperature environment. The heat generated drives off volatiles from the unburned wood beneath while limiting oxygen exposure, thereby inducing pyrolysis. As lower layers become charred and combustion threatens to reach them, they are extinguished or smothered - either by adding fresh green wood, soil, or by dousing with water - to preserve the biochar structure and prevent it from oxidizing to ash.

Applications

- *Agriculture and Environmental Remediation* - Biochar enhances soil health by improving structure, water retention, and nutrient availability. It aids in carbon sequestration, regulates pH, and acts as a slow-release fertilizer carrier. In livestock management, it absorbs moisture and odors in stalls and enhances silage preservation. Environmentally, biochar can filter pollutants from water, immobilizes soil contaminants, controls odors, and reduces methane emissions in landfills. It also mitigates stormwater runoff, preventing nutrient leaching (Lehman et.al., 2015).
- *Energy, Industrial and Construction Uses* - Biochar supports renewable energy through syngas production and as a low-emission solid fuel. It is processed into activated carbon for industrial adsorption. In construction, biochar strengthens cement, improves asphalt durability, and enhances insulation in eco-friendly buildings. It is also used in biodegradable plastics and industrial filtration (Lehman et.al., 2015).
- *Animal Husbandry and Household Uses* - As a livestock feed additive, biochar improves digestion and reduces methane emissions. It aids manure treatment and aquaculture

water filtration. Household applications include air purification, personal care (toothpaste, skincare), and deodorization (Lehman et.al., 2015).

- *Climate Mitigation* - Increasingly important in climate mitigation, it qualifies for carbon credit trading, supports reforestation, and reduces wildfire risks.

Feedstock Considerations

Biochar production begins with the sourcing of forest biomass feedstock, which includes residues such as branches, bark, sawmill waste, thinning from forest management, logging slash, deadwood, and occasionally whole trees. These materials are collected from logging and land-clearing operations and transported to a processing facility, where they are chipped or shredded to improve transport and handling efficiency. Preprocessing involves drying the biomass - crucial because freshly harvested wood can contain 30–50% moisture - to reduce the moisture content below 20% for effective pyrolysis. On average, producing one ton of biochar requires approximately four bone-dry tons of biomass or up to eight green tons if the moisture content is around 50%.

The *Biochar Now* facility in Berthoud, CO, which is the principal biochar production facility in the vicinity of Boulder County, currently sources its feedstock primarily from dead trees under stewardship contracts, wooden pallets, and biomass removed from regional reservoirs.[4]

Economic Considerations

Biochar production costs vary based on feedstock procurement, transportation, processing, and market dynamics. The estimated feedstock costs can range from $30 to $40 per bone dry ton (BDT) delivered. Preprocessing, including drying and chipping, adds further costs depending on equipment and energy prices. The pyrolysis process itself has a production cost ranging from $0.14 to $3.66 per pound, influenced by reactor design and operational efficiency.

The biochar market price varies widely, with bulk biochar averaging $243 per cubic yard, while retail prices in small bags can reach $1,143 per cubic yard. Logistics costs also impact pricing, with transportation up to 500 miles increasing costs to $540 per ton. These prices are based on current information from one of the largest producers in the United States (based in California) and can be used to gauge how much biochar purchased in bulk is worth. That pricing is reported for truckloads in Table 2.7.[5]

Table 2.7. Example biochar prices.

Full Truckload Size – 90+ Cubic Yards (CY)/15 tons	1 to 11 Truckloads	12 to 100 Truckloads	100+ Truckloads
Purchased at Facility	$50/CY, $300/ton	$40/CY, $240/ton	$35/CY, $210/ton
Delivery up to 200 miles	$60/CY, $360/ton	$50/CY, $300/ton	$45/CY, $270/ton
Delivery up to 300 miles	$70/CY, $420/ton	$60/CY, $360/ton	$55/CY, $330/ton
Delivery up to 500 miles	$90/CY, $540/ton	$80/CY, $480/ton	$75/CY, $450/ton
Delivery up to 700 miles	$100/CY, $600/ton	$90/CY, $540/ton	$85/CY, $510/ton

[4] Personal communication with James Gaspard, CEO, Biochar Now.

[5] Personal communication with Josiah Hunter, CEO, Pacific Biochar.

Biochar production from forest wood not only offers environmental benefits but also presents economic opportunities through carbon dioxide removal (CDR) credits. The revenue potential from these credits depends on several factors, including the amount of CO_2 sequestered per ton of biochar and the prevailing market price for carbon credits.

The amount of CO_2 sequestered per ton of biochar varies based on factors such as feedstock type, production methods, and carbon content. According to data from Puro Earth (puro. Earth), biochar derived from wood feedstocks can sequester between 2.57 to 3.26 tons of CO_2 per ton of biochar produced, with an average sequestration factor of 2.83 (Biochar International, 2023).

The value of biochar carbon credits has seen significant fluctuations, influenced by factors such as demand, certification standards, and market dynamics. Notable data include:

- Puro.Earth CORCHAR Index - As of January 2025, the CORCHAR index price was approximately $151 USD per ton of CO_2 equivalent (PuroEarth, 2025).
- Other Biochar Credit Price Index - Recent Averages - In 2024, prices for biochar carbon credits averaged $190 USD per ton of CO_2 equivalent.
- Potential Carbon Credits Revenue - One ton of biochar × 2.83 tons CO_2/ton × $190/ton CO_2 (the average between the two referenced prices) = $537.70.

When entering the carbon credit market, several key considerations must be considered. Certification costs can significantly impact net revenue, as obtaining accreditation for carbon credits involves expenses related to compliance, verification, and ongoing monitoring. Additionally, market variability presents a challenge, as carbon credit prices are subject to fluctuations based on demand, certification standards, and broader economic conditions.

Other challenges impact the economic viability and scalability of biochar production. High transportation and preprocessing costs can make feedstock sourcing expensive, particularly when handling wet biomass that requires drying. The cost of pyrolysis equipment varies significantly, and advanced separation technologies for biochar, bio-oil, and syngas require capital investment. Additionally, obtaining certification for carbon credits involves costs that may reduce net revenue. Market variability in biochar demand and carbon credit pricing further complicates financial planning. Local policies, permitting, and infrastructure limitations can also pose barriers to large-scale biochar implementation.

Environmental Considerations

Biochar production has significant environmental benefits, including carbon sequestration, soil enhancement, and waste biomass utilization. By converting waste wood into a stable form of carbon, biochar reduces greenhouse gas emissions and mitigates wildfire risks by removing excess biomass from forests. It also enhances soil fertility and water retention, reducing the need for chemical fertilizers. However, sustainability concerns arise from energy consumption in processing, emissions from transportation, and potential land-use changes affecting feedstock availability. Optimizing pyrolysis efficiency and utilizing renewable energy sources can mitigate some of these impacts (Lehman et.al., 2015).

Infrastructure and Technology Considerations

Establishing a centralized biochar production facility requires infrastructure for biomass collection, preprocessing, pyrolysis, post-processing, storage, and distribution. Facilities must include equipment for drying, chipping, and feeding biomass into reactors, as well as cooling and stabilization systems to prevent biochar re-ignition. Storage solutions, such as silos or covered bulk areas, are essential to maintain biochar quality. Efficient transportation networks are also necessary to ensure cost-effective distribution to end-users.

Also, as described above, there are potential in-forest “place-based” mobile biochar production systems which can be, and have been used, in the Boulder Region.

Currently there is an operating wood waste to biochar facility near Boulder County in Berthoud, CO. The *Biochar Now* facility in Berthoud, CO, currently processes up to 18 tons of biomass daily, with stated plans to expand to 700-800 tons per day depending on financing (and feedstock availability), highlighting the scale of infrastructure required for commercial biochar production. To achieve these quantities, *Biochar Now* must use waste biomass from forests, agriculture, urban, and industrial sources.

Even though this facility was not included in Table 2.1 (above) as it was the only commercial biochar production facility in the 50-mile radius, cost information is added nonetheless:

- One-Way Distance (miles): 41.4
- Estimated Delivery Cost ($): 691.60
- Cost per Ton Delivered ($/ton): 34.58

In addition to the Biochar Now facility, Boulder County awarded funds to High Plains Biochar (Laporte, CO) to deploy small-scale biochar production kilns at 5 to 15 farms across Boulder County.[6] Although these units will be at farmland locations and likely using both forest and agricultural sourced biomass, it is another step in increasing infrastructure in the Boulder County region.

Summary of Benefits and Drawbacks

Benefits

- *Carbon Sequestration:* Converts unstable biomass carbon into more stable biochar, reducing greenhouse gas emissions.
- *Waste Utilization:* Provides a productive outlet for excess, hazardous, or low-value forest residues.
- *Wildfire Mitigation:* Removes flammable material from forests, reducing fire risk.

Drawbacks

- *Permitting Complexity:* Emissions and site operations may trigger air quality and land-use permitting.
- *Feedstock Logistics:* Collecting and transporting dispersed forest residues can be costly and labor-intensive.
- *Variable Quality:* Heterogeneous feedstock can produce inconsistent biochar characteristics.

[6] https://bouldercounty.gov/news/boulder-county-announces-2024-climate-innovation-fund-recipients/

Composting

Overview

Composting forest-sourced wood waste is a controlled biological process that breaks down woody organic materials into a stable, nutrient-rich humus-like substance. Given the high lignin and cellulose content in wood waste, successful composting depends on maintaining a proper balance of carbon and nitrogen, ensuring adequate moisture, providing sufficient aeration, and fostering microbial activity. Managing these factors is essential to accelerate decomposition and produce high-quality compost.

The wood composting process begins with collecting and sorting suitable wood waste materials, including wood chips, sawmill residues, bark, sawdust, small branches, leaves, and pine needles. However, chemically treated, painted, or engineered wood products should be excluded due to contamination risks and slow decomposition rates. Preprocessing, such as chipping and shredding, is necessary to reduce particle size and increase microbial colonization. Since woody materials have a high carbon-to-nitrogen (C:N) ratio (300:1 to 500:1), nitrogen-rich materials such as manure or green waste must be added to achieve the ideal ratio of 25:1 to 30:1. Maintaining moisture between 40% and 60% is crucial to sustain microbial activity and prevent anaerobic conditions.

Various composting methods are used depending on the scale of operations and resource availability. Windrow composting, where long piles are periodically turned, takes six to twelve months. Aerated static pile (ASP) composting accelerates the process to three to six months by supplying forced air. Industrial-scale in-vessel composting, which occurs in enclosed systems, produces compost in six to eight weeks by precisely controlling temperature, moisture, and aeration. Passive pile composting is the simplest method, where wood waste is left to decompose naturally over one to two years, requiring minimal labor but taking longer to complete.

Several key factors must be monitored to ensure effective composting. Temperatures between 131°F and 160°F promote pathogen destruction and organic matter breakdown. Oxygen levels must be maintained through turning, forced aeration, or passive airflow to support microbial activity. Moisture should be carefully managed, and adjustments made if it is too high or too low. To further enhance microbial activity, composters may introduce fungi-rich inoculants such as white-rot fungi or apply compost teas to boost microbial populations and improve compost quality.

After active composting, the material undergoes a four to eight-week curing phase, where beneficial microbes stabilize the organic matter and reduce harmful compounds. The compost is then screened using a sieve (3/8 to 1/2 inch) to remove large undecomposed wood particles, ensuring a fine, uniform final product. Any oversized particles can be reused in new compost batches as bulking agents or applied separately as mulch.

Finished compost offers multiple benefits across agricultural, economic, and environmental dimensions. In terms of applications, compost improves soil structure, enhances moisture retention, and provides a slow-release source of macronutrients and micronutrients, making it suitable for use in agriculture, landscaping, erosion control, and land reclamation.

Economically, compost reduces the need for synthetic fertilizers, lowers irrigation costs through improved water retention, and provides a marketable product from organic waste streams, supporting local waste diversion efforts. From a carbon sequestration perspective, compost contributes to long-term soil organic matter buildup, stabilizes organic carbon in soils, and reduces methane emissions by diverting biodegradable materials from landfills (Brown, 2015)

Application

Compost has a wide range of applications across agricultural, environmental, and urban settings, each leveraging its ability to enhance soil quality, support plant growth, and improve ecosystem health. In agriculture, compost is used as a soil amendment to boost soil organic matter, increase nutrient availability, and improve water retention, reducing the need for synthetic fertilizers and irrigation. This makes it particularly valuable in regenerative and organic farming systems. In land restoration and reclamation projects, compost is applied to degraded soils to promote vegetation establishment, stabilize soils, and reduce erosion, making it a key tool for rehabilitating mine lands, construction sites, and wildfire-impacted areas. Compost is also commonly used in landscaping and urban green spaces to support healthy lawns, gardens, and tree plantings by improving soil structure and fertility.

In stormwater management, compost-based products like compost blankets and filter socks are used to reduce runoff, filter pollutants, and control sediment on construction sites and along roadways. Compost's ability to support microbial life also makes it valuable for bioremediation efforts, helping break down contaminants in soils and water. Additionally, compost is increasingly used in carbon farming initiatives, where its application to rangelands and croplands can help sequester atmospheric carbon, contributing to climate change mitigation goals. Each of these applications underscores compost's versatility as an environmentally beneficial product that supports soil health, water conservation, pollution control, and greenhouse gas reduction.

Feedstock Considerations

Woody biomass materials such as tree trimmings, brush, wood chips, mulch, sawdust, wood shavings, and bark waste are commonly used in composting when properly processed. Tree trimmings and brush provide a rich carbon source but must be chipped or ground to enhance decomposition. Wood chips and mulch improve pile aeration and structure, though their high lignin content slows breakdown, requiring mixing with nitrogen-rich materials. Sawdust and wood shavings are fine and absorbent, aiding moisture control but necessitating balance with high-nitrogen inputs to avoid nutrient deficiencies. Bark waste, while slow to decompose due to its dense and tannin-rich composition, adds beneficial structure and porosity when shredded and properly incorporated into the composting matrix.

Woody biomass can be used in compost, but it should generally make up no more than 20-30% of the total compost mix by volume. This is because woody materials, such as branches, wood chips, and sawdust, have a high carbon-to-nitrogen (C:N) ratio and decompose much more slowly than other organic materials.

To ensure proper composting with forest wood included:

- Balance carbon-rich and nitrogen-rich materials - Woody biomass is high in carbon, so the addition of nitrogen-rich materials (like food scraps, manure, or grass clippings) is needed to accelerate decomposition.
- Shred or chip the wood - smaller pieces break down faster.
- Monitor moisture and aeration - woody materials can dry out compost, so maintaining adequate moisture is important.
- If too much woody biomass is added, it can slow down the composting process and lead to poor decomposition. However, if managed properly, it can improve aeration and create a well-structured compost.

Economic Considerations

Composting woody biomass into marketable compost involves a wide range of costs depending on material sourcing, preprocessing, composting method, and refinement steps (Table 2.8). Sourcing wood waste may cost between $0 - $50 per ton, with potential savings if materials come from forestry operations but added costs when transport is required. Sorting to remove contaminants, particularly from urban wood waste streams, adds another $10 - $25 per ton. Transportation to a composting facility typically ranges from $5 - $30 per ton. Preprocessing, such as chipping and shredding, varies significantly depending on equipment type and fuel costs, ranging from $50 - $200 per hour, with industrial chipper purchases exceeding $100,000. Supplementing nitrogen (e.g., with manure or food waste) adds another $20–$100 per ton, and moisture control measures cost $5–$25 per ton. Labor expenses for preprocessing typically run $15–$30 per hour.

The choice of composting method - windrow, aerated static pile, or passive pile - substantially affects total costs. Windrow composting involves land preparation ($1,000 -$10,000), equipment purchases (up to $200,000 for turners), and ongoing fuel and labor costs. Aerated static piles require upfront investments in aeration systems ($10,000 -$100,000) but reduce labor needs. Passive pile composting has minimal equipment costs but entails longer processing times, tying up land for up to two years. Monitoring processes - such as tracking temperature, oxygen levels, and moisture - add $10 - $50 per ton, depending on the complexity of the system. Curing and refinement steps, including space rental and equipment for screening and sorting compost, contribute an additional $10 - $60 per ton. Altogether, the total estimated cost to produce one ton of finished compost ranges from approximately $75 to $535, depending heavily on operational scale, method chosen, and feedstock characteristics.

On the revenue side, high-quality compost can be sold at prices typically ranging from $20 to $50 per cubic yard at the wholesale level, and up to $75 or more per cubic yard at the retail level, depending on the compost's nutrient value, certification (e.g., OMRI listing for organic farming), and market demand. Since one ton of compost roughly equates to about 1.3 to 1.5 cubic yards (depending on moisture content and density), gross revenue per ton could range from approximately $30 to $110, or higher in specialty markets. Thus, while composting can generate modest revenue streams, especially when markets are well-developed and product quality is high, it typically does not fully offset all production costs without subsidies, tipping fees for green waste intake, or value-added markets like landscaping, agriculture, or reclamation projects. Successful compost operations often rely on a combination of sales revenue, waste disposal fees, and partnerships with municipalities, agriculture, or land restoration projects to maintain financial viability.

To summarize key cost factors and optimization strategies:

- Scale Matters **-** Larger operations benefit from economies of scale, reducing per-ton costs.
- Equipment Selection **-** Renting vs. buying equipment depends on long-term usage.
- Composting Method **-** Passive pile composting is cheapest but slowest; in-vessel composting is fastest but highest in cost.
- Labor Efficiency **-** Automated systems reduce labor costs but require higher upfront investment.

Table 2.8. Composting cost and price.

Expense Item	Estimated Cost Range	Notes
Materials Selection Costs		
Wood Waste Sourcing	$0–$50 per ton	May be free if sourced from forestry waste but can incur costs when transported.
Sorting & Contamination Removal	$10–$25 per ton	Labor cost to remove treated/painted wood and other contaminants possible in urban sourced woody green waste.
Transport Costs	$5–$30 per ton	Based on distance from source to facility and fuel costs.
Preprocessing Costs		
Chipping & Shredding	$50–$200 per hour	It depends on chipper/shredder type, fuel, and labor costs.
Equipment Purchase (Chipper/Shredder)	$10,000–$100,000+	Higher costs for large-scale industrial machines.
Nitrogen Supplementation	$20–$100 per ton	Manure, food scraps, or green waste costs.
Moisture Control (Water Supply, Bulking Agents)	$5–$25 per ton	Cost of adding water or dry bulking agents (wood chips, straw).
Labor for Processing	$15–$30 per hour per worker	Based on wages and required workforce.
Windrow Composting		
Land Preparation	$1,000–$10,000	Grading and setup of composting area.
Turning Equipment (Tractors/Windrow Turners)	$20,000–$200,000	Purchase or rental costs.
Fuel & Maintenance	$10–$50 per ton	Diesel, electricity, and repair costs.
Labor for Turning	$5–$20 per ton	Based on frequency of turning.
Aerated Static Pile Composting		
Aeration System (Pipes, Blowers, Controls)	$10,000–$100,000	Capital investment for forced aeration.
Electricity for Aeration	$1–$10 per ton	Powering blowers for oxygen circulation.
Labor (Lower than Windrow)	$2–$10 per ton	Reduced turning frequency saves labor costs.
Passive Pile Composting		
Land Use Costs	$500–$5,000 per acre	Minimal infrastructure needed.
Lower Equipment Costs	$0–$10 per ton	No aeration or turning needed.
Longer Processing Time	Indirect cost	Ties up land for 1–2 years.
Process Monitoring Costs		
Temperature Sensors	$50–$500 per unit	Needed for tracking microbial activity.
Oxygen Monitoring	$100–$1,000	Sensors or manual testing costs.
Moisture Control Costs	$5–$25 per ton	Water application or drying agent expenses.
Microbial Inoculants (Fungal Additives, Compost Tea)	$50–$500 per application	Optional but speeds decomposition.

Expense Item	Estimated Cost Range	Notes
Curing and Refinement Costs		
Curing Space Rental/Land Use	$500–$5,000 per acre	Space needed for 4–8 weeks.
Screening Equipment	$5,000–$50,000	Machinery for refining compost texture.
Labor for Screening & Sorting	$10–$30 per ton	Manual or machine-assisted process.
Reuse of Oversized Material	Minimal cost	Can be reintroduced as bulking agents.
Total Estimated Costs Per Ton of Compost		
Material Selection & Transport	$15–$75	
Preprocessing	$30–$150	
Composting (Varies by Method)	$10–$200	
Monitoring & Quality Control	$10–$50	
Curing & Refinement	$10–$60	
Total Cost Per Ton	$75–$535	

Environmental Considerations

Compost provides a wide range of environmental benefits that make it a valuable tool for sustainable land management and climate resilience. By returning organic material to the soil, compost improves soil structure, enhances water retention, and promotes healthy microbial activity, all of which supports plant growth and reduces the need for chemical fertilizers. Applying compost helps sequester carbon by increasing soil organic matter, thereby playing a role in mitigating climate change. Additionally, composting organic waste reduces the volume of material sent to landfills, which in turn lowers methane emissions - a potent greenhouse gas - generated from anaerobic decomposition in landfill environments. Compost also helps prevent soil erosion by improving soil aggregation and stability, and it can filter pollutants, reducing nutrient runoff into waterways and protecting water quality. Overall, composting transforms organic waste from a liability into a critical environmental asset that enhances soil health, reduces emissions, and supports ecosystem services.

However, composting also poses some environmental challenges that require effective management. Air quality concerns include the emission of odors, greenhouse gases like methane and nitrous oxide, and the release of airborne particulates and bioaerosols, which can affect both workers and nearby communities. If compost piles are not properly aerated, anaerobic conditions can develop, intensifying these impacts. There are methods to control odors and air emissions from composting operations such as covered piles or in-vessel composting, forced aeration or composting in an enclosed structure with biofilters, activated carbon filters, or chemical scrubbers, as well as best management practices which include mixing in of wood chips (to reduce odors) and optimizing composting conditions to ensure aerobic decomposition.

Water and soil quality must also be safeguarded. Leachate and stormwater runoff can transport nutrients, pathogens, and contaminants to surface and groundwater, necessitating well-designed drainage and containment systems. Robust feedstock screening can reduce the introduction of persistent chemicals, heavy metals, or plastics into the compost, which negatively affect soil health and the usability of the final product.

Additional considerations include the attraction of pests, potential pathogen survival from insufficient thermophilic conditions, and negative community impacts such as noise, odor, and visual disruption - especially when facilities are sited near residential areas. Ensuring regulatory compliance, maintaining operational controls, and implementing best management practices are essential for minimizing environmental risks while maximizing the sustainability benefits of composting.

Composting facilities are governed by environmental regulations aimed at safeguarding public health and the environment, with specific attention to water quality, air quality, and overall environmental integrity. In Colorado, the Colorado Department of Public Health and Environment (CDPHE) regulates these facilities under the Solid Waste Regulations, which classify operations into three categories—Class I, II, and III. Recent revisions to these regulations are intended to streamline the permitting process while reinforcing environmental protections, supporting the state's broader organics diversion and sustainability goals. Additionally, in Boulder County, commercial composting facilities must secure a Special Use Permit from the Community Planning & Permitting Department, which requires detailed site design, engineering and operational reviews, traffic assessments, and environmental impact analyses, with all necessary mitigation measures implemented before approval.

Infrastructure and Technical Considerations

Composting at substantive commercial level occurs in the region around Boulder County at the A1 Organics facilities in Eaton, Keenesburg, and most recently Sheridan, CO. As the principal composter of organic waste in the region, A1 Organics requires a substantial amount of wood waste, both from urban and rural lands. A1 Organics can receive wood waste in all forms, and will accept branches, limbs, whole logs, leaves and needles, and brush from liability biomass management activities.

The Keenesburg composting facility is considered by A1 Organics as a potential prime receiver of liability biomass and has been taking in forest biomass from the Boulder County sort yards (i.e., the Nederland facility).[7] The facility does charge a tipping fee which can be as high as $15 per cubic yard of waste delivered to site. That is in addition to the removal, processing, and transportation costs incurred by the liability biomass generator.

The $15 per cubic yard tipping fee is affected by the state in which the wood is received (i.e., the density of the material). Chipped wood in the Boulder Region that is fresh, and green is in the range of 500 pounds per cubic yard, with dry chips coming in at 250 to 350 pounds per cubic yard. Whole pine logs, recently cut, can range from 1,500 to 2,500 pounds per cubic yard. Clearly, the state of the liability wood waste affects the total cost of moving liability biomass to the composting.

Although a more costly alternative, discussions with A1 Organics management indicate that the Keenesburg facility could potentially take all the liability biomass that could be generated within Boulder County according to the estimates presented in Chapter 1, especially all the liability biomass not managed directly by the U.S. Forest Service. The facility rotates approximately 400,000 cubic yards of composting materials annually,[8] which could equate to a need of 100,000 cubic yards of green wood chips, which weighing in at a conservative 1,000 pounds per cubic could be 50,000 tons per year.

Boulder County is also conducting technology pathway feasibility and siting study for a potential compost facility within Boulder County. As of February 2025, the current study underway has

[7] Personal communications with Travis Bahnsen, President, A1 Organics

[8] Rotating refers to the practice of systematically turning, moving, or cycling composting materials to ensure proper decomposition and nutrient distribution.

recommended that a new centralized composting facility in the form of turning windrows and aerated static piles is likely the best composting approach in Boulder County. Composting can take all forms of organic waste materials generated in the County, including liability biomass in appropriate amounts. The study has now moved into site identification, and financial and end market analyses.

The advantages of incorporating forest wood waste into composting include promotion of sustainable waste management by diverting organic materials from landfills and burn piles. Wood waste enhances compost structure by improving aeration and preventing compaction, thereby supporting aerobic microbial activity.

The slow decomposition of wood waste presents a major challenge due to its high lignin and cellulose content. Without nitrogen supplementation or microbial inoculation, breakdown is significantly delayed. Moisture management is also critical, as dry, coarse materials can lose moisture too quickly, while fine sawdust may absorb too much, leading to anaerobic conditions. Contaminants, such as treated or painted wood, can introduce harmful chemicals into compost. Improperly managed wood piles may become habitats for pests, fungi, or pathogens. Additionally, processing wood waste requires specialized equipment, increasing operational costs. Some types of wood, like pine needles, can acidify compost, requiring pH adjustments for optimal microbial activity.

To optimize the composting of wood waste, proper particle size management is essential. Chipping and shredding materials to one to three inches enhance microbial colonization and decomposition. Fine materials like sawdust should be mixed with coarser materials to prevent compaction. Since woody materials are carbon-rich, nitrogen supplementation is necessary, typically by mixing with manure, green waste, or food scraps in a three-to-one carbon-to-nitrogen ratio. Moisture control between 40% and 60% is vital for microbial activity, and excess moisture should be managed by improving aeration or adding dry bulking agents. Aeration should be maintained through regular turning or forced airflow to prevent anaerobic conditions. Monitoring temperature and pH ensures effective decomposition, with compost temperatures maintained at 131–160°F to destroy pathogens. Acidic compost can be balanced using alkaline materials like lime or biochar.

Summary of Benefits and Drawbacks

Benefits

- *Scalability*: Composting is highly scalable, from small-scale household systems to large industrial facilities, but the level of scalability depends on waste availability, infrastructure, public participation, and market demand for finished compost. Large scale composting requires significant infrastructure, including large processing facilities, trucks for waste collection, and advanced monitoring equipment. Composting technologies like turned and aerated static piles enable processing at a variety of scales.
- *Waste Diversion:* Reduces the amount of organic material sent to landfills, lowering methane emissions.
- *Soil Health Improvement:* Enhances soil structure, water retention, and nutrient content through increased organic matter.
- *Carbon Sequestration:* Helps store carbon in soils, contributing to climate change mitigation efforts.
- *Erosion Control:* Improves soil stability and aggregation, helping to reduce erosion on vulnerable landscapes.

- *Pollution Reduction:* Filters and retains nutrients, minimizing nutrient runoff into waterways and protecting water quality.
- *Support for Local Agriculture:* Produces a valuable soil amendment for farmers, landscapers, and restoration projects.
- *Market Potential:* Compost can be sold for landscaping, agriculture, reclamation, and retail gardening, creating a modest revenue stream.
- *Lower Air Emissions Compared to Burning:* Avoids air quality impacts associated with open pile burning or combustion.

Drawbacks

- *High Preprocessing Costs:* Woody material requires chipping or shredding before composting, adding significant labor and equipment costs.
- *Nitrogen Supplementation Required:* Wood is carbon-rich but nitrogen-poor, so additional green materials (e.g., manure, food waste) must be mixed to maintain proper decomposition rates.
- *Longer Processing Time:* Woody biomass decomposes more slowly than food or green waste, requiring longer composting and curing periods.
- *Land Use Requirements:* Large areas may be needed for windrows, aerated piles, or passive piles, tying up land resources for extended periods.
- *Variable Market Prices:* Compost prices can be modest and may not fully cover operational costs without tipping fees or subsidies.
- *Contamination Risks:* Urban-sourced woody waste can contain treated or painted wood, requiring additional labor for sorting and contaminant removal.
- *Water Needs:* Moisture must be carefully managed, requiring water input during dry periods, which can add operational complexity.
- *Regulatory Compliance:* Composting facilities must often meet permitting requirements for water runoff, air emissions, and operational standards, adding administrative and compliance costs.

Fire/Fuel Wood Pathway

Overview

The commercial firewood production process is a structured and mechanized operation focused on maximizing efficiency, sustainability, and product quality. It encompasses a series of coordinated stages from raw material acquisition to final distribution, leveraging specialized equipment and best practices in forestry management, processing, drying, and logistics to deliver consistent and market-ready product.

The process begins with sourcing and transportation, where wood is obtained from logging residues, forest thinning, salvage logging, and short-rotation coppicing. Efficient transportation methods - such as log trucks, biomass haulers, and mobile chipping units - are employed to optimize logistics and minimize environmental impact. Upon delivery, the reception and storage phase involve sorting logs by species, size, and moisture content to streamline downstream processing. Storage practices, including open-air piles and covered storage areas, help preserve wood quality and support consistent drying.

In the cutting and splitting stage, logs are processed into firewood-length sections using chainsaws or mechanized firewood processors. Hydraulic log splitters with varying wedge designs enhance production speed and ensure uniform product sizing. The drying process is critical for combustion efficiency and emission reduction. Firewood is dried either naturally - via ventilation and sunlight over several months - or artificially through kiln drying, which uses controlled heat and airflow to reduce moisture content to below 20% within days.

Following drying, the cleaning and quality control stage removes bark and debris using tumblers or disc screeners, while quality is verified through moisture testing and visual inspection to ensure compliance with market standards. Packaging and storage methods vary by market channel, with firewood offered in bulk, palletized, or bagged formats. Automation in packaging systems contributes to operational efficiency and consistency. Finally, distribution and sales are carried out through wholesale (e.g., hotels, restaurants), retail (e.g., supermarkets, hardware stores), and direct-to-consumer channels, including online platforms and subscription models. For international markets, compliance with phytosanitary regulations is mandatory to prevent pest and disease transmission.

Application

Firewood has a range of practical applications that have remained important both historically and today, particularly in rural, forested, and colder regions such as Boulder County. Its most common use is as a residential heating source, where it provides warmth through fireplaces, wood stoves, and modern high-efficiency wood-burning appliances. In many areas, especially where access to natural gas or electricity is limited or costly, firewood remains a reliable and affordable form of home heating. Another key application is in outdoor recreation: firewood is widely used for campfires, cooking in fire pits, and heating in cabins and campsites, providing not only utility but also a cultural and social experience.

Firewood also plays a role in emergency preparedness. During power outages caused by storms, wildfires, or other disasters, wood stoves and fireplaces fueled by firewood offer a critical, off-grid heat source. In agricultural and homestead settings, firewood is sometimes used for heating greenhouses, workshops, or small outbuildings, extending its utility beyond just homes.

Additionally, artisanal uses of firewood - such as wood-fired ovens for baking bread or pizzas and traditional smoking of meats - are valued for the distinctive flavors and cultural practices they preserve.

However, while firewood offers versatile and accessible applications, its use must balance with environmental and health considerations. Older wood-burning technologies can emit substantial particulate matter and contribute to local air quality problems, prompting the need for cleaner-burning certified stoves and responsible firewood sourcing and burning practices. In modern biomass strategies, firewood remains a practical option for using lower-grade woody biomass but often fits best at smaller scales or when paired with improved technologies to reduce emissions and maximize efficiency.

Feedstock Considerations

Roundwood logs are the primary and most desirable form of woody biomass used in firewood production. These logs are typically sourced from whole-tree harvesting operations and range from approximately 6.5 to 20 feet in length, with diameters between 4 and 16 inches. Their straight form and structural integrity make them well-suited for mechanical processing, including cutting and splitting.

Forest thinning and logging residues, which include tops and large-diameter branches left behind after forest management and timber harvests, can also be utilized in firewood production. These materials must be carefully sorted to exclude unsuitable or excessively irregular pieces that could hinder processing efficiency or product uniformity.

Salvage wood from dead or damaged trees, such as those affected by storm events, insect outbreaks, or forest fires, can serve as a viable input for firewood production if the wood remains structurally sound. While some decay is acceptable, heavily deteriorated or overly brittle material is unsuitable. Salvage wood is especially relevant from site undergoing forest health treatments, where removal of compromised trees is necessary to reduce fire risk and improve ecosystem resilience.

Economic Considerations

Producing and selling firewood involves a wide range of capital, operational, and logistical costs across multiple stages (Table 2.9). Sourcing and transportation costs include the initial investment in harvesting equipment, ranging from $600,000 to $2,000,000, with operational and maintenance costs between $120 and $650 per hour depending on machinery type. Labor for harvesting typically costs $20–$50 per hour per worker, and transportation expenses vary widely depending on distance and fuel costs, typically $5 – $20 per ton-mile.

Processing costs are substantial, requiring about $389,000 for facility setup, including firewood processing equipment ($171,000), site preparation ($88,000), and project management and permitting ($95,000). Machine operation for cutting and splitting firewood typically costs $50 – $150 per hour, with additional annual maintenance costs of $5,000 – $20,000.

For drying and seasoning, installing a kiln system requires about $800,000 in capital investment, with kiln operation costs estimated at $50 – $300 per cord. Alternatively, air drying presents lower capital costs but requires longer processing times and careful yard management, costing about $10 – $30 per cord.

Table 2.9 - Firewood production costs.

Cost Component	Estimated Cost	Notes
Sourcing and Transportation		
Harvesting Equipment	$600,000 - $2,000,000 (capital investment)	Includes logging machinery for cutting and processing.
Harvesting Operation & Maintenance	$120 - $650 per hour	Cost depends on equipment type and utilization.
Transportation	Varies based on distance and fuel costs	Dependent on location and logistical factors.
Processing		
Capital Investment for Facility	$389,000.00	Covers equipment, site preparation, and project management.
Firewood Processing Equipment	$171,000.00	Includes firewood processors, kilns, bundling machines, and log transfer systems.
Site Preparation & Building Costs	$88,000.00	Covers footings, shell building, and installation.
Project Management & Permits	$95,000.00	Includes licenses, engineering, and regulatory compliance.
Drying and Seasoning		
Kiln Drying System	$800,000 (installation and equipment)	Provides rapid moisture reduction for higher efficiency.
Air Drying	Lower capital cost, but requires longer time	Requires space for proper stacking and seasoning.
Packaging and Distribution		
Firewood Bundle Wrapping Machine	$1,500.00	Used for packaging firewood for retail sale.
Transportation and Distribution	Varies	Includes fuel, vehicle maintenance, and labor.
Waste Management & Environment		
Waste Management	Varies	Costs depend on handling sawdust, chips, and by-product sales.
Environmental Compliance	Varies	Covers permits, sustainability certifications, and impact assessments.
Sourcing and Transportation		
Harvesting Labor	$20 - $50 per hour per worker	Costs depend on region, workforce size, and skill level.
Equipment Fuel & Maintenance	$120 - $650 per hour	Includes fuel, repairs, and parts replacement for harvest machinery.
Log Transportation	$5 - $20 per ton-mile	Dependent on distance, fuel prices, and truck capacity.
Machinery		
Machine Operation (Firewood Processor)	$50 - $150 per hour	Covers fuel, electricity, and routine maintenance.
Labor for Cutting & Splitting	$15 - $30 per hour per worker	Varies by facility size and automation level.

Cost Component	Estimated Cost	Notes
Equipment Maintenance	$5,000 - $20,000 annually	Covers wear and tear, repairs, and replacement parts.
Kiln or Air Drying		
Kiln Operation (Fuel, Electricity, Labor)	$50 - $300 per cord	Higher cost than air drying but provides faster turnaround.
Air Drying Yard Management	$10 - $30 per cord	Includes stacking, monitoring, and space management.
Packaging and Distribution		
Labor for Packaging	$12 - $25 per hour per worker	Costs vary based on automation level.
Bundling and Wrapping Materials	$0.50 - $2 per bundle	Includes plastic wrap, mesh bags, and labeling.
Transportation & Delivery	$0.50 - $2 per mile	Dependent on fuel costs, truck size, and route distance.
Waste Management & Environment		
Waste Disposal or Processing	$5 - $50 per ton	Costs vary if selling sawdust/chips vs. landfill disposal.
Environmental Permits & Compliance	$1,000 - $10,000 annually	Includes emissions monitoring, sustainability certifications, and regulatory compliance.
Firewood Prices		
Firewood per cord	$300 to $400	Prices vary per vendor contacted and is subject to seasonality.

Packaging and distribution involve purchasing a bundle wrapping machine (~$1,500) and incurring labor costs of $12 – $25 per hour for packaging. Bundling materials add an extra $0.50 – $2 per bundle, and transportation and delivery costs range from $0.50 – $2 per mile.

Waste management and environmental compliance must also be accounted for, with disposal or processing costs for by-products (e.g., sawdust and chips) ranging from $5–$50 per ton. Annual environmental compliance costs, including permits and certifications, are estimated between $1,000 and $10,000.

Finally, firewood market prices typically range from $300 to $400 per cord, subject to seasonal variations and local demand. Successful operations must balance these substantial capital and operating costs with market dynamics, regulatory requirements, and the seasonal nature of firewood demand to maintain profitability.

On the revenue side, firewood typically sells for between $300 and $400 per cord in local and regional markets, with premium kiln-dried firewood sometimes commanding even higher prices - up to $450 per cord in certain retail markets. Firewood can also be sold in smaller bundles (typically 0.75 – 1.0 cubic foot per bundle) at retail outlets such as grocery stores, gas stations, and campgrounds, with retail bundle prices ranging from $5 to $10 per bundle. A single cord of wood can produce approximately 85 – 100 retail-sized bundles, potentially generating $425 to $1,000 in gross revenue per cord if sold in the retail market rather than bulk. Therefore, retail firewood sales offer significantly higher revenue per cord compared to wholesale, but they require additional labor, packaging, marketing, and distribution logistics.

In consideration of possible firewood markets in Boulder County, a cord of firewood is 128 cubic feet of tightly stacked wood (4' x 4' x 8'). The conversion from green tons (or dry tons) to cords depends on the species and moisture content of the wood. However, an approximating rule of thumb is one green ton of forest wood yields 1.5 to 2 cords. To convert dry tons of forest wood to cords, an approximate metric is one dry ton yields 1 to 1.6 cords.

Anecdotal evidence indicates that individual households in similar climates to Boulder County consume between 2.5 to 4 cords of firewood per winter season. Assuming an average consumption of 3.25 cords per household and considering that 1 cord of seasoned forest wood weighs approximately 1.3 tons, each household would use about 4.3 tons of firewood annually.

Boulder County has approximately 135,000 households, and the 2022 U.S. Census Bureau estimated that 1,162 households heat with wood which is less than 1% of the households in Boulder County (U.S. Census Bureau, 2022). Multiplying this by the average consumption per household, the total annual firewood usage in Boulder County would be approximately 3,777 cords equivalent to 4,997 tons of wood.

The scalability of firewood production facilities in the Boulder, Colorado region is influenced by a combination of ecological, regulatory, and market conditions specific to the area. The availability of raw material - primarily sourced from forest thinning, wildfire mitigation, and deadwood removal - is sufficient to support small to medium-scale operations, especially when coordinated with public land management agencies such as the Colorado State Forest Service and Boulder County Parks & Open Space.

However, scaling to larger operations introduces constraints, particularly due to Boulder County's strict land use and zoning regulations, environmental protection requirements, and community sensitivities. Larger facilities may trigger more intensive permitting processes, including Special Use Reviews and environmental impact assessments, especially if located in the Wildland-Urban Interface or near protected ecosystems. Additionally, the region's air quality regulations and fire risk management protocols impose operational limits that affect production volume and storage capacity. Labor scalability can also be challenging due to the physical nature of the work and limited seasonal workforce availability. Market demand in the Boulder Region is present but is largely seasonal and consumer-driven, with opportunities for growth probably limited if more restrictions on wood burning for heat are put into place. Overall, while firewood production is technically scalable in Boulder County, any expansion requires careful navigation of regulatory frameworks, sustainable sourcing strategies, and alignment with local environmental and community standards.

Overall, while capital and operational costs for firewood operations are substantial, particularly for kiln drying and compliance, the ability to generate diversified revenue streams (bulk cords, retail bundles, premium kiln-dried wood) improves financial viability. Profitability will depend heavily on operational efficiency, local market conditions, distribution partnerships, and the ability to differentiate products (e.g., kiln-dried or sustainably sourced firewood) to capture premium pricing.

Environmental Considerations

Firewood production in Boulder, Colorado must comply with strict air quality standards due to the region's ozone non-attainment status. Processing activities such as cutting, splitting, and kiln drying can generate particulate matter (PM10/PM2.5) and volatile organic compounds (VOCs). Dust suppression methods and emissions controls are necessary, particularly for kiln operations. Oversight by the Colorado Department of Public Health and Environment (CDPHE) and Boulder County Public Health ensures adherence to local and state air quality regulations.

Firewood use is also of concern as it can contribute to air quality impacts in the Boulder Region. Firewood combustion releases particulate matter, carbon monoxide, volatile organic compounds, and nitrogen oxides.

Sustainable sourcing is critical to minimizing environmental impact. Firewood should originate from forest health treatments, wildfire mitigation, or salvage operations, following guidance from the Colorado State Forest Service. To prevent the spread of invasive pests like the emerald ash borer, facilities must comply with transport regulations. Public land harvesting may require permits and coordination with agencies such as Boulder County Parks & Open Space.

Facilities must manage stormwater to prevent runoff of wood debris and pollutants into nearby waterways. Compliance with the Clean Water Act and potential CDPHE stormwater discharge permitting is required. Operations near riparian zones must take additional precautions to avoid ecological disruption and water quality degradation.

Wood storage in the Wildland-Urban Interface (WUI) can increase fire hazard. Facilities must create defensible space and adhere to Boulder County fire codes. Seasonal fire restrictions may limit operations during high-risk periods. Mitigation measures such as spacing, fuel breaks, and fire safety protocols are essential.

Zoning rules in Boulder County do not explicitly categorize firewood production facilities as a standalone land use (County of Boulder, 2024). Such operations may be permissible in broader land use classifications, contingent upon the specific zoning district. These include:

- Agricultural (A) District: This district is primarily intended for agricultural activities. Uses like Agricultural Products Processing and Storage are allowed subject to Special Review, which involves a public hearing process to assess potential impacts
- Forestry (F) District: While not explicitly detailed in the provided excerpts, the Forestry district typically accommodates uses related to forest management and may allow for firewood production, subject to specific use classifications and reviews.
- Rural Residential (RR) and Estate Residential (ER) Districts: These districts are primarily residential. Firewood production in these areas would likely be limited to accessory or home occupation uses, with strict limitations to minimize impacts on residential character.

Infrastructure and Technical Considerations

The technical feasibility for firewood production facilities is good, particularly in regions such as Boulder with access to suitable woody biomass, established forestry infrastructure, and a demand for heating fuel. Key technical considerations include feedstock availability, site requirements, processing equipment, labor, and compliance with environmental and safety regulations. When these factors are adequately addressed, firewood production can be scaled to serve residential, commercial, or institutional markets.

Feedstock availability is a primary determinant of feasibility. A consistent local and regional supply of appropriate woody biomass is needed to ensure product quality and market competitiveness. Sources may include roundwood from logging operations, salvage wood, and larger-diameter forest thinning and logging residues. In addition, site selection is critical for a new firewood production facility - the facility must have sufficient space for log reception, storage, processing, drying, and packaging, while also allowing for truck access and adherence to zoning and environmental permitting requirements.

The core of the technical operation involves processing equipment such as firewood processors, hydraulic splitters, tumblers, kilns (for accelerated drying), and automated packaging systems. These technologies are commercially available and widely used in North American and European markets. Equipment selection should align with desired production capacity, feedstock characteristics, and labor availability. Natural air drying may suffice in certain climates, but kiln drying can be used for its speed, consistency, and moisture control. Additionally, staffing needs include operators skilled in equipment handling, quality control, and logistics coordination.

Firewood production facilities are technically feasible to establish with a well-structured design and operational plan. The modular nature of the processing equipment allows for phased expansion, and the industry's relatively low technological barrier to entry supports adaptability to local conditions. When backed by a sound supply chain and proper facility layout, such operations can deliver consistent, high-quality firewood while adhering to environmental and safety standards.

The Boulder region supports a comprehensive infrastructure for firewood production and distribution, integrating municipal programs, private enterprises, and community initiatives to meet the area's demand for firewood. Municipal efforts play a pivotal role in firewood provision. The City of Boulder operates a Firewood Program that repurposes wood from forest management activities. This program offers firewood to permit holders at designated locations, such as the South Boulder Creek West Trailhead and the Parks & Recreation Forestry Lot. Participants are required to obtain a permit and adhere to specific collection guidelines (City of Boulder, 2025).

In the private sector, numerous businesses contribute significantly to firewood production and distribution. For instance, Morgan Forest Agriculture, located in Boulder, emphasizes sustainable practices by thinning overstocked forest stands to reduce fire hazards, thereby supplying firewood while enhancing wildlife habitats. Additionally, United Wood Products Inc., situated in Longmont, offers a diverse range of wood products, including firewood, logs, and lumber, with delivery services available to the Boulder area.

Community initiatives further bolster the region's firewood distribution network. The Firewood Bank Assistance Program has funded numerous firewood distribution programs, enhancing accessibility for residents. For example, the Four Mile Fire Protection District west of the City of Boulder received funding from this program for a community wood lot (Alliance for Green Heat, 2025).

Collectively, these municipal programs, private enterprises, and community efforts establish a robust and sustainable firewood production and distribution infrastructure in the Boulder Region, effectively addressing both environmental management objectives and the community's heating needs.

Summary of Benefits and Drawbacks

Benefits

- *Reliable Heat Source:* Provides an affordable and dependable source of heating, especially in rural or off-grid areas.
- *Low Technological Barrier:* Processing firewood requires relatively simple and widely available technologies (splitters, kilns, basic sawmills).

- *Market Familiarity:* Firewood has an established market with predictable seasonal demand, particularly in colder climates.
- *Higher Revenue Potential with Retail Sales:* Kiln-dried or bundled firewood sold through retail channels (e.g., grocery stores, campgrounds) can achieve higher per-unit revenue.
- *Utilization of Lower-Quality Wood:* Firewood production can make use of small-diameter trees, defect-laden logs, or other wood not suitable for sawmills or higher-value products.
- *Local Economic Benefits:* Supports small businesses, provides rural jobs, and keeps heating dollars circulating within local economies.
- *Disaster Resilience:* Offers an independent, off-grid energy source during power outages or natural disasters.

Drawbacks

- *Air Quality Impacts:* Burning firewood releases particulate matter (PM2.5), volatile organic compounds (VOCs), and other pollutants that can harm human health and degrade air quality.
- *Climate Considerations:* Although burning wood is sometimes considered "carbon neutral," emissions from inefficient combustion can contribute to localized greenhouse gas and pollutant loads.
- *Labor and Handling Costs:* Processing, drying, stacking, bundling, and delivering firewood are labor-intensive and require ongoing operational management.
- *Capital Costs for Kiln Drying:* Installation of modern kiln systems for faster drying and improved air quality compliance can require significant upfront investment.
- *Seasonal Demand:* Firewood sales are strongly seasonal, with limited demand in warmer months, which can affect cash flow stability.
- *Regulatory Constraints:* Increasingly, local and regional air quality regulations may restrict or discourage residential wood burning, reducing long-term market growth potential.
- *Lower Scalability:* Compared to industrial-scale biomass pathways (e.g., bioenergy production), firewood operations are typically suited for small to medium scales.
- *Resource Competition:* High-value wood could potentially be diverted to higher-end uses (e.g., lumber, mass timber), reducing available feedstock for firewood operations.

Profiles of Other Utilization Pathways

With the top three pathways addressed in detail (above), the remaining pathways that had the support of the Biomass Core Team are discussed below. These include:

- Small sawmill
- Animal bedding
- Biomass heat
- Mass timber
- Air curtain burner
- Pellets/fuel bricks
- Bio-oil
- Post and pole
- Fungal Decomposition

Small Sawmill

Overview

A small-scale sawmill is a compact, often portable facility designed to convert logs into lumber for personal or local use. These mills are ideal for landowners, small forestry operations, or woodworking businesses, offering efficient timber processing with lower cost and complexity than industrial mills. Core components include bandsaws, circular saws, or chainsaws - each with trade-offs in precision, speed, and waste. Power sources (gasoline, diesel, electric, or power take-off [PTO]) influence efficiency and mobility. Production typically ranges from a few hundred to a few thousand board feet per day, depending on mill size and feedstock availability. Small sawmills are well-suited for custom cuts, small builds, and niche lumber sales.

Applications

Applications include the production of dimensional lumber, live-edge slabs, green building materials, and specialty products for local builders, artisans, and remodelers. Small mills also supply secondary products like firewood, mulch, and even biochar. Markets are driven by the demand for unique, sustainably sourced wood for furniture making, custom construction, and crafts.

Feedstock Considerations

The primary feedstock consists of logs between 6 and 36 inches in diameter. Smaller logs are inefficient for milling, while larger logs may require specialized handling equipment. Feedstock sources include:

- *Forest Timber:* Harvested from managed forests, salvage operations (fire, beetle kill), or forest restoration projects.
- *Urban Timber:* Sourced from landscape tree removals, utility clearances, or storm damage; offers unique species but can contain metal contaminants.

Feedstock quality affects yield and mill efficiency. Urban logs can offer high value but may have inconsistencies.

Product Yield:

- Softwoods: ~200–250 board feet (green) to ~275–325 board feet (dry) per ton.
- Hardwoods: ~175–225 board feet (green) to ~250–300 board feet (dry) per ton.

Economic Considerations

Using small-diameter or liability biomass from forest thinning is cost-effective for fire-prone regions like Boulder County but requires careful economic management:

- *Feedstock Costs:* $0–$30 per ton (public thinning programs); transportation adds $10–$30 per green ton.
- *Processing Costs:* Capital investment of $50,000–$250,000 for bandsaws, edgers, kilns. Labor costs $15–$35/hour; fuel and maintenance add $10–$25 per ton.
- *Product Value:* Lumber prices range from $1.00–$5.00 per board foot depending on species and quality. Firewood ($150–$300/cord), mulch ($15–$35/ton), and biochar ($300–$600/ton) provide secondary revenue streams.

- *Profitability:* Stronger when all tree components are utilized and operations maintain diversified product offerings.

Success depends on operational efficiency, proximity to feedstock, and diversified product lines.

Environmental Considerations

Environmental impacts center on air, water, and noise pollution, and sustainable sourcing practices:

- *Air Quality:* Kiln operations and biomass combustion may require air quality controls.
- *Water Quality:* Sawdust and runoff management is needed to prevent soil and water contamination.
- *Noise:* Mitigation may be needed near residential areas.
- *Sustainable Sourcing:* Utilizing thinning residues aligns with wildfire mitigation and forest health goals in Boulder County. Compliance with Colorado Department of Public Health & Environment regulations and Boulder County's strong environmental standards is crucial.

Infrastructure and Technical Considerations

Modern portable bandsaw and resaw technologies support flexibility and relatively low capital investment for small mills.

- *Technical Feasibility:* Portable mills are advantageous in mountainous terrains and can process logs, on-site, into lumber, slabs, and niche products efficiently.
- *Infrastructure Needs:* A flat, accessible site with space for log storage, drying yards, and waste handling.
- *Challenges:* Regulatory permitting for air emissions, stormwater, and noise become more demanding at scale. Transporting logs from remote sites can be logistically complex.
- *Market Context:* Boulder County's artisan and construction markets support specialty wood sales. Institutions like the University of Colorado contribute skilled labor and research support.

Example: Golden West Pine Mills (Ault, CO) demonstrates successful small sawmill scaling, processing 4–5 million board feet annually with state and federal support.

Summary of Benefits and Drawbacks

Table 2.10 summarizes the key benefits and drawbacks associated with implementing a small-scale sawmill pathway in Boulder County. While small sawmills offer numerous advantages, including flexibility, low capital investment, and alignment with local sustainability goals, they also present challenges related to operational scale, regulatory compliance, and logistics. Understanding these trade-offs is critical for evaluating the feasibility and strategic fit of small-scale sawmilling as part of a broader biomass utilization plan.

Table 2.10. Summary of potential benefits and drawbacks from small sawmill for different decision categories.

Category	Benefits	Drawbacks
Capital Investment	Lower upfront capital costs compared to industrial mills.	Scaling up requires significant additional investment.
Flexibility	Supports custom cuts, specialty lumber, and use of diverse wood species.	Limited processing capacity compared to larger, industrial-scale sawmills.
Mobility	Portable mills enable on-site operations, useful in mountainous and remote areas.	Logistical challenges transporting feedstock from remote thinning sites.
Environmental Synergy	Utilizes liability biomass from thinning projects, supporting forest health and wildfire mitigation.	Requires compliance with strict environmental regulations (air emissions, waste management).
Market Demand	Strong demand for sustainable, locally sourced wood products (e.g., slabs, green building materials).	Niche markets may be seasonal; success depends on diversified product lines.
Workforce	Access to skilled labor and technical support from local institutions.	Labor- and maintenance-intensive operations.
Regulatory Environment	Fits Boulder County's sustainability and local sourcing values.	Expansion constrained by zoning laws, permitting complexity, and operational restrictions

Animal Bedding

Overview

Wood-derived animal bedding is widely used for pets, livestock, and laboratory animals because of its strong moisture absorption, odor control, and comfort. Common types include wood shavings, pellets, chips, and sawdust, with softwoods like pine and aspen often preferred. These products are biodegradable and compostable, offering environmental benefits. However, fine dust particles can cause respiratory issues in sensitive animals, and certain woods, such as cedar, may contain harmful aromatic oils. The production process involves sourcing clean, untreated wood residues, processing them into specific bedding forms, and ensuring drying, screening, and packaging to maintain product quality and safety.

Applications

Animal bedding products serve diverse applications across livestock farming and pet care sectors. Shavings are commonly used for horses, poultry, and small mammals, while pellets - made from compressed sawdust - expand when wet and are ideal for stalls, coops, and litter boxes. Coarser wood chips are better suited for outdoor livestock environments, providing durable ground cover with moderate absorbency. Fine sawdust, known for its excellent moisture absorption, is often used in deep litter systems for poultry, swine, and cattle, although dust control is essential to protect animal health. Overall, wood-derived bedding enhances hygiene, animal comfort, and odor management in a variety of agricultural and domestic settings.

Feedstock Considerations

Suitable feedstocks for animal bedding production include bark, wood from trunks and large branches, and sawdust. Bark, although coarse and less absorbent, is used in outdoor livestock environments or mixed with finer materials. Solid wood yields shavings and chips that offer structural integrity and moderate moisture control. Sawdust, generated during milling and sawing operations, provides high absorption but must be carefully processed to limit dust hazards. Needles and leaves are generally excluded due to poor absorbency and potential phytotoxicity. Feedstock sourcing emphasizes clean, untreated material to avoid chemical contamination and ensure animal safety.

Animal bedding yields vary by product type. From one ton of wood, estimated outputs are approximately 90–110 cubic feet of shavings, 45–55 cubic feet of pellets, 70–90 cubic feet of chips, and 90–110 cubic feet of sawdust. Actual yields depend on species, moisture content, and processing efficiency.

Economic Considerations

Production costs for animal bedding depend on product type and processing method (Table 2.11). Chipping and shaving operations typically cost \$20–\$50 per ton, while drying adds \$15–\$40 per ton. Pellet production, involving grinding and extrusion, is more expensive at \$50–\$100 per ton. Screening and dust collection add an additional \$10–\$25 per ton. Packaging contributes another \$20–\$40 per ton depending on bagging or baling needs. Labor costs in Boulder County range from \$20–\$35 per hour, with total annual labor costs between \$50,000 and \$100,000. Overhead for utilities and administrative expenses adds \$15–\$30 per ton. Capital investments for small to medium-sized facilities range from \$50,000 to \$300,000.

Production costs generally range from \$90–\$160 per ton for shavings and sawdust, \$60–\$110 per ton for wood chips, and \$130–\$220 per ton for pellets. Despite these costs, strong market potential exists, with retail prices reaching $300–$500 per ton for bagged shavings, $400–$700 per ton for pellets, and $100–$200 per ton for bulk chips (Table 2.11). Animal bedding thus represents an economically promising pathway for biomass utilization, particularly when leveraging low-cost or subsidized feedstocks.

Table 2.11. Key cost and revenue metrics for animal bedding production.

Metric	Estimated Range	Notes
Feedstock (Wood Type)	Softwood logs, sawdust, chips, bark	Preferably clean, untreated material
Yield per Ton (1,000 lbs)	- Shavings: 90–110 ft^3 - Pellets: 45–55 ft^3 - Chips: 70–90 ft^3 - Sawdust: 90–110 ft^3	Varies based on moisture content and wood species
Production Costs	- Shavings: $90–$160 per ton - Chips: $60–$110 per ton - Pellets: $130–$220 per ton	Includes processing, drying, screening, packaging
Capital Investment	$50,000–$300,000	For equipment like chippers, planers, dryers, pelletizers
Labor Costs	$20–$35 per hour	Based on Boulder County wage rates
Overhead Costs	$15–$30 per ton	Utilities, administration, compliance
Retail Revenue Potential	- Shavings: $300–$500 per ton - Pellets: $400–$700 per ton - Chips: $100–$200 per ton	Higher revenue for bagged and specialty products
Market Demand	High	Driven by livestock and pet sectors in Boulder County
Environmental Benefit	High	Compostable, diverts biomass waste, supports soil health

Environmental Considerations

Environmental impacts vary depending on the processing intensity. Chipping and shaving have relatively low energy requirements, while pelletizing and kiln drying are more energy-intensive and can increase emissions if fossil fuels are used. However, utilizing forest residues for bedding instead of landfill disposal or open burning generally results in a net climate benefit.

Air quality is a key consideration, as processing generates fine particulates that require dust management to protect worker health and meet air pollution standards. Water use for dust suppression and runoff management must also be carefully controlled. Spent bedding, when properly composted, returns valuable organic matter and nutrients to soils, although contamination with animal waste requires careful handling to avoid nutrient runoff and water quality degradation. Overall, replacing non-renewable materials like sand or peat with forest-derived bedding improves sustainability outcomes.

Infrastructure and Technical Considerations

The technical feasibility of animal bedding production in Boulder County is generally favorable but depends on feedstock availability, processing infrastructure, and market access. While Boulder County itself lacks large-scale timber processing facilities, nearby sawmills, logging contractors, and biomass processors can provide raw materials. Equipment such as chippers, grinders, dryers, and screeners are commercially available and technically mature, but producing finer, dust-free, kiln-dried bedding requires additional capital investment.

The Boulder County region presents strong market opportunities, driven by its agricultural sector. According to the 2022 USDA Agricultural Census, the county hosts thousands of livestock, including cattle, horses, sheep, goats, and poultry, supporting consistent demand for bedding products. However, only three identified bedding production facilities are located within 50 miles, suggesting that new operations or partnerships would be needed to scale production efficiently.

Summary of Benefits and Drawbacks

Table 2.12 outlines the key benefits and drawbacks associated with utilizing woody biomass for animal bedding production. While this pathway offers strong opportunities to enhance animal welfare, support environmental sustainability, and create economic value, it also presents operational and regulatory challenges that must be carefully managed. These trade-offs are helpful to understand for assessing the feasibility and strategic fit of animal bedding production within Boulder County's broader biomass utilization and forest health objectives.

Table 2.12. Summary of benefits and drawbacks of animal bedding production.

Category	Benefits	Drawbacks
Animal Health & Comfort	Excellent moisture absorption, odor control, and insulation improve animal hygiene and welfare	Fine particulates (especially from sawdust) can pose respiratory risks without dust control
Environmental Impact	Biodegradable and compostable; composted spent bedding enriches soils and reduces landfill use	Spent bedding mixed with animal waste requires careful handling to avoid nutrient runoff or odors
Market Potential	Strong demand from livestock and pet sectors in Boulder County and regionally	Market competition and seasonality may affect pricing and sales stability
Use of Biomass	Efficiently uses forest residues and sawmill byproducts; supports wildfire mitigation efforts	Not all liability biomass (e.g., leaves, needles) is suitable for bedding production
Economic Viability	Attractive profit margins for bagged and pelletized products; diverse product options	High-quality kiln-dried or pelletized bedding requires significant capital investment
Technical Feasibility	Mature technologies are available for grinding, drying, and pelletizing	Infrastructure in Boulder County is limited; few existing facilities require new development
Regulatory Considerations	Generally low impact if dust and emissions are managed	Dust, air quality, and water runoff must be regulated and mitigated to meet compliance standards

Biomass Heat

Overview

Institutional and commercial biomass heating systems offer a viable, sustainable alternative to fossil fuel-based heating. Utilizing forest-sourced wood fuels such as wood chips, pellets, cordwood, and residuals like bark and sawdust, these systems deliver thermal energy for space heating, water heating, and industrial processes. Biomass heating aligns closely with carbon emission reduction goals, supports sustainable forest management practices, and strengthens local and regional energy security. When properly designed and maintained, biomass heating systems can achieve combustion efficiencies of 80 - 90% or higher while meeting stringent environmental regulations through advanced emission control technologies. Boulder County has already demonstrated leadership in this area with biomass heating installations at the Boulder County Open Space and Transportation Complex and the Boulder County Jail, both fueled by wood sourced from forest management activities aimed at wildfire risk reduction.

Applications

Biomass heating systems are highly adaptable and are widely used across various sectors. Applications include space heating for schools, healthcare facilities, municipal buildings, and commercial enterprises, as well as supplying process heat for industries such as agriculture and light manufacturing. Systems can range from small installations for individual buildings to large district heating networks, and they can integrate with thermal storage or hybrid energy systems for enhanced operational flexibility. Boulder County's own installations exemplify biomass heating's versatility, supporting both administrative complexes and correctional facilities with reliable, renewable thermal energy sourced from local forests.

Feedstock Considerations

Woody biomass used for heating is available in several forms, each with distinct handling, storage, and combustion characteristics. Wood chips are commonly used due to their availability and compatibility with automated systems, though their variable size and moisture content require careful management. Wood pellets offer consistent quality and high combustion efficiency, ideal for highly automated systems, but are susceptible to moisture damage and dust-related hazards. Cordwood is less suitable for commercial operations due to manual handling requirements and inconsistent combustion. Residual materials like bark and sawdust help utilize wood waste streams but present additional feeding and combustion challenges. The energy yield from biomass varies with moisture content; a ton of dry wood (~20% moisture) contains about 16 million BTUs, while wood chips with 30–50% moisture produce between 9–13 million BTUs per ton.

Economic Considerations

Biomass heating can be economically competitive with conventional energy sources, depending on feedstock costs, operational expenses, and capital investment. Compared to natural gas, where 16 MCF (thousand cubic feet) costing around $158 is needed to match the energy in one ton of dry wood, or electricity costing approximately $562 to produce the same energy, biomass heating presents a lower-cost alternative when wood is affordably sourced. Using an example 10 MW thermal biomass system, total heating cost - including feedstock, operation and maintenance, and capital recovery - is about $5.88 per kW thermal produced. Capital investment for biomass boilers and handling systems is substantial, often requiring grants, subsidies, or favorable financing mechanisms to offset upfront costs. Long-term, however, lower fuel costs and carbon incentives can make biomass heating financially attractive, particularly in sectors with consistent, high thermal energy demand.

Table 2.13. Key metrics for biomass heating systems.

Category	Metric/Range	Notes
Feedstock Energy Content	- Dry wood (~20% moisture): ~16 million BTU/ton - Wood chips (30–50% moisture): ~9–13 million BTU/ton	Moisture content significantly affects energy yield
Combustion Efficiency	80%–90%	Advanced boiler designs with proper maintenance
Heating Cost Comparison	- Wood biomass (dry): lower than natural gas or electricity - Natural gas: ~$158 for equivalent energy - Electricity: ~$562 for equivalent energy	Biomass generally offers lower operational fuel costs
Total Heating Cost (10 MW system)	~$5.88 per kW thermal produced	Includes feedstock, operations, and capital recovery
Capital Investment	High (varies by scale, commonly in millions for larger systems)	Requires grants, loans, or public funding support for feasibility
Air Emissions	- PM, NO_x, CO, VOCs	Requires emission control technologies (e.g., electrostatic precipitators, baghouse filters)
Dust and Noise Management	Required	Enclosures and suppression systems necessary for handling and storage
Ash Production	1%–3% of feedstock weight	Ash can be reused as soil amendment if tested and certified
Infrastructure Needs	- Fuel storage - Handling systems - Space requirements	More land area needed compared to fossil fuel systems
Climate Impact	Positive (when sustainably sourced)	Displaces fossil fuels and supports carbon neutrality goals
Maintenance Requirements	Moderate to High	Includes fuel system upkeep, combustion system cleaning, ash handling, and emissions monitoring

Environmental Considerations

Environmental impacts of biomass heating center around air emissions, dust management, noise, and ash disposal. Combustion of woody biomass produces particulate matter (PM), nitrogen oxides (NO_x), carbon monoxide (CO), and volatile organic compounds (VOCs). Effective combustion design, along with emission controls like electrostatic precipitators and baghouse filters, are essential to meet air quality standards and reduce environmental impact. Dust and noise generated during fuel handling must be managed through enclosures and suppression systems to protect local communities and worker health. Ash, while potentially usable as a soil amendment, must be tested for contaminants before reuse or disposal. Overall, biomass heating systems that utilize sustainably sourced biomass contribute positively to climate goals by displacing fossil fuel use and promoting carbon neutrality, provided that environmental controls are diligently applied.

Infrastructure and Technical Considerations

The technical feasibility of woody biomass heating is high, with mature, proven systems commercially available for a wide range of building sizes and energy needs. Key components such as fuel storage, handling systems, combustion chambers, and heat exchangers are well-developed and increasingly automated, improving operational efficiency and reliability. Systems can operate with minimal on-site oversight when equipped with automation and remote monitoring technologies. Boulder County's existing systems at the Open Space Complex and the Jail demonstrate the viability of such systems at institutional scales. Infrastructure needs include reliable local biomass sourcing, properly designed storage facilities to manage moisture and dust, and robust handling equipment to ensure consistent fuel delivery. Boulder County's forest management activities - producing biomass from thinning, urban tree removals, and beetle-killed trees - create a strong foundation for expanding biomass heating efforts, especially if integrated into additional public and private sector facilities.

Summary of Benefits and Drawbacks

Table 2.14 summarizes the primary benefits and drawbacks associated with implementing woody biomass heating systems. While these systems offer significant environmental, economic, and local resilience advantages, they also present challenges related to capital investment, operational complexity, and regulatory compliance. Understanding these trade-offs is important for evaluating the role of biomass heating in Boulder County's broader forest health, wildfire risk reduction, and climate action strategies.

Table 2.14. Benefits and drawbacks of biomass heating systems.

Category	Benefits	Drawbacks
Carbon Impact	Carbon-neutral when sourcing biomass sustainably; displaces fossil fuel use	Emissions of PM, NO_x, CO, and VOCs require advanced emission controls to meet air quality standards
Economic Viability	Potential long-term cost savings over natural gas and electricity, especially with low-cost feedstock	High upfront capital costs for boiler systems, storage, handling, and emissions control infrastructure
Local Benefits	Strengthens local energy security; creates rural forestry and maintenance jobs	Requires reliable local biomass supply and quality control (moisture, size, cleanliness)
Technical Maturity	Proven, commercially available systems with modular scalability; high automation potential	Larger systems increase permitting, environmental review, and maintenance complexity
Environmental Resilience	Supports wildfire risk reduction by utilizing excess forest biomass	Dust, noise, and ash management are necessary to minimize local environmental impacts
Operational Flexibility	Suitable for a wide range of applications (schools, municipal buildings, district heating)	Requires more on-site space for fuel storage and handling compared to traditional fossil fuel systems
Policy Support	Eligible for grants, carbon incentives, and state/federal renewable energy programs	Dependence on evolving policy and grant landscapes to improve financial feasibility

Mass Timber

Overview

Mass timber production transforms sustainably harvested wood and wood waste into engineered wood products for structural applications in construction. The process integrates sustainable forestry practices with advanced manufacturing techniques, utilizing both virgin timber and wood waste from sawmills and construction debris. Logs, primarily from species like spruce, pine, fir, and Douglas fir, are debarked, kiln-dried, and processed into products like cross-laminated timber (CLT), glued-laminated timber (Glulam), laminated veneer lumber (LVL), and oriented strand board (OSB). These materials undergo adhesive bonding, pressing, and precision cutting, with rigorous quality control ensuring structural integrity, fire resistance, moisture performance, and compliance with safety standards. Mass timber supports eco-friendly construction by promoting carbon storage, resource efficiency, and the repurposing of wood byproducts into bioenergy.

Applications

Mass timber products are increasingly used in residential, commercial, and institutional construction. Applications include structural framing for mid-rise and high-rise buildings, flooring systems, roofing panels, wall assemblies, and architectural elements like exposed timber facades. In Boulder County, projects such as The Loading Dock (2017) and the upcoming Alpine-Balsam redevelopment illustrate growing local adoption. Mass timber appeals to architects and developers due to its aesthetic qualities, faster construction timelines, lighter weight compared to concrete, and its contributions to carbon reduction goals. Future trends suggest expanding applications across multi-family housing, civic infrastructure, educational facilities, and mixed-use developments.

Feedstock Considerations

Preferred feedstocks for mass timber include softwoods like spruce, pine, fir, and Douglas fir, selected for their strength-to-weight ratios and workability. Small-diameter logs from thinning projects and sustainable forestry operations are prime candidates, offering an important use for liability biomass. However, the mechanical variability, dimensional instability, and shorter log lengths of such biomass require careful processing. Machine stress grading, adapted visual grading, kiln drying, finger-jointing, and hybrid panel designs help mitigate these challenges, enabling the use of lower-grade wood in non-structural layers of products like CLT (Table 2.15). On average, one ton of raw wood produces approximately 700–900 kilograms of finished mass timber products, with byproducts like sawdust and offcuts repurposed for bioenergy or other uses.

Table 2.15. Estimated mass timber yield per one ton of wood.

Mass Timber Product	Yield from One Ton of Raw Wood (kg)	Conversion Efficiency	Average Price per Square Foot*
Cross-Laminated Timber (CLT)	650–800 kg	65–80%	$50
Glued-Laminated Timber (Glulam)	700–850 kg	70–85%	N/A
Oriented Strand Board (OSB)	850–950 kg	85–95%	$0.75–$1.10
Particleboard / MDF	900–1,000 kg	90–100%	$0.85–$1.40

* Source: The Beck Group (2015)

Economic Considerations

Mass timber production involves substantial initial capital investment, including hydraulic presses, kilns, adhesive systems, and precision machining equipment. However, automated and modular production lines enhance efficiency and scalability over time. Market demand is rising, with higher prices commanded for CLT panels (~$50/sq ft) and OSB panels ($0.75–$1.10/sq ft). Operational models that vertically integrate forestry, sawmilling, and panel manufacturing further streamline supply chains and reduce costs. Regional coalitions like the Colorado Mass Timber Coalition, and trends toward green building standards, provide financial and policy incentives that strengthen the business case. Although Boulder County currently lacks mass timber production facilities, strong regional market growth suggests a supportive environment for future investment.

Environmental Considerations

Mass timber construction offers significant environmental advantages, particularly through carbon storage and reduced embodied emissions compared to concrete or steel. Sustainable sourcing certifications (FSC, PEFC, SFI) ensure that raw materials support biodiversity and forest regeneration. Additionally, wood's low-energy production profile contributes to carbon-neutral or carbon-negative construction outcomes. However, environmental trade-offs exist, particularly concerning adhesives. Some resins used in mass timber products emit volatile organic compounds (VOCs), impacting indoor air quality and complicating end-of-life disposal or recycling. To minimize these impacts, manufacturers are increasingly using low-emission, formaldehyde-free adhesives. Optimizing energy use during kiln drying and lamination further protects the environmental benefits of mass timber production.

Infrastructure and Technical Considerations

Although Boulder County currently has no mass timber production facilities, the region demonstrates growing market readiness through pioneering projects like The Loading Dock and the Alpine-Balsam redevelopment. Architectural firms such as OZ Architecture have led the adoption of CLT and Glulam in local construction. The Colorado Mass Timber Coalition (formed in 2023) further supports infrastructure development through advocacy, education, and industry coordination. Scalability is feasible given mass timber's modular manufacturing systems, which allow phased expansion by adding press lines or machining centers. Key technical challenges include managing feedstock variability, ensuring adhesive compatibility, and certifying products against rigorous structural and fire safety standards (APA, ANSI, ICC-ES). Infrastructure needs - such as proximity to feedstock, skilled labor, transport links, and urban market access - will influence where future facilities are best located.

Summary of Benefits and Drawbacks

Table 2.16 summarizes the primary benefits and drawbacks associated with the production and use of mass timber products. Mass timber offers environmental, economic, and construction advantages, aligning with sustainability and carbon reduction goals. However, it also presents notable challenges related to production costs, feedstock variability, adhesive use, and infrastructure development.

Table 2.16. Benefits and drawbacks of mass timber production and use.

Category	Benefits	Drawbacks
Carbon and Sustainability	Stores carbon; significantly lower embodied emissions compared to steel and concrete	Environmental concerns from adhesives (e.g., VOC emissions) complicate recyclability and indoor air quality
Feedstock Utilization	Efficient use of small-diameter logs and sawmill byproducts, supporting forest health and resource efficiency	Liability biomass introduces challenges like dimensional instability and mechanical variability
Market and Demand	Strong and growing demand for sustainable construction materials; favored by architects and developers	High product costs may limit adoption in low-margin or smaller projects
Economic Development	Supports local and regional green building industries; opportunities for modular, scalable production	High initial capital investment required for presses, kilns, and precision machining equipment
Technical Viability	Mature, automated technologies available for scalable, high-precision production	Certification of non-standard feedstocks requires additional testing, increasing costs and timelines
Policy and Incentives	Strong support through green building standards, low-carbon construction policies, and carbon accounting frameworks	Dependent on continued growth of supportive regulatory frameworks and construction market acceptance
Regional Readiness	Emerging regional leadership (e.g., Colorado Mass Timber Coalition); example projects in Boulder County	As of 2025, no mass timber production facilities currently exist in Boulder County

Air Curtain Burner

Overview

Air curtain burners (ACBs) are specialized combustion systems designed for the controlled disposal of woody biomass, such as logging slash, tree trimmings, and storm debris, through high-temperature incineration. Unlike open burning, ACBs use a high-velocity air curtain projected over the combustion chamber to enhance oxygen delivery, contain emissions, and promote complete combustion. This technology achieves up to a 90% reduction in particulate emissions compared to open burning. ACBs can also produce ash as a soil amendment or, when combustion is adjusted, generate biochar for carbon sequestration markets. Leading manufacturers include Air Burners, Inc., with models ranging from portable units like the BurnBoss T24 to large-scale PGFireBox systems capable of producing electricity, and Tigercat, offering the Carbonizer focused on biochar production. ACBs offer an effective, regulatory-compliant solution for on-site biomass disposal, supporting forest health and wildfire risk reduction efforts.

Applications

ACBs are highly adaptable and find application across forestry operations, land-clearing projects, disaster debris management, and wildfire mitigation efforts. In forestry, they enable efficient disposal of thinning slash, undergrowth, and deadwood, eliminating the need for costly transportation or landfilling. ACBs also provide on-site solutions for urban forestry operations, park maintenance, and utility right-of-way clearing. Certain models, such as the PGFireBox, integrate waste-to-energy capabilities, enabling electricity generation alongside biomass disposal. Additionally, biochar production with ACBs offers new applications in soil enhancement and carbon credit generation. Their ability to operate in rugged, remote locations makes them ideal for Boulder County's wildland-urban interface (WUI) areas and public land management activities.

Feedstock Considerations

ACBs are engineered to efficiently process a wide range of woody biomass types commonly generated from forest management, land clearing, and storm events. Suitable feedstocks include logging slash, dead or diseased trees, brush, undergrowth, and tree trimmings. Materials such as small- to medium-diameter logs, chunked wood sections, and rounds are ideal, while unchipped material is generally preferred to maximize combustion performance. Although chipped material can be processed, it typically requires careful handling. Stumps and root balls may also be utilized if preprocessed. ACBs accommodate variable feedstock moisture contents and particle sizes, making them highly adaptable to the diverse biomass profile found across Boulder County.

Economic Considerations

Capital and operational costs for ACBs vary by model and system size. Typical capital costs include:

- BurnBoss T24: $85,000–$125,000
- FireBox S220/S330: $150,000–$350,000
- PGFireBox: $750,000+ (includes power generation capabilities)

Operating costs are driven primarily by diesel fuel consumption (0.35–3 gallons per hour), with minimal maintenance compared to grinders and hauling systems. Daily operating costs for larger systems are approximately $1,200, with typical daily biomass throughput of 10–20 tons. Labor requirements are low, typically needing only one operator and possibly a spotter for fire safety compliance.

Compared to grinding and hauling operations, ACBs offer significant savings by eliminating transportation and landfill tipping fees. Furthermore, the production and sale of biochar, and participation in carbon markets, offer additional revenue streams that can offset operational costs. Tigercat's Carbonizer has similar operational costs but a higher upfront price due to its specialized design for biochar recovery.

Environmental Considerations

ACBs provide key environmental benefits by dramatically reducing emissions compared to open burning. Sustained high combustion temperatures and the air curtain containment system reduce particulate matter, carbon monoxide, volatile organic compounds (VOCs), and other pollutants by more than 80% (San Joaquin Valley Air Pollution Control District, 2017). ACBs also contribute to wildfire risk mitigation by enabling rapid removal of hazardous fuels without extensive transport. Where combustion is carefully managed, ACBs can produce biochar, further supporting carbon sequestration goals. However, careful site selection is critical to avoid localized environmental impacts such as soil compaction, excessive localized heat, or minor noise pollution. Only clean, untreated biomass should be burned to avoid toxic emissions.

Infrastructure and Technical Considerations

Boulder County is well-positioned to deploy ACBs due to its extensive wildfire mitigation programs, slash pile sites, and defensible space zones, which provide accessible staging areas. Public agencies such as Boulder County Parks and Open Space, the City of Boulder’s Open Space and Mountain Parks, and the U.S. Forest Service are potential partners for widespread implementation. Mobile models like the BurnBoss and TrackBoss can navigate rugged terrain, while stationary FireBox units could be installed at centralized treatment areas (Table 2.17). ACBs require minimal infrastructure: basic site access, fuel delivery for blowers, and ash management. Regulatory pathways exist through the Colorado Department of Public Health and Environment (CDPHE) for air quality compliance, and Community Wildfire Protection Plans (CWPPs) can facilitate operational integration. Scalability is supported through modular deployment of multiple units, enabling flexibility for projects of varying size and urgency.

Table 2.17 - Air Curtain Burner Model Summary

Series Type	Model Number	Processing Amount (tons/hour)	End Products
FireBox Series	S220	5.0	Ash, Biochar
FireBox Series	S330	13.0	Ash, Biochar
TrackBoss/BurnBoss	BurnBoss T24	1.5	Ash, Biochar
TrackBoss/BurnBoss	TrackBoss	3.0	Ash, Biochar
Power Series	PGFireBox	Up to 20.0	Ash, Biochar, Electricity

Summary of Benefits and Drawbacks

The following table summarizes the primary benefits and drawbacks associated with the use of air curtain burner (ACB) systems for woody biomass management (Table 2.18). ACBs offer significant environmental and operational advantages, particularly for reducing emissions, lowering biomass disposal costs, and supporting wildfire risk reduction strategies. However, they also present considerations related to operational costs, fuel use, and regulatory compliance. Understanding these trade-offs is essential for evaluating the suitability of ACB systems within Boulder County's broader forest health and biomass utilization efforts.

Table 2.18. Benefits and drawbacks of air curtain burner (acb) system.

Category	Benefits	Drawbacks
Air Quality Impact	Reduces particulate emissions by over 80% compared to open burning; supports regulatory compliance	Still produces emissions; requires permitting for air quality and fire safety
Operational Flexibility	Portable and stationary units allow use in remote, rugged, or urban-edge areas	Site-specific management needed to prevent localized soil compaction and thermal impacts
Cost Savings	Avoids hauling and landfill tipping fees; can reduce biomass disposal costs substantially	Daily operational costs (~$1,200/day for larger units) accumulate over long-duration projects
Feedstock Versatility	Handles a wide range of unprocessed biomass: slash, brush, storm debris, deadwood	Performance varies slightly depending on moisture content and feedstock size
Revenue Potential	Opportunities to produce and sell biochar or generate carbon credits	Biochar production requires specific burn management and market development
Infrastructure Needs	Minimal infrastructure required (basic site access and fuel supply)	Requires reliable diesel fuel supply for blower operation
Scalability and Deployment	Easily scalable by deploying multiple units; rapid setup and takedown enable project flexibility	Larger units (e.g., PGFireBox) have significantly higher capital and operational costs

Pellet and Fuel Brick

Overview

Pellet and fuel brick (briquette) production transforms forest-sourced wood waste into dense, energy-rich biofuels that provide a renewable alternative to fossil fuels. This process offers a dual benefit: reducing wildfire-prone biomass in forests and producing a standardized, clean-burning fuel suitable for residential, institutional, and industrial applications. Production begins with sorting and cleaning to remove contaminants, followed by drying the biomass to 8–12% moisture content using systems like rotary drum, flash, or belt dryers. Material is then size-reduced to uniform particles (typically ¼–½ inch) using chippers or hammer mills. Densification occurs in pellet mills via compression through dies at temperatures around 194°F, activating lignin as a natural binder. Pellets are cooled, screened, and packaged. Fuel bricks follow a similar pathway but often use finer particles and are densified using hydraulic or mechanical presses.

Applications

Pellets are primarily used in residential stoves and boilers, while fuel bricks are better suited for industrial-scale heating systems and combined heat and power (CHP) plants. Both products appeal due to their high energy density, ease of handling, clean combustion, and compatibility with automated feeding systems. Their standardized size and moisture content ensure consistent performance and make them viable in applications ranging from home heating to institutional and industrial energy systems. In Boulder County, these fuels are well-aligned with existing biomass heating infrastructure and climate resilience goals.

Feedstock Considerations

Suitable feedstocks for pellet and brick production include a wide array of forest residues such as logging slash, thinning waste, sawmill byproducts (sawdust, shavings, chips), and storm-damaged or insect-infested wood. The material must be clean, untreated, and preferably below 15% moisture content to ensure quality and efficiency. Liability biomass - though abundant - presents challenges due to its heterogeneity, ash content, and contamination risks (e.g., dirt, nails, treated wood). Preprocessing steps such as drying, magnetic separation, and screening are critical. Blending feedstocks is common to balance calorific value and ash content. One ton (2,000 lbs) of dry wood typically produces 1,800 - 1,900 lbs of pellets or fuel bricks.

Economic Considerations

Pellet and fuel brick production is capital-intensive, particularly for drying and densification equipment. Key cost components include energy use, emissions controls, and labor. Despite high upfront costs, the market for biomass fuels continues to expand. In Boulder County as of March 2025, heating pellets retail for approximately $300 per ton (in 40-lb bag format). Production efficiencies range from 90–95%, with modest losses in dust and fines. Commercial viability depends on consistent feedstock supply, market access, and the ability to meet product certification standards (e.g., ISO 17225-2).

Economies of scale reduce per-ton costs, but large centralized plants require steady feedstock flow and efficient logistics. A hub-and-spoke model, with distributed preprocessing and centralized pelletizing, may improve viability. Operational costs are also sensitive to moisture control and contamination management, which influence equipment wear and product quality.

Environmental Considerations

Pellets and bricks made from liability biomass offer lifecycle carbon neutrality when sourced sustainably. Their use displaces fossil fuels and supports wildfire risk mitigation. However, emissions during production - particularly from dryers - can release particulate matter (PM), volatile organic compounds (VOCs), and greenhouse gases. These impacts are especially relevant in Boulder County, which lies within a federal ozone nonattainment area. Compliance with Colorado Department of Public Health and Environment (CDPHE) air quality regulations is mandatory, and technologies such as cyclones, baghouses, and thermal oxidizers are often required.

End-use combustion emissions (PM2.5, CO, NO_x) are lower than traditional wood but still pose local air quality concerns, particularly during winter inversions. EPA-certified stoves and boilers are necessary to mitigate impacts. Dust management in production facilities also improves worker safety and fire risk. Water usage is minimal and largely confined to dust suppression.

Infrastructure and Technical Considerations

Pellet and fuel brick production from liability biomass is technically feasible but requires robust infrastructure. Feedstock collection and preprocessing (drying, milling, contaminant removal) are essential to produce consistent, high-quality fuel. Pellet systems must be equipped to handle variable input material and meet performance standards for durability, ash content, and calorific value. Failure to do so limits access to premium residential and commercial markets.

In Boulder County, existing infrastructure - including biomass-fueled boilers and support from the Colorado State Forest Service's Wood to Energy Program - provides a foundation for scaling up. However, new investments in preprocessing yards, drying systems, and pellet mills will be necessary. Certification under programs like the Sustainable Biomass Program (SBP) or Forest Stewardship Council (FSC) can strengthen market access and ensure responsible sourcing.

Summary of Benefits and Drawbacks

The following table summarizes the key benefits and drawbacks of using forest-sourced biomass to produce pellets and fuel bricks (Table 2.19). These densified fuels offer a valuable opportunity to convert liability biomass into clean, energy-dense products that support climate goals and forest health objectives. However, their production is capital-intensive and subject to stringent environmental controls, particularly in regions like Boulder County with sensitive air quality considerations. The following table provides a structured comparison of the major advantages and challenges associated with this pathway.

Table 2.19. Benefits and drawbacks of pellet and fuel brick production.

Category	Benefits	Drawbacks
Fuel Quality & Efficiency	High energy density (6,900–8,200 BTU/lb); low ash and moisture improve combustion efficiency	Requires intensive drying and contaminant removal to meet fuel quality standards
Feedstock Utilization	Makes productive use of forest residues, sawdust, and liability biomass	Variability in liability biomass can complicate consistent processing and fuel certification
Climate & Carbon Impact	Near carbon-neutral lifecycle emissions when sustainably sourced; displaces fossil fuel use	Emissions from drying and combustion must be tightly controlled, especially in air quality-sensitive areas
Market Viability	Expanding market demand for renewable fuels in residential and institutional heating	Sensitive to commodity pellet pricing and limited by regulatory classification of fuel quality
Infrastructure Readiness	Compatible with existing biomass heating systems; scalable via modular equipment	High capital investment required for drying, milling, densification, and emissions control equipment
Environmental Regulation	Production can meet air quality standards with proper controls; low water use	Requires permits for PM, VOCs, and NO_x emissions; dust and noise must also be managed
Storage & Distribution	Pellets and bricks are compact, transportable, and compatible with automated feed systems	Highly moisture-sensitive; requires dry storage and proper packaging to avoid degradation

Bio-oil

Overview

Bio-oil production from forest-sourced wood waste represents an emerging pathway for sustainable energy generation and long-term carbon sequestration. Produced via fast pyrolysis - a thermochemical process that rapidly heats biomass in low-oxygen environments - bio-oil is a dark, viscous liquid rich in oxygenated organic compounds. The process also yields biochar and syngas, each with its own value-added applications. Bio-oil can be combusted for energy, refined into biofuels and biochemicals, or injected into deep geological formations to achieve stable, long-term carbon removal. Charm Industrial, a leading company in this space, operates mobile pyrolysis units out of its Ft. Lupton, Colorado facility, with field deployments near Boulder County. These units allow onsite biomass conversion, reducing transportation costs and emissions while offering a scalable model for Pyrolytic Carbon Capture and Storage (PyCCS).

Applications

Bio-oil can serve multiple end uses depending on its stabilization and refinement. In sequestration-focused applications, bio-oil can be injected into deep geological formations such as depleted oil and gas reservoirs or saline aquifers, where its high viscosity and microbial resistance ensure permanence. It may also be stabilized into long-lived industrial materials, including asphalt binder replacements, adhesives, and resin feedstocks, effectively embedding carbon in infrastructure. On the energy side, upgraded bio-oil can be refined into green diesel, aviation fuel, or marine bunker fuel. However, these energy applications require large-scale refineries and are not yet widely commercialized. Additionally, bio-oil contains chemical precursors - such as phenols, furans, and levoglucosan - that are of interest in bioplastics and pharmaceuticals. Biochar and syngas produced during pyrolysis can be utilized for soil health and energy recovery, respectively.

Feedstock Considerations

Bio-oil production is compatible with a wide range of forest-sourced woody biomass, including sawdust, bark, thinnings, slash, and other liability biomass residues. Fast pyrolysis yields the highest bio-oil output, typically producing 60–75% by weight of feedstock. Softwoods such as pine and spruce, as well as mixed residues, fall within this yield range, generating approximately 1,200–1,400 lbs of bio-oil per ton of biomass (Table 2.20). Co-products include biochar (10–25%, or ~200–500 lbs/ton) and syngas (10–15%, or ~200–300 lbs/ton), enhancing the system's carbon value.

Table 2.20. Expected Bio-Oil Yield from One Ton of Forest Wood Waste.

Feedstock	Bio-Oil Yield (%)	Bio-Oil Production (lbs/ton)
Softwood (e.g., pine, spruce)	60–70%	1,200–1,400
Liability Biomass (mixed)	60–70%	1,200–1,400

Economic Considerations

The current economic value of bio-oil production in Boulder County primarily derives from its carbon sequestration potential. Deep injection of bio-oil yields carbon dioxide removal (CDR) credits. Given that bio-oil is about 60% carbon, each ton stores ~0.6 tons of elemental carbon, equating to 2.2 tons of CO_2 when oxidized (using a 44:12 molecular weight conversion ratio). At 2024 market rates of ~$750 per ton CO_2 removed in the voluntary carbon market, one ton of bio-oil sequestered could yield ~$1,650 in CDR revenue.

Charm Industrial's Ft. Lupton facility supports mobile deployment of 2 - 10 ton/day pyrolysis units. The estimated cost of biomass delivery from Boulder County to the facility is $30.03/ton, with a one-way distance of 32.8 miles. While capital and operational costs for mobile pyrolyzers are high, the revenue potential from carbon removal and tax incentives can offset these expenses, especially as Charm scales to meet commercial contracts such as Google's 2025 pledge to remove 100,000 tons of CO_2 by 2030.

Environmental Considerations

Bio-oil production and sequestration present both environmental opportunities and challenges. When responsibly managed, the process can achieve net-negative carbon emissions by removing atmospheric CO_2 and storing it in stable forms. However, pyrolysis systems must be equipped with emissions controls to manage particulates, VOCs, and NO_x generated during biomass conversion. Additionally, bio-oil is acidic, viscous, and chemically reactive - requiring corrosion-resistant storage, spill containment, and leak detection.

Subsurface injection introduces geotechnical risks similar to those in traditional carbon capture and storage (CCS), including induced seismicity, brine displacement, and wellbore failure. Proper site characterization, monitoring, and pressure management are necessary to ensure safe containment. Despite these risks, the use of mobile units reduces environmental impacts from biomass transport and supports distributed mitigation strategies.

Infrastructure and Technical Considerations

Bio-oil systems require both pyrolysis and sequestration infrastructure. Charm's mobile units reduce the need for centralized plants by enabling on-site biomass processing. Each unit includes drying, pyrolysis, and storage functions, and they are staged and supported out of Ft. Lupton, CO. Bio-oil must then be transported to permitted injection wells, currently located in nearby states. The infrastructure also requires robust quality control for feedstock, corrosion-resistant tanks and pipelines, and rigorous safety protocols.

Fast pyrolysis operates at 450–550°C, is technically mature (TRL 6–8), and has been commercially demonstrated. However, bio-oil must be stabilized to prevent degradation. Technologies like hydrogenation and buffering are under development to improve storage integrity. Despite challenges, net-negative emissions can be achieved, especially if systems are powered by renewable energy and integrate co-product reuse (e.g., biochar as a soil amendment).

Summary of Benefits and Drawbacks

The following table summarizes the key benefits and drawbacks associated with converting woody biomass into bio-oil through fast pyrolysis (Table 2.21). Bio-oil offers a unique value proposition within the biomass utilization landscape, combining carbon removal potential with co-product recovery and flexible deployment. However, technical complexity, regulatory oversight, and infrastructure demands introduce challenges that must be carefully managed. This table outlines the major considerations to help assess the feasibility and strategic fit of bio-oil systems in Boulder County's biomass management and climate resilience efforts.

Table 2.21. Benefits and drawbacks of bio-oil production and sequestration.

Category	Benefits	Drawbacks
Carbon and Climate Impact	Achieves permanent carbon removal through geological injection of bio-oil; supports net-negative emissions	Requires long-term monitoring of injection sites to manage risks like seismicity or brine migration
Feedstock Utilization	Converts low-value woody biomass and liability fuels into high-value carbon removal and energy products	Biomass variability can reduce pyrolysis efficiency and affect product consistency
Revenue Potential	Generates premium carbon removal credits (≈$750/ton CO_2); strong corporate demand (e.g., Google)	High capital and operational costs; economic viability currently hinges on voluntary carbon market pricing
Deployment Flexibility	Mobile pyrolysis units allow on-site processing, reducing biomass transport and emissions	Bio-oil is chemically unstable and corrosive, requiring specialized handling, storage, and transportation
Co-Product Value	Produces biochar and syngas, enabling additional climate and soil benefits	Co-product markets are still emerging and may require investment in additional processing or logistics
Environmental Performance	Lower lifecycle emissions than fossil fuels; supports wildfire mitigation and forest health	Emissions from pyrolysis (PM, VOCs, NO_x) must be controlled with appropriate air quality systems
Technical Viability	Fast pyrolysis is commercially demonstrated (TRL 6–8); adaptable to regional biomass conditions	Limited regional infrastructure for injection and stabilization may constrain near-term scalability

Post and Pole

Overview

The production of wood posts and poles offers an efficient and sustainable use of small-diameter trees and residual biomass generated from forest thinning, wildfire mitigation, and land management operations. Common softwoods such as lodgepole pine, ponderosa pine, Douglas fir, and red pine are primarily used due to their straight form and ease of peeling and treatment. The process begins with mechanical or high-pressure debarking, followed by shaping, sizing, and drying - either by air or in kilns. Finished products typically undergo preservative treatment (e.g., pressure impregnation with copper-based chemicals or thermal modification) to enhance durability, especially for outdoor applications. Throughout processing, byproducts like bark, sawdust, and trimmings are repurposed into mulch, pellets, or composite wood products. With proper handling and compliance, post and pole production supports wildfire risk reduction, forest health goals, and local economic development.

Applications

Posts and poles serve a wide variety of practical applications. These include agricultural fencing, utility infrastructure, trail construction, structural supports, landscaping features, and erosion control measures like retaining walls and riverbank stabilization. In Boulder County, demand is driven by agricultural operations, local construction, and restoration projects. For example, United Wood Products and JKC Woods LLC provide locally sourced materials for fencing, beams, and decorative landscaping features. The widespread utility and aesthetic versatility of wood posts make them suitable for both functional and design-based uses, reinforcing their market relevance across urban and rural settings.

Feedstock Considerations

The ideal feedstock consists of straight, solid roundwood with minimal taper, sweep, or visible defects such as knots, spiral grain, or rot. Preferred species include lodgepole pine, ponderosa pine, Douglas fir, and southern yellow pine, which respond well to peeling and treatment. Some hardwoods, such as black locust and eucalyptus, are used when natural durability is preferred. Standard log lengths range from 6 to 12 feet, though utility poles may exceed 25 feet. Diameter requirements vary: fence posts are typically 3 - 6 inches in diameter, while utility poles range from 8 to 12 inches or more (Table 2.22). Yield depends on wood species, moisture content, and size. Processing waste (10–30%) and green vs. dry weight differences also affect output.

Table 2.22. Estimated yields from one ton of wood.

Post/Pole Size (Dia x Length)	Volume per Post (ft^3)	Weight per Post (lbs, dry)	Posts per Ton (2,000 lbs)
4" x 6' (Fence Post)	~0.5 ft^3	~17 lbs	~115 posts
4" x 8'	~0.67 ft^3	~23 lbs	~87 posts
6" x 8'	~1.5 ft^3	~52 lbs	~38 posts
6" x 12'	~2.25 ft^3	~78 lbs	~26 posts
8" x 20' (Utility Pole)	~7 ft^3	~245 lbs	~8 posts
10" x 25'	~13.6 ft^3	~476 lbs	~4 posts

Economic Considerations

Economic viability depends on biomass characteristics, product specifications, labor, and scale. Debarking and peeling cost between $20 - $40 per ton, with trimming, grading, and sorting adding

$10 - $25 per ton. Preservative treatments cost $0.50 - $1.50 per linear foot, and drying (especially kiln drying) adds another $20 - $35 per ton. Labor, typically ranging from $20 - $35 per hour, is a significant cost factor, along with safety compliance and insurance. Equipment investments range from $50,000 for small setups to over $250,000 for mechanized systems.

Production costs vary based on treatment and finish:

- Untreated posts: $0.80 - $2.50 per linear foot
- Treated/final products: $2.00 - $4.50 per linear foot
- Total processing and delivery: $80 - $160 per ton

Costs are competitive with other low-tech biomass pathways and scale moderately with production volume.

Environmental Considerations

Environmental impacts are mostly associated with processing rather than harvest. Pressure-treated posts - particularly those using copper-based preservatives - can pose contamination risks if runoff is not managed. Treatment facilities must include containment, spill response systems, and proper permitting. Kiln drying can emit VOCs, particulates, and GHGs, requiring emissions controls. Dust from debarking and trimming may pose health risks without filtration and PPE.

Wood waste (e.g., bark, trimmings, defects) should be reused as mulch, compost, or biomass fuel to minimize landfill disposal. Properly managed, post and pole production supports forest thinning, reduces wildfire risk, and contributes to carbon sequestration by displacing emissions-intensive building materials. Siting facilities away from sensitive communities and applying best management practices further mitigates noise and visual impacts.

Infrastructure and Technical Considerations

Post and pole production is technically mature and readily scalable. Small to medium operations can be established using mobile or fixed processing equipment. Air or kiln drying, mechanical peeling, and preservative treatment systems are commercially available and adaptable to a variety of biomass types. Harvesting liability biomass for poles is feasible with existing forestry equipment, and technical standards such as ASTM and AWPA ensure product reliability. In Boulder County, existing agricultural and construction markets, plus regional sustainability goals, support infrastructure development. Local suppliers like JKC Woods and United Wood Products already serve relevant markets, indicating strong integration potential.

Summary of Benefits and Drawbacks

The table below outlines the key benefits and drawbacks of using small-diameter woody biomass for post and pole production (Table 2.23). This pathway offers a practical, low-tech solution to convert thinning residues and other liability biomass into durable, market-ready wood products. With well-established applications in agriculture, construction, and landscaping, post and pole production supports wildfire risk reduction while stimulating local economies. However, the use of chemical treatments, air emissions, and feedstock constraints introduce operational and regulatory challenges that must be addressed. The following table provides a side-by-side evaluation of these trade-offs to support decision-making in biomass utilization planning.

Table 2.23. Benefits and drawbacks of post and pole production.

Category	Benefits	Drawbacks
Feedstock Utilization	Effectively uses small-diameter logs and liability biomass from forest thinning	Requires straight, defect-free logs—limiting use of some irregular or lower-grade materials
Market Demand	Consistent demand for fence posts, utility poles, landscaping materials, and erosion control	Market saturation possible at scale; product value depends on species, treatment, and finish
Economic Viability	Modest capital investment; low-tech operations can be locally scaled	Treatment, grading, and drying add processing costs; labor and compliance raise overhead
Environmental Co-benefits	Supports forest health, reduces fire risk, and displaces emissions-intensive alternatives	Treated wood may leach chemicals; kiln drying and debarking emit particulates and VOCs
Byproduct Recovery	Bark, trimmings, and sawdust easily repurposed for mulch, compost, or fuel	Requires systems to manage and store processing residues to prevent waste or fire risk
Infrastructure Readiness	Commercially available equipment; compatible with mobile or fixed facilities	Chemical treatment systems require containment, spill response, and permitting
Technical Maturity	Proven technologies with standardized products and grading systems (e.g., ASTM, AWPA)	Requires skilled handling and grading to meet quality and safety standards

Fungal Decomposition

Overview

Induced fungal decomposition - also known as fungal decay - is a biologically driven technique that accelerates the breakdown of lignocellulosic woody materials through the intentional cultivation of saprotrophic fungi. This method leverages native or locally adapted fungal species to manage woody biomass on-site, enhance soil health, and improve nutrient cycling without the need for industrial processing. Though fungi have long been known to decompose wood in natural ecosystems, the targeted application of fungal decay as a forest biomass management strategy is relatively new, with the first long-scale trial launched by the Coalition for the Upper South Platte in 2014. Field-scale implementation can process forest by-products such as slash, chips, and small-diameter limbs over a 3-to-5-year period, reducing fire risk and supporting ecological restoration.

Applications

Fungal decomposition offers a promising biomass management tool for wildfire mitigation, ecological restoration, and soil enrichment. It is particularly well-suited for remote or ecologically sensitive areas where traditional biomass removal or industrial processing is impractical or costly. Applications include in-forest chip pile decomposition, restoration of degraded soils, and on-site recycling of forest thinning residues. The process can also be integrated into agricultural land applications where mycelium-enriched substrates may benefit soil structure and fertility. Locally, Boulder Mushroom and MycoReach have piloted the use of active mycelium to decompose excess biomass in forests and urban-agricultural interfaces, in partnership with Boulder County and City of Boulder agencies.

Feedstock Considerations

Fungal decomposition requires a clean, lignin-rich substrate, free of excessive soil, rocks, or chemical contaminants. Ideal feedstocks include freshly chipped tops, limbs, and small boles. Materials that have been masticated, or that contain substantial dirt, are not suitable due to poor air flow and contamination. These feedstock constraints may necessitate modified forest treatment prescriptions, which could raise upfront costs. However, when compared with high-cost alternatives such as chip-and-haul, fungal decomposition may offer significant savings in situations where biomass cannot be economically transported or processed.

Economic Considerations

The economics of fungal decomposition vary based on project size, fungal strain sourcing, and application method. Small projects that require custom or native strain development incur higher costs due to the labor and time needed to clean, propagate, and condition fungi. In contrast, larger projects that can reuse existing, locally sourced inoculum are more cost-effective. Treatment costs have been reported in the range of $45 to $150 per bone-dry ton (BDT) of wood chips. Although commercial fungal strains could reduce costs, their use is discouraged due to potential ecological risks. Thus, balancing cost savings with ecological integrity is central to project design.

Environmental Considerations

When properly applied using native fungal species, fungal decomposition carries very low environmental risk. The process promotes nutrient retention, minimizes emissions by avoiding combustion, and may enhance long-term soil carbon sequestration. Because fungal decay occurs at the treatment site, it eliminates the need for transportation and reduces labor and fuel inputs. However, ecological risks arise if non-native or commercial fungal strains are used without strict biosecurity controls. Successful implementation requires adherence to chain-of-custody protocols and ecological safeguards, as inappropriate inoculation could lead to the spread of invasive fungal species.

Infrastructure and Technical Considerations

Fungal decomposition requires specialized expertise in mycology, microbiology, and ecological restoration. It also demands strict biosecurity and standardized protocols to avoid cross-contamination or ecological disruption. Currently, there are few commercial facilities capable of producing high-quality fungal inoculum. The two notable examples in the Boulder region are MycoReach in Wheat Ridge and Boulder Mushroom, which have demonstrated the viability of fungal decay at small scales. Due to the difficulty and cost of transporting fungal spawn over long distances, a decentralized model - where localized facilities produce and apply inoculum - is considered the most promising for scale-up. Despite its potential, the technique lacks standardized protocols, and there is currently no National Environmental Policy Act (NEPA) assessment to guide its application on federal lands, which limits broader adoption.

Summary of Benefits and Drawbacks

The following table (Table 2.24) summarizes the key benefits and drawbacks of using fungal decomposition as a biomass management strategy. This emerging pathway offers a low-impact, decentralized solution for forest restoration, wildfire mitigation, and soil enhancement, particularly in areas where transportation and industrial processing of woody biomass are not feasible. However, fungal decomposition is still an experimental practice that requires specialized expertise, careful ecological controls, and further regulatory development.

Table 2.24. Benefits and drawbacks of fungal decomposition pathway.

Category	Benefits	Drawbacks
Environmental Impact	Low-impact, in-situ decomposition with no combustion or transport emissions	Use of non-native fungi poses ecological risks if not properly controlled
Soil and Ecosystem Health	Enhances nutrient cycling, microbial activity, and long-term soil carbon sequestration	Effectiveness may vary with site conditions, fungal strain, and feedstock quality
Cost Efficiency	Avoids chip hauling and industrial processing; cost range of $45–$150 per BDT is competitive	Higher costs if custom or native fungal strains must be developed or scaled
Infrastructure Needs	Requires minimal physical infrastructure and supports decentralized implementation	Limited access to commercial inoculum; few specialized facilities currently exist
Technical Feasibility	Once inoculated, the process is low-maintenance and passive	Requires expertise in mycology, microbiology, and ecological site assessment
Scalability and Access	Rapid inoculum expansion possible; well-suited to small and remote sites	No standardized protocols or NEPA assessment limits applicability on federal and state-managed lands
Feedstock Compatibility	Works well with clean, freshly chipped material from thinning or slash piles	Not suitable for dirty, masticated, or soil-contaminated biomass

Life Cycle Assessment of Selected Biomass Utilization Pathways

Life Cycle Assessment (LCA) is an analytical approach used to evaluate the environmental impacts associated with all stages of a product's life - from raw material extraction through processing, distribution, use, and eventual disposal. In the context of biomass utilization pathways selected by the project's Core Team for more in-depth evaluation, such as composting, biochar production, and firewood production and consumption, LCA serves as an appropriate method for quantifying greenhouse gas (GHG) emissions and comparing the relative magnitude of impact of the different pathways. By assessing each phase of these processes, LCA provides insights into the carbon footprint and overall sustainability of these biomass applications.

Composting, for instance, involves the aerobic decomposition of organic materials, resulting in the release of carbon dioxide (CO_2) and, under certain conditions, methane (CH_4), a potent GHG. An LCA can help determine the net GHG emissions by accounting for factors such as the energy consumed during composting operations and the potential for methane emissions if managed improperly. Studies have shown that while composting emits GHGs, it can also lead to carbon sequestration in soils and reduce the need for synthetic fertilizers, thereby offsetting some emissions (e.g., Nordahl et al., 2020).

Biochar production entails the pyrolysis of biomass, a process that thermally decomposes organic material in an oxygen-limited environment to yield a stable form of carbon (Wang and Wang, 2019). When applied to soil, biochar can sequester carbon for long periods, potentially mitigating climate change. However, the overall GHG impact of biochar systems depend on various factors, including feedstock type, pyrolysis conditions, and the fate of co-products like syngas and bio-oil. LCAs of biochar systems have demonstrated that, under optimal conditions, the carbon sequestration benefits can outweigh the emissions associated with biochar production and application (Wang and Wang, 2019).

As a renewable heat energy source, firewood can offer a sustainable alternative to fossil fuels (e.g., natural gas) when harvested and burned responsibly. It is typically used in residential wood stoves, fireplaces, and larger-scale heating systems like district heating plants or industrial boilers. From an energy perspective, firewood provides a significant amount of heat per unit of mass, although its efficiency varies depending on moisture content, combustion technology, and stove design (Calvo et al., 2014).

The overall goal of the LCA for this project was to analyze the GHG emissions and carbon sequestration potential of each of the three biomass utilization pathways for the Boulder County region as identified by the project's Core Team. Since no biomass volumes were specified for these pathways, we calculated GHG emission impact for a processing capacity of 10,000 dry green short tons as feedstock.

Specific objectives of this task included:

- Estimate temporal and spatial scales of GHG fluxes.
- Estimate GHG emissions from all segments of the biomass supply chain, informed by the feedstock estimates and their associated uncertainties.
- Estimate carbon sequestration losses and gains, including any temporal changes and amounts of sequestration.

Approach

To complete a life cycle analysis (LCA) of biomass utilization pathways for greenhouse gas (GHG) impacts associated with composting, biochar, and firewood, we followed a structured, comparative approach grounded in ISO 14040 (ISO, 2006a) and 14044 standards (ISO, 2006b; Finkbeiner et al., 2006). The process began by defining the goal and scope of the study, including the functional unit - often a specific mass of biomass (e.g., one metric ton of feedstock) - and the system boundaries, which encompass all relevant stages from feedstock collection to end-use application. For composting and biochar, this includes biomass collection (e.g., forest residues), transportation, processing (composting or pyrolysis), and land application on rangelands, accounting for carbon sequestration benefits and soil emissions. For firewood, the system covered harvesting, transportation, processing (e.g., drying), combustion for heat, and associated emissions. Inventory analysis involves gathering data on energy inputs, fuel use, equipment emissions, and carbon storage potential. Emission factors were used to quantify direct and indirect GHG emissions for the alternative (utilized) and baseline (pile burnt, not utilized) scenarios. The impact assessment phase converts inventory data into GHG emission equivalents (e.g., CO_2e), allowing comparison among the pathways.

Assessment Boundaries and Functional Units

Unless noted otherwise in the specific technology pathways described below, the following assessment boundaries apply:

- GHG emissions considered were restricted to emissions associated with the production process and operations itself, as well as the fate of the product.
- The temporal and spatial boundaries differ by pathway based on available information (e.g., longevity of compost or biochar in soils) and are described for the different pathways evaluated.
- The assessed impact category was climate impact, and wherever possible, included carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) emissions as well as black carbon and particulate matter ($PM_{2.5}$) for pile burn related GHG emissions.
- The functional unit in an LCA provides the ultimate unit to report results and compare the (GHG) impact of different choices as explored in an LCA. The functional unit in this context is metric tonnes (or mega grams [Mg]) of carbon dioxide equivalents (100-year Mg CO_2e) for the entire system analyzed with a time horizon of 100 years for GHG-relevant activity impacts. This functional unit allows to also consider non-CO_2 emissions (e.g., methane, nitrous oxide) in its impact analysis which can be cross walked into CO_2e through an established value that defines the global warming potential (GWP) relative to CO_2. This GWP considers both radiative forcing and longevity/temporal residence time functions in the atmosphere as it might differ compared to CO_2.
- Some GHG impact categories, while quantifiable, fall under a '*de minimis*' approach or rule where the lack of overall significance of a given impact category for the overall GHG assessment does not merit the assessment effort involved. The application of the *de minimis* rule is mentioned in the specific biomass technology pathways below where applicable.

Life Cycle Assessment Model Development and Application

The LCA models used were custom developed for the utilization pathways evaluated (compost, biochar, firewood) relying on latest scientific data and peer reviewed literature. All pathways were analyzed with an *Excel* based spreadsheet tool developed for this purpose. Inputs for pile burning were derived from various sources (Springsteen et al. 2015; IPCC 5th Assessment Rep. 2014, Ebert et al. 2023). Key input variables for the pile burning GHG flux calculations are detailed in Table 2.25.

Table 2.25. Key input variables for the pile burn GHG flux calculations.

General Inputs	Global Warming Potential (Mg CO2e)	Value (MtCO2e/ Mg dry biomass)	Source
Carbon Dioxide (CO_2)	1	1.71	Springsteen et al. 2015; IPCC 5th Assessment Rep. 2014
Carbon Monoxide (CO)	1.8	0.12	Springsteen et al. 2015; IPCC 5th Assessment Rep. 2014
Methane (CH_4)	28	0.14	Springsteen et al. 2015; IPCC 5th Assessment Rep. 2014
Non-methane Organic Compounds (NMOC)	5	0.01	Springsteen et al. 2015; Ebert et al. 2023
Particulate Matter (PM2.5)	9	0.05	Springsteen et al. 2015; Ebert et al. 2023
Black Carbon (BC)	900	0.29	Springsteen et al. 2015; IPCC 5th Assessment Rep. 2014 Table 8.A.6
Modified Combustion Efficiency (%)	N/A	94%	Springsteen et al. 2015

Utilization Pathways Analysis

The Core Team, with supporting analysis described in the previous section of this report, identified three utilization pathways for LCA, namely composting, biochar, and firewood. For each pathway, we added the climate benefits generated through the fuel reduction treatments. These were calculated using the 200,826 metric tons CO_2e that were generated when implementing all fuel treatments combined (see following section on Avoided Wildfire Emissions section in Chapter 3 of this report). These fuel treatments were assessed to generate a total of ~12,700 dry metric tons of biomass (see Chapter 1) and hence a climate benefit of 1.66 metric tons of CO_2e per dry metric ton of liability biomass. While this additional benefit is only realized if all treatments are implemented and the pathways assessed below could also receive feedstock from other biomass sources (e.g., urban), this additional climate benefit should be applied with caution as it assumes woody biomass from treatments are utilized.

Compost - Life Cycle Assessment

Feedstock

This pathway explores the climate impact of adding 10,000 dry short tons of wood chips to a composting process with 20-30% of the final compost product being derived from wood. To determine the scale of the GHG impact of this pathway, it was assumed that the biomass would be pile burnt if not used for composting (baseline scenario). Only a minimum of the feedstock would be used for mulching instead of composting and was considered *de minimis* in this context.

While compost (as well as biochar) can also be applied to other land-use types at potentially higher rates and volumes (e.g., irrigated cropland), this analysis focused on rangeland applications to allow for a more transparent comparison across pathways that contain a soil amendment component.

Process and Analytical Boundary

Key assumptions on process and analytical boundary for the compost pathway included:

- Composting follows the windrow method with minimal processing efforts (e.g., no in-vessel composting).
- Compost production adds GHG emissions due to feedstock transport to the facility and compost transport to end use, compared to on-site burning.
- No process heat is required to produce compost.
- Fossil fuel emissions to operate the composting process (turning/aeration) were considered *de minimis* (per Mondello et al., 2017; 0.5 liters diesel and 0.145 MWh electricity per Mg wet food waste).
- Baseline scenario pile burn emissions from woody biomass account for a portion of the biomass that remains stored as charcoal (around 4%) on site. Non-CO_2 GHG emissions during the pile burn process are considered, including black carbon.
- Compost applications on rangelands do not replace mineral nitrogen fertilizer.
- Compost is applied once over the overall temporal impact boundary of 20 years (see also Table 2.25). Such a one-time application and the respective rate is also supported by Ryals et al. (2015) and Ryals and Silver (2013) with the latter concluding that "*a single application of composted organic matter can significantly increase grassland C storage, and that effects of a single application are likely to carry over in time.*"

Products

The product associated with this pathway is compost.

Baseline and Enhancement Assumptions

Besides the assumptions outlined above concerning process boundaries, the LCA relied on key inputs described in 2.26, and Table 2.25 (above) for pile burn related GHG fluxes. We also assumed that the composting process is well designed and non-CO_2 GHG emissions (CH_4 and N_2O) due to low turning frequency and non-uniform aeration are avoided (Serafini et al., 2023).

Table 2.26. Key inputs for compost production and associated baseline assumptions.

Variable	Unit	Value	Source	Comment
General Inputs				
Liability Biomass	Short tons (dry)	10,000		Internal assumption
Compost Conversion Rate	Mg compost (dry)/Mg feedstock (dry)	0.5		Internal assumption
Compost Moisture Content	% of total weight	50%		Internal assumption
Carbon Content Feedstock	% of dry weight	50%		
Carbon Content Compost	% of dry weight	20%	Ryals and Silver (2013)	1.42 kg C/m^2 or 7.0 kg of dry matter /m^2 at 1.3 cm application rate
Processing Emissions				
Machinery		N/A		Fossil fuel input (machinery) *de minimis*
Transport to Compost Facility	Miles (return trip)	60		Assumed transport distance to compost processing facility.
Transportation to End Use	Miles (return trip)	60		Assumed transport distance to end use
Truck Emissions	Mg CO_2e/short ton/mi	0.002	EPA (2023)	Total GWP; truck emissions
Compost Application on Rangeland				
Application Rate	Mg (dry)/acre	15.4	CMCDA (2020), based on Ryals and Silver (2013)	One time application, 35 cubic yards (17 tons compost)/acre (1/4")
Sequestration Factor	Mg CO_2e/acre/year	1.49	CMCDA (2020), based on Ryals and Silver (2013)	Compared to Terracount (Tukman, 2018) Activity sheets (soil amendments: grassland/irrigated pasture): 4.45 Mg CO_2e/ac/year (10 yrs)
Sequestration Lifespan	Years	20	CMCDA (2020), based on Ryals and Silver (2013)	Compared to Terracount (Tukman, 2018) Activity sheets (soil amendments: grassland/irrigated pasture): 4.45 Mg CO_2e/ac/year (10 yrs)

Results from LCA - Composting

The total 100-year GHG benefits for this pathway are in the range of 9,550 Mg CO_2e (Table 2.27) with around 18,000 Mg (dry) compost produced (recall that ~25% of compost is derived from wood-based feedstock) and 1,200 acres of rangeland treated per year. Most of the benefits are associated with avoided pile burn emissions (Figure 2.1). When only considering soil amendment related benefits, the net GHG benefits per treated acre of rangeland over the 20-year time horizon for a one-time compost application are in the range of ~1.5 Mg CO_2e/acre/year (~29 Mg CO_2e/acre over 20 years). This result supports results from Ryals and Silver (2013) and Silver et al. (2018) who estimated 1.68 Mg CO_2e/acre/year, and 1.42 Mg CO_2e/acre/year, respectively, for similar application rates. GHG benefits assumed in Terracount for compost applications on rangeland is considerably higher (4.45 Mg CO_2e/acre/year; Tukman, 2018) but also includes the substitution of mineral nitrogen fertilizer which is unlikely to be applied on rangeland. Up to ~1,200 acres of rangeland could receive compost annually, sustaining a total treatment of ~24,000 acres over 20 years. Notably, Boulder County Open Space has 7,400 acres of rangeland for comparison.[9]

Table 2.27. GHG relevant results for the composting technology pathway. Primary outputs refer to the GHG emission impact analysis (LCA) while secondary outputs are of additional informational value. GHG benefits are accruing and are being reported on an annual basis but include GHG fluxes out to 100 years post application.

Output Variable	Unit	Value
Primary Outputs		
100-Year GHG Benefits from Compost Application	Mg CO_2e/year	1,800
Biogenic Emissions During Production Process	Mg CO2e/year	(9,900)
Liability Biomass Transport Emissions	Mg CO_2e/year	(2,400)
Compost Transportation Emissions	Mg CO_2e/year	(950)
Avoided Pile Burn Emissions	Mg CO_2e/year	21,000
Total GHG Benefits	**Mg CO_2e/year**	**9,550**
Secondary Outputs		
Compost Produced	Mg (dry)/year	18,000
Treated Rangeland	Acres/year	1,200
100-year GHG Benefits per Unit of Compost	Mg CO_2e/Mg compost (dry)	1.9
100-year GHG Benefits per Unit of Feedstock	Mg CO_2e/Mg feedstock (dry)	1.0
100-year GHG Benefits Per Unit of Feedstock Including AWE (assuming 2.7% ABP)	Mg CO2e/Mg feedstock (dry)	2.7
100-year GHG Benefits per Treated Acre and Year (soil amendment only)	Mg CO_2e/acre/year	1.5

[9] https://bouldercounty.gov/open-space/management/agriculture/statistics-and-acres/

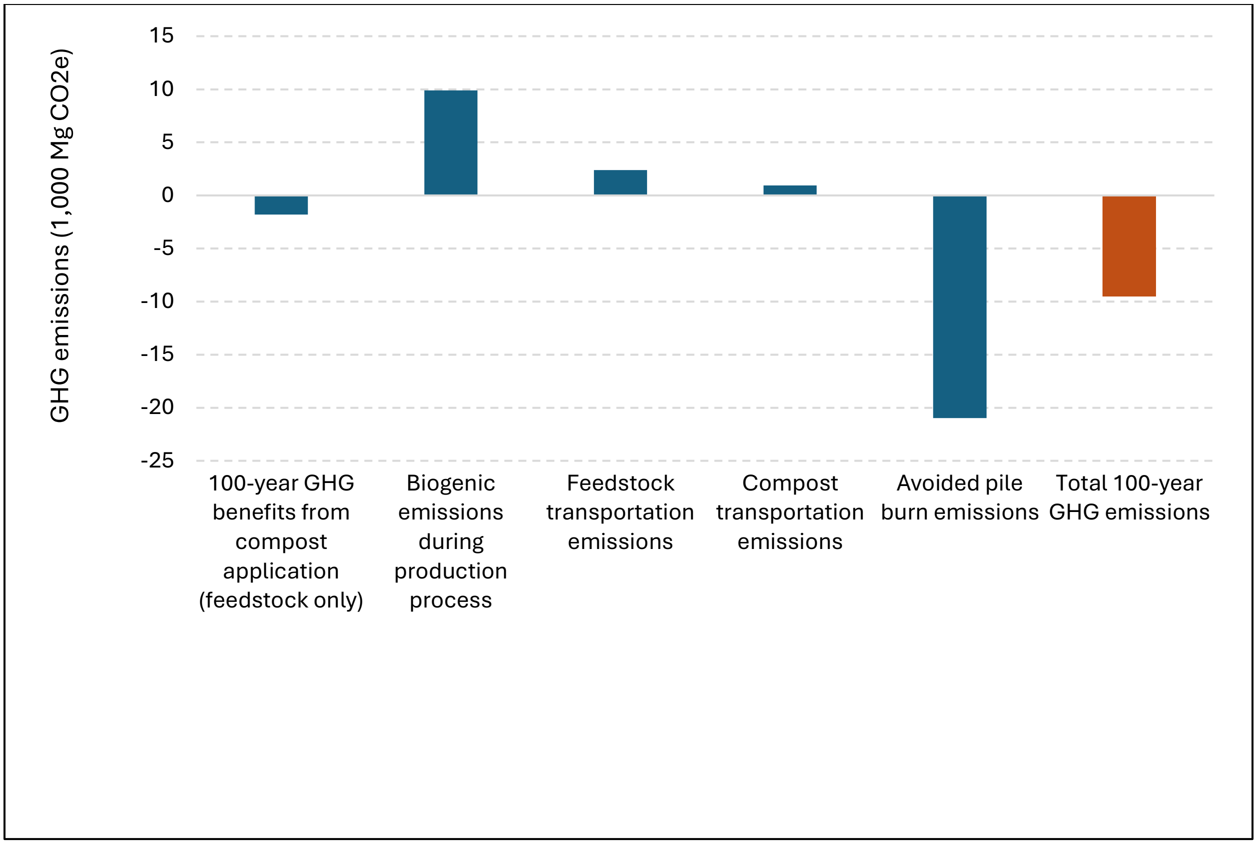


Figure 2.1: GHG benefits from compost production by accounting element and total.

Biochar – Life Cycle Assessment

Feedstock

This pathway explores the climate impact of a biochar production system similar to what *Biochar Now*[10] utilizes. Results are presented for 10,000 dry short tons of biomass feedstock processed. To determine the scale of the GHG impact of this pathway, it was assumed that the biomass would be pile burnt on site if not used for biochar production.

While biochar can also be applied to other land-use types at potentially higher rates and volumes (e.g., irrigated agriculture), this analysis focused on rangeland applications to allow for a more direct comparison across technology pathways that contain a soil amendment component. Fractions of biochar can also be used for remediation work for gas wells or water filtration. The GHG benefits of non-biological applications of biochar were not considered for this effort.

Process and Analytical Boundaries

Key assumptions on process and analytical boundary for the compost pathway included:

- Biochar production can result in additional GHG emissions due to the transportation of feedstock to the production facility and its subsequent transport to the end use location, such as rangeland, compared to the baseline scenario of on-site pile burning.
- The biochar process is well maintained and produces high-quality biochar (high carbon content associated with long residence time).
- The heat required for biochar production is derived from the unit itself (e.g., Timonen et al., 2019).
- Syngas is flared (i.e., no CH_4 emissions, no electricity production or other use of excess heat production).
- Baseline scenario pile-burn emissions from woody biomass account for a portion of the biomass that remains stored as charcoal (around 4%) on site. Non-CO_2 GHG emissions during the pile burn process are considered, including black carbon
- Biochar applications on rangelands do not replace mineral nitrogen fertilizer.

Products

The product associated with this pathway is biochar.

Baseline and Enhancement Assumptions

Besides the assumptions outlined above concerning process boundaries, the LCA relied on key inputs described in Table 2.28.

[10] Biochar Now - https://biocharnow.com/

Table 2.28. Key inputs for biochar production and associated baseline assumptions.

Variable	Unit	Value	Source	Comment
General Inputs				
Forest Biomass	Short tons (dry)	10,000		
Biochar Yield	% of dry weight	35%		Focus on biochar production. Regular pyrolysis (focus on electricity generation): 5-25%
Carbon Biosolid Converted to CH_4	% of dry weight	5%	EPA (2014)	
Energy Content Biogas	MWh/m^3 LHV	0.006	IEA (2023)	Equivalent to ~700BTU/ft^3
Processing Emissions				
Internal Electricity Need	% of Generating Capacity	10%		Internal electricity needs
Transport to Biochar Facility	Miles (return trip)	60		
Transport to End Use (Rangeland)	Miles (return trip)	60		
Truck Emissions	Mg CO_2e /short ton/mi	0.002	EPA (2023)	Total GWP; truck emissions
Biochar Application on Rangeland				
Biochar Sequestration Lifespan	Years	100	Woolf et al. (2021)	
Biochar GHG Impact Factor	Mg CO_2e /acre	5		Output calculations; entirely based on data from Woolf et al., 2021
Biochar GHG Impact Factor	Mg CO_2e /Mg biochar	2		Output calculations; entirely based on data from Woolf et al., 2021

Results - Biochar

Total 100-year GHG benefits for this pathway are in the range of ~11,200 Mg CO_2e (Table 2.29) with around ~3,200 Mg biochar produced. Most of the benefits are associated with the avoided pile burn emissions (Figure 2.2). The net GHG benefits per treated acre of rangeland are expected to be in the range of ~1.2 Mg CO2/acre/year and are assumed to be maintained for 100 years (Table 2.29). The 100-year GHG benefits per Mg of biochar equals ~1.0 Mg CO_2e which is in line with estimations of Brown et al. (2023) on grassland in the temperate zone.[11] Due to the longevity of GHG benefits associated with a one-time biochar application, as much as 1,300 acres of rangeland could be treated annually with no follow up treatment required (i.e., a total of 130,000 acres over 100 years). For comparison, Boulder County Open Space has 7,400 acres of rangeland. Total GHG benefits could be increased by ~25% to a total of ~14,200 Mt CO_2e if a fraction of the excess syngas was

[11] Brown et al. (2023) estimated an optimistic carbon storage value of 4.8 Mg CO_2e/Mg biochar at a loading rate of 8 Mg/acre. The assumptions in this report include a loading rate of 2.5 Mg biochar/acre which translates to 1.5 Mg CO_2e/Mg biochar when using Brown et al. (2023) results.

used.[12] For example, industrial process heat substituting for natural gas use (heating greenhouses, hot water, residential heat, etc.).

Table 2.29. GHG relevant results for the biochar technology pathway. Primary outputs refer to the GHG emission impact analysis (LCA) while secondary outputs are of additional informational value. GHG benefits are accruing and are being reported on an annual basis but include GHG fluxes out to 100 years post application.

Output Variable	Unit	Value
Primary Outputs		
100-year GHG Benefits from Biochar Application	Mg CO_2e/year	3,700
Biogenic Emissions During Production Process	Mg CO2e/y	(10,800)
Liability Biomass Transport Emissions	Mg CO_2e/year	(2,400)
Biochar Transportation Emissions	Mg CO_2e/year	(300)
Avoided Pile Burn Emissions	Mg CO_2e/year	21,000
Total GHG Benefits	**Mg CO_2e/year**	**11,200**
Secondary Outputs		
Biochar Produced	Mg (dry)/year	3,200
Treated Rangeland	Acres/year	1,300
100-year GHG Benefits per Unit of Biochar	Mg CO_2e/Mg biochar	1.0
100-year GHG Benefits per Unit of Feedstock	**Mg CO_2e/Mg feedstock (dry)**	**1.2**
100-year GHG Benefits Per Unit of Feedstock Including AWE (2.7%ABP)	Mg CO2e/Mg feedstock (dry)	2.9
100-year GHG Benefits per Treated acre & year (soil amendment only)	Mg CO_2e/acre/year	1.2

[12] This refers only to excess flared syngas and unrecovered exhaust heat not utilized to maintain the biochar process. Substituting for other energy sources serving energy needs (fuel oil, propane, etc.) or applications (e.g. evaporative cooling) would impact results.

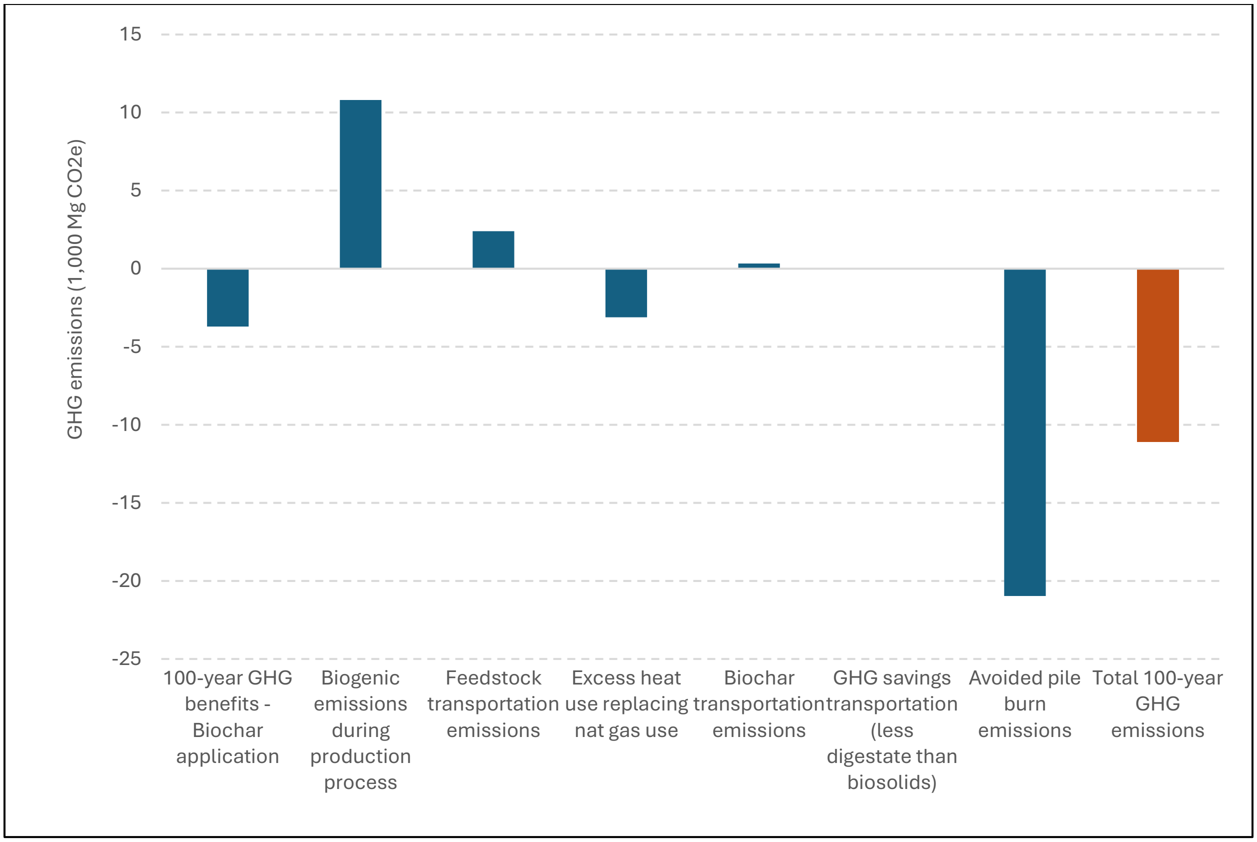


Figure 2.2: GHG benefits from biochar production by accounting element and totals.

Firewood - Life Cycle Assessment

Feedstock

This pathway explores the climate impact of a firewood production system. Results are presented for 10,000 dry short tons of biomass feedstock processed. To determine the scale of the GHG impact of this pathway, it was assumed that the biomass would be pile burnt if not used for firewood production. Notably, this pathway could only use liability biomass meeting certain standards (e.g., boles only of minimum diameter).

Process and Analytical Boundary

Key assumptions on process and analytical boundary for the firewood pathway included:

- Firewood production is assumed to add GHG emissions for transport of feedstock to the firewood facility as well as of firewood to end use compared to the baseline scenario of on-site pile burning.
- The firewood is air dried from ~40% to ~15% of moisture content on a wet basis. No fossil fuel is being spent to generate process heat for drying.
- Firewood use replaces the need for a mix of natural gas, propane, and heating oil at equal parts (33% of energy needs for each fossil fuel type).

Products

The product associated with this pathway is firewood produced to heat residential buildings.

Baseline And Enhancement Assumptions

Besides the assumptions outlined above concerning process boundaries, the LCA relied on key inputs described in Table 2.30. We also assumed that biomass in the absence of firewood production would be pile burnt (see Table 2.25, above, for key assumptions). We did not assume any loss of feedstock along the production line.

Table 2.30: Key inputs for firewood production and associated baseline assumptions.

Variable	Unit	Value	Source	Comment
General Inputs				
Liability Biomass	Short tons (dry)	10,000		
Moisture Content Firewood	Wet basis	40%		Moisture content wood
Feedstock Energy Content	MWh/Mg (dry); HHV	5.6	Freund et al., 2012	Feedstock energy content
Conversion Efficiency Firewood Heating	%	70%		Conversion efficiency firewood heating
Baseline Assumptions				
Natural Gas	Mg CO2e/MWh heat	0.267	Hennigar et al., 2013	
Natural Gas, Including Leakage	Mg CO2e/MWh heat	0.43	The Economist, 2016	
Diesel Fuel	Mg CO2e/MWh heat	0.357	Hennigar et al., 2013	
Propane	Mg CO2e/MWh heat	0.29	Hennigar et al., 2013	
Propane, Including Leakage	Mg CO2e/MWh heat	0.308	The Economist, 2016	fraction of natural gas distribution loss for propane production
Conversion Efficiency Baseline Heating	%	90%		Internal assumption
Processing Emissions				
Diesel Consumption	g/short ton split	1.5		Internal assumption
Diesel Emissions	Mg CO2e/g	0.01019	EIA, 2024	
Processing Emissions Firewood	Mg CO2e/MWh heat	0.007		Based on diesel emissions
Transport to Compost Facility	Miles (return trip)	60		
Transport to End Use	mi (return trip)	60		
Truck Emissions	Mg CO_2e /short ton/mi	0.002	EPA, 2023	Total GWP; truck emissions

Results

Total GHG benefits for this pathway are in the range of 10,900 Mg CO_2e (Table 2.31) with around 35,000 MWh of residential heat produced from firewood annually (Figure 2.3). Assuming an average heating demand of 103 million BTUs per household and year (EIA, 2009), this volume of firewood could heat around 1,170 homes. The 100-year GHG benefits per short ton of air-dried firewood equals 0.7 Mg CO2e which translates to 1.2 Mg CO2e/Mg feedstock (dry) or 2.9 Mg CO2e/Mg feedstock (dry) when including AWE benefits.

Table 2.31. GHG relevant results for the firewood production technology pathway. GHG benefits are accruing and are being reported on an annual basis but include GHG fluxes out to 100 years post application

Output Variable	Unit	Value
Primary Outputs		
100-y GHG Benefits - Firewood	Mg CO_2e/y	10,800
Biogenic emissions firewood use	Mg CO2e/y	(16,600)
GHG emissions – Liability Biomass Transportation	Mg CO_2e/y	(2,400)
GHG emissions – Firewood Transportation	Mg CO_2e/y	(1,800)
Avoided Pile Burn Emissions	Mg CO_2e/y	21,000
Total 100-y GHG Benefits	Mg CO_2e/y	10,900
Secondary Outputs		
Residential Heat Provided	MWh/y	35,000
Firewood Produced	Short Tons	10,000
Homes Heated	#	1,170
100-year GHG Benefits per Unit of Firewood	Mg CO_2e/short ton firewood (15% moisture)	0.6
100-year GHG Benefits per Unit of Feedstock	Mg CO_2e/Mg feedstock (dry)	1.2[13]
100-year GHG Benefits per Ton of Feedstock Including AWE (2.7% ABP)	Mg CO2e/Mg firewood	2.9

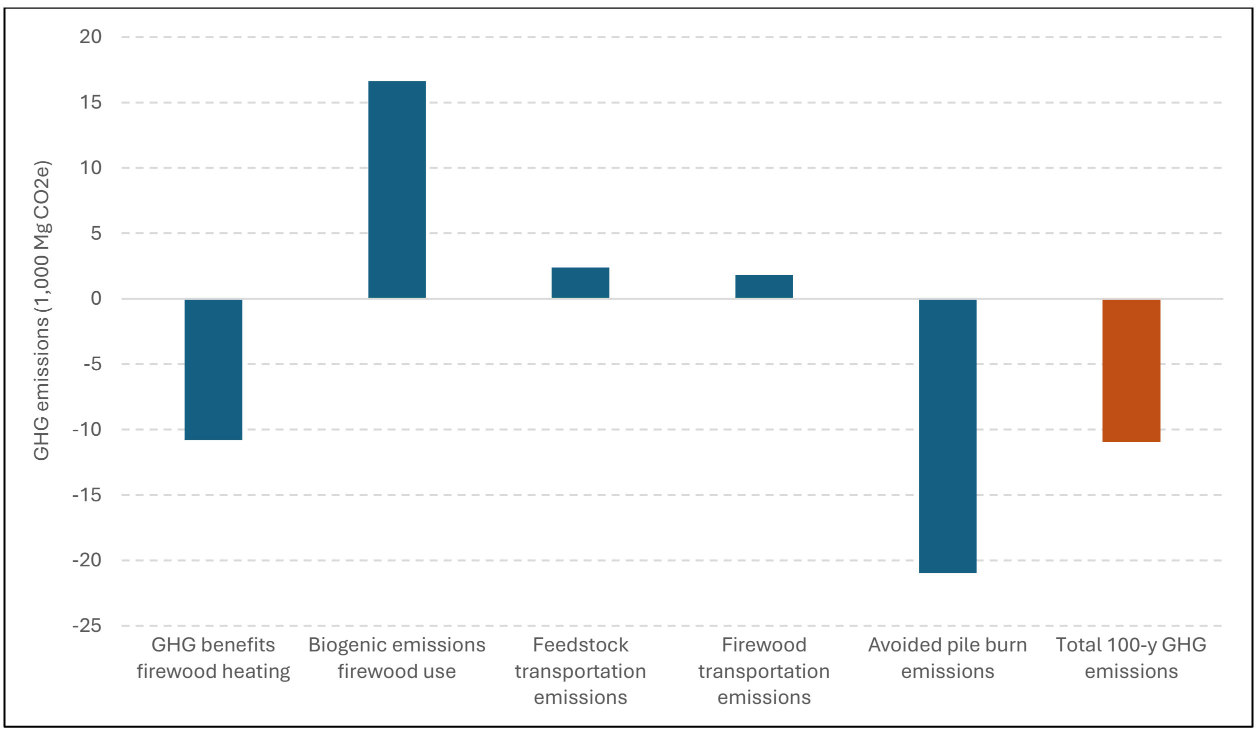


Figure 2.3: GHG benefits from firewood production by accounting element and totals.

[13] Results range from 1.05 to 1.4 Mg CO2e/Mg if firewood replaces natural gas or only oil, respectively. Propane substitution falls within that range.

Discussion - Life Cycle Assessment Results

The climate impacts across the three biomass utilization pathways - composting, biochar production, and firewood use - are relatively similar. Biochar and firewood pathways each achieve about 1.2 metric tons of CO_2-equivalent (Mg CO_2e) reduction per metric ton of dry liability biomass processed, while the composting pathway achieves slightly less, at about 1.0 Mg CO_2e per metric ton processed. In all cases, the baseline assumption - pile burning of biomass - has the largest influence on the overall climate benefit. For example, processing 10,000 dry metric tons of liability biomass annually would yield approximately 9,550 Mg CO_2e in annual benefits through composting, 11,200 Mg CO_2e through biochar production, and 11,000 Mg CO_2e through firewood use.

Given that the climate outcomes are comparable among the pathways, other factors become important in decision-making. These include the presence of existing infrastructure (such as operational composting facilities), the potential acreage improved (e.g., biochar production may benefit more acres than compost production), and air quality considerations (such as firewood use regulations that address smoke emissions).

Greenhouse gas (GHG) benefits from utilizing liability biomass can also help offset climate impacts in cases where avoided wildfire emissions (AWE) benefits are not realized at the forest site, such as those discussed in Chapter 3 under scenarios with an Avoided Burn Probability (ABP) of less than 2.7%. In other words, if a fuel treatment like mechanical thinning results in initial carbon losses that cannot be fully offset over time through improved fire behavior, the resulting "carbon debt" can still be partially mitigated through the climate-beneficial biomass utilization pathways described above.

However, using firewood as a heat source brings both benefits and challenges, particularly concerning health impacts and wood stove efficiency. Burning wood releases pollutants such as fine particulate matter (PM2.5), carbon monoxide (CO), volatile organic compounds (VOCs), and other hazardous air pollutants. Exposure to these emissions, especially PM2.5, has been linked to respiratory and cardiovascular diseases, including asthma, bronchitis, and heart disease. Communities that rely heavily on wood burning during the colder months often experience significant declines in air quality, posing additional public health risks. In terms of efficiency, older, uncertified wood stoves typically have low combustion efficiency, meaning they burn wood incompletely and produce higher levels of smoke and emissions. In contrast, modern EPA-certified wood stoves and advanced combustion technologies offer much higher efficiency, often exceeding 70%, and release significantly fewer emissions. These newer stoves burn wood more completely, reducing both the amount of wood needed and the impact on indoor and outdoor air quality. Even with these improvements, proper stove operation, the use of dry and seasoned wood, and regular maintenance are critical to achieving high efficiency and minimizing health risks associated with wood heating.

Chapter 3. Evaluation of Co-Benefits of Fuels Reduction Projects

Chapter 3 Summary

The evaluation of fuels reduction projects across Boulder County reveals a direct and measurable relationship between the scale and geographic distribution of treatments and the likely benefits they produce. Treatments evaluated - spanning completed, planned, and proposed projects - were modeled across diverse vegetation types, including ponderosa pine and lodgepole forest types, and topographies, encompassing a reasonably large treatment footprint (~ 58,000 acres) selected for wildfire risk mitigation based largely on treatment areas proposed in the 2024 Boulder County Community Wildfire Protection Plan. A literature review and modeling with the Forest Carbon Analysis Tool (FCAT) were used to illustrate multiple co-benefits in treated versus untreated scenarios using vegetation growth and wildfire simulations.

The findings demonstrate that larger-scale treatments - especially those proposed under the Boulder County CWPP (2024; modeled to occur by 2027) - yield climate benefits, including over 200,000 metric tonnes of avoided greenhouse gas emissions over 40 years if the annual burn probability is 2.7% or higher. Modeled treatments also indicated reductions in particulate matter and nitrogen oxide emissions by 17% and 52% respectively, indicating a likely benefit to public health if populations were exposed. At this scale, forest health metrics evaluated improved: treated areas exhibited 43% tree mortality (in terms of basal area) by 2047 compared to 75% tree mortality in untreated areas, and lower stand density index values indicated healthier forest structure with reduced competition and greater resilience. Canopy cover reductions in treated areas lowered the risk of high-severity crown fires while aligning with historical forest conditions.

A spatial analysis completed in combination with modeled outputs related to fire severity revealed that treated areas overlapping with special ecological designations - such as high biodiversity areas, wildlife corridors, and critical habitats - showed reduced long-term exposure to high-severity fire, illustrating how location-specific treatments confer biodiversity maintenance and habitat resilience. The chapter also underscores that fuel reduction and invasive species management are synergistic tools essential to maintaining ecological resilience in Boulder County. Furthermore, through a literature review, fuels treatments were found to mitigate cascading post-fire impacts like sedimentation, erosion, and water quality degradation, particularly in high-risk watersheds. These benefits were most pronounced in accessible, forested areas with moderate slopes near roads, where implementation was feasible at meaningful scales.

The chapter also reviews the implications of wildfire for recreation and tourism. While literature on economic impacts is mixed, wildfires in Boulder County can reduce visitation, damage infrastructure, and affect regional economies. Overall, the chapter supports the premise that thoughtfully planned and strategically implemented fuels treatments not only reduce fire risk but yield meaningful ecological and community co-benefits.

Chapter 3 Introduction

Wildfires can have profound effects on social, environmental, and economic values, often causing immediate and long-term impacts on communities, ecosystems, and regional economies (Thomas et al., 2017; Troy et al., 2022). Socially, wildfires threaten lives, displace communities, and create long-lasting trauma. They disrupt daily life by destroying homes, schools, and infrastructure while placing significant stress on emergency services. Public health can also suffer from smoke and poor air quality, which aggravates respiratory conditions and affects vulnerable populations. High-severity wildfires can alter landscapes, damage wildlife habitats, and disrupt ecosystems. They can cause soil degradation, increase erosion, and reduce water quality due to ash and sediment runoff into waterways. Economically, wildfires can impose enormous costs through firefighting efforts, property destruction, and loss of tourism and recreational opportunities. They can also disrupt industries like agriculture and forestry, while recovery and rebuilding demand significant financial resources. Despite these challenges, wildfires can also provide opportunities for rethinking land management, improving resilience, and fostering community collaboration to mitigate future risks. Importantly, in many ecosystems (including those in Boulder County), lower severity wildfire plays a critical and natural role in tree and understory plant regeneration, biodiversity, soil nutrient cycling, pest and pathogen control, and creation of open areas that benefit habitat diversity.

Wildfire activity in the western US and Boulder County has increased due to climate change, historical fire suppression practices, and expanding human development within the wildland-urban interface (WUI; Agee and Skinner, 2005; Abatzoglou and Kolden, 2013; Brenkert-Smith et al., 2013; Westerling 2016; Addington et al, 2018; Radeloff et al., 2018; Karau et al., 2024). Incidents such as the Fourmile Canyon Fire (2010), Calwood Fire (2020), and Marshall Fire (2021) highlight the region's exposure to high-severity and damaging fire events. The 2024 Boulder County Community Wildfire Protection Plan (Boulder County CWPP, 2024) identifies a trend of increasing wildfire frequency and severity, along with associated socio-ecological impacts.

The complex climate, topography and ecological diversity of Boulder County contribute to wildfire risk. Boulder County experiences hot, dry summers and seasonal high winds[14], particularly the Chinook or mountain wave winds (Durran, 1990), which can exceed 100 mph and rapidly spread fire (e.g., as experienced in the 2021 Marshall Fire; Karau et al., 2024; FEMA, 2025). Drought conditions and high temperatures, exacerbated by climate change, dry out vegetation and increase fuel aridity, making ignition and fire spread more likely in the western US (Abatzoglou and Kolden, 2013; Hagmann et al., 2021). Boulder County's landscape includes grasslands, shrublands, and lower to upper montane forests, creating varied fuel types that can facilitate intense and rapid fire spread. Concurrently, urban development encroaching into fire-prone areas increases risks to human settlements and infrastructure (Boulder County CWPP, 2024).

Fuel reduction treatments - when carefully planned for site specific conditions, implemented as designed, and maintained - can result in ecosystem and social benefits including climate benefits through avoided wildfire emissions. Depending on forest and vegetation type, reductions in forest stocking of live and dead biomass to an appropriate level through thinning, mechanical treatments, and/or prescribed burns can reduce the probability of future catastrophic wildfire, which in turn avoids a wide array of costs, but it also results in healthier forests with enhanced ecosystem function (Agee and Skinner, 2005; Stephens et al, 2012; Prichard et al, 2021, Davis et al., 2024). The following provides a general framing of the co-benefits that we address in this evaluation.

- *Forest Health and Resilience:* Landscape fuel treatments have been found to have a positive effect on competition dynamics, stand density, and post-disturbance regeneration, not only by reducing severe wildfire (Fallon et al., 2024) but also by creating a more favorable stand structure (Stephens et al. 2009; Davis et al., 2024). A combination of literature review and spatial modeling was used here to assess treatment impacts on forest

[14] Seasonal winds typically occur November to April, peaking December through February.

health, namely in terms of measures of forest structure, vegetation type conversion, soils, habitat and biodiversity, and invasive species.

- *Watershed Protection and Disaster Risk Mitigation:* Forested watersheds are critical to maintaining the timing and quality of water supply. The yield and timing of water supply from a watershed are strongly related to forest cover. High-severity, stand-replacing fire result in greatly increased surface runoff after storm events which causes erosion and sediment transport, compromising downstream water supplies (Jones et al 2017). Here we conducted a literature review on the influence of fuel reduction treatments on sedimentation rate, water quality, and flood and landslide susceptibility.
- *Climate and Carbon* - Wildfires play a critical role in the carbon cycle by influencing carbon storage and emissions in forests (Hall et al., 2024). Wildfires release large amounts of carbon dioxide (CO_2), methane (CH_4), and other greenhouse gases into the atmosphere, contributing to climate change. Burning trees and organic soil layers reduce the amount of carbon stored in forest biomass and soil. Post-fire ecosystems may take decades to recover carbon sequestration capacity, depending on fire severity and regeneration rates. Intense fires can cause soil carbon loss through volatilization and erosion, while moderate fires may enhance soil carbon by increasing charcoal deposition. Frequent or severe wildfires can shift forests from being carbon sinks (absorbing CO_2) to carbon sources (releasing CO_2), accelerating climate change. For this assessment we used an established carbon accounting framework to quantify anticipated GHG emission reductions from the implementation of fuel treatments in forests in Boulder County.
- *Human Health* - Wildfire smoke contains fine particulate matter (PM2.5), carbon monoxide, volatile organic compounds (VOCs), and other toxic pollutants, which can impact on human health when a population is exposed (Reid et al. 2016). Health effects include respiratory issues, cardiovascular effects, eye and throat irritation, neurological effects and potential cognitive impairments and mental health. Increased mortality risk, especially for vulnerable groups such as children, the elderly, pregnant women, and those with pre-existing conditions. Long-term exposure to wildfire smoke can lead to chronic respiratory diseases, weakened immune function, and higher risks of lung cancer. We used modeling to complete a comparative assessment of wildfire smoke pollutant emissions that could impact human health – comparing emissions associated with lands when fuels reductions were applied and when fuel reductions were not applied.
- *Recreation and Tourist Economic Impacts* - Outdoor recreation is an important industry in the Boulder County and if catastrophic fire were to occur in areas of prime recreational importance, this could have a notable and lasting economic impact on many sectors of the region's economy. We present a literature review that addresses catastrophic wildfire's possible effects on the regional tourism industry, and its downstream economic effects.

The goal of the evaluation was not to be exhaustive, but to illuminate some of the potential co-benefits of completing fuels reduction treatments compared to not conducting treatments. This evaluation used a mixed-methods approach, incorporating Forest Carbon Accounting Tool (FCAT) model simulations, geospatial analytics, and literature review (e.g., Hurteau et al., 2016).

Study Area for Modeling

The area of interest (AOI) or "treatment footprint" primarily encompasses forested zones in Boulder County where fuels reduction treatments have been completed, are planned, or have been proposed based on wildfire risk identified in the 2024 Boulder County Community Wildfire

Protection Plan (Boulder County CWPP, 2024). We identified a treatment footprint within Boulder County to include:

Completed Projects - OSMP and Boulder County Parks and Open Space (BCPOS) projects were modeled with a thin from below to a residual basal area of 70 ft^2 (Figure 3.1). In areas where there was no information on treatment prescription for the ponderosa pine type, the treatment assigned was a thin from below to a basal area target of 60 ft^2. Lodgepole pine stands received clear-cut treatments for all DBH size classes (non-lodgepole trees within lodgepole type were not clear cut). Treatments that occurred between 2017 and 2021 were assigned to the treatment year of 2017. The total area lodgepole related clear-cuts in 2017 was 438 acres. Treatments that occurred between 2022 and 2024 were assigned to the treatment year of 2022. The total area lodgepole related clear-cuts in 20ww was 377 acres.

Planned Projects **–** Only OSMP planned project areas were included (Figure 3.2) as other agencies did not provide polygons representing planned treatments. Ponderosa pine forest types (and others) were modeled with a thin from below to achieve a residual basal area of 70 ft^2. Lodgepole pine stands did not receive clear-cut treatments because these areas were mostly dominated by the ponderosa pine forest type. Planned treatments were modeled to occur in 2027.

Proposed Projects – were areas across Boulder County that were highlighted in the 2024 Boulder County CWPP as priority areas for targeted fuels reduction due to elevated fire hazard (Figure 3.2). Proposed project areas were filtered from overall CWPP priority areas using GIS to represent areas that are mostly forested and reasonably accessible for fuel treatments by removing areas that were more than one half mile from a known road and removing areas that have greater than 40% slopes. "*Completed*" and "*Planned*" treatments were also removed from the proposed areas to avoid double counting. Ponderosa pine forest types (and others) were modeled with a thin from below to achieve a residual basal area of 60ft^2. Lodgepole pine stands did not receive a clear-cut treatment. Proposed project area treatments were modeled to occur in 2027.

Only the thin below residual 60ft^2 basal area treatment prescription (rather than 30ft^2 residual basal area) was modeled and evaluated for "planned" and "proposed" treatment areas because of the uncertainty on how these treatments would ultimately be implemented. Additionally, this treatment prescription represented a conservative estimate of effects for the purpose of exploring possible co-benefits of treatments.

The overall treatment footprint combined completed, planned and proposed project areas for this analysis and was mostly aligned with the biomass availability analysis footprint, with areas reflecting a mosaic of forest associated vegetation types. The treatment footprint also captured variations in topography, vegetation density, and ownership boundaries, enabling a overall understanding of how treatments are distributed across the county.

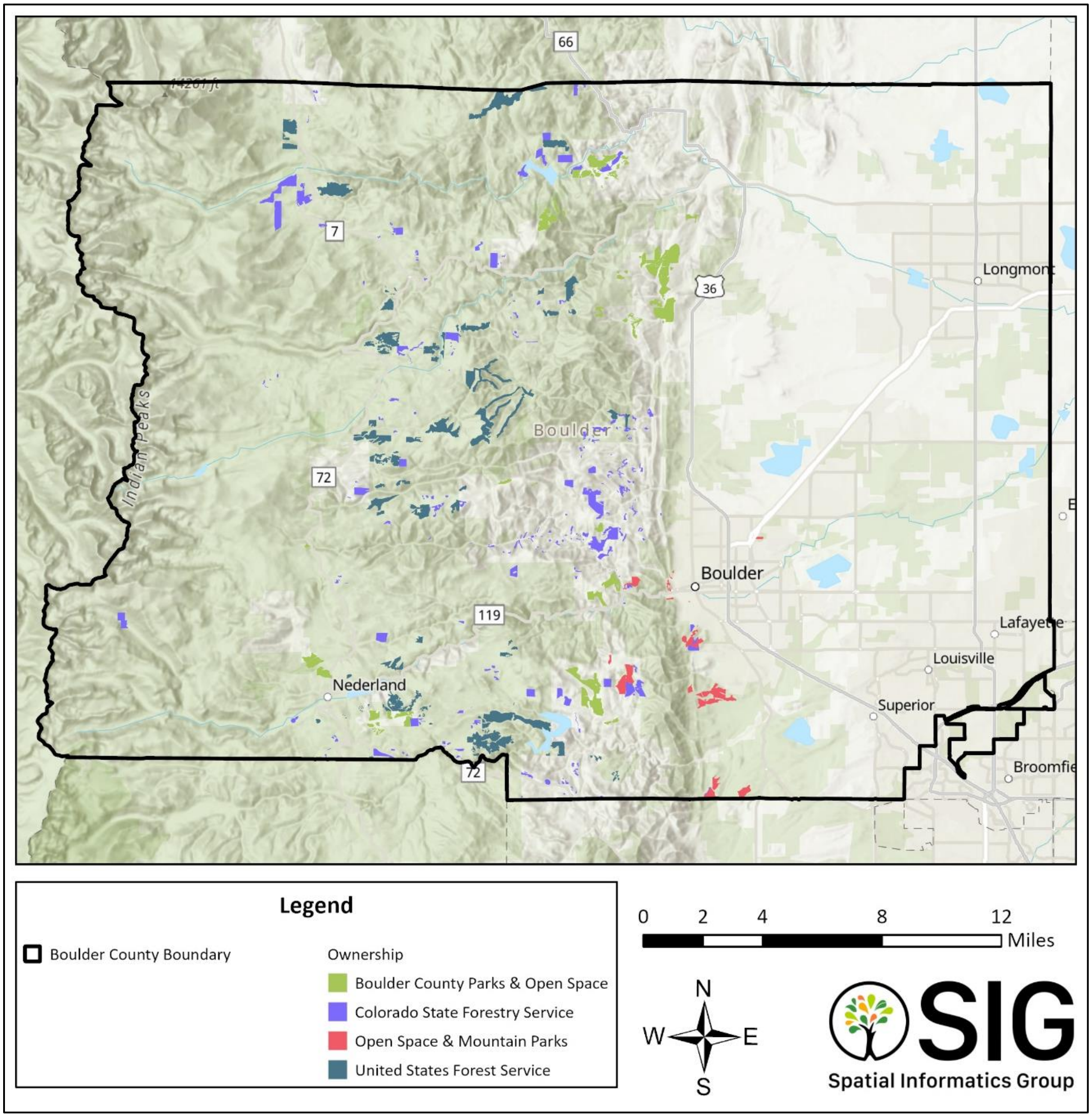


Figure 3.1. Completed fuel treatments as of 2024 by ownership category in Boulder County, CO.

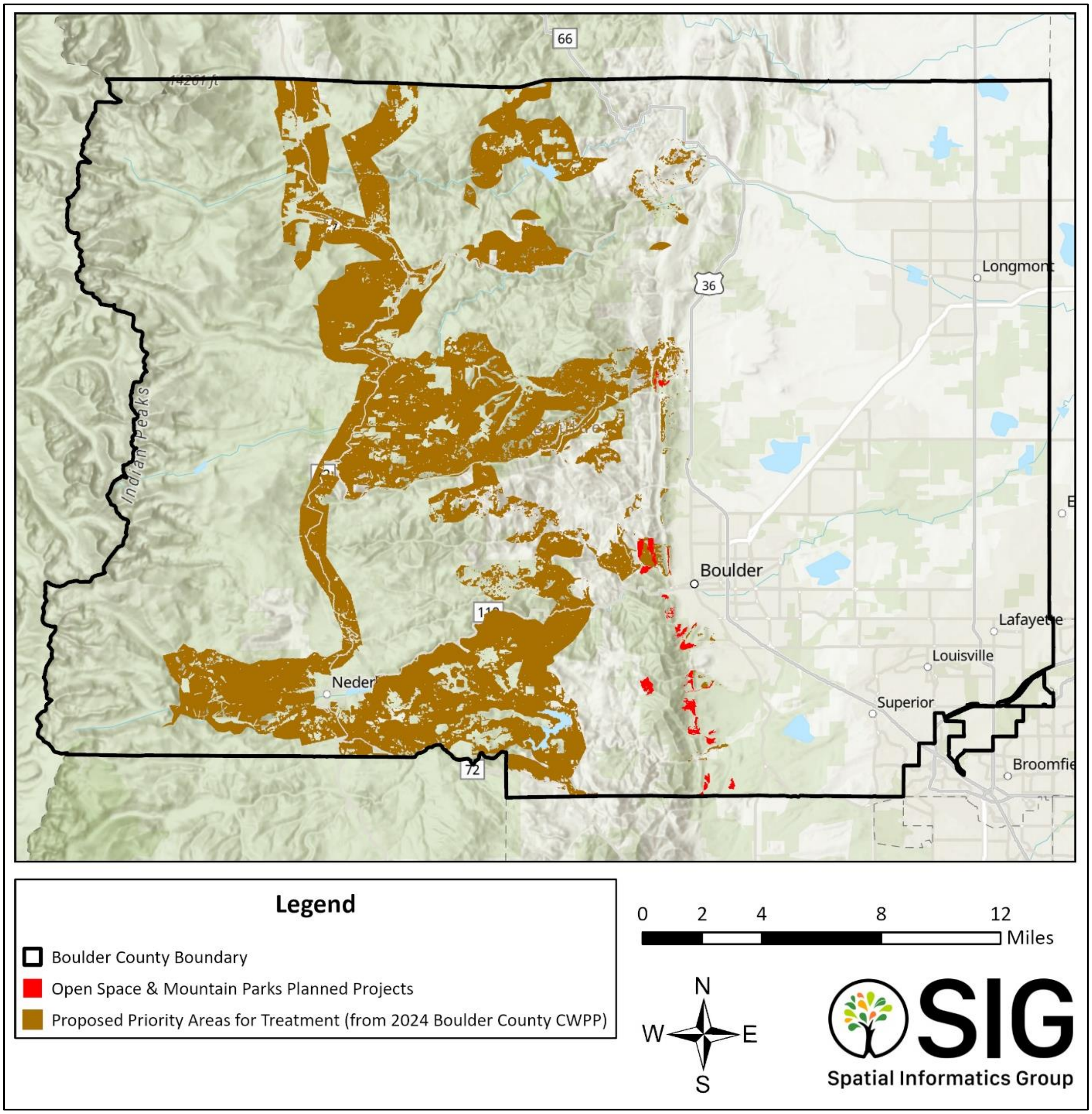


Figure 3.2. Planned and proposed (see 2024 Boulder County CWPP priority areas) fuel treatment project areas in Boulder County, CO.

Methods

Modeling

Spatial Informatics Group (SIG) developed the Forest Carbon Accounting Tool (FCAT) - a semi-automated command-line tool that integrates multiple modeling microservices (See Appendix 3A). FCAT is designed to assess how different stand-specific fuel treatments impact forest conditions.

By leveraging advanced modeling techniques, FCAT simulates and forecasts key forest-related metrics, including measures of forest structure, fire behavior, and wildfire emissions (including greenhouse gas and criteria pollutants). It operates using pixel-based vegetation data to model changes in vegetation type, structure, and wildland fuels.

FCAT consists of several specialized components:

- GIS Processing – Spatial data analysis and mapping.
- Forest Vegetation Simulator (FVS) – Models vegetation growth with and without fuel treatments.
- GridFire Monte Carlo Simulations – Predicts wildfire behavior such as flame length.
- First Order Fire Effects Model (FOFEM) – Estimates smoke emissions.
- Carbon Quantification Module – Calculates carbon dynamics.

All data sources and models used in FCAT are publicly available.

For wildlife carbon emission assessments, we use a FCAT workflow that follows the Reduced Emissions from Megafires (REM) framework (Climate Forward, 2023), which enables fuel treatment projects to be listed on the carbon market under Climate Forward, a sub-platform of the Climate Action Reserve's registry.

For the modeling forest health/resilience response to fuel treatments, we use FCAT model to produce outputs associated with forest structure to illustrate how those metrics might change through time under two scenarios:

1. Baseline scenario – No fuel treatments applied.
2. Alternative scenario – Fuel treatments applied.

The difference between these scenarios was plotted over a 40-year project period for Avoided Wildfire Emissions and over a 30-year project period for other forest health metrics, at 5-year increments. A detailed description of the FCAT modeling workflow can be found in Appendix 3A.

FCAT was used to assess co-benefit metrics associated with:

- Avoided Wildfire Emissions
  - GHGs
  - Criteria Pollutants
- Forest Health and Resilience
  - Forest Structure – Tree mortality, canopy cover, and stand density index.
  - Habitat and Biodiversity – fire severity assessed for 1) critical wildlife habitats, 2) wildfire migration corridors, 3) high biological diversity areas, 4) significant natural areas, 5) Environmental Conservation Areas, and 6) Abert's squirrel habitat.

Literature Review

A literature review was completed for several of the co-benefit issue areas identified by the Boulder Core Team. Literature review was completed for vegetation type conversion, soils, invasive species, watershed protection, and tourist/recreation economy.

Avoided Wildfire Emissions

Wildfires are significant sources of both greenhouse gases (GHGs; van der Werf et al., 2017) and other air pollutants (Reid et al., 2016; Jaffe et al., 2020;), contributing to climate change and adversely affecting air quality (Liu et al., 2017). The primary GHG emitted during wildfires is carbon dioxide (CO_2), produced by the combustion of organic materials. methane (CH_4) and nitrous oxide (N_2O) are also released in smaller quantities; despite their lower concentrations, these gases have higher global warming potentials than CO_2, making them potent climate change contributors.

In addition to GHGs, wildfires emit several criteria pollutants that pose risks to human health and the environment. These include carbon monoxide (CO), particulate matter (PM), nitrogen oxides (NO_x), and volatile organic compounds (VOCs). Carbon monoxide is a colorless, odorless gas that can be harmful when inhaled in large amounts. Particulate matter, especially fine particles less than 2.5 micrometers in diameter ($PM_{2.5}$), can penetrate deep into the lungs, causing respiratory and cardiovascular issues (Reid et al., 2016). Nitrogen oxides and VOCs contribute to the formation of ground-level ozone, which can exacerbate asthma and reduce lung function.

The composition and quantity of emissions from wildfires depend on factors such as the type of vegetation burned, fire intensity, and combustion conditions. For instance, smoldering fires tend to produce more CO and CH_4, while flaming combustion emits higher levels of NO_x (Jaffe et al., 2020). Understanding these emissions is crucial for assessing the impact of wildfires on climate change and air quality, as well as for developing strategies to mitigate their adverse effects.

When quantifying *avoided wildfire emissions* (AWE) from fuels reduction treatments, determining *annual burn probabilities* (ABP) is an influential factor in shaping whether a suite of fuels reduction treatments will result in beneficial impacts related to GHG and air pollutants. Annual burn probability refers to the likelihood that a specific area of land will experience wildfire within a single year. It is typically expressed as a percentage or a decimal, representing the chance of fire occurrence based on historical data, climate conditions, vegetation type, topography, and other environmental factors. This metric is typically used in fire risk assessments and land management planning to identify areas at higher probability of burning, helping to inform decisions related to resource allocation, fire prevention strategies, and emergency preparedness. By estimating how frequently a location might burn annually, land managers and policymakers can better anticipate potential wildfire impacts and implement more effective mitigation measures.

With AWE accounting, identifying precise ABPs for the current day and particularly for the forthcoming decades for an area of interest presents challenges because it requires integrating a complex set of dynamic and interrelated factors (Finney, 2005; Carlson et al., 2025). Wildfire occurrence is influenced by variables such as weather patterns, fuel types and conditions, topography, human activity, ignition location and frequency, and historical fire regimes - all of which can vary significantly over time and space. Additionally, climate change introduces further uncertainty, altering temperature and precipitation patterns that directly affect fire behavior. The stochastic nature of fire ignition, spread, and suppression adds another layer of unpredictability, making it difficult to accurately model fire probabilities. Reliable data may also be limited or inconsistent across regions, and even advanced fire simulation models must make assumptions and simplifications that can affect the precision of the results. These complexities make estimating annual burn probability a scientifically rigorous but inherently uncertain task.

To address this uncertainty, we conducted the AWE analysis using a sliding scale of ABPs, starting with an ABP of 0.46 (equal to roughly 1 wildfire occurring every 200 years within the treatment area) calculated by Kearns et al. (2022), to ascertain which static ABP would yield climate benefits fuel treatments over the next 40 years. Notably, the Climate Forward Reduced Emissions from Megafires (REM) methodology - which underpins this effort - is currently updating its ABP maps (due in June 2025) for the region because ABPs for the western US show an increasing trend. Additionally, with respect to acreage treated, climate benefits generally increase when a larger proportion of the landscape is treated.

When considering all treatments combined - including completed, planned, and proposed projects - a climate benefit was observed over a 40-year period with an annual burn probability (ABP) of at least 2.7% (Figure 3.3, Table 3.1). With this ABP, fuels treatments are estimated to generate over 200,000 metric tonnes of carbon dioxide equivalents (CO_2e) of accumulated Avoided Wildfire Emissions (AWE) throughout the project period, equivalent to approximately 3 metric tonnes CO_2e per treated acre (Table 3.2). The type of fuel treatments drive AWE results as well. Typically, mechanical thinning outperforms mastication in terms of AWE benefits. Treatments where biomass is removed from the forest (pile burn, wood chip export) outperform mastication treatments where biomass remains in the forest and can continue to contribute to fuel loads for a considerable time.

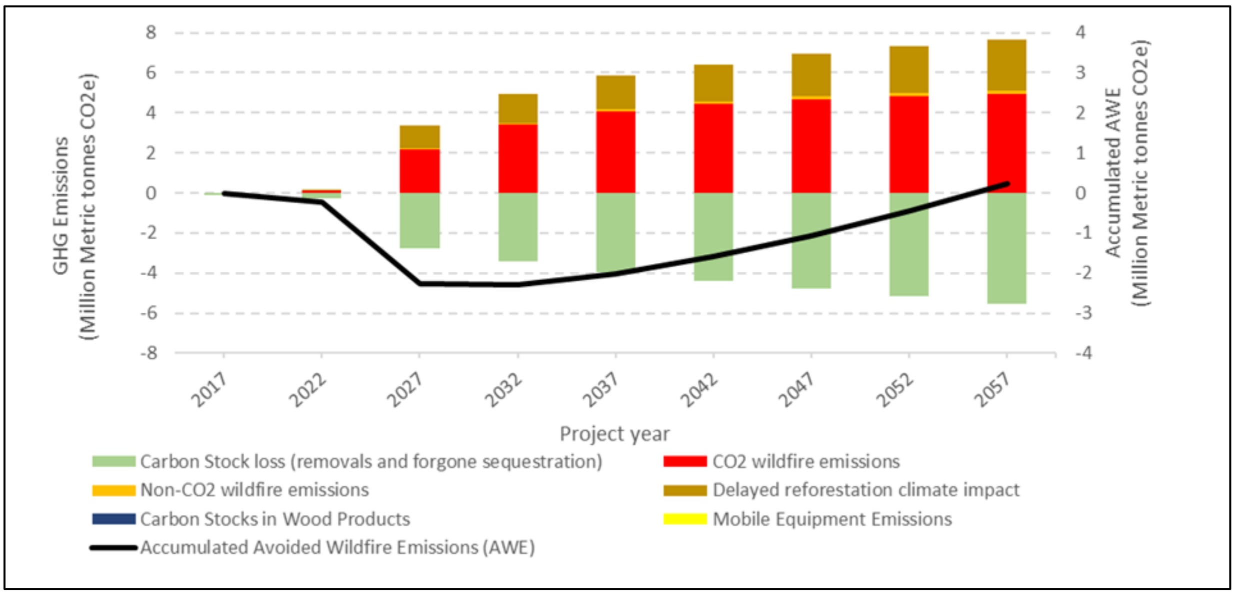


Figure 3.3. GHG emissions accounting for all of the combined fuel treatment calculated with a 2.7% ABP over the entire project period following the Reduced Emissions from Megafire (REM) methodology. The project years are represented on the x-axis, with year 0 representing 2017 and year 40 representing 2057. Upward pointing bars are positive GHG emissions (positive values are climate liability) while downward pointing bars are saved GHG emissions (negative values are climate benefits). Total accumulated AWEs over time are shown with the black line and are represented with the y axis on the right. The black line initially drops below zero, pointing out a climate liability. Eventually, as reduced emissions from wildfires and reduced risk for foregone sequestration from delayed reforestation increase, the project starts to show climate benefits starting around project year 2055. Carbon stocks in wood products and mobile equipment fossil fuel emissions (see legend) are not shown due to their minimal and insignificant impact. Fuels reduction treatments in this analysis were applied in 2017 and 2022 for completed project areas, and in 2027 for planned and proposed project areas (the largest proportion of the landscape.

Table 3.1. AWE results from all fuel treatment projects combined. The fuel treatments start to generate climate benefits when applying an ABP of 2.7% or higher. An ABP of 0.46% as proposed by Kearns et al. (2022) for the area of interest and the current year would not generate climate benefits over the project period. Following the REM methodology, a 10% discount to account for uncertainty is applied to the AWEs calculated. Carbon stocks in wood products and mobile equipment fossil fuel emissions were not accounted for due to their minimal impact on overall emissions.

Year	Calculated with a 0.46% ABP		Calculated with a 2.7% ABP	
	Metric Tons CO_2e	Metric Tons CO_2e per acre	Metric Tons CO_2e	Metric Tons CO_2e per acre
2022	(215,834)	(3)	(200,030)	(3)
2027	(2,390,651)	(31)	(2,036,848)	(27)
2032	(2,914,227)	(38)	(2,064,435)	(27)
2037	(3,244,976)	(42)	(1,805,754)	(24)
2042	(3,516,068)	(46)	(1,428,953)	(19)
2047	(3,741,404)	(49)	(952,034)	(12)
2052	(3,926,540)	(51)	(398,858)	(5)
2057	(4,100,155)	(53)	200,826	3

GHG emissions (CO_2 and CH_4) are shown across project duration (2017 to 2057) for the with (project) and without (baseline) fuel reduction treatments scenarios in Figure 3.4. CO_2 emissions exhibited the greatest magnitude in difference between the treated and untreated scenarios, with a difference of 1.6 million metric tons or a reduction of 37% by the end of the project period.

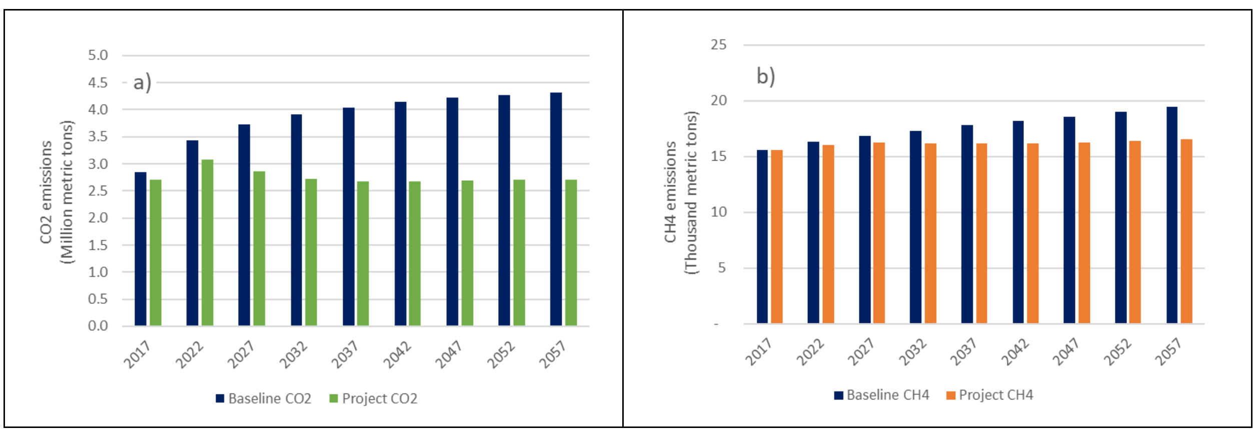


Figure 3.4. Modeled estimates (metric tons) of a) carbon dioxide (CO_2) and b) methane (CH_4) emissions with (project) and without (baseline) fuel reduction treatments within the treatment footprint. The emissions presented here are discounted by an annual wildfire burn probability of 2.7%.

Estimates of criteria pollutant emissions ($PM_{2.5}$ and NO_X) for with and without (baseline) fuels treatments scenarios are shown in Figure 3.5. The modeled estimates of criteria pollutant emissions associated with fuels reduction treatment scenario indicate a reduction over the duration of the evaluation period (2017 to 2057). $PM_{2.5}$ is 17% lower at the end of the project period with fuel treatments implemented. Further, NO_X emissions are 52% lower by the end of the project period.

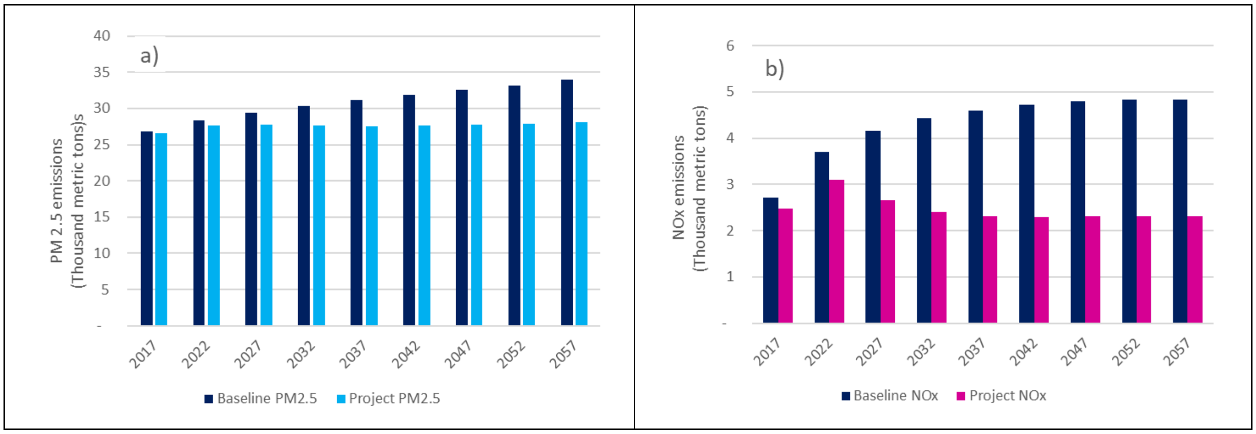


Figure 3.5. Modeled estimates (metric tons) of a) particulate matter ($PM_{2.5}$) and b) nitrous oxides (NO_X) emissions with (project) and without (baseline) fuel reduction treatments within the treatment footprint. The emissions presented here are discounted by an annual wildfire burn probability of 2.7%.

Forest Health and Resilience

Tree Mortality

Tree mortality is an indicator commonly used to assess forest health, as it reflects the cumulative effects of various stressors on forest ecosystems. Elevated rates of tree death can signal underlying problems such as drought stress, insect infestations (e.g., bark beetles), disease outbreaks, air pollution, or competition in overly dense stands (van Mantgem et al., 2009; Stephens et al, 2018). Monitoring patterns of mortality - both in terms of rate and spatial distribution - helps forest managers detect declining stand vigor and anticipate broader ecological shifts. For example, widespread mortality following prolonged drought can indicate that a forest is no longer resilient under changing climate conditions, prompting management actions like thinning or species diversification to reduce vulnerability. Additionally, distinguishing between background (natural) and elevated (stress-induced) mortality helps identify when intervention is necessary. Tree mortality data, often collected through aerial surveys and ground-based plots, contribute to forest health assessments by providing insights into stand dynamics, carbon cycling, and habitat changes. As such, it serves as both a diagnostic tool and a trigger for adaptive management strategies aimed at restoring forest resilience and function.

Addington et al. (2018) discusses tree mortality in Colorado’s front range primarily in the context of natural ecological processes, fire regimes, insect outbreaks, and restoration practices. Historically, tree mortality occurred because of mixed-severity fire regimes, which included both low-intensity surface fires and more severe crown fires that created openings and influenced forest structure. These natural mortality patterns helped maintain forest heterogeneity and resilience. However, due to decades of fire suppression and changes in forest structure, current patterns of tree mortality are often more severe and widespread. High tree densities and homogeneous stands can facilitate the spread of insect infestations and crown fires, particularly by bark beetles and pathogens (Schoennagel et al., 2012). The result has been extensive areas of complete tree mortality in large high-severity fire patches, such as those seen in the 2002 Hayman Fire (Graham, 2003). These areas can persist as treeless landscapes for decades or longer due to poor regeneration conditions and lack of nearby tree seed sources (Guiterman et al., 2022).

To demonstrate how tree mortality might respond to fuel reduction treatments over time, the FCAT model was used to compare treated and untreated scenarios within the treatment footprint. The FCAT model predicted that fuel reduction treatments would reduce the proportion of tree mortality (in terms of % tree basal area killed) in treated stands when compared to untreated stands (Figure 3.6, Table 3.2). Treated stands exhibited lower tree mortality than untreated stands across all modeled intervals (2017 to 2047). By 2047, the percentage of tree mortality in untreated areas is estimated to exceed 75%, whereas treated stands maintained lower mortality by year 2047 (43%). While the proportion of dead trees remain greater than 60% between 2017 to 2032 for both treated and untreated areas, by 2037 the level of tree mortality diverges considerably.

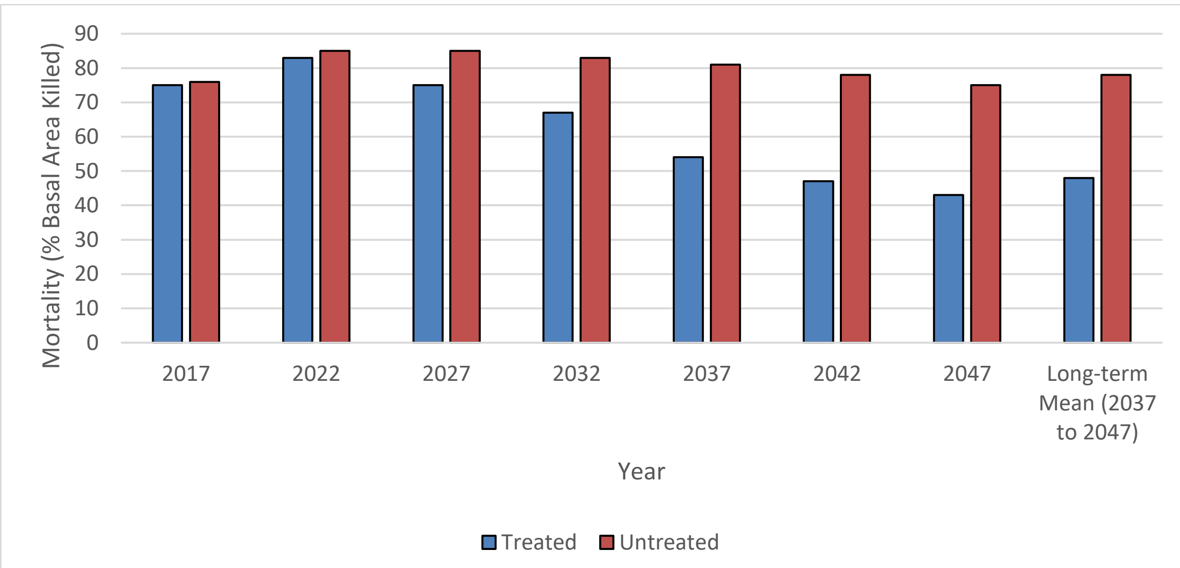


Figure 3.6. Comparison of modeled percent tree mortality (% basal area killed) of treated and untreated over time (2017 to 2047) within the treatment footprint.

Table 3.2. Summary of results for the different forest structure metrics modeled for treated and untreated forests using FCAT (2017 to 2047).

Forest Structure Metrics	Unit of Measure	Treatment Status	2017	2022	2027	2032	2037	2042	2047	Long-term Mean (2037 to 2047)
Tree Mortality	% of Basal Area	Treated	75	83	75	67	54	47	43	48
		Untreated	76	85	85	83	81	78	75	78
Canopy Cover	%	Treated	40	40	26	27	27	28	29	28
		Untreated	44	45	47	48	49	50	50	50
Stand Density Index	Unitless	Treated	175	177	106	113	120	127	133	127
		Untreated	192	208	223	237	251	263	274	263

Canopy Cover

Canopy cover is an important indicator of forest health, as it reflects the extent and continuity of tree crowns over an area and provides insights into ecological function, vegetation structure, and habitat quality (Jennings et al., 1999). High canopy cover generally indicates a mature, closed-canopy forest that can offer critical ecosystem services such as temperature regulation, moisture retention, and carbon sequestration. However, excessively dense canopy cover may also signal overcrowded stands, which can lead to increased competition for resources, reduced tree vigor, and heightened vulnerability to stressors like drought, insects, and disease. In fire-prone ecosystems, dense canopy cover can facilitate crown fire spread, posing risks to forest resilience and public safety. Conversely, very low canopy cover might indicate over-thinning, past disturbance, or declining forest health. Monitoring canopy cover helps land managers assess changes in forest condition over time, prioritize areas for treatment, and maintain a balance between ecological integrity, fire risk reduction, and biodiversity goals.

Canopy cover is a key element in understanding and restoring ponderosa pine and dry mixed-conifer forests in Colorado's Front Range according to Addington et al. (2018). Historically, these forests exhibited a wide range of canopy cover values, shaped by factors such as fire regimes, topography, and natural disturbances. Frequent, low- to mixed-severity fires helped maintain open, heterogeneous forest structures, often characterized by low to moderate canopy cover, which in turn supported diverse understory communities and reduced the likelihood of severe wildfires (Addington et al. 2018).

Over time, however, fire suppression, grazing, and logging have led to increased forest density and more continuous, closed-canopy conditions in Colorado's front range (Brown et al., 2015; Addington et al, 2018; Battaglia et al., 2018,). This densification has decreased spatial heterogeneity and increased fuel loads, thereby elevating the risk of large, high-severity fires. In restoration efforts, Addington et al. (2018) recommends reducing canopy cover where it exceeds historical ranges of variability - particularly in lower montane areas - and reintroducing more open, patchy structures. Specifically, restoration practices should aim to create a mosaic of canopy cover ranging from low (10–40%) to medium (41–70%), depending on the site's historical structure, elevation, and ecological context. Such variation is essential for enhancing resilience, promoting biodiversity, and maintaining key ecosystem functions across scales.

FCAT modeling of overall canopy cover revealed a distinct divergence between treated and untreated stands in 2027 when most of the fuel treatment area was modeled to occur (Figure 3.7, Table 3.2). Modeled untreated areas retained higher percent canopy cover (>40%), which can indicate elevated risk of crown fires and/or overly stocked trees, although within appropriate limits identified by Addington et al (2018). Treated stands, meanwhile, displayed a reduced level of canopy cover which could dampen the likelihood of carrying a high-severity crown fire.

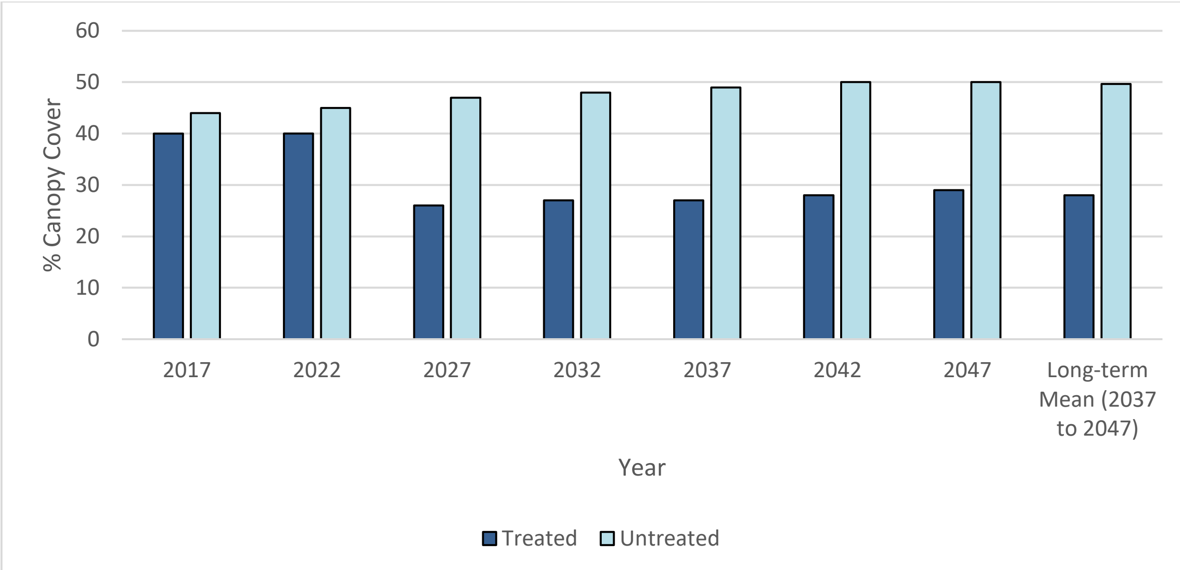


Figure 3.7. Comparison of modeled canopy cover of treated and untreated over time (2017 to 2047) within the treatment footprint.

Stand Density Index

Stand Density Index (SDI) is a widely used quantitative measurement tool in forestry that helps evaluate and compare forest stand conditions based on tree density and size. It standardizes the relationship between the number of trees per unit area (acres) and their average diameter at breast height (DBH, inches), enabling foresters to assess how crowded or open a stand is relative to its potential maximum density. SDI is particularly useful because it allows comparisons across different forest types, ages, and species compositions. It helps inform decisions about thinning and fuels management by identifying stands that are overly dense and therefore more susceptible to stressors such as drought, insect outbreaks, and high-severity wildfires. When SDI values approach a species-specific maximum (often referred to as the "self-thinning line"), it indicates intense competition among trees for resources like light, water, and nutrients. Lowering SDI through thinning can improve forest health by reducing competition, promoting tree growth, and decreasing fire risk. Thus, SDI is a key metric in guiding forest management to achieve desired structural conditions, balancing ecological resilience, wildlife habitat needs, and fuel reduction objectives.

In ponderosa pine forests in Colorado's front range, an SDI of 155 signals resource competition - translating to a relative density of 34% (SDI/SDI max; 155/446). According to Dr. Michael Battaglia (Pers. Comm., 2025), a relative density of 25-34% indicates competition onset, while 35-55% signifies full site occupancy and reduced individual tree growth, though the stand achieves maximum volume with active competition. An SDI of 250 or >56% reveals severe competition, self-thinning, and stagnation of new growth.

Addington et al. (2018) emphasized that historical forests in Colorado's front range likely had lower SDI values due to frequent fire, which maintained open canopy structures and reduced competition among trees. Addington et al. (2018) indicated that not all areas should be uniformly thinned and that varying SDI across a treatment unit can better mimic natural forest patterns.

For the treatment footprint evaluated with FCAT, SDI was consistently higher in untreated stands (SDI exceeding 250 or 56% relative density starting in 2032), suggesting intensified competition for resources (Figure 3.8, Table 3.2). In contrast, treated stands demonstrated lower SDI values (106 to

133 or relative densities of 24% to 30% starting in 2027), conditions conducive to healthier more resilient forest tree growth and reduced competition for resources (i.e., nutrient, water and sunlight).

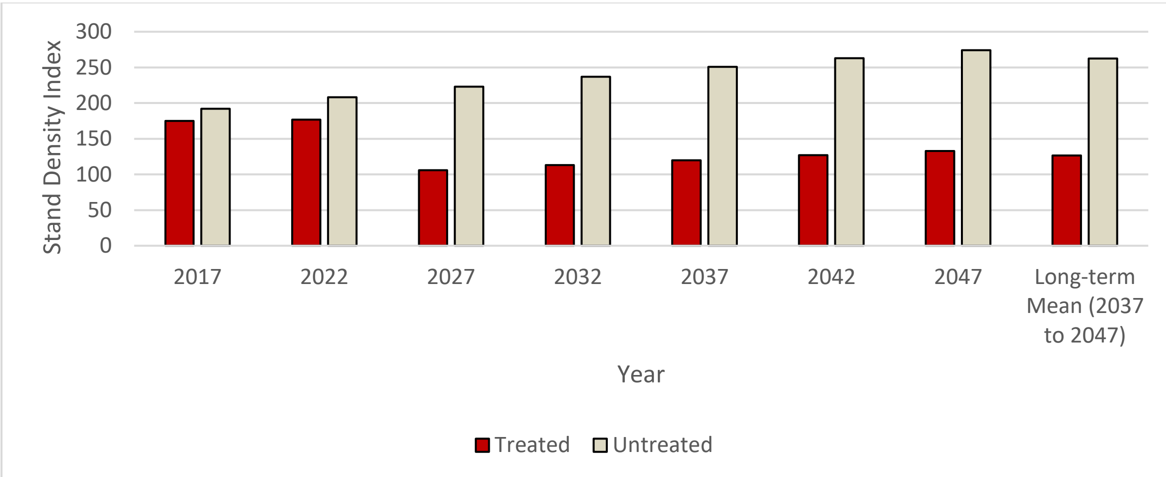


Figure 3.8. Comparison of modeled stand density index of treated and untreated within the treatment footprint over time (2017 to 2047) within the treatment footprint.

Biodiversity and Habitat

Fuels reduction projects, aimed at mitigating wildfire risks through methods like thinning dense vegetation and conducting controlled burns, have complex and varied impacts on wildlife habitat and biological diversity. These effects can be beneficial or detrimental, depending on the implementation and ecological context.

From a benefits standpoint, ecologically sound planned and implement fuels reduction projects can restore historical disturbance regimes, promoting habitat heterogeneity that benefits certain species. For instance, in dry coniferous forests, thinning and prescribed burns can reduce understory density, encouraging the growth of diverse plant species that serve as food and cover for wildlife (Demerest et al. 2023). This approach has been shown to increase the abundance and diversity of various taxa, as the removal of excessive vegetation can create a more open and varied habitat structure (Rupp et al., 2012, Demarest et al., 2023). Forest thinning and prescribed fire can improve understory plant diversity, benefiting native species and reducing the spread of invasives. For example, Stephens et al. (2012) found that prescribed burning had a stronger and more enduring effect on increasing understory species richness than thinning alone, especially for native annual plants, without promoting non-native invasives. This enhancement of habitat complexity supports a broader range of flora and fauna across spatial and temporal scales. Studies like Andrus et al. (2021) emphasize the importance of fire refugia - patches of unburned or low-severity areas within a burn perimeter - that can serve as places of protection for wildlife species, particularly forest birds. Fuels reduction treatments can help maintain these refugia by moderating fire behavior and preserving structural diversity across the landscape.

In fire-prone ecosystems, such as ponderosa pine forests in Boulder Country, restoring forest structure to a more open forest condition via thinning and prescribed burning can mimic historical fire regime effects. This benefits fire-adapted and rare plant species that rely on light availability and reduced competition for regeneration (Lydersen et al., 2017). Treatments that recreate a mosaic of habitat structures also help maintain essential ecological processes and species niches. Fuels reduction can also support wildlife recovery post-fire. For example, small mammals can survive within unburned patches maintained through thoughtful fire and fuels planning, as shown by Kelly et al. (2020). Post-fire survivors play a crucial role in ecosystem function, from seed dispersal to predator-prey dynamics.

However, if not carefully planned, fuels reduction can negatively impact wildlife habitats in both time and space. The removal of vegetation can lead to habitat fragmentation, disrupting the connectivity essential for species movement and genetic exchange, and/or remove cover (e.g., course woody debris and canopy cover) needed for life history requirements. For example, with excessive vegetation removal, large-scale fuel break projects have been criticized for causing damage to vegetation and soils, potentially degrading habitats for various wildlife species (Ingalsbee, 2005). Additionally, the creation of access roads for fuel treatments can further fragment habitats and introduce edge effects that alter species composition (e.g., provide pathways for invasive species introductions; Dodson and Fielder, 2006). In terms of duration of fuel reduction impacts, in the short term, these treatments often lead to habitat disturbances (Underwood et al., 2010), including the removal of vegetation that provides food and shelter for various species. For instance, studies have shown that such disturbances can negatively impact species like the California spotted owl by altering their nesting habitats and reducing demographic rates (Tempel et al., 2015). However, when these treatments are followed by wildfires, they may confer long-term benefits by reducing fire severity and preserving essential habitat structures.

Generally, by reducing forest density and reintroducing fire in ecologically informed ways (e.g., to mimic a natural fire regime expected for a location), fuels reduction projects can maintain and enhance biodiversity. To balance wildfire mitigation with ecological preservation, it is important to integrate wildlife conservation into fuels reduction planning. This includes maintaining habitat connectivity, preserving critical habitat features, and considering the specific life history requirements of local species. Collaborative approaches that involve ecologists, land managers, and local communities can help design treatments that reduce fire risk while supporting biodiversity.

Overall, when implemented strategically and adaptively, fuels reduction projects play a vital role in sustaining forest ecosystem health. They can maintain or enhance biodiversity, support rare and sensitive species, and increase the ecological resilience of forests under growing pressures from altered fire regimes – especially when considering the alternative of a severe fire decimating habitat across large swaths of a landscape for decades.

This section explores the differences in modeled fire severity of treated and untreated areas within the context of different special area designations across Boulder County. Namely, we used the same treatment footprints (completed, planned and proposed project) used in the biomass available assessment Chapter 1. Notably, only portions of the treatment footprint overlap with the different special area designations. Thus, modeled results are based on those portions of the special area designation where treatments were delineated.

The following describes the different special area designations that were identified by the Boulder Core Team for this assessment.

Abert's Squirrel Habitat (Figure 3.9) - Abert's squirrels (*Sciurus aberti*) are closely associated with ponderosa pine (*Pinus ponderosa*) forests (Allred et al., 1994), which provide essential resources such as food, nesting sites, and cover (Davis and Bissell, 1989; Halloran and Bekoff, 1994). In Boulder County, Colorado, these squirrels inhabit montane ponderosa pine forests (Davis and Bissell, 1989), typically found at elevations ranging from 6,000 to 8,500 feet (Addington et al., 2018). Suitable habitats are characterized by uneven-aged stands with tree densities between 152 and 253 trees per hectare, predominantly featuring trees over 12 inches in diameter at breast height (DBH). Abert's squirrels prefer forests with open understories, allowing for easier movement and access to food sources. They often select nest trees with crowns comprising 35% to 55% of the total tree height and DBH ranging from 14 to 16 inches (Halloran and Bekoff, 1994). However, human activities such as logging, grazing, and fire suppression have altered these forests, leading to denser, even-aged stands that may not support the same squirrel densities as the original habitats (Yarborough et al., 2015). Despite these changes, Abert's squirrels remain a notable component of Boulder County's montane ponderosa pine ecosystems.

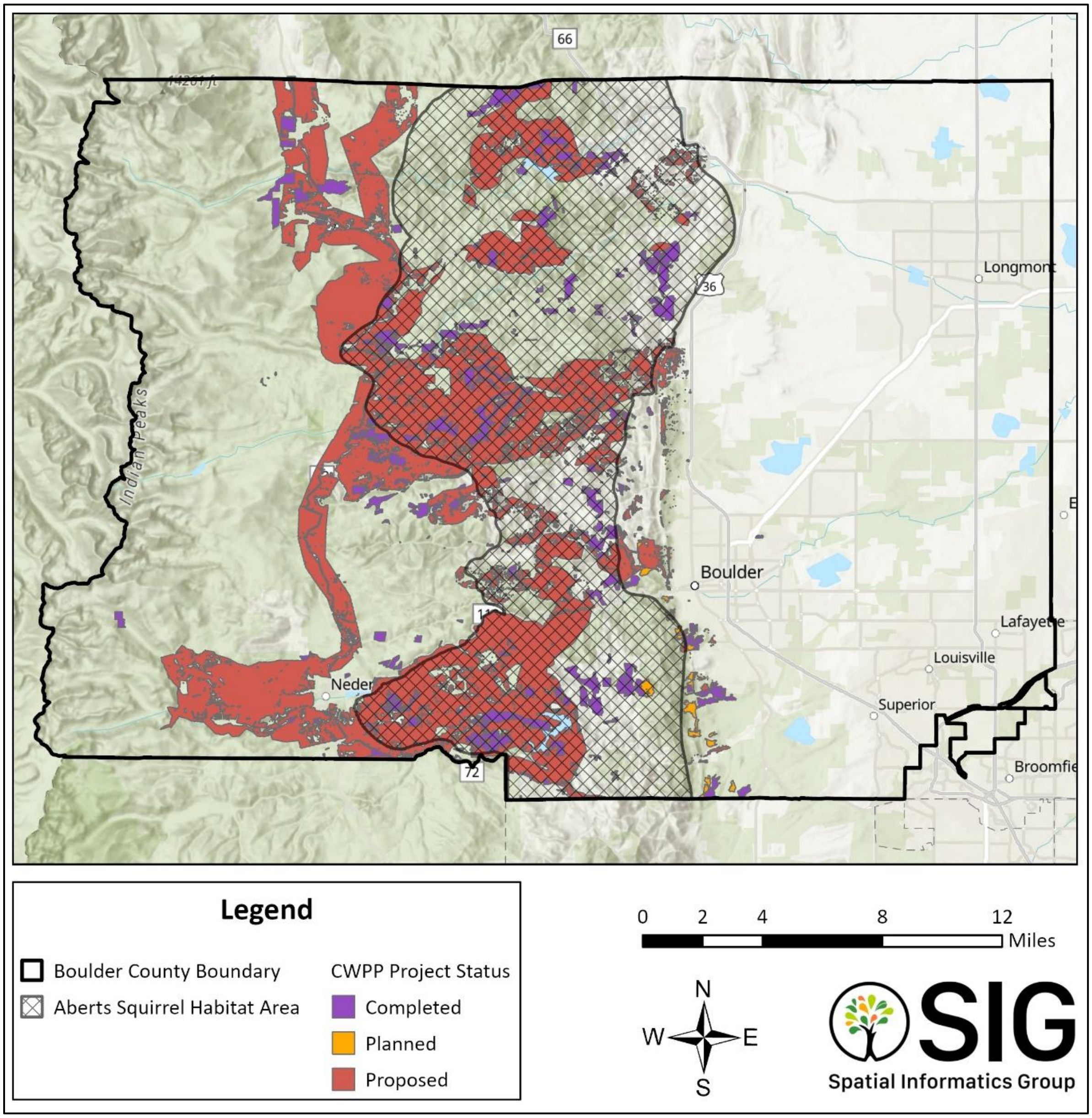


Figure 3.9. Map of suitable Abert's squirrel habitat relative to treatment areas.

Critical Wildlife Habitat (Figure 3.10) - Boulder County has established a framework for designating Critical Wildlife Habitats (CWH) to conserve and preserve native wildlife populations by protecting essential habitats. These areas are considered rare, irreplaceable, or difficult to replace, and are vital to the conservation of wildlife in the county. The criteria for designating CWH include:

- *High Biodiversity Support*: Habitats that support a high degree of biodiversity of wildlife species native to Boulder County.
- *Concentration Areas*: Discrete, identifiable locations that support significant concentrations of one or more native wildlife species during vulnerable life-history stages necessary for self-sustaining populations (e.g., breeding or nesting sites, calving and wintering grounds).

- *Vital Habitat Features*: Areas providing physical and biological habitat features crucial for the maintenance, successful recovery, or reintroduction of one or more wildlife Species of Special Concern.
- These designations guide land use decisions and resource management within the county, ensuring that development and other activities consider the preservation of critical wildlife habitats. The Boulder County Comprehensive Plan integrates these designations, reflecting the county's commitment to sustaining and protecting native species, natural ecosystems, and regional biodiversity.

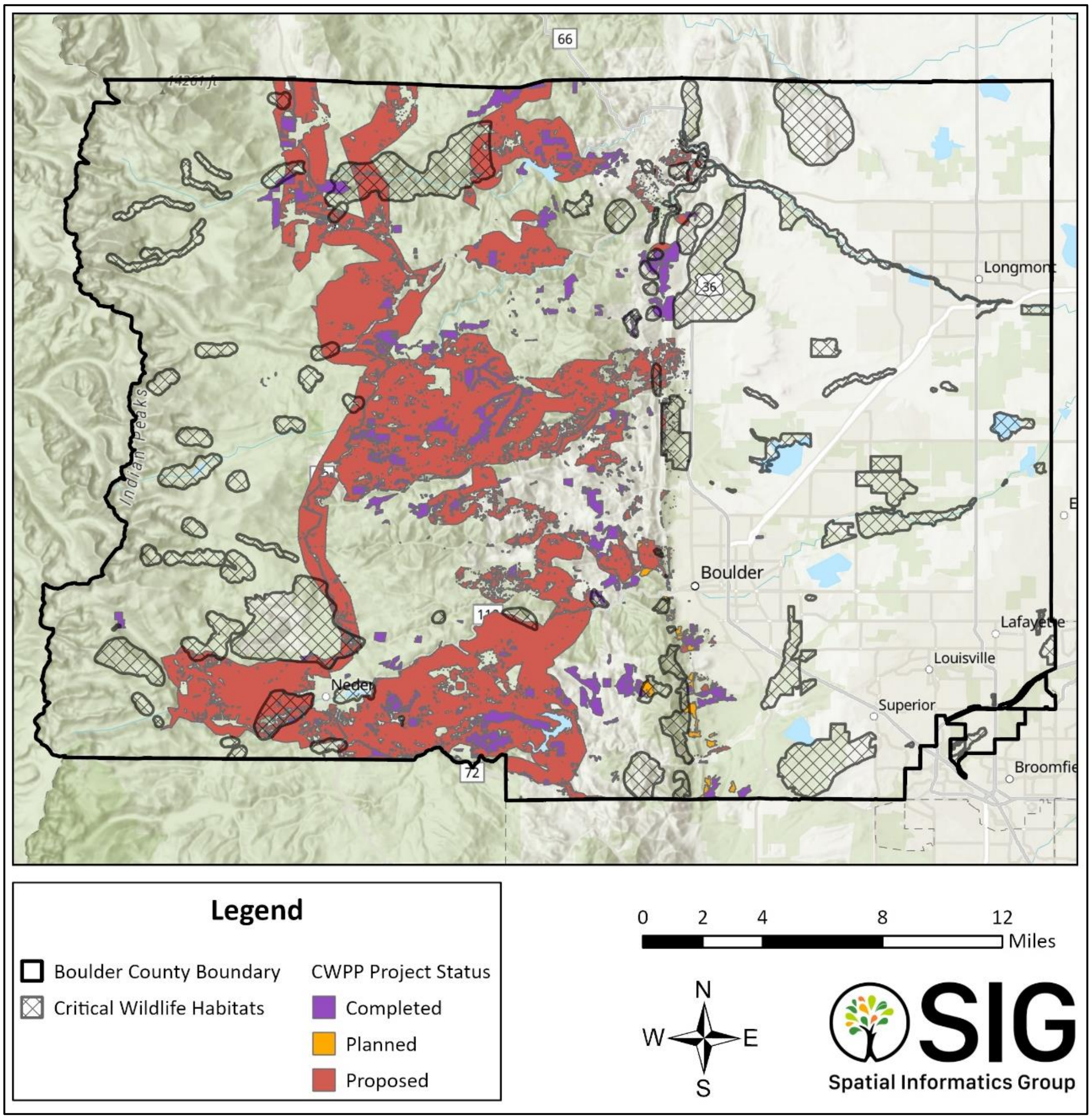


Figure 3.10. Map of critical wildlife habitat relative to treatment areas.

Environmental Conservation Areas - Boulder County has designated Environmental Conservation Areas (ECAs) to safeguard regions of significant ecological value (Figure 3.11). These ECAs encompass diverse habitats and species, ensuring the preservation of the county's rich biodiversity. The largest ECA, centered on the Indian Peaks Wilderness and Rocky Mountain National Park, spans 112,344 acres - over 20% of Boulder County. This area serves as a vital habitat for species such as lynx, wolverine, elk, and bighorn sheep. It also contains old-growth forests and significant wetlands, including the Copeland Willow Carr Natural Area. Conservation efforts here have focused on protecting montane parklands and facilitating wildlife movement corridors to lower elevations.

The North Saint Vrain area covers 38,133 acres west of Lyons. This region features some of the best roadless foothill habitats along the Front Range, with old-growth ponderosa pine forests, elk winter concentration areas, and golden eagle nesting sites. The North Saint Vrain Creek is recognized as a Wild Trout Stream and supports a population of the rare plant Larimer aletes (*Aletes humilis*). Conservation initiatives have included land acquisitions and designations to prevent habitat degradation. The South Saint Vrain and Foothills ECA, encompassing 25,929 acres, is characterized by old growth forests and serves as critical winter range for elk. Efforts in this area have been aimed at preserving private lands through conservation easements and open space acquisitions, enhancing the protection of its ecological values. These areas (and others) protect critical resources, including rare plant communities, wetlands, riparian zones, and wildlife habitats, while providing essential habitat connectors linking various life zones from plains to alpine environments.

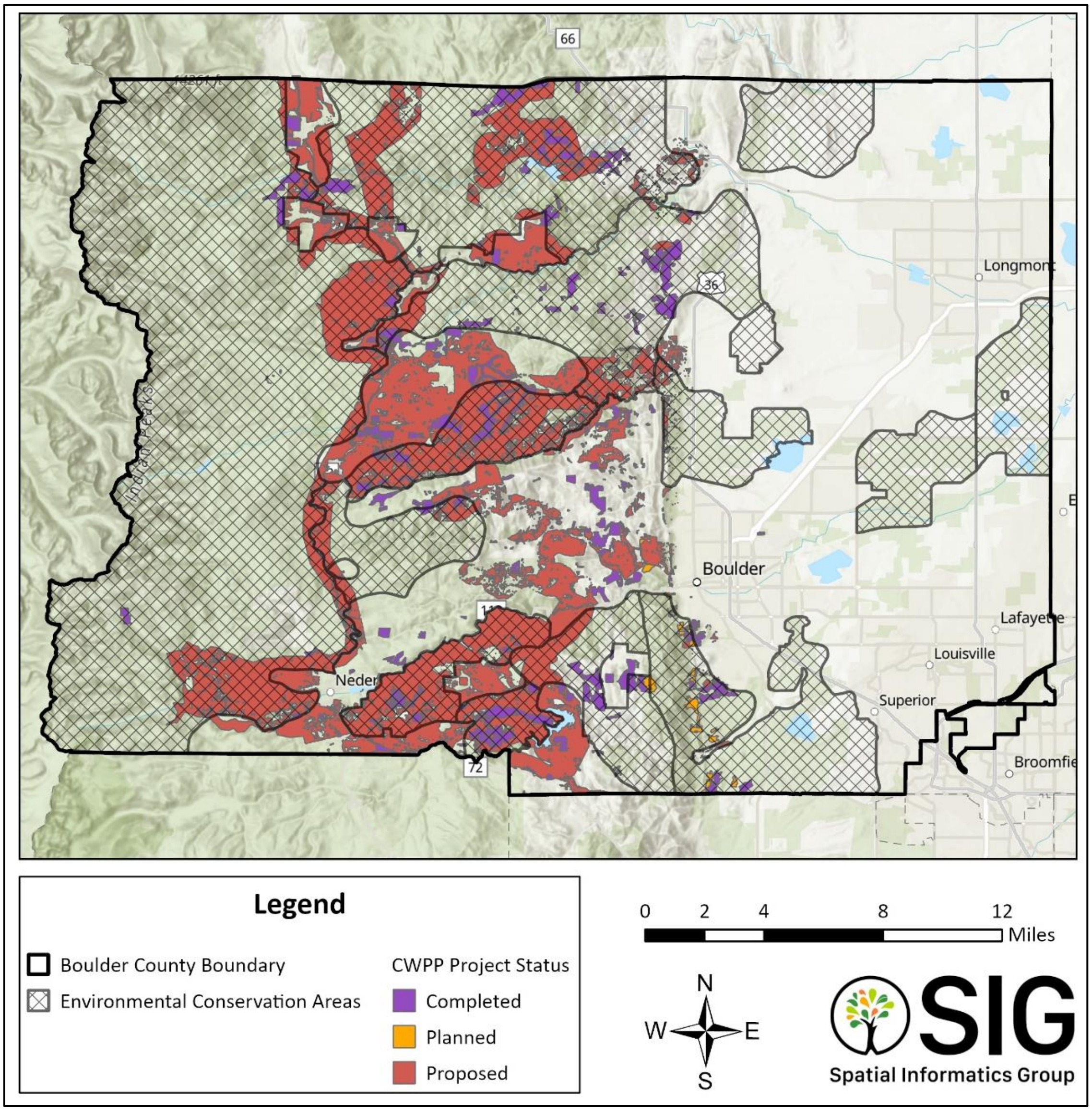


Figure 3.11. Map of Environmental Conservation Areas relative to treatment areas.

High Biodiversity Areas (Figure 3.12) - Boulder County designate High Biodiversity Areas (HBAs) as regions that support a rich variety of native species, rare or sensitive plant and animal communities, and high-quality natural habitats. These areas are identified through scientific surveys and ecological assessments, often highlighting places with unique geology, hydrology, or microclimates that foster biological richness. The HBA designation is used to guide land use planning, conservation efforts, and resource management, helping protect the county's ecological integrity. While the designation itself does not impose regulatory restrictions, it informs county decisions and encourages conservation partnerships with landowners and other stakeholders.

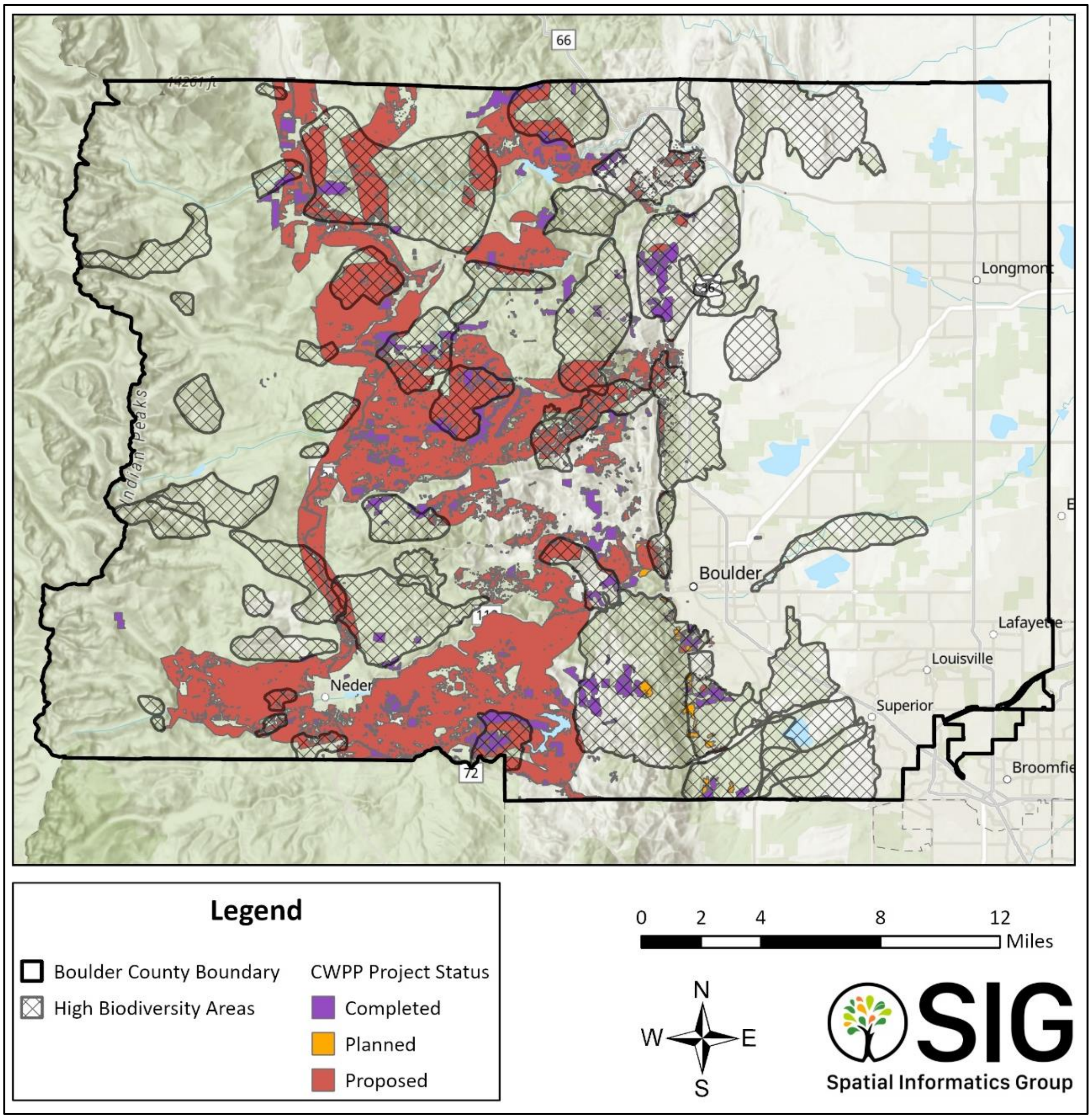


Figure 3.12. Map of High Biodiversity Areas relative to treatment areas

Significant Natural Communities (Figure 3.13) - Boulder County's Significant Natural Communities designation identifies areas characterized by critical plant associations that are limited in distribution and occurrence. These areas often encompass multiple important environmental resources that co-occur and interact, featuring species and ecological processes that remain relatively undisturbed by human activities, thus existing in their natural state. The primary goal of this designation is to conserve and preserve these communities to maintain living examples of natural ecosystems, provide a baseline for understanding ecological processes and functions, and enhance the region's biodiversity. By recognizing and protecting these unique areas, Boulder County aims to sustain the ecological integrity and natural heritage of the region for future generations.

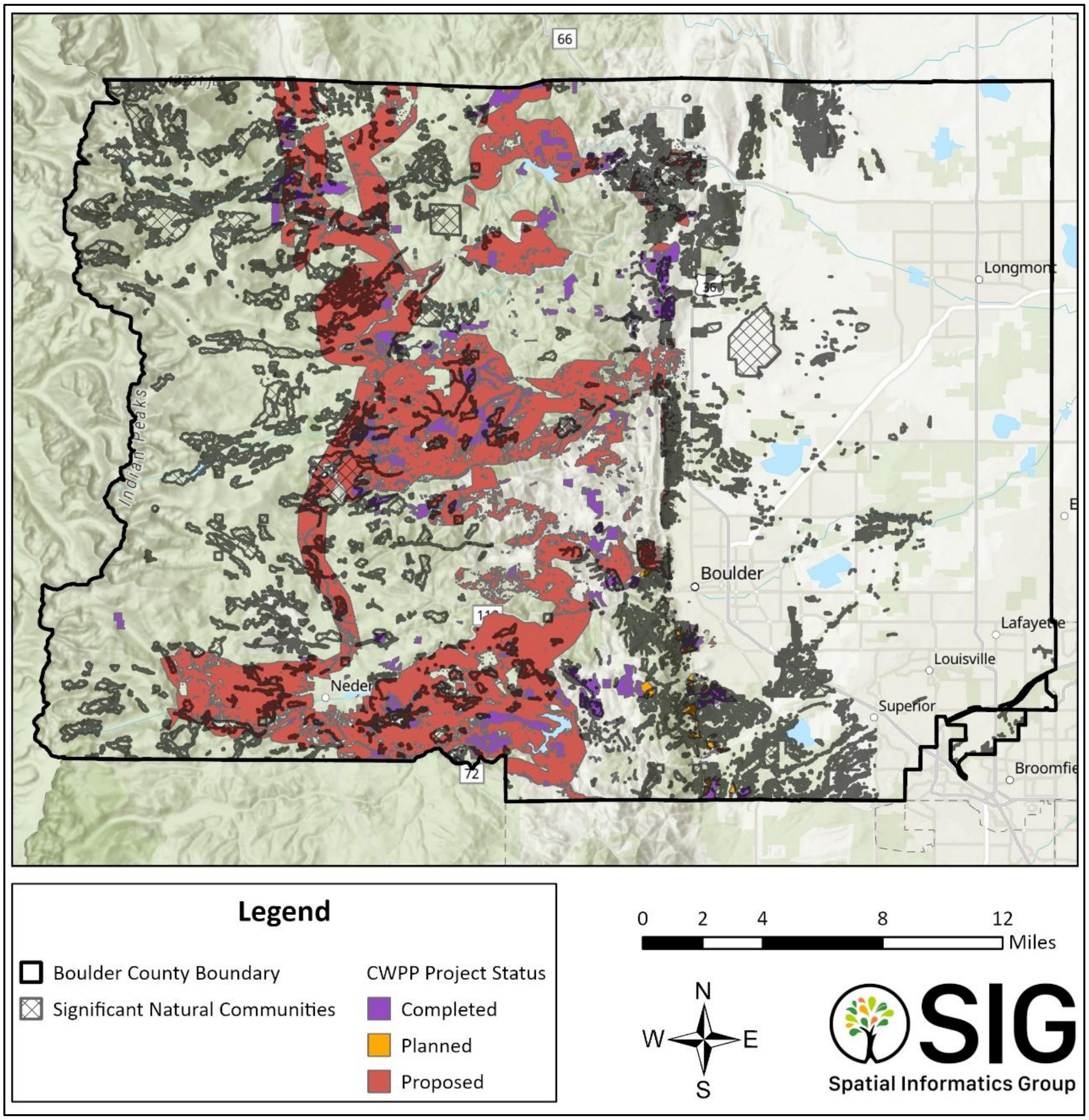


Figure 3.13. Map of Significant Natural Communities relative to treatment areas.

Wildlife Migration Corridors (Figure 3.14) - Boulder County, Colorado, has identified and designated Wildlife Migration Corridors as part of its commitment to preserving biodiversity and ensuring the health of native wildlife populations. These corridors are specific areas that facilitate the seasonal movement of wildlife, such as elk and deer, between essential habitats. By recognizing these pathways, the county aims to maintain ecological connectivity, allowing species to access necessary resources like food, water, and breeding grounds, which is vital for their survival and reproduction.

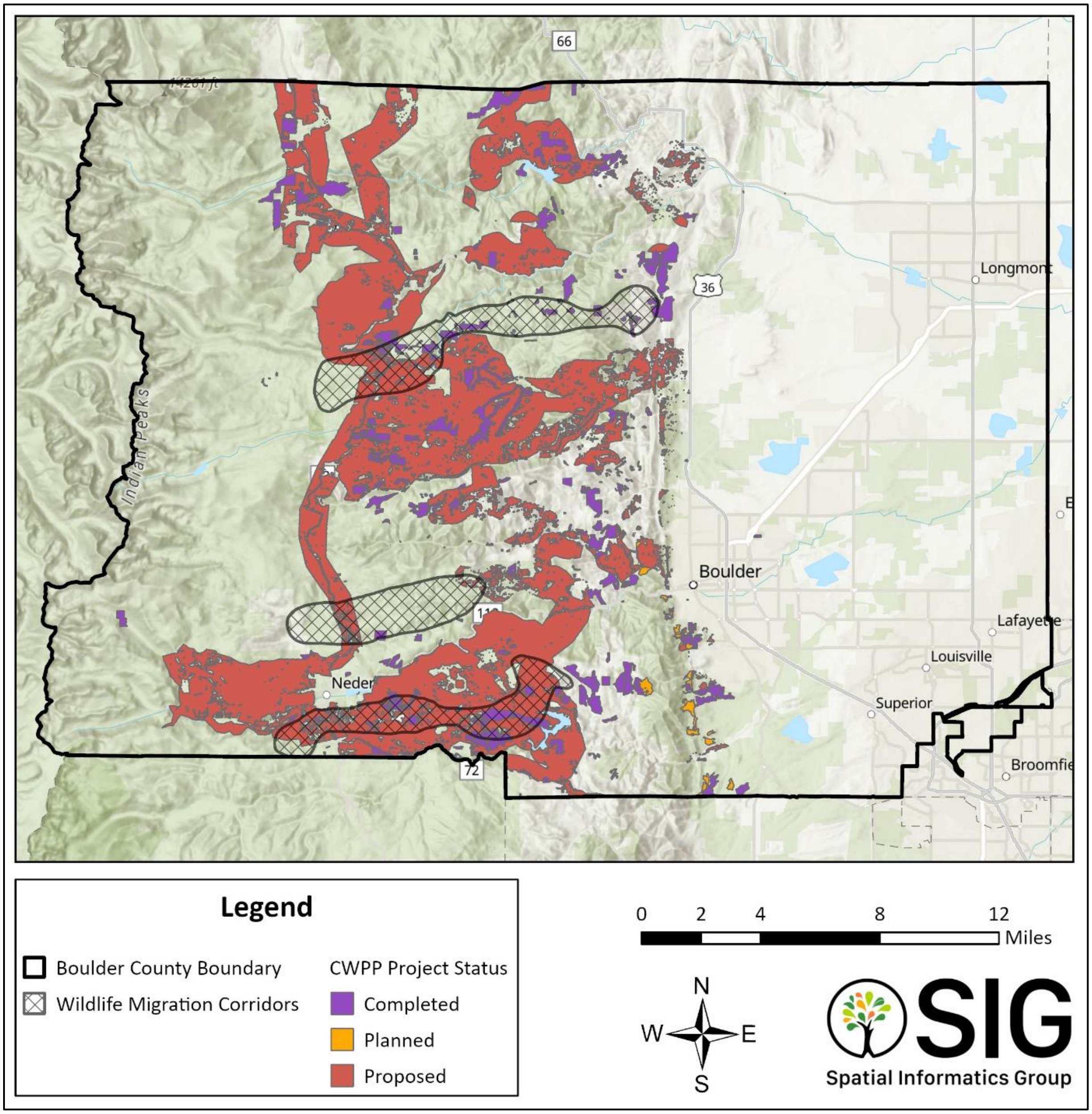


Figure 3.14. Map of Wildlife Migration Corridors relative to treatment areas.

Modeled results indicated that where fuels reduction treatments were applied, there is a greater proportion of treated areas than untreated areas exposed to high severity fire across all the special area designations in the years (2027 and 2032) immediately following treatments (Table 3.3). However, over the long term (year 2037 to 2047), treated areas had a reduced exposure to high-severity fire when compared to untreated areas (Figure 3.15).

Table 3.3. Summary of the modeled proportion of high fire severity (areas with >7ft flame length) between 2017 and 2047 within treatment footprints and relative to different special area designations.

		Percent of Treatment Footprint Exposed to High Severity Fire (flamelength >7ft)										
Special Area Designation (SAD)	Treatment Status	2017	2022	2027	2032	2037	2042	2047	Long-term Mean (2037 to 2047)	Total SAD (Acres)	Acres of Treatment Footprint within SAD	% of Treatment Footprint Within SAD
Abert's Squirrel Habitat	Treated	3	9	49	31	8	2	1	4	126,406	46,290	37%
	Untreated	2	6	8	7	7	10	10	9			
Critical Wildlife Habitat	Treated	3	7	44	25	7	3	2	4	48,227	4,005	8%
	Untreated	3	5	9	9	9	14	14	12			
Environmental Conservation Areas	Treated	2	10	51	30	7	3	2	4	265,894	43,034	16%
	Untreated	3	6	9	9	9	13	13	12			
High Biodiversity Areas	Treated	3	10	46	28	9	3	1	4	129,097	18,172	14%
	Untreated	2	5	9	9	9	12	11	11			
Significant Natural Areas	Treated	2	9	47	26	6	4	4	5	54,694	8,555	16%
	Untreated	2	5	10	10	10	14	13	12			
Wildlife Migration Corridors	Treated	2	9	44	27	5	2	1	3	22,172	7,395	33%
	Untreated	2	5	11	12	12	19	17	16			

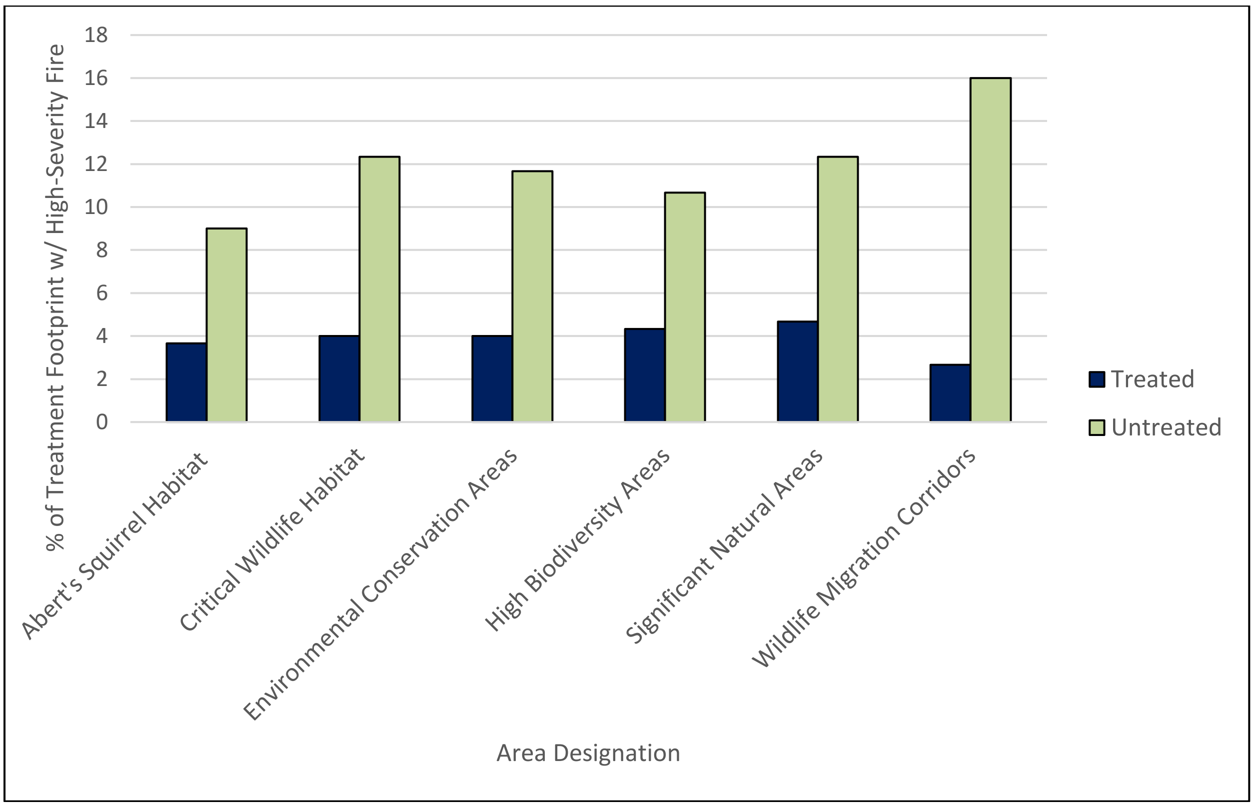


Figure 3.15. Comparison of the long term mean percent (2037 to 2047) of the treatment footprint exposed to high-severity fire within the context of different special area designations, treated and untreated, within Boulder County, CO.

The modeling results indicating higher fire severity immediately following fuels treatments are not unusual for fuels reduction projects because treatments, such as thinning or mechanical clearing are implemented, often leave behind a significant amount of surface debris - commonly referred to as "slash" - including branches, bark, and foliage. This accumulation of fine and coarse fuels on the forest floor can increase fire intensity and flame length, particularly if the material is not removed, chipped, or burned in follow-up treatments (Scott, 2012; Banaerjee et al., 2020; Davis et al., 2024). Additionally, opening the forest canopy through tree removal allows more wind and sunlight to reach the surface, which can accelerate the drying of fuels and increase oxygen availability during a fire, both of which contribute to higher flame lengths (Banerjee, 2020). The reduced shading also lowers surface fuel moisture, further enhancing flammability (Banerjee et al., 2020). Although these treatments are effective at reducing the risk of high-severity crown fires in the long term, the initial aftermath can temporarily create conditions more conducive to intense surface fires, making short-term fire behavior more severe until the residual fuels break down or are otherwise managed Banerjee, 2020).

Invasive Species

Severe wildfires often create conditions favorable for the proliferation of invasive species (Foxcroft et al., 2013; Wasserman and Mueller, 2023). Non-native plant species, particularly fire-adapted invaders such as cheatgrass (*Bromus tectorum*) and Russian thistle (*Salsola tragus*), establish quickly after wildfires and alter fire regimes by increasing fuel loads and fire return intervals (Boulder County CWPP, 2024). Wildfires disrupt native plant communities and create open niches that invasive species utilize (Epstein et al., 2024). Fire-adapted invasives, like cheatgrass and kochia (*Bassia scoparia*), prosper in burned areas, outcompeting native vegetation and forming continuous fuel beds that facilitate recurrent fires (Foxcroft et al., 2013; Boulder County CWPP, 2024). Studies indicate that high-severity burns create ideal conditions for non-native grass dominance, which increases the likelihood of frequent, fast moving and high-intensity wildfires (Vukomanovic and Steelman, 2019). This fire-invasive feedback loop can lead to significant ecosystem transitions, particularly in Ponderosa Pine and mixed-conifer forests (Wasserman and Mueller, 2023).

Post-fire landscapes are prone to soil erosion and hydrophobicity, worsening invasive species spread. Invasive plants degrade soil, increase sediment loads, and reduce moisture retention (Paul et al., 2022; Elliott et al., 2024). Colorado's Front Range shows untreated forests generate up to 50% more sediment runoff than treated areas. This degradation favors invasive plants, allowing quicker establishment in disturbed soils. Vegetation recovery varies with fire severity, climate, and invasive presence (Epstein et al., 2024). Northern Rocky Mountains research indicates 85% regeneration in burned areas, but sites with multiple burns show slower regrowth. Colorado surveys identify Russian thistle and diffuse knapweed as dominant colonizers in high-severity burn sites (Boulder County CWPP, 2024), consistent with broader Western U.S. studies on struggling native species regeneration in untreated, high-severity burn areas (Wasserman and Mueller, 2023).

Effective post-fire invasive species management typically requires a combination of mechanical removal, herbicide application, and native species restoration (Foxcroft et al., 2013; Palaiologou et al., 2020). Targeted removal efforts are critical in mitigating fire-adapted invasive species such as cheatgrass and kochia (Boulder County CWPP, 2024). Mechanical removal and herbicide application have proven effective in reducing invasive plant fuel loads (Foxcroft et al., 2013), although the long-term impacts herbicides on native species recruitment in Boulder County remains lacking (Brett Kencairn, pers. comm). Prescribed burns can suppress fire-adapted invasive species, though their efficacy is site-dependent (Robinson et al., 2014). Strategic native species replanting efforts post-fire can outcompete invasive species and enhance ecosystem recovery (Vukomanovic and Steelman, 2019). Prescribed fire has been successfully implemented in Boulder County to reduce invasive grass fuel loads, effectively lowering wildfire risk and improving native plant recovery (Boulder County CWPP, 2024). However, controlled burns must be carefully timed to avoid exacerbating invasive species expansion (Palaiologou et al., 2020).

Integrating invasive species removal into wildfire mitigation plans is crucial for reducing long-term fire risk (Foxcroft et al., 2013). Reintroducing native species post-fire enhances ecosystem resilience and prevents ecosystem conversion to invasive-dominated landscapes (Vukomanovic and Steelman, 2019). Long-term monitoring of invasive species post-wildfire is necessary to evaluate the effectiveness of management interventions (Elliott et al., 2024). Assessing the role of climate change in altering fire regimes and invasive species dominance in Rocky Mountain ecosystems is critical for developing adaptive management strategies (Wasserman and Mueller, 2023).

Fuels reduction treatments and post-fire invasive species control are integral strategies for addressing the ecological challenges posed by increasingly severe wildfires in Boulder County (Boulder County CWPP, 2024). According to the 2024 Boulder County Community Wildfire Protection Plan (Boulder County CWPP, 2024), fuel treatments such as mechanical thinning, prescribed burning, and targeted vegetation management are essential for creating resilient landscapes that can withstand and recover from fire, drought, invasive species, and climate change disturbances. These treatments help reduce hazardous fuel loads, thereby decreasing fire intensity and the likelihood of large, high-severity wildfires that disrupt ecosystem processes and increase susceptibility to invasive species. The plan recommends combining pre-fire fuel treatments with post-fire restoration to effectively prevent invasive species establishment and to support native plant and wildlife habitat recovery. This integrated approach is supported by Boulder County's history of fuels reduction accomplishments and invasive control efforts on public lands such as Hall Ranch and Heil Valley Ranch. In summary, the 2024 CWPP underscores that fuel treatments and invasive species control are not standalone actions, but complementary tools in a larger, adaptive management strategy designed to foster ecological resilience, protect biodiversity, and support long-term forest and grassland health in the face of growing wildfire threats.

In conclusion, the proliferation of fire-adapted invasive species in post-fire landscapes presents significant ecological and management challenges. In Colorado and the Rocky Mountains, targeted invasive species control, prescribed fire, and strategic replanting are essential for maintaining long-term ecosystem resilience. By implementing adaptive management and continued research, land managers can mitigate the long-term ecological impacts of invasive species on wildfire-prone landscapes. Wildfire poses significant challenges to biodiversity conservation, particularly in sensitive or fragmented habitats. High-severity fires create ecological niches conducive to the spread of invasive species such as cheatgrass and Russian thistle, which alter fire regimes and disrupt native successional pathways. Untreated stands have proven disproportionately vulnerable to these dynamics, generating a feedback loop wherein invasive species perpetuate increased fire severity. By contrast, fuels reduction treatments not only diminish the likelihood of severe burns but also curtail the post-fire establishment of invasive taxa by limiting the extent of soil and canopy disturbances. Management strategies - including prescribed burns, mechanical removal, and replanting native vegetation - have demonstrated success in sustaining species diversity and maintaining habitat functionality.

Vegetation Type Conversion

Wildfire plays a pivotal role in shaping ecosystems, particularly in fire-adapted landscapes such as the Rocky Mountains, Colorado, and Ponderosa Pine forests. However, shifts in fire frequency and severity - driven by climate change, historical fire suppression, and anthropogenic land use - have upset the relationship between fire and biodiversity. Fire regimes (the type, frequency, intensity, seasonality, and spatial dimensions of recurrent fire) within a normal range of variability help to maintain biodiversity, in part through the creation of heterogeneous landscape mosaics (Nasi et al., 2002; Kelly, 2020). However, substantial shifts in the severity of wildfire can negatively impact vegetation communities and the animal populations that depend on them (Kelly et al., 2020). For example, in forests, a more frequent and intense fire regime can impede plant succession, such as a shrub community, instead of maturing to a climax forest. Ultimately, over the long-term, this can result in a permanent "vegetation type conversion" from forest to non-forest, something that has been occurring in recent years throughout the western, and particularly the southwestern, United States (Guiterman et al. 2022). For native animals, more frequent and/or intense fire regimes (partially due to climate change) can reduce the availability of food and shelter, limiting a population's capacity to recolonize a particular habitat for an extended period (Shaffer et al. 2018). That can be particularly notable on old growth species (Rockweit et al., 2017).

From a landscape ecology perspective, increasing severity of wildfire can be seen to contribute to the problem of habitat fragmentation. Intense fire has been found to create edges and drives edge effects, to affect patch quality, and to significantly alter connectivity; furthermore, where fragmentation is already present, wildfire can interact with it synergistically, multiplicatively, antagonistically or additively, in some cases leading to local extinctions (Driscoll et al. 2021). Ultimately, increased fragmentation through fire may benefit edge species but will almost certainly negatively impact interior species.

There is considerable variation, however, in how different taxa or communities respond to severe wildfire. For instance, while aquatic ecosystems, including trout and macroinvertebrates, do experience immediate die-offs following severe fire, they have been found to recover completely within three years (Rust et al. 2019). And other taxa have been found to benefit from fire. For instance, in one of the few studies on post-wildfire biodiversity impacts specific to Boulder County (focused on the Fourmile Canyon Fire burn scar), it was found that bee diversity across five families increased after severe fire, with abundances remaining unchanged (Gelles et al. 2022).

Soils

Unmitigated wildfires have adverse effects on soil health, ecosystem stability, and hydrological processes (Elliott et al., 2024; Paul et al., 2022). The impacts of wildfire on soil include significant alterations in nutrient dynamics, microbial composition, hydrophobicity, and erosion susceptibility, often resulting in long-term degradation (Richardson et al., 2024). The severity of these impacts is contingent on pre-fire land management practices, particularly whether forests have undergone fuel reduction strategies such as thinning, prescribed burning, or biomass removal (Paul et al., 2022; Agee and Skinner, 2005). This review synthesizes contemporary research on wildfire-soil interactions, emphasizing differential responses in treated versus untreated landscapes and the broader implications for post-fire soil resilience.

Wildfires significantly disrupt soil structure, porosity, and aggregate stability, frequently inducing the formation of hydrophobic layers and the volatilization of soil organic matter (Elliott et al., 2024; Richardson et al., 2024). High severity burns result in the combustion of soil organic carbon, reducing moisture retention capacity and exacerbating surface runoff. Empirical studies indicate that post-fire soil erosion rates can surge up to 30-fold in severely burned areas compared to unburned regions, with ash deposition and sedimentation deteriorating adjacent aquatic ecosystems (Paul et al., 2022; Clyatt et al., 2017). Furthermore, biomass combustion releases macronutrients, including nitrogen, phosphorus, and potassium, into the soil matrix; however, these elements are rapidly lost via volatilization, leaching, and surface erosion, thereby precipitating long-term declines in soil fertility (Richardson et al., 2024; Flamenco et al., 2019). High severity burns also diminish cation exchange capacity (CEC), impeding nutrient retention and slowing soil recovery trajectories (Elliott et al., 2024).

Soil microbial communities are highly sensitive to fire-induced thermal stress, as elevated temperatures can decimate fungal and bacterial populations critical for nutrient cycling and organic matter decomposition (Paul et al., 2022; Agee and Skinner, 2005). In unmanaged forests with substantial fuel accumulation, wildfires exhibit prolonged high intensity burns, resulting in greater microbial mortality and protracted post-fire recolonization periods (Richardson et al., 2024). By contrast, fuel-treated forests experience moderate fire intensity, preserving microbial reservoirs and facilitating expedited post-fire biogeochemical recovery (Elliott et al., 2024). Post-fire nutrient cycling undergoes substantial alterations, with organic nitrogen undergoing rapid transformation into ammonium (NH_4^+) and nitrate (NO_3^-), leading to increased nitrate leaching and heightened risks of eutrophication in downstream water bodies (Paul et al., 2022; Elliott et al., 2024), can markedly disrupt watershed stability by increasing sediment transport, soil erosion, and mass-wasting risks. High-severity fires often induce hydrophobic soil conditions, reduce infiltration capacity, and precipitate large-scale erosion events, which can elevate sediment loads downstream. Empirical data from untreated sites indicate an up to a 30-fold increase in post-fire erosion rates, impacting water supply infrastructure and aquatic habitat.

Pre-fire fuel reduction treatments—including mechanical thinning, prescribed burning, and biomass extraction—profoundly influence wildfire intensity and its subsequent effects on soil integrity. Empirical evidence underscores that fuel-treated forests exhibit diminished fire severity, thereby mitigating soil thermal loading, organic matter volatilization, and hydrophobicity formation (Richardson et al., 2024; Agee and Skinner, 2005). Moderate-intensity prescribed burns have been shown to enhance soil nutrient retention by cycling organic matter without inducing severe volatilization losses (Paul et al., 2022; Clyatt et al., 2017). Conversely, untreated forests with excessive fuel accumulation foster high-intensity wildfires, exacerbating soil degradation through increased organic material combustion, microbial depletion, and compromised infiltration capacity (Elliott et al., 2024; Flamenco et al., 2019). These conditions prolong post-fire recovery and elevate the risks of secondary soil degradation phenomena, such as desertification and hydrological instability.

Soil erosion is a predominant concern in post-wildfire landscapes, particularly in untreated forested terrains where fire-induced hydrophobicity inhibits infiltration, leading to elevated runoff and sediment transport (Paul et al., 2022; Agee and Skinner, 2005). Research indicates that fuel-treated forests experience 30–50% lower erosion rates than unmanaged ones, primarily due to retained root structures and preserved soil cohesion (Elliott et al., 2024; Clyatt et al., 2017). Notably, studies from the Lake Tahoe Basin highlight the complex trade-offs between erosion mitigation and wildfire hazard reduction, demonstrating that strategically applied fuel treatments effectively mediate both risks (Flamenco et al., 2019).

Water quality outcomes in post-fire landscapes also vary considerably between treated and untreated sites. High-severity wildfire zones in untreated forests have been found to contribute disproportionately high loads of sediment, heavy metals, and organic pollutants to downstream reservoirs (Richardson et al., 2024; Flamenco et al., 2019). Conversely, fuel-managed forests maintain greater soil stability, reducing sediment flux and improving post-fire hydrological integrity (Paul et al., 2022). The trajectory of post-fire soil recovery is contingent upon multiple factors, including burn severity, vegetation composition, climatic variability, and pre-fire management strategies (Richardson et al., 2024). Biomass harvesting has noticeable effects on soil CO_2 efflux and net ecosystem exchange, influencing post-fire microbial activity and nutrient dynamics (Flamenco et al., 2019). In high severity burn areas, the depletion of vegetative cover and root networks amplifies the likelihood of soil erosion, landslides, and landscape degradation (Paul et al., 2022). However, empirical studies indicate that forests subjected to proactive thinning and prescribed burns exhibit accelerated soil stabilization and organic matter retention due to reduced fire severity (Elliott et al., 2024).

In conclusion, wildfire-induced soil degradation poses challenges to ecological resilience, water quality preservation, and post-fire landscape stability. Most evidence indicates that high-severity wildfires in unmanaged forests cause increased soil erosion, nutrient depletion, and microbial community disruption. However, fuel-reduction strategies, including thinning and prescribed burning, clearly mitigate these harmful effects by reducing burn severity, preserving soil organic matter, and enhancing microbial recolonization rates (Paul et al., 2022; Richardson et al., 2024). A rigorous integration of fuel management, erosion control measures, and post-fire restoration protocols is essential to bolstering soil resilience and fostering long-term ecosystem sustainability (Elliott et al., 2024).

Watershed Protections and Mitigating Risk of Cascading Events

Increasingly severe wildfire has resulted in hydrological disturbances (Littell et al., 2018). The yield and timing of water supply from a watershed are strongly related to vegetation cover. Healthy watersheds yield consistent and predictable surface flows that both recharge groundwater and supply streams with reliable base flow. The presence of native vegetation, tree roots, and corresponding healthy soils all serve to mitigate peak flows during and after storms and to promote infiltration that in turn helps make stream base flow more consistent. Stand-replacing fire results in greatly increased surface runoff rates after storm events, which means too much water flows through the system in a short time period. By replacing the gradual timing of surface flows characteristic of a healthy watershed with short and high-volume flow events, water supply can be compromised, not only because the capacity of inflows and reservoirs is exceeded, but also because base flow is lowered in between storm events, compromising supply during drier periods.

This loss of vegetative cover, organic soil layers, and root structures, coupled with higher velocity peak flows, can also lead to increased sediment transport, erosion, mass wasting, and post-fire flooding (Paul et al., 2022; Murphy et al., 2015). The severity of these impacts is largely dictated by fire intensity, precipitation dynamics, topography, and watershed conditions before the fire (Saxe et al., 2018).

One way that wildfires increase surface runoff and alter infiltration rates relates to the combustion of organic soil layers and the formation of hydrophobic soils (Murphy et al., 2015). These effects reduce soil permeability and increase the likelihood of flash flooding and debris flows following precipitation events (Moody and Martin, 2004). A study in the Colorado Front Range found that water repellency continued to be found in soils around burned ponderosa and lodgepole pine forests up to 22 months after high severity fire, with repellency effects down to 2 inches of depth, although that repellency can gradually break down at between 3 and 12 months (Huffman et al. 2001).

A major hydrological consequence of post-wildfire hydrology is increased sediment yield. A three-year study in the Colorado Front Range found that post-wildfire precipitation events resulted in sediment and chemical transport levels 10 to 156 times higher than pre-fire conditions, primarily due to precipitation exceeding 10 mm of rainfall per hour (Murphy et al., 2015). This research underscored that burn severity and post-fire precipitation intensity are important drivers of hydrological impairment. A study by Saxe et al. (2018) analyzed streamflow responses in burned watersheds across the Western U.S. and found that sediment transport increased three to fivefold in the first two years following wildfire, with longer recovery times in steep, high-elevation landscapes. Post-fire sedimentation can have long-term consequences for reservoirs and drinking water supplies.

The *Cost-Benefit Analysis of Denver's Forests to Faucets Program* (Jones et al., 2019) provides a comprehensive assessment of how sediment loads from wildfire-affected areas can diminish water storage capacity and increase water treatment costs. The report explains that post-fire erosion significantly raises levels of turbidity and total suspended solids (TSS), both of which degrade water quality. This decline in quality results in higher treatment costs due to increased filtration demands, elevated chemical usage (for treatment of drinking water), and in some cases, the need to switch to alternative water sources.

In streams within Colorado's Front Range that were impacted by wildfire, turbidity and TSS levels increased by five to over thirty times compared to pre-fire conditions. Compounding these issues, contaminants such as nutrients, heavy metals, and fire retardants are often transported alongside sediment, further complicating treatment processes (Jones et al., 2022).

These water quality impacts translate into substantial economic burdens for water utilities. Following the 1996 Buffalo Creek and 2002 Hayman fires, Denver Water spent over $33 million on erosion control, post-fire rehabilitation, and dredging—much of it to address sediment accumulation in Strontia Springs Reservoir. Jones et al. (2021) used sediment reduction modeling and avoided-cost estimates to quantify the economic benefits of proactive wildfire mitigation. At Strontia Springs Reservoir, dredging costs were estimated at $130 per cubic meter of sediment, and when factoring in additional costs related to lost hydropower generation, increased treatment needs, and recreation impacts, the total rises to approximately $150 per cubic meter of sediment avoided.

Similar outcomes were documented in the Fourmile Creek watershed, where wildfire-driven runoff caused turbidity spikes that exceeded regulatory thresholds for drinking water quality (Murphy et al., 2015). In Denver Water's supply system, sediment yields were so high that even moderate storms temporarily dammed the South Platte River. Over roughly a decade, nearly 750,000 cubic meters of sediment were deposited in Strontia Springs Reservoir, significantly reducing its capacity (MacDonald et al., 2013). These findings align with those of Moody and Martin (2004), who reported that post-fire sediment deposition reduced reservoir capacity by 10–30% across several major water supply systems in the Western United States—underscoring the long-term economic and infrastructural consequences of wildfire-related erosion.

In steeper, mountainous watersheds, wildfire-induced loss of root cohesion and soil destabilization significantly increases the likelihood of mass wasting events such as landslides and debris flows (Micheletty et al., 2014). Burned landscapes are particularly susceptible to rainfall-triggered landslides in the first two to five years post-fire (Belongia et al., 2023). For instance, after the 2010 Fourmile Canyon Fire in Colorado, post-fire debris flows blocked roads, damaged homes, and deposited large volumes of sediment into local waterways, leading to millions of dollars in infrastructure damage (Murphy et al., 2015). Studies have shown that even moderate-intensity storms (10–20 mm/h) can trigger catastrophic debris flows in recently burned watersheds (Saxe et al., 2018).

Post-fire landscapes are also prone to flash flooding, as the loss of vegetation and soil infiltration capacity dramatically increases peak discharge rates (Moody and Martin, 2004). In the Southwest U.S., post-wildfire floods have caused damage to homes and infrastructure, with peak flows exceeding 100 times normal discharge levels (Paul et al., 2022). The higher runoff volumes associated with flash flooding also have significant impacts on stream channels themselves, including channel incision that can lead to armored channel beds (Legleiter et al 2003), and widening, which in turn can lead to greater solar exposure and higher stream temperatures, negatively impacting fish populations (Dunham et al. 2007). A case study in the Sierra Nevada found that burned watersheds produced twice as much runoff as unburned control sites, a phenomenon exacerbated by rapid snowmelt due to loss of forest canopy (Micheletty et al., 2014).

Not only are fuel treatments likely to reduce the probability of severe wildfire occurring, but if it does, they can positively affect fire behavior, post-fire hydrology, and long-term watershed recovery trajectories (Raymond and Peterson, 2005). For instance, in a study by Raymond and Peterson (2005) of an Oregon watershed, thinned and underburned forests exhibited significantly lower post-fire erosion rates, with mass wasting events occurring five times more frequently in untreated stands. Further, a study in the Colorado Front Range found that forests subjected to thinning and prescribed burns exhibited 40% lower runoff rates and 50% lower sediment yields following wildfire (Cannon et al., 2018).

Strategies that can be employed after a wildfire to help mitigate hydrologic impacts include stabilization measures and hydrological interventions, erosion control treatments, such as mulching, sediment barriers, and channel stabilization projects, and the use of beaver dams to restore natural hydrologic processes (Moody and Martin, 2004; Belongia et al., 2023). However, the efficacy of these approaches varies significantly between watersheds that had been treated versus untreated prior to wildfire.

In conclusion, wildfire-induced watershed disturbances - including sedimentation, erosion, mass wasting, and flooding - pose significant risks to water supply systems, infrastructure, and ecosystem health. These impacts are most severe in untreated watersheds, where high severity burns lead to destabilized slopes, increased debris flows, and impaired water quality. However, fuel treatments, beaver-based restoration, and hydrological interventions have been shown to reduce post-fire hydrological hazards and enhance watershed resilience and to yield a positive return on investment for water providers, relative to untreated watersheds (Jones et al., 2017). Future research should expand monitoring of post-fire hydrological recovery in treated vs. untreated watersheds to refine management strategies for climate-adaptive wildfire mitigation.

Impacts on Recreation and Tourism

Wildfires can have devastating short- and long-term regional effects on nature-based recreation and tourism as landscapes are degraded, thereby making recreation undesirable, unsafe, or inaccessible. In the short term this can result in costs in rebuilding tourism infrastructure and restoring degraded landscapes, while in the long term this can result in the decline or loss of recreation industry businesses in the region, even after landscapes may have recovered. However, the literature on this topic is not in agreement about the magnitude or duration - and in some cases, the direction - of such economic impacts.

While plenty of anecdotal evidence exists, relatively few economic studies have been done recently to quantify wildfire impacts on recreation and tourism, and fewer still in the context of Colorado's Front Range. One reason for this paucity is the recognized difficulty of isolating the economic impacts to a region specifically from wildfire, controlling for all other possible trends that might influence recreation demand. That is, it is extremely difficult to know with certainty that changes to recreational economic activity that occurred after a wildfire are directly attributable to wildfire (Englin et al., 2008). One way to control for larger trends that might confound results is to look at the change in one region affected by fire in comparison to changes in the larger region to which it belongs. For instance, Franke (2000) found that visitation actually increased in the years immediately following the 1988 Yellowstone wildfires, which could suggest to some that the wildfires caused increased visitation but, in fact, the entire state of Montana saw increases significantly greater, suggesting, counter-factually, that Yellowstone had lower visitation rates than it would have had in the absence of those wildfires. By contrast, a later study of fire in the Yellowstone region that used a "contemporaneous" travel cost econometric approach to examine the effects of current monthly wildfire and lagged monthly wildfire on visitation over 25 years (1986-2011) did find a consistent loss in visitation due to fire, averaging about 1.3%, which translated into a loss of $206 million in net present value terms for that period and $159 million in forgone expenditures by visitors to the 17 county greater Yellowstone region (Duffield et al., 2013). This shows that the results from wildfire-impact studies are highly sensitive to evaluation methods used.

Much of the earlier literature is summarized in a 2017 review paper (Bawa, 2017). The papers it covers, including both 'stated choice' (respondents observing photographic representations of post-wildfire effects and hypothesizing about their behaviors as a result) and 'revealed preference' (looking at how wildfire actually impacted consumer behavior) studies, found that consumer welfare losses are both quantifiable and substantial, often in the millions of dollars per site, but that they vary significantly based on activity, ecosystem, region and, importantly, fire severity.

Relatively few studies have isolated these impacts in precise financial terms. One that did so to some extent used surveys from five National Forests in New Mexico, coupled with travel cost and contingent valuation, and found that a hypothetical catastrophic fire would reduce visits to forests the following year by 7% and result in $81 million in lost economic output and 1,900 lost jobs (Starbuck et al., 2006). Another looked at the 2018 Ferguson Fire, which closed Yosemite National Park for three weeks during the peak season, and found that it resulted in an estimated $46 million decrease in visitor direct and indirect spending in neighboring Mariposa County and a $1.1 million reduction in local tax revenue in that county (Wilson et al., 2020). Their survey found that 42% of respondents said that wildfire activity would likely influence their desire to visit the Sierra Nevada region. A study of post-wildfire economic impacts at five National Parks in Utah found that aggregate visitation losses were between 0.5% and 1.5% during a typical fire year relative to a non-fire year. That was estimated to result in a negative regional economic impact across parks of between $2.7 and $4.5 million, with an associated loss of 31 to 53 jobs, although this result depended on the extent and severity of burning (M. Kim and Jakus, 2019).

In addition to the literature finding negative impacts from wildfire on tourism, there are others that find no impact, an equivocal impact, or even a positive one. For instance, increases in visitation were found in the period following low intensity fire in Southern California (Sánchez et al., 2016). Another study found no impact of wildfires on tourism and leisure employment, and only slight impacts on sectoral wages, following a series of fires in the Trinity County region of Northern California (Davis et al., 2014). Yet another study looking at wildfire in Florida used a survey instrument of repeat-visitors to Florida to query how wildfire might affect their hypothetical travel decisions, finding that the for the vast majority, wildfire would have no impact (Thapa et al., 2004). A study using surveys to assess travel cost preferences in Colorado found no impact of major crown fires to hiking visits but did find a negative impact on mountain biking visits (Loomis et al., 2001). Finally, a study looking at the impacts of wildfire smoke at campgrounds, most of them not adjacent to the wildfire locations, found only very minimal impacts on campground use (Gellman et al., 2022) although a later study by the same authors found there was a theoretical $2.3 billion annual welfare loss from the smoke impacts to campground users (Gellman et al., 2023).

The most relevant study to Boulder County was a 2003 report on the impacts of the 2002 Hayman Fire (Kent et al., 2003). Using counterfactual modeling, in which economic scenarios were simulated for relevant sectors assuming there was no fire for the months in question, it found that the Hayman Fire had some significant consequences for tourism and recreation, leading to economic losses in several counties, although the results were mixed. The fire forced the closure of three Ranger Districts of the Pike-San Isabel National Forest, during the peak summer tourist season. Some closures only last a few weeks, while others were longer, as some campgrounds did not reopen until the following year. These closures, combined with concerns over air quality and landscape fire damage, led to a sharp decline in visitation to outdoor recreation areas. Concessionaires managing recreation sites reported revenue losses in the mid six figures (approximately $380,000 in 2002 or $672,000 today) compared to the previous year. Businesses dependent on these natural areas accordingly suffered economically. Off-road vehicle (ORV) and snowmobile businesses were particularly hard hit, with one concessionaire reporting an 80% drop in business. The Lost Valley Guest Ranch, a major tourism-dependent business, was forced to close for nearly three months, resulting in estimated losses between $1.9 million and $2.0 million (between $3.36 and $3.54 million in today's dollars). Similarly, summer camps such as the Girl Scouts Wagon Wheel Council camp and the Mile High Council camp suffered financial setbacks, with reported losses in the low six figures. Outfitter and guide operations, which depend on access to public lands, also saw a significant reduction in business, with total client days falling to 75% of previous levels.

These direct impacts had broader economic ripple effects throughout the region. The decline in tourism led to some degree of reduced revenue for hotels, restaurants, and retail businesses, in turn leading to reduced sales tax revenue. Property values were also impacted, as assessments in burned areas were reduced by up to 50% for some land and up to 100% for some structures, depressing property tax revenue. Table 3.4 below, from the report, summarizes the impacts to property, assessment value and tax revenue for four impacted counties in original dollar values, while Table 3.5 provides those figures as inflation adjusted dollars for 2025.

Table 3.4. Summary of the impacts on property, property assessed value and tax revenue for four impacted counties in original dollar values (from Kent et al. 2003)

	Teller	Douglas	Park	Jefferson	Total
Property Value Lost	$13.74 M	$8.13 M	$1.77 M	$108.97K	$423.75 M
Assessed Value	$1.97 M	$1.15 M	$261.4 K	$ 9.97 K	$3.40 M
Annual losses in tax revenue	$127.4 K	$97.8 K	$11.64 K	$997	$237.8 K

Table 3.5. Summary of the inflation adjusted dollars for 2025 impacts on property, property assessed value and tax revenue for four impacted counties in original dollar values (adapted from Kent et al. 2003)

	Teller	Douglas	Park	Jefferson	Total
Property Value Lost	$24.36 M	$14.42 M	$3.14 M	$193 K	$42.12 M
Assessed Value	$3.50 M	$2.04 M	$463 K	$18 K	$6.03 M
Annual losses in tax revenue	$225 K	$173 K	$21 K	$1.8 K	$420 K

The study also found that some of that recreational economic activity was simply displaced rather than eliminated. While outfitter and guide business revenue declined in the immediate vicinity of the fire, much of that loss was offset by gains in those same sectors in other locations, as recreationalists simply altered their destinations. This last point is known in the literature as "*contemporaneous substitution*" and is yet another challenge in estimating recreational economic impacts from wildfire, since often wildfires don't affect overall spending, but rather slightly alter the geographic pattern (Englin et al. 2008). Likewise, this substitution can also occur in time, with prospective visitors often just delaying their visits to a burned site.

More recent fires in Colorado have received less attention in terms of studying their impacts on recreation and tourism. What little information exists comes from more anecdotal evidence. For instance, it was found that the Cameron Peak and East Troublesome Fires (2020) significantly impacted vacation rental markets in nearby areas as potential visits reconsidered travel plans due to air quality and closures, with drops in reservations of up to 35%, while Colorado as a whole saw increases of 26% in the same period (Key Data 2024).

One area that has received slightly more coverage of wildfire's recreational impacts is the west coast. For instance an industry group found that 11 percent of travelers to California said in 2018 (the year of the Camp Fire and other major incidents) that wildfires prompted them to cancel trips, representing a loss of $20 million to the state's tourism economy (Visit California, 2018). Oregon's tourism industry group found greater losses in 2017, of $51 million, due to wildfire.

While no data exists on how recent and nearby fires have affected the tourism and recreation economies of Boulder County or its neighbors, it is informative to look at the magnitude of that economy both locally and statewide to get a sense of what the impacts could potentially be. A 2024 study found, for instance, that outdoor recreation contributes 3% of the state's GDP (based on data from the Bureau of Economic Analysis) and that statewide economic output related to outdoor recreation amounted to $65 billion in 2023, yielding $11.2 billion in tax revenue, and supporting over 400,000 jobs, or 12% of Colorado's labor force (DeLoss, 2024). This study also found that 90% of that consumer spending went towards trip-related costs, like food, fuel and lodging, which suggests that those sectors are tightly coupled with the recreation economy in certain areas.

The nearest National Forest to Boulder - The Arapahoe and Roosevelt National Forest - is of vital economic importance for its recreation opportunities, with over 4.4 million recreational visitors who spend over $168 million annually, supporting over 3,300 jobs (US Forest Service, 2023). The largest share of these jobs (almost 900) is in the accommodation and food services industries. Labor income totals over $200 million annually.

Drilling down to the local level, both Boulder County and City of Boulder have exceedingly high levels of outdoor tourism and recreation, making them vital to the local economy. While data on their economic impact is not known of or available currently, visitation numbers speak to the likely impact. For instance, in 2023, the minimum number of visits to Boulder County Parks and Open spaces was estimated at over 1.82 million, across 23 properties and 6 regional trails, with biking and hiking as the overwhelmingly dominant activities (Marotti, 2023). The City of Boulder's Open Space and Mountain Parks system receives even greater visitation, despite its smaller size. In 2017, the last year for which system-wide summary statistics are available, it hosted 6.26 million annual visits, representing a 34% increase from the 2004-05 time frame, which was the last time the systemwide reporting was done (Leslie, 2018).

Based on this, we can infer that a major wildfire in the Boulder County backcountry could have significant impacts on tourism, recreation, and associated industries, as well as on tax revenues.

However, predicting the magnitude of these impacts with certainty is difficult given the paucity of recent studies and sectoral economic data.

Chapter 4. Conclusions and Recommendations

Conclusions

The assessment of woody biomass availability in Boulder County reveals a substantial and consistent supply of material that can support long-term utilization strategies. By integrating reported removals and modeled projections from multiple jurisdictions and agencies, the study provides a clearer picture of current and potential biomass volumes. While current removal rates average approximately 55,000 green tons per year, projections based on planned wildfire mitigation treatments suggest that annual production could increase to roughly 135,000 green tons. This represents an opportunity to transform liability woody biomass into a sustainable resource. However, not all biomass is accessible or economically feasible to remove, and many treatments still involve on-site burning or chipping. Continued collaboration among stakeholders, improved data tracking, and targeted investment in removal and processing infrastructure will be essential to capitalize on the biomass potential outlined in this chapter.

For the City of Boulder and Boulder County, woody biomass production estimates, and the datasets from which they are derived, are detailed in Chapter 1 of this report. For the six years analyzed (2019 to 2024), the City of Boulder produced and removed an estimated total of 32,489 green tons of woody biomass from the urban forest and 4,685 tons from City of Boulder-owned Open Space and Mountain Parks (OSMP), for an estimated total of 37,174 tons (Chapter 1). Over the same timeframe, OSMP had a modeled biomass production of 11,332 green tons of which 6,643 green tons was estimated to be in the form of logs (i.e., merchantable; Chapter 1). The difference of 6,647 is slash and small trees that are chipped and spread on site, which is a potential additional biomass source depending on utilization markets.

The annual average reported biomass production for the urban forest is 6,498 tons per year. Alternatively, the Cambium Carbon (2020) report for the City of Boulder estimated that the urban forest produces 10,000 tons of biomass a year, an estimate which includes production by private arborists. The OSMP modeled production average is 1,889 tons per year for a total annual average of ~8,378 – 11,889 green tons for the City of Boulder as a whole, in alignment with estimates reported in the Cambium Carbon (2020) report.

Boulder County Parks and Open Space (BCPOS) produced 22,115 green tons of woody biomass between 2019 to 2024, of which 16,740 green tons were removed. The remaining 5,375 tons was from the 2024 Riverside Ranch project in which the biomass was inaccessible. In general, BCPOS makes a point of removing and utilizing woody biomass generated as a byproduct of wildfire mitigation projects.

In summary, based on the reported biomass production per year, the annual woody biomass production for City of Boulder and Boulder County are as follows:

- City of Boulder: 8,378 – 11,889 tons/year
- Boulder County: 3,686 tons/year

The Biomass Utilization Analysis in Chapter 2 highlighted the broad range of existing infrastructure in the Boulder region capable of processing woody biomass, including over 40 facilities across 13 wood product categories. Boulder County's own sort yards and the Western Disposal Services facility play key roles in managing fire mitigation biomass. The analysis also evaluates transportation and delivery costs, providing a realistic understanding of the financial logistics involved. Most importantly, a structured selection and scoring process identified 12 promising biomass utilization pathways, with biochar, composting, and firewood emerging as the most viable based on regional needs, scalability, and environmental co-benefits. These top-ranked pathways reflect Boulder County's growing interest in low-emission, circular economy solutions that simultaneously mitigate wildfire risk and support local markets. The findings underscore the importance of tailored strategies that match feedstock types with appropriate technologies, infrastructure, and end-use markets.

Finally, the evaluation of co-benefits associated with fuel reduction projects demonstrated that biomass removal provides value beyond fire risk mitigation. Modeled outcomes showed reductions in wildfire emissions, increased forest resilience, and improvements in key forest health indicators such as tree mortality, canopy cover, and stand density. Additional environmental benefits include protection of biodiversity, soil and water resources, and recreational assets. The co-benefit analysis confirms that strategic fuels treatments, when thoughtfully planned and implemented, can serve as a foundation for broader environmental and community gains, especially when paired with effective biomass utilization. These findings reinforce the potential for Boulder County to align climate action, conservation, and public safety goals through integrated biomass management planning. Going forward, prioritizing projects with strong co-benefits can help maximize the ecological return on investment and enhance public support for fuels reduction initiatives.

Recommendations

The biomass supply (Chapter 1) and existing utilization facility analysis (Chapter 2) from this project demonstrated that there is ample processing capacity to accept the modest current woody biomass supply of 55,000 green tons a year. Despite that, there is an inherent inefficiency to the system given that almost all of the wood products produced are low value by volume, which results in no net positive economic value in the wood at the forest management project site. The priorities for increasing biomass utilization therefore focus on improving transportation and processing to reduce costs between the project site and end user, thereby increasing the economic value of the wood at the project site and increasing utilization.

As demonstrated by the Avoided Wildfire Emissions (AWE) analysis in Chapter 3, wildfire mitigation projects result in net carbon emissions over the next forty years even when taking avoided wildfire emissions into account. This is due in part to carbon emissions from biomass that is masticated and left to decompose, burned, or landfilled. Increasing utilization of woody biomass in a manner that sequesters more of the carbon embodied in the biomass will further improve the climate benefit of wildfire mitigation projects in Boulder County.

The following recommendations were developed to increase the utilization of woody biomass produced by wildfire mitigation projects in Boulder County in ways that provide additional economic value and sequester more of the carbon embodied in the woody biomass. A diversified approach is recommended that implements a variety of these recommendations, as directed by the Core Team working group or equivalent.

Enhance Capabilities of Existing Community Forestry Sort Yards

Boulder County currently owns and operates two Community Forestry Sort Yards (CFSYs) in Nederland and Meeker Park, proximate to most of the forest treatments taking place. Since these facilities are already sited and permitted, it is likely much easier to improve the existing facilities than site, plan, and permit a new one. These facilities are currently capacity-limited because they are intended to receive material from residential and small-scale projects. Improvements to the CFSY facilitates will allow forestry operations generating biomass to have a reliable, nearby place to take material, as well as provide utilizers with a reliable and well-known high-volume source. Near-term recommendations to improve the capacity of the existing CFSYs are:

- **Increase Operating Hours.** Both community forestry sort yards are only open seasonally, Wednesday – Saturday. Being open for the full work week will allow better access for professional forestry operations that are active during the work week.
- **Increase staffing**. Currently only one person usually staffs each CFSY. Having at least two staff members working will allow one person to receive material and one to process, which will increase throughput and minimize waiting times for offloading biomass.
- **Provide facilities for staff**. Currently the CFSYs do not have heated facilities for staff during inclement weather. A warming hut / receiving station at each CFSY would allow staff to more comfortably work during inclement weather, which can help extend the operating hours and season of the sort yard. Additionally, a dedicated workstation may make tracking inbound and outbound material easier, which would also benefit offloading material with an efficient process.
- **Provide a hard surface**. Pave or build a concrete hard-surface pad at each CFSY that can be used to sort and process material while minimizing contamination with dirt and rocks, which will in turn increase the value of the processed material.
- **Invest in Processing Equipment / Infrastructure.** Work with CFSY staff and others to inventory existing equipment and make recommendations for additional equipment that will increase processing capacity and efficiency. For example, consider investing in a large grinder sufficient in size to process whole trees and a loader for each location.

Community Forestry Sort Yards Supply Agreements

In addition to upgrading the CFSY facilities, Boulder County should work with existing biomass utilizers to develop supply agreements for woody biomass from the CFSYs. Supply agreements with established utilizers will allow the CFSY to sort and process material to the utilizer's specifications and establish transportation agreements that can leverage economies of scale. This can also reduce the residency time of material at the CFSY. Throughput can be increased at the CFSY if there is a known destination for the biomass and it can be transported on a regular schedule. Known uses and volumes for the biomass would also allow the CFSY to process material to specifications required by the utilizer in exchange for payment or increased prices for the material. Pre-processed material will also have a higher value per volume / weight, making transportation costs more efficient. Some potential supply agreements include:

- Provide roundwood (logs) to sawmills, which is likely the highest-value use.
- Continue to provide biomass to the Boulder County biomass heat generation. facilities at the Jail and Parks & Open Space facility.
- Pre-process and provide material for biochar production.
- Pre-process and provide material for bio-oil production.
- Pre-process material for composting.

Incentivize Small-scale and Project-site Utilization

As discussed in Chapter 2, The cost of transporting green wood is high due to the volume and weight of the material and increases substantially with distance. On-site processing and utilization at either the forest management project site or a local site (like CFSY) that is close to the forest can reduce transportation costs by controlling long-haul transportation to higher-value, lower weight / volume products. The following provides some recommendations to facilitate on- and/or near-site biomass processing.

Develop a Permit for Project-site Processing

Encouraging the efficient processing of woody biomass directly at forest project sites will require the development of a more accessible and streamlined permitting process. While this effort would demand significant up-front staff time from Boulder County and the City of Boulder, it represents one of the most cost-effective strategies available. Currently, land zoned for non-industrial uses - including forestry - requires a Special Use Permit even for small-scale processing activities, such as the use of a mobile sawmill. To address this barrier, a permitting pathway specifically designed for biomass processing and utilization should be created, offering a more predictable and efficient approval process.

It is recommended that Boulder County and City of Boulder staff form a team to review existing regulations related to biomass processing at project sites. Based on this review, they should design a new, accessible permitting framework - potentially using tools like a simplified environmental checklist - to streamline regulatory review. Anticipated constraints will likely center around air quality standards and fire safety considerations, particularly for pyrolysis technologies producing biochar or bio-oil. Additional limitations, such as establishing minimum landing sizes for processing equipment, may also be necessary. However, the focus should remain on creating a clear, efficient process that actively incentivizes on-site biomass processing by reducing regulatory uncertainty and administrative burden.

Explore Community Forestry Sort Yards Public-Private Partnerships

Consider leasing space at the Community Forestry Sort Yard (CFSY) to support the processing of woody biomass into products such as biochar, bio-oil, lumber, and firewood. Existing companies already engaged in biomass utilization could be strong candidates to establish satellite facilities at the CFSY, expanding their operations while supporting local resource management goals. However, several limitations must be addressed: available space at the CFSY may be limited; additional infrastructure would likely be needed to support processing activities; and there would be associated costs for planning, permitting, and developing a public-private partnership agreement. Recommended potential on-site utilization partnerships include:

- **Firewood Production**. Firewood is an in-demand product in the mountain communities near the CFSYs, and offsets fossil-fuel based heating. Firewood processing equipment is also not as capital intensive as other pathways. Revenue from firewood can offset processing costs, while providing low cost or free firewood to low-income households in rural mountain communities could also have substantial social benefits.
- **Biochar Production.** Biochar is very scalable, and therefore the number of units can be determined based on the biomass supply at the CFSY and the space available. Due to both emissions concerns and the results of the Life Cycle Assessment (LCA), it is recommended that this only be implemented on a Boulder County owned and operated site if the syngas produced by the biochar kilns is captured and utilized.

- **Bio-oil Production.** Bio-oil production is scalable in the same manner as biochar.
- **Fungal Inoculation.** For low-value woody biomass, a fungal inoculation and decomposition pathway at the CFSYs can process biomass in a manner that will require minimal post-processing transportation.

Invest in Direct Community Forestry Sort Yards On-site Processing

In place of a private-public partnership, Boulder County can directly produce products at the CFSY. This would be more costly for the County than a public-private partnership and require marketing the end-product but would give the County more control over the process and end-use of the product. For example, biochar produced could be spread on land owned by Boulder County and the City of Boulder, both improving soil quality and sequestering carbon.

Work with Partners to Develop New Facilities

Enhance the Planned Boulder County Compost Facility

The Life Cycle Assessment (LCA) demonstrated that composting sequesters a similar amount of carbon of the three key pathways analyzed (compost, firewood, and biochar). Boulder County and the City of Boulder are currently scoping the development of a publicly operated compost facility to process municipal organic waste. It is beneficial to include 20% - 30% woody biomass by volume in a compost operation, and therefore there are strongly aligned incentives to developing a facility that can process both municipal organic waste and woody biomass.

It is recommended to work with the team scoping the potential Boulder County compost facility to add woody biomass receiving, sorting, and processing capacity. Higher value woody biomass can be sold or provided to utilizers or processed on site. Low value woody biomass will be available for the collocated compost operation. A biomass processing facility on the plains in eastern Boulder County will also be closer to most utilizers, reducing transportation costs from the facility. The amount of wood diverted to compost or other uses can be adjusted based on the needs of the compost operation to maintain the 20% - 30% woody material balance.

If there is substantially more woody biomass than the composting operation can accept, then direct on-site processing or a private-public partnerships similar to those discussed for the CFSYs above are also applicable.

Partner with Larimer County on a Biomass Processing Facility

If Larimer County pursues developing a biomass sorting and processing facility, there are efficiencies to scale in creating a single facility that serves both counties. If this facility is sited near Estes Park, it will likely be redundant to the Meeker Park CFSY from a Boulder County perspective, but it could have considerable value if sited in eastern Boulder / Larimer County. If the potential Boulder County compost facility is sited near the Larimer-Boulder County line, Larimer County could also invest in building out the woody biomass processing capacity at that facility, which is likely the most economically efficient solution.

Subsidize Transportation

Although subsidizing transportation does not have the robust co-benefits or cost efficiencies of the other recommendations discussed herein, it is an option with a low barrier to entry that could help move more biomass from forest project sites to utilizers. Options include:

- **Directly subsidize transportation.** Offset the transportation cost to existing biomass utilization facilities in the Boulder Region (see Chapter 2). Depending on the facility there could be a purchase of the biomass (particularly in whole log form) or acceptance of the material with no tipping fee in exchange for subsidized transportation.
- **Provide transportation between mountain and plains CFSYs.** If a new biomass processing facility is developed on the plains of eastern Boulder or Larimer County, transportation of biomass between the mountain CFSYs (Nederland and Meeker Park) and the new facility could be subsidized or directly provided by Boulder County. The biomass feedstock would then be closer to utilizers, which are primarily in the eastern counties. The drawback to this approach is that it is less financially efficient to unload and reload biomass at an intermediary facility than take it directly to the end use facility. If a substantial amount of the biomass is used for compost at the new facility, the efficiency of this option increases markedly.

Leverage Carbon Financing

Payment for carbon storage through established methodologies and the sale of carbon credits is already taking place by biomass utilizers, notably Biochar Now (biochar) and CHARM (bio-oil). This could be expanded to other liability biomass utilization pathways such as inclusion in compost, or sequestration in such bioproducts as lumber. Boulder County can enter the carbon finance market directly if they invest in a utilization pathway at sufficient scale to make the development and issuance of carbon credits worth the transaction cost. They can also partner with existing organizations utilizing carbon financing to increase the pace and scale of credit issuances in a way that increases utilization and sequestration of biomass.

Urban Wood Flows

Woody biomass from the City of Boulder's urban forestry program and other Boulder County municipalities offers a compelling opportunity to turn what has historically been a waste product into a resource. Urban wood that comes from tree maintenance is usually chipped, although it can be transported in larger slash form if there is a benefit to doing so. Urban-derived woody biomass is also much closer to most utilizers than forest products from western Boulder County. Given that most urban woody biomass is chipped, the best use is likely as an input for compost production.

Forest Restoration and Wildfire Mitigation Projects

The co-benefits evaluation in Chapter 3 underscored that thoughtfully planned and implemented fuel reduction treatments can mitigate wildfire risks and enhance ecological resilience, protect public health, and support economic stability in Boulder County. Long-term investment in adaptive management strategies, community engagement, and integrated wildfire planning will be critical to sustaining these benefits (and providing for a reliable source of feedstock for biomass utilization) in the face of increasing wildfire risks. The following are some high-level recommendations and consideration drawn from that evaluation. Notably, each recommendation would benefit from additional dialogue and strategic planning among Boulder County stakeholders.

Forest Health and Resilience

- **Expand Fuel Reduction Treatments in CWPP Priority Areas**: Implement strategic thinning and prescribed burning to reduce stand density and improve tree health.

- **Enhance Biodiversity Protection**: Thoughtfully plan and implement fuels reduction treatments within and/or adjacent to sensitive areas (e.g., high-biodiversity areas, significant natural areas, and critical wildlife habitats) to reduce the potential of vegetation type conversion and associated habitat loss.

Watershed Protection & Disaster Mitigation

- **Watershed Fuel Treatments**: Focus on reducing the potential for post-fire erosion risks by thinning forests within watersheds that provide critical water sources and to protect critical infrastructure.
- **Post-Fire Erosion Control Measures**: Implement sediment barriers, wood strand mulching, and revegetation strategies to stabilize soils and prevent runoff. Woody biomass from other wildfire mitigation projects can be used to directly produce wood shreds or wood strand mulch.

Human Health Protection

- **Reduce Wildfire Smoke and Fire Exposure**: Continue to implement fuel treatments adjacent to and within populated areas to minimize air quality and fire impacts.
- **Improve Public Health Preparedness**: Educate vulnerable populations about air quality risks and emergency response strategies.

Economic and Tourism Resilience

- **Protect High-Value Recreational Areas**: Target fuel reductions surrounding key tourism and outdoor recreation sites to mitigate economic losses.
- **Develop Post-Fire Recovery Plans**: Consider the creation of financial safety nets and rebuilding programs for businesses impacted by wildfires.

Policy and Community Engagement

- **Enhance Cross-Agency Collaboration**: Continue to strengthen partnerships with federal, state, and local agencies for wildfire risk management.
- **Increase Public Education and Outreach**: Continue to engage communities in fire-adapted strategies and encourage homeowner participation in defensible space initiatives.
- **Secure Long-Term Funding for Fuel Reduction**: Continue to advocate for state and federal grants to support ongoing fuel management programs.

Literature Cited

Abatzoglou, J. T., and C. A. Kolden. 2013. Relationships between climate and burned area in the western United States. *International Journal of Wildland Fire* 22(7),1003-1020.

Addington, R. N., K. J. Barrett, M. A. Battaglia, J. S. Briggs, J. B. Cannon, A. S. Cheng, P. J. Fornwalt, B. M. Gannon, and J. L Underhill. 2018. Collaborative restoration effects on forest structure in ponderosa pine-dominated forests of Colorado. Forest Ecology and Management, 424, 191–204.

Agee, J. K., and C. N. Skinner. 2005. Basic principles of forest fuel reduction treatments. Forest Ecology and Management, 211, 83–96.

Alliance for Green Heat. 2025. Firewood Banks Funding Program. https://www.firewoodbanks.org/grantees-24-25

Allred, W. S., W. S. Gaud, J. S. States. 1994. Effects of herbivory by Abert squirrels (*Sciurus aberti*) on cone crops of ponderosa pine, Journal of Mammalogy, Volume 75, Issue 3, Pages 700–703, https://doi.org/10.2307/1382518

Andrus, R. A., A. J. Martinez, G. M. Jones, and A. J. H. Meddens. 2021. Assessing the quality of fire refugia for wildlife habitat. Forest Ecology and Management, Volume 482. https://doi.org/10.1016/j.foreco.2020.118868

Axios Energy and Climate. 2025. Google partners with startup to cut 100,000 tons of carbon (article). https://www.axios.com/2025/01/16/google-carbon-removal-charm-industrial-biochar.

Banerjee T. 2020. Impacts of forest thinning on wildland fire behavior. Forests, 11(9), 918; https://doi.org/10.3390/f11090918

Banerjee, T., W. Heilman, S. Goodrick, J. K. Hiers, and R. Linn. 2020. Effects of canopy midstory management and fuel moisture on wildfire behavior. Scientific reports, 10(1), 17312.

Carbon Direct and Ecoengineers. 2022. Bio-oil sequestration, prototype protocol for measurement, reporting & verification. https://charmindustrial.com/Bio-oil_Sequestration__Protocol_for_Measurement_Reporting_and_Verification.pdf

Dixon, 2025. Essential FVS: a user’s guide to forest vegetation simulator. USDA Forest Service. https://www.fs.usda.gov/sites/default/files/essential-fvs.pdf

Durran, D.R. (1990). Mountain waves and downslope winds. In: Blumen, W. (eds) Atmospheric Processes over Complex Terrain. Meteorological Monographs, vol 23. American Meteorological Society, Boston, MA. https://doi.org/10.1007/978-1-935704-25-6_4

Battaglia, M. A., B. Gannon, P. M. Brown, P. J. Fornwalt, A. S. Cheng, and L. S. Huckaby. 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.

Bawa, R. S. (2017). Effects of wildfire on the value of recreation in western North America. Journal of Sustainable Forestry, 36(1), 1–17.

Belongia, M. F., Hammond Wagner, C., Quesnel Seipp, K., and Ajami, N. K. (2023). Building water resilience in the face of cascading wildfire risks. Science Advances, 9, eadf9534.

Boulder County CWPP. 2024. Boulder County Community Wildfire Protection Plan (CWPP). https://assets.bouldercounty.gov/wp-content/uploads/2024/10/boulder-county-community-wildfire-protection-plan-2024.pdf

Boulder Watershed Collective. (2024). Proactive planning for wildfire and flood sediment in the North, Middle, and South Boulder Creek Watersheds.

Brenkert-Smith, H., P. A., Champ, and A. L. Telligman. 2013. Understanding change: Wildfire in Boulder County, Colorado. Res. Note RMRS-RN-57. Fort Collins, CO: U.S. Department of Agriculture, Forest Service. 46 p.

Brown, S. 2015. Greenhouse gas accounting for landfill diversion of food scraps and yard waste. Compost Science & Utilization, 24(1), 11–19. https://doi.org/10.1080/1065657X.2015.1026005

Brown, R. W., D. R. Chadwick, T. Bott, H. M West, P. Wilson, G. R. Hodgins, et al. 2023. Biochar application to temperate grasslands: challenges and opportunities for delivering multiple ecosystem services. *Biochar*, *5*(1), 33. https://doi.org/10.1007/s42773-023-00232-y

Buchholz, T., D. Saah, D. Schmidt, and J. Barbuto. 2019. Quantifying occurrence and carbon emissions from delayed reforestation in Californian forests following high-severity wildfire (p. 13). Spatial Informatics Group LLC (SIG).

Buchholz, T., D. Schmidt, B. Springsteen, S. Harroun, J. Moghaddas, and S. Saah. 2019. Greenhouse gas offset protocol: avoided wildfire emissions (p. 75). Spatial Informatics Group LLC (SIG).

Cambium Carbon. 2022. Biochar-Urban Forestry Strategy: Boulder, Colorado Biochar Feedstock Assessment. Prepared for the City of Boulder.

Cannon, J. B., K. J. Barrett, B. M. Gannon, R. N. Addington, M. A. Battaglia, P. J. Fornwalt, G. H. Aplet, A. S. Cheng, J. L. Underhill, J. S. Briggs, and P. M. Brown. 2018. Collaborative restoration effects on forest structure in ponderosa pine-dominated forests of Colorado. Forest Ecology and Management, 424, 191–204.

Chandrasekhar, D., D., Finn, S. Contreras and T. T. Isaba. 2023. Land use adaptations to wildfire in unincorporated communities in Colorado (Natural Hazards Center Quick Response Research Report Series, Report 361). Natural Hazards Center, University of Colorado Boulder. https://hazards.colorado.edu/quick-response-report/land-use-adaptations-to-wildfire-in-unincorporated-communities-in-colorado

Carlson, J., T.J. Hawbaker, L. S. Bair, C. M. Hoffman, J. R. Meldrum, L. S. Baggett, and P. F. Stebleim. 2025. Evaluating a simulation-based wildfire burn probability map for the conterminous US. International Journal of Wildland Fire 34. https://doi.org/10.1071/WF23196

City of Boulder. (2025). City of Boulder Firewood Program. https://bouldercolorado.gov/services/firewood-program

City of Boulder. (2025). Project Overview: Alpine Balsam Implementation. https://bouldercolorado.gov/projects/alpine-balsam-implementation

Climate Forward. 2023. Reduced Emissions from Megafires (REM) Forecast Methodology. https://climateforward.org/program/methodologies/reduced-emissions-from-megafires/

Clyatt, K. A., J. S. Crotteau, and P. Morgan. 2017. Fuel reduction and forest restoration treatments influence plant communities and fuels. Forest Ecology and Management, 394, 78–88.

Colorado Mass Timber Coalition. 2025. About Us. https://www.comasstimber.org

Colorado State Forest Service. (2023). Biomass utilization and renewable energy initiatives.

Davis, E. J., C. Moseley, M. Nielsen-Pincus, and P. Jakes. 2014. The Community Economic Impacts of Large Wildfires: A Case Study from Trinity County, California. Society and Natural Resources, 27, 983–993.

Davis, R. and S. J. Bissell. 1989. Distribution of abert's squirrel (*Sciurus aberti*) in Colorado: Evidence for a Recent Expansion of Range. The Southwestern Naturalist. Vol. 34, No. 2 (Jun., 1989), pp. 306-309. https://doi.org/10.2307/3671751

Davis, K. T., J. Peeler, J. Fargione, R. D. Haugo, K. L. Metlen, M. D. Robles, and T. Woolley. 2024. Tamm review: a meta-analysis of thinning, prescribed fire, and wildfire effects on subsequent wildfire severity in conifer dominated forests of the Western US. Forest Ecology and Management, Volume 561. https://doi.org/10.1016/j.foreco.2024.121885.

Demarest, A. B., P. J. Fornwalt, B. H. Wolk, K. C. Rodman, M. D. Redmond. 2023. Mechanical forest restoration treatments stimulate understory plants in the Colorado Front Range. Forest Ecology and Management. Volume 548, ISSN 0378-1127, https://doi.org/10.1016/j.foreco.2023.121322.

Dodson, E. K., and C. E. Fiedler. 2006.

DeLoss, J. (2024). The total value of Colorado outdoor recreation. SOURCE (November 12, 2024). https://source.colostate.edu/benefits-of-outdoor-recreation/

Driscoll, D. A., D. Armenteras, A. Bennett, L. Brotons, M. F. Clarke, T. S. Doherty, A. Haslem, L. T. Kelly, C. F. Sato, C. F., Sitters, H., Aquilué, N., Bell, K., Chadid, M., Duane, A., Meza-Elizalde, M. C., Giljohann, K. M., González, T. M., Jambhekar, R., Lazzari, J., ... Wevill, T. 2021. How fire interacts with habitat loss and fragmentation. Biological Reviews, 96(3), 976–998. https://doi.org/10.1111/brv.12687.

Duffield, J. W., C. Neher, D. A. Patterson, and A. M. Deskins. 2013. Effects of wildfire on national park visitation and the regional economy: A natural experiment in the northern Rockies. International Journal of Wildland Fire, 22, 1155–1166.

Dunham, J. B., A. E. Rosenberger, C. H. Luce, and B. E. Rieman. 2007. Influences of wildfire and channel reorganization on spatial and temporal variation in stream temperature and the distribution of fish and amphibians. Ecosystems, 10(2), 335–346. https://doi.org/10.1007/s10021-007-9029-8.

EIA. 2009. *Household Energy Use in Colorado* (p. 2). Retrieved from https://www.eia.gov/consumption/residential/reports/2009/state_briefs/pdf/co.pdf

Elliott, S. M., M. I. Hornberger, D. O. Rosenberry, R. J. Frus, and R. M. Webb. 2024. A conceptual framework to assess post-wildfire water quality: state of the science and knowledge gaps. Water Resources Research, 60, e2023WR036260.

Emergency Watershed Protection Program (EWP). (2022). Technical and financial services for post-fire watershed repair on public and private lands. https://www.nrcs.usda.gov/programs-initiatives/ewp-emergency-watershed-protection#:~:text=The%20EWP%20Program%20offers%20technical,disasters%20that%20impair%20a%20watershed.

Energy Sage. 2025. Electricity costs in Boulder County, CO. https://www.energysage.com/local-data/electricity-cost/co/boulder-county/

Englin, J., T. P. Holmes, and J. Lutz. 2008. Wildfire and the economic value of wilderness recreation. In T. P. Holmes, J. P. Prestemon, and K. L. Abt (Eds.), The economics of forest disturbances: wildfires, storms, and invasive species (pp. 191–208). Springer Netherlands. https://doi.org/10.1007/978-1-4020-4370-3_10

EPA. (2014). *Project Development Handbook - A Handbook for Developing Anaerobic Digestion/Biogas Systems on Farms in the United States* (No. EPA 430-B-20-001) (p. 132). Washington DC: US Environmental Protection Agency.

EPA. (2023). GHG emission factors hub [Data set]. Retrieved from https://www.epa.gov/system/files/documents/2023-03/ghg-emission-factors-hub.xlsx

Epstein, M. D., C. A. Seielstad, and C. J. Moran. 2024. Impact and recovery of forest cover following wildfire in the northern Rocky Mountains of the United States. Fire Ecology, 20, 56.

Fallon, K., J. Abatzoglou, M. Hurteau, R. J. Butz, B. Buchanan, J. L. Pierce, J.P. McNamara, M. Cattau, M. Sadegh. 2024. Fuel treatment efficacy across California's forests: how do wildfire covariates impact the treatment outcome? http://dx.doi.org/10.22541/essoar.172590227.72370322/v1

FEMA. 2025. Marshall fire: building performance, observations, recommendations, and technical guidance. Mitigation Assessment Team Report. FEMA P-2320.

Finney, M. A. 2001. Design of regular landscape fuel treatment patterns for modifying fire growth and behavior. Forest Science, 47(2), 219–228.

Finney, M. A. 2005. The challenge of quantitative risk analysis for wildland fire. Forest Ecology and Management, Vol.211, Issue 1-2, pg 97-108. https://doi.org/10.1016/j.foreco.2005.02.010

Flamenco, E. A., L. Rubino, and J. McDonald. 2019. Trade-offs in forest management: fuel reduction vs. erosion mitigation. Environmental Management, 54(2), 301–313.

Franke, M. A. (2000). Yellowstone in the afterglow: Lessons from the fires (First Edition). Yellowstone Center for Resources, Yellowstone National Park.

Foxcroft, L. C., D. M. Richardson, P. Pyšek, and P. Genovesi. 2013. Invasive alien plants in protected areas: Threats, opportunities, and the way forward.

Gelles, R. V., T. S. Davis, and C. S. Stevens-Rumann. 2022. Wildfire and forest thinning shift floral resources and nesting substrates to impact native bee biodiversity in ponderosa pine forests of the Colorado Front Range. Forest Ecology and Management, 510, 120087. https://doi.org/10.1016/j.foreco.2022.120087.

Gellman, J., M. Walls, and M. Wibbenmeyer. 2022. Wildfire, smoke, and outdoor recreation in the western United States. Forest Policy and Economics, 134, 102619.

Gellman, J., M. Walls, and M. Wibbenmeyer. 2023. Welfare losses from wildfire smoke: evidence from daily outdoor recreation data (No. Working Paper 23-31). Resources for the Future.

Graham, R. T., (Technical Editor). 2003. Hayman fire case study. Gen. Tech. Rep. RMRSGTR-114. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 396 p.

Guiterman, C. H., R. H. Gregg, L. A. E. Marshall, J. J. Beckmann, P. J. van Mantgem, D. A. Falk, J. E. Keeley, A.C. Caprio, J. D. Coop, P. J. Fornwalt, C. Haffey, R. K. Hagmann, S. T. Jackson, A. M.

Lynch, E. Q. Margolis, C. Marks, M. D. Meyer, H. Safford, A. D. Syphard, and J. T. Stevens. 2022. Vegetation type conversion in the US Southwest: frontline observations and management responses. Fire Ecology, 18(1), Article 1. https://doi.org/10.1186/s42408-022-00131-w

Hagmann, R. K., P. F. Hessburg, S. J. Prichard, N. A. Povak, P. M. Brown, P. Z. Fulé, R. E. Keane, E. E. Knapp, J. M. Lydersen, K. L. Metlen, M. J. Reilly, A. J. Sánchez Meador, S. L. Stephens, J. T. Stevens, A. H. Taylor, L. L. Yocom, M. A. Battaglia, D. J. Churchill, L. D. Daniels, D. A. Falk, P. Henson, J. D. Johnston, M. A. Krawchuk, C. R. Levine, G. W. Meigs, A. G. Merschel, M. P. North, H. D. Safford, T. W. Swetnam, and A. E. M. Waltz. 2021. Evidence for widespread changes in the structure, composition, and fire regimes of western North American forests. Ecological Applications 31(8). https://doi.org/10.1002/eap.2431.

Hall, J., M. E. Sandor, B. J. Harvey, S. A. Parks, A. T. Trugman, A. P. Williams, and W. D. Hansen. 2024. Forest carbon storage in the western United States: distribution, drivers, and trends. Earth's Future, 12, https://doi.org/10.1029/2023EF004399

Halloran, M. E., and M. Bekoff. 1994. Nesting behaviour of Abert squirrels (Sciurus aberti). *Ethology*, *97*(3), 236-248.

Harrington, W. 2021. *Boulder County community forestry sort yard: 2021 annual report*. https://assets.bouldercounty.gov/wp-content/uploads/2022/05/cfsy-annual-report-2021.pdf

Huffman, E. L., L. H. MacDonald, and J. D. Stednick. 2001. Strength and persistence of fire-induced soil hydrophobicity under ponderosa and lodgepole pine, Colorado Front Range. Hydrological Processes, 15(15), 2877–2892. https://doi.org/10.1002/hyp.379.

Hurteau, M. D., S. Liang, K. L. Martin, and M. P. North. 2016. Restoring forest structure and process stabilizes forest carbon in wildfire-prone forests. Ecological Applications, 26(2), 382–391.

Ingalsbee, T. 2005. Fuelbreaks for wildland fire management: a moat or a drawbridge for ecosystem fire restoration? *Fire Ecol.* **1**, 85–99 (2005). https://doi.org/10.4996/fireecology.0101085

IPCC. 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland, 151 pp. https://www.ipcc.ch/site/assets/uploads/2018/02/SYR_AR5_FINAL_full.pdf

ISO. 2006a. *International Standard ISO 14040 - Environmental management - Life cycle assessment - Principles and framework* (No. ISO 14040:2006(E)) (p. 28). Geneva, Switzerland: International Organization for Standardization.

ISO. 2006b. *ISO 14044 - Environmental management — Life cycle assessment — Requirements and guidelines* (No. ISO 14044:2006(E)) (p. 54). Geneva, Switzerland: International Organization for Standardization.

Jaffe, D. A., D. Chand, W. Hafner, A. Westerling, and D. Spracklen. 2008. Influence of fires on O^3 concentrations in the western U.S. Environmental Science & Technology 2008 42 (16), 5885-5891. DOI: 10.1021/es800084k

Jennifer, L. 2025. The biochar gold rush: why companies are scrambling to lock in carbon credits. Carbon Credits.com. https://biochar-international.org/wp-content/uploads/2023/12/BIOCHAR_Carbon-sheet_DIGITAL.pdf

Jennings, S.B., N. D. Brown, and D. Sheil. 1999. Assessing forest canopies and understory illumination: canopy closure, canopy cover and other measures, Forestry: An International

Journal of Forest Research, Volume 72, Issue 1, Pages 59- 74. https://doi.org/10.1093/forestry/72.1.59

Jones, K. W., J. B. Cannon, F. A. Saavedra, S. L. Kampf, R. N. Addington, A. S. Cheng, L. H. MacDonald, C. Wilson, and B. Wolk. 2017. Return on investment from fuel treatments to reduce severe wildfire and erosion in a watershed investment program in Colorado. Journal of Environmental Management, 198, 66–77. https://doi.org/10.1016/j.jenvman.2017.05.023.

Jones, K. W., et al. (2019)

Jones, K., l. Chamberlain, B. Gannon, and B. Wolk. 2021. A cost-benefit analysis of Denver's forests to faucets program, 2011-2019. CFRI-2102.

Jones, K.W., Gannon, B., Timberlake, T., Chamberlain, J. L., Wolk, B. 2022. Societal benefits from wildfire mitigation activities through payments for watershed services: insights from Colorado." Forest Policy and Economics 135: 102661. https://doi.org/10.1016/j.forpol.2021.102661.

Karau, E. B. Hanberry, and G. Dillon. 2024. Fire risk and climate change in the Colorado Front Range (Chapter 9). USDA, Forest Service, RMRS-GTR-438. Pg. 323-360.

Kearns, E. J., D. Saah, C. R. Levine, C. Lautenberger, O. M. Doherty, J. R. Porter, M. Amodeo, C. Rudeen, K. D. Woodward, G. W. Johnson, K. Markert, E. Shu, N. Freeman, M. Bauer, K. Lai, H. Hsieh, B. Wilson, B. McClenny, A. McMahon. And F. Chishtie, F. 2022. The construction of probabilistic wildfire risk estimates for individual real estate parcels for the contiguous United States. Fire, 5(4), Article 4. https://doi.org/10.3390/fire5040117

Kelly, L. T., et al. 2020. Fire and biodiversity in the anthropocene. Science, Vol. 370, NO. 6519. https://www.science.org/doi/abs/10.1126/science.abb0355

Kent, B., K. Gebert, S. McCaffrey, W. Martin, D. Calkin, E. Schuster, I. Martin, H. Bender, G. Alward, Y. Kumagai, P. Cohn, M. Carroll, D. Williams, and C. Ekarius. 2003. Social and Economic Issues of the Hayman Fire. USDA Forest Service. General Technical Report RMRS-GTR-114.

Keydata. 2024. Wildfire impact on vacation rental fall performance.

Kim, E., and Y. J. Kwon. 2023. Analyzing indirect economic impacts of wildfire damages on regional economies. Risk Analysis, 43(12), 2631–2643. https://doi.org/10.1111/risa.14106

Kim, M. K., and P. M. Jakus. 2019. Wildfire, national park visitation, and changes in regional economic activity. Journal of Outdoor Recreation and Tourism, 26, 34–42.

Legleiter, C. J., R. L. Lawrence, M. A. Fonstad, W. Andrew Marcus, and R. Aspinall. 2003. Fluvial response a decade after wildfire in the northern Yellowstone ecosystem: A spatially explicit analysis. Geomorphology, 54(3), 119–136. https://doi.org/10.1016/S0169-555X(02)00332-X

Lehmann, J., and S. Joseph (Eds.). 2015. Biochar for environmental management: science, technology and implementation (2nd ed.). Routledge. https://doi.org/10.4324/9780203762264

Leslie, C. (2018). 2016-17 Visitation estimate report: City of Boulder open space and mountain parks. City of Boulder Open Space and Mountain Parks.

Littell, J. S., D. McKenzie, H. Y. Wan, and S. A. Cushman. 2018). Climate change and future wildfire in the western United States: An ecological approach to nonstationarity. Earth's Future, 6, 1097–1111.

Liu, J. C., L. J. Mickley, M. P. Sulprizio, F. Dominici, X. Yue, K. Ebisu, G. B Anderson, R. F. A. Khan, M. A. Bravo, and M. L. Bell. 2016. Particulate air pollution from wildfires in the Western US under climate change. Clim Change, 138(3):655-666. https://doi.org/10.1007/s10584-016-1762-6.

Lydersen, J. M., B. M. Collins, M. L. Brooks, J. R. Matchett, K. L. Shive, N. A. Povak, V. R. Kane, and D. F. Smith. 2017. Evidence of fuels management and fire weather influencing fire severity in an extreme fire event. Ecological Applications. Vol. 27(7), pg 2013-2030. https://doi.org/10.1002/eap.1586.

Loomis, J., A. González-Cabán, and J. Englin. 2001. Testing for differential effects of forest fires on hiking and mountain biking demand and benefits. Journal of Agricultural and Resource Economics, 26(2), 508–522.

MacDonald, L. H., J. Wagenbrenner, P. Nelson, and D. Brogan. 2013. Predicting post-fire flooding and sediment delivery at the watershed scale: an urgent need for upscaling. EGU2013-6641. EGU General Assembly Conference Abstracts.

Marotti, M. (2023). Boulder County Parks and Open Space Annual Visitation Report. Boulder County Parks and Open Space.

Maxwell, J. D., A. Call, and S. B. St. Clair, S. B. 2019. Wildfire and topography impacts on snow accumulation and retention in montane forests. Forest Ecology and Management, 432, 256–263.

Micheletty, P. D., A. M. Kinoshita, and T. S. Hogue. 2014. Application of MODIS snow cover products: Wildfire impacts on snow and melt in the Sierra Nevada. Hydrology and Earth System Sciences, 18, 4601–4615.

Moody, J. A., and D. A. Martin. 2004. Wildfire impacts on reservoir sedimentation in the Western United States. The Ninth International Symposium on River Sedimentation, 1095–1102.

Nordahl, S. L., C. V. Preble, T. W. Kirchstetter, and C. D. Scown. 2023. Greenhouse gas and air pollutant emissions from composting. Environmental Science & Technology, 57(6), 2235-2247.

Nasi, R., R. Dennis., E. Meijaard, G. Applegate, and P. Moore. 2002. Forest fire and biological diversity. UNASYLVA-FAO-, 36-40.

NIFC. 2022. National Interagency Fire Center Maps. https://www.nifc.gov/fire-information/maps

Nordahl, Sarah L., et al. "Greenhouse gas and air pollutant emissions from composting." *Environmental science & technology* 57.6 (2023): 2235-2247.

Otrahshenko, V., and L. Nunes. 2022. Fire takes no vacation: impact of fire on tourism. Environment and Development Economics, 27, 86–101.

Oz Architecture. 2017. The Boulder loading dock project. https://ozarch.com/our-work/the-loading-dock

Oz Architecture. 2025. OZ timber: leading the way in Colorado. https://ozarch.com/insights/oz-timber-leading-the-way-in-colorado

Palaiologou, P., K. Kalabokidis, M. A. Day, and V. Kopsachilis. 2020. Evaluating socioecological wildfire effects in Greece with a novel numerical index. Fire, 3(4), 63.

Paul, M. J., S. D. LeDuc, M. G. Lassiter, L. C. Moorhead, P. D. Noyes, and S. G. Leibowitz. 2022. Wildfire induces changes in receiving waters: A review with considerations for water quality management. Water Resources Research, 58, e2021WR030699.

Pena, N., and N. Bird. 2010. The upfront carbon debt of bioenergy. http://www.nobiomassburning.org/OLD/BAP/Climate_Change_files/Bioenergy_Joanneum_Research.pdf

Prichard, S. J., P. F. Hessburg, R. K. Hagmann, N. A. Povak, S. Z. Dobrowski, M.D. Hurteau, V. R. Kane, R. E. Keane, L. N. Kobziar, C. A. Kolden, M. North, S. A. Parks, H. D. Safford, J. T. Stevens, L. L. Yocom, D. J. Churchill, R. W. Gray, D. W. Huffman, F. K. Lake, and P. Khatri-Chhetri. 2021. Adapting western North American forests to climate change and wildfires: 10 common questions. Ecological Applications, 31(8), e02433. https://doi.org/10.1002/eap.2433

PuroEarth. 2025. CORC carbon removal indexes. https://puro.earth/corc-carbon-removal-indexes

Radeloff, V. C., D. P. Helmers, H. A. Kramer, M. H. Mockrin, P. M. Alexandre, A. Bar-Massada, V. Butsic, T. J. Hawbaker, S. Martinuzzi, A. D. Syphard, and S. I. Stewart. Rapid growth of the US wildland-urban interface raises wildfire risk, Proc. Natl. Acad. Sci. U.S.A. 115 (13) 3314-3319, https://doi.org/10.1073/pnas.1718850115

Raymond, C. L., and D. L. Peterson. 2005. Fuel treatments alter the effects of wildfire in a mixed-evergreen forest, Oregon, USA. Canadian Journal of Forest Research, 35, 2981–2995.

Ravage, J. 2024. The chatfield mushroom degradation trial – https://cusp.ws/wp-content/uploads/2024/03/Chatfield-Mushroom-Degradation-Trial_Submission_Template.pdf

Reid C.E., M. Brauer, F. H. Johnston, M. Jerrett, J. R. Balmes, and C. T. Elliott. 2016. Critical review of health impacts of wildfire smoke exposure. Environ Health Perspect. 124:1334–1343; http://dx.doi.org/10.1289/ehp.1409277

Richardson, C., M. Montalvo, S. Wagner, R. Barton, A. Paytan, M. Redmond, and M. Zimmer. 2024. Exploring the complex effects of wildfire on stream water chemistry: Insights from concentration-discharge relationships. Water Resources Research, 60, e2023WR034940.

Robinson, N. M., S. W. J. Leonard, A. F. Bennett, and M. F. Clarke. 2014. Refuges for birds in fire-prone landscapes: the influence of fire severity and fire history on the distribution of forest birds. Forest Ecology and Management, 318, 110–121.

Rockweit, J. T., A. B. Franklin, and P. C. Carlson. 2017. Differential impacts of wildfire on the population dynamics of an old-forest species. Ecology, 98(6), 1574–1582. https://doi.org/10.1002/ecy.1805.

Rupp, S. P., L. Bies, A. Glaser, C. Kowaleski, T. McCoy, T. Rentz, S. Riffell, J. Sibbing, J. Verschuyl, and T. Wigley. 2012. Effects of bioenergy production on wildlife and wildlife habitat. Wildlife Society Technical Review 12-03. The Wildlife Society, Bethesda, Maryland, USA. https://wildlife.org/wp-content/uploads/2014/05/Effects-of-Bioenergy-on-Wildlife.pdf

Rust, A. J., J. Randell, A. S. Todd, and T. S. Hogue. 2019. Wildfire impacts on water quality, macroinvertebrate, and trout populations in the Upper Rio Grande. Forest Ecology and Management, 453, 117636. https://doi.org/10.1016/j.foreco.2019.117636.

Ryals, R. and W. L. Silver, W. L. 2013. Effects of organic matter amendments on net primary productivity and greenhouse gas emissions in annual grasslands. *Ecological Applications*, *23*(1), 46–59. https://doi.org/10.1890/12-0620.1

Ryals, R., M. D. Hartman, W. J. Parton, M. S. DeLonge, and W. L. Silver. 2015.. Long-term climate change mitigation potential with organic matter management on grasslands. *Ecological Applications*, *25*(2), 531–545. https://doi.org/10.1890/13-2126.1

Sánchez, J. J., K. Baerenklau, and A. González-Cabán. 2016. Valuing hypothetical wildfire impacts with a Kuhn–Tucker model of recreation demand. Forest Policy and Economics, 71, 63–70.

San Joaquin Valley Air Pollution Control District. 2017. Air curtain incinerator emission factors determination. https://www.valleyair.org/busind/pto/emission_factors/Criteria/Criteria/Air-Curtain-Incinerators/EF-Determination- Analysis.pdf

Saxe, S., T. S. Hogue, and L. Hay. 2018. Characterization and evaluation of controls on post-fire streamflow response across western U.S. watersheds. Hydrology and Earth System Sciences, *22,* 1221–1237.

Schoennagel, T., T. T. Veblen, J. F. Negron, J. M. Smith, 2012. Effects of mountain pine beetle on fuels and expected fire behavior in lodgepole pine forests, Colorado, USA. https://doi.org/10.1371/journal.pone.0030002

Scott, J. H. 2012. Introduction to wildfire behavior modeling. National Interagency Fuel, Fire, and Vegetation Technology Transfer. https://pyrologix.com/wp-content/uploads/2014/04/Scott_20121.pdf

Shaffer, K. E., S. J. Hedwall, and W. F. Laudenslayer. 2018. Chapter nine. fire and animal interactions. *In* J. W. van Wagtendonk (Ed.), Fire in California's Ecosystems (pp. 123–146). University of California Press. https://doi.org/10.1525/9780520961913-012.

Springsteen, B., T. Christofk, R. A. York, T. Mason, S. Baker, E. Lincoln, B. Hartsough and T Yoshioka. 2015. Forest biomass diversion in the Sierra Nevada: Energy, economics and emissions. doi: 10.3733/ca.v069n03p142. http://californiaagriculture.ucanr.edu/landingpage.cfm?article=ca.v069n03p142&fulltext=yes.

Starbuck, C. M., R. P. Berrens, and M. McKee, (2006). Simulating changes in forest recreation demand and associated economic impacts due to fire and fuels management activities. Forest Policy and Economics, 8(1) 52–66.

Stephens, S.L., J. J. Moghaddas, C. Edminster, C. E. Fiedler, S. Haase, M. Harrington, J. E. Keeley, E. E. Knapp, J. D. McIver, K. Metlen, C. N. Skinner, and A. Youngblood. 2009. Fire treatment effects on vegetation structure, fuels, and potential fire severity in western US forests". Forest Management Faculty Publications. 17. https://scholarworks.umt.edu/forest_pubs/17 Stephens, S. L., J. D. McIver, R. E. J. Boerner, C.J. Fettig, J. B. Fontaine, B. R. Hartsough, P. L. Kennedy, and D. W. Schwilk. 2012. The effects of forest fuel-reduction treatments in the United States. BioScience, 62(6), 549–560. https://doi.org/10.1525/bio.2012.62.6.6

Stephens, S. L., B. M. Collins, C. J Fettig, M. A. Finney, C. M. Hoffman, E. E. Knapp, M. P. North, H. Safford, R. B. Wayman. 2018. Drought, Tree Mortality, and Wildfire in Forests Adapted to Frequent Fire, BioScience, Volume 68, Issue 2, Pages 77-88. https://doi.org/10.1093/biosci/bix146

Stevens-Rumann, C. S. and P. J. Fornwalt. 2019. Managing wildfire risk in changing forested landscapes. *Forest Ecology and Management, 434,* 228–239.

Tempel, D. J., R. J. Gutiérrez, J. J. Battles, D. L. Fry, Y. Su, Q. Guo, M. J. Reetz, S. A. Whitmore, G. M. Jones, B. M. Collins, S. L. Stephens, M. Kelly, W. J. Berigan, and Z. M. Peery. 2015. Evaluating short-and long-term impacts of fuels treatments and simulated wildfire on an old-forest species. Ecosphere, 6(12), 1-18. https://doi.org/10.1890/ES15-00234.1

Thapa, B., S. Holland, and J. Absher. 2004. The relationship between wildfires and tourist behaviors in Florida: An exploratory study. USDA Forest Service, Pacific Southwest Research Station.

The Beck Group. 2015. California assessment of wood business innovation opportunities and markets. Prepared for the National Forest Foundation. https://www.nationalforests.org/assets/pdfs/California-Assessment-Wood-Biomass-Innovation-Interim-Report-June-2015.pdf.

Thomas, D. S. G., D. Butry, S. Gilbert, D. Webb, and J. Fung. 2017. The costs and losses of wildfires. NIST Special Publication, 1215(11). https://nvlpubs.nist.gov/nistpubs/SpecialPublications/NIST.SP.1215.pdf

Timonen, K., T. Sinkko, S. Luostarinen, E. Tampio, and K. Joensuu. 2019. LCA of anaerobic digestion: emission allocation for energy and digestate. *Journal of Cleaner Production*, *235*, 1567–1579. https://doi.org/10.1016/j.jclepro.2019.06.085

Troy, A., T. Pusina, S. Romsos, J. Moghaddas, and T. Buchholz. 2022. The true cost of wildfire in the western U.S.: 2022 Report. Western Forestry Leadership Coalition. https://www.thewflc.org/sites/default/files/TrueCostofWildfire.pdf

Tukman, M. (2018). *TerraCount Tool Manual* (p. 38). Tukman Geospatial LLC.

Underwood, E. C., J. H. Viers, J. F. Quinn, and M. North, M. 2010. Using topography to meet wildlife and fuels treatment objectives in fire-suppressed landscapes. Environmental Management, 46, 809-819. https://doi.org/10.1007/s00267-010-9556-5

U.S. Census Bureau. 2022. Selected housing characteristics, Boulder County, CO. https://data.census.gov/table/ACSDP5Y2023.DP04?g=040XX00US08_050XX00US08013&tid=ACSDP5Y2023.DP04

USDA. 2024. Direct Download, Monitoring Trends in Burn Severity (MTBS). https://mtbs.gov/direct-download.

U.S. Forest Service Bulletin. 2024. *Biochar is ready for prime time: ground-truthed decision trees for land managers*. https://research.fs.usda.gov/rmrs/products/sycu/biochar-ready-prime-time-ground-truthed-decision-trees-land-managers

US Forest Service. 2023. Forest level economic contributions dashboard – 2019. US Forest Service. https://www.fs.usda.gov/about-agency/policy/analysis/economic-contributions-dashboard

van der Werf, G. R., J. T. Randerson, L. Giglio, T. T. Van Leeuwen, Y. Chen, B. M. Rogers, M. Mu, M. J. E. Van Marle, D. C. Morton, G. J. Collatz, R. J. Yokelson, P. S. Kasibhatla. 2017. Global fire emissions estimates during 1997–2016. Earth Syst. Sci. Data, 9, 697–720. https://doi.org/10.5194/essd-9-697-2017

van Mantgem, P. J., N. L. Stephenson, J. C. Byrne, L. D. Daniels, J. F. Franklin, P. Z. Fulé, M. E. Harmon, A. J. Larson, J. M. Smith, A. H. Taylor, and T. T. Veblen. 2009. Widespread increase of tree mortality rates in the western United States. Science, 323(5913), 521-524. https://doi.org/10.4996/fireecology.0502116.

Visit California. (2018). *The west is open for business*. https://media.visitcalifornia.com/story-inspiration/press-releases/the-west-is-open-for-business

Vukomanovic, J., and T. Steelman. 2019. A systematic review of relationships between mountain wildfire and ecosystem services. *Landscape Ecology, 34,* 1179–1194.

Wang, J. and S. Wang. 2019. Preparation, modification and environmental application of biochar: A review. *Journal of Cleaner Production*, *227*, 1002-1022.

Wasserman, T. N. and S. E. Mueller. 2023. Climate influences on future fire severity: a synthesis of climate-fire interactions and impacts on fire regimes, high-severity fire, and forests in the western United States. *Fire Ecology, 19,* 43.

Western Disposal. 2025. Western disposal services recycling rates 2025. https://www.westerndisposal.com/materials-management-center/

Westerling, A.L. 2016. Increasing western US forest wildfire activity: sensitivity to changes in the timing of spring. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *371*(1696), p.20150178.

Wood, T. K., Gurgan, I., Howley, E. T., & Riedel-Kruse, I. H. (2023). Converting methane into electricity and higher-value chemicals at scale via anaerobic microbial fuel cells. *Renewable and Sustainable Energy Reviews*, *188*, 113749. https://doi.org/10.1016/j.rser.2023.113749

Woolf, D., Lehmann, J., Ogle, S., Kishimoto-Mo, A. W., McConkey, B., & Baldock, J. (2021). Greenhouse Gas Inventory Model for Biochar Additions to Soil. *Environmental Science & Technology*, *55*(21), 14795–14805. https://doi.org/10.1021/acs.est.1c02425

Xcel Energy Gas Rates (2023). https://www.xcelenergy.com/staticfiles/xe-responsive/Company/Rates%20%26%20Regulations/Summary_of_Gas_Rates_as_of-02-01-2023.pdf

Appendices

Appendix 1.A. Sources of Reported Woody Biomass Removals and Associated Spreadsheets File Names.

Source of Reported Woody Biomass Removals	Spreadsheet File Name[a]
Biomass Calculations	Boulder Biomass Reported V4.1.xlsx
Boulder County Parks and Open Space (BCPOS)	Boulder County Parks Open Space.xlsx
Boulder County Community Forestry Sort Yards	CFSY DATA from 2008 till 2024.xlsx
City of Boulder - Urban Forestry Program	City of Boulder – Urban Biomass Estimates.xlsx
City of Boulder - Open Space and Mountain Parks	City of Boulder OSMP Forest biomass.xlsx
Longmont and Boulder Valley Conservation Districts	Conservation District_Boulder_Biomass_Assessment_Completed_Projects_2024.xlsx
[a] Access spreadsheets at the following link - https://drive.google.com/drive/folders/1AIUxdJhYuJWqypgmAJ-D6RTFXF1B22MM?usp=drive_link	

Appendix 2.A. Wood Products Facilities in the Boulder Region

Table 1 - Boulder Region Firewood & Fuelwood Facilities

Firewood & Fuelwood								
Facilty Number	Name	Phone	Address	Total Distance (miles)	Estimate Delivery Cost	Est $/ton Delivered	Facility Contact Notes	Facility Size
9	Crown Hill Landscaping LLC	(303) 618-0731	1380 Simms St. Lakewood, CO 80215	27.6	$544.00	$27.20	Mileage needs recalculated. Supplies firewood buys log by the truckload delivers to Boulder.	S
10	Deerwood Forest Products Co.	(303) 590-5225	400 Eagles Nest Trail Evergreen, CO 80439	43.7	$715.70	$35.80	Small family group that harvests their own trees and sells a little firewood	S
15	LumberJacks Logging & Firewood	(720) 212-1875	5324 Highway 72 Black Hawk, CO 80422	22.8	$492.90	$24.60	Open and as stated	S
18	Morgan Forest Agriculture	(720) 818-2316	2883 Lee Hill Dr. Boulder, CO 80302	7.2	$327.00	$16.40	In Boulder county. Log their own property and sell firewood.	S
22	TimberScapes	(970) 819-9767	1543 Walnut St. Windsor, CO 80550	47.3	$754.60	$37.70	Buys logs	M
24	Rocky Mountain Log & Saw Co. LLC	(970) 482-3790	2318 W. County Road 54G Fort Collins, CO 80524	69.6	$992.00	$49.60	On going concern. Firewood rough cut, sells squared blanks to other mills. Buys logs.	M
27	Shreiner Enterprises	(970) 689-8788	4719 Arthur Mae Ln. Laporte, CO 80535	71.9	$1,017.20	$50.90	Mitigation Logging, firewood	s
36	Morgan Timber Products	(970) 484-4065	2532 County Road 54G Fort Collins, CO 80524	69.8	$994.00	$49.70	The real Deal, Mill, Logging, sales of anything woody. Old description is correct.	L
37	Summerhill Tree Farm	(970) 669-1238	1854 Quillan Gulch Rd. Loveland, CO 80537	46.1	$742.10	$37.10	Small famaily operation	S
39	TC Woods, Tree Recycling Center	(303) 666-8989	9850 Arapahoe Lafayette, CO 80026	7.9	$333.80	$16.70	Operational. Noinfo changed.	M
40	United Wood Products Inc.	(303) 652-2872	7860 Diagonal Hwy. Longmont, CO 80503	11.8	$376.00	$18.80	Operational all info still accurate.	L
42	Wood Butcher Ltd.	(701) 720-0808	16 Tracy Trail Rd. Loveland, CO 80537	40.8	$685.40	$34.30	One man show, still cutting and selling products. Not buying.	S

Figure 1 - Firewood and Fuelwood Facility Locations

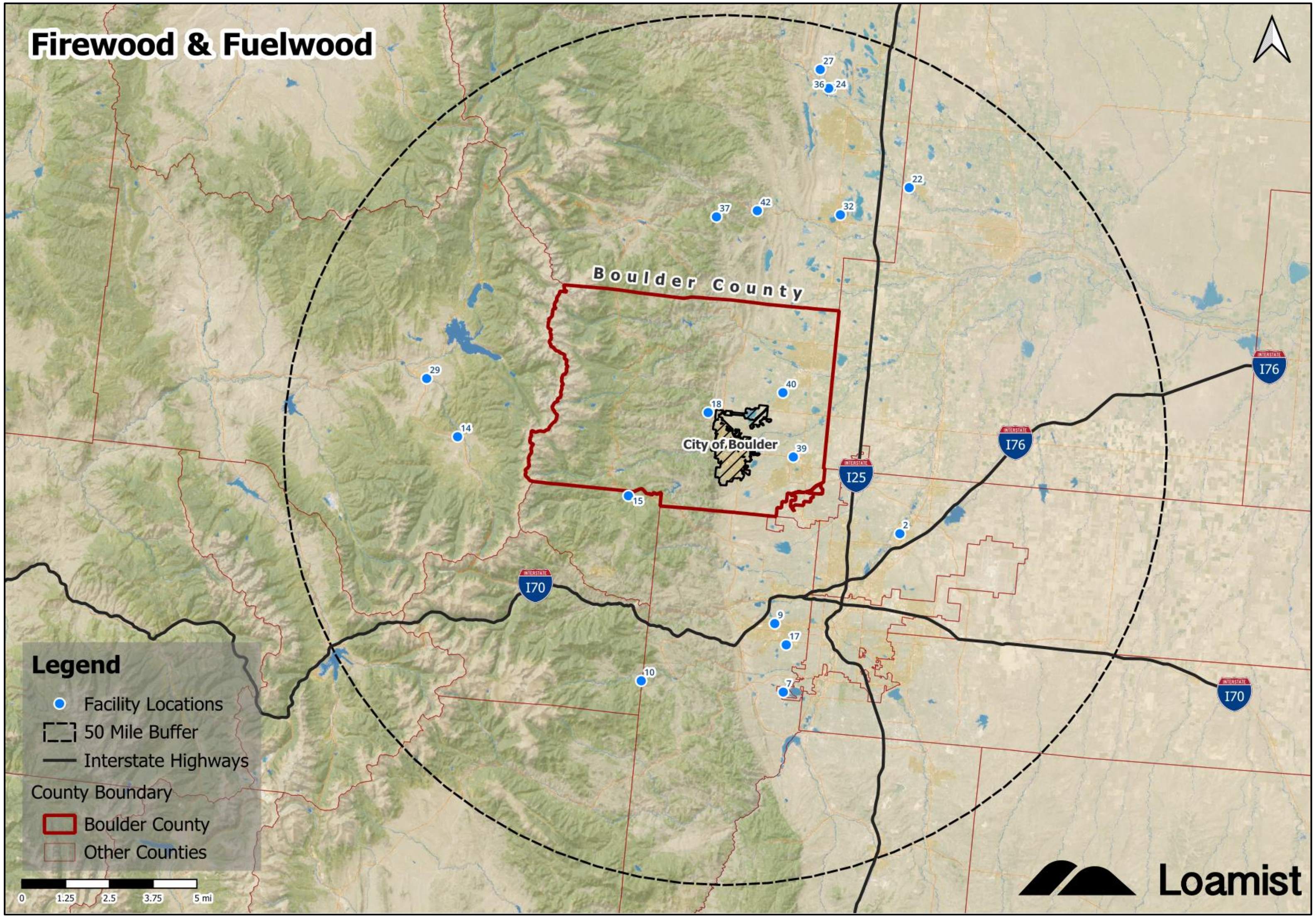


Table 2 - Boulder Region Composting Facilities

Compost								
Facilty Number	Name	Phone	Address	Total Distance (miles)	Estimate Delivery Cost	Est $/ton Delivered	Facility Contact Notes	Size
2	JCK Corp.	(303) 288-0654	11481 Brishton Rd. Henderson, CO 80640	30.5	$575.10	$28.80	Ongoing concern. Does not use any wood in compost	N/A
5	A1 Organics - Eaton	970-454-3492	16350 County Road 76 Eaton, CO 80615	70.6	$1,003.50	$50.20	One of the Largest producers that take waste biomass.	L
21	A1 Organics - Keenesburg	970-454-3492	12002 WCR 59, Keenesburg, CO 80643	54	$826.50	$41.30	One of the Largest producers that take waste biomass.	L

Figure 2 - Composting Facility Locations

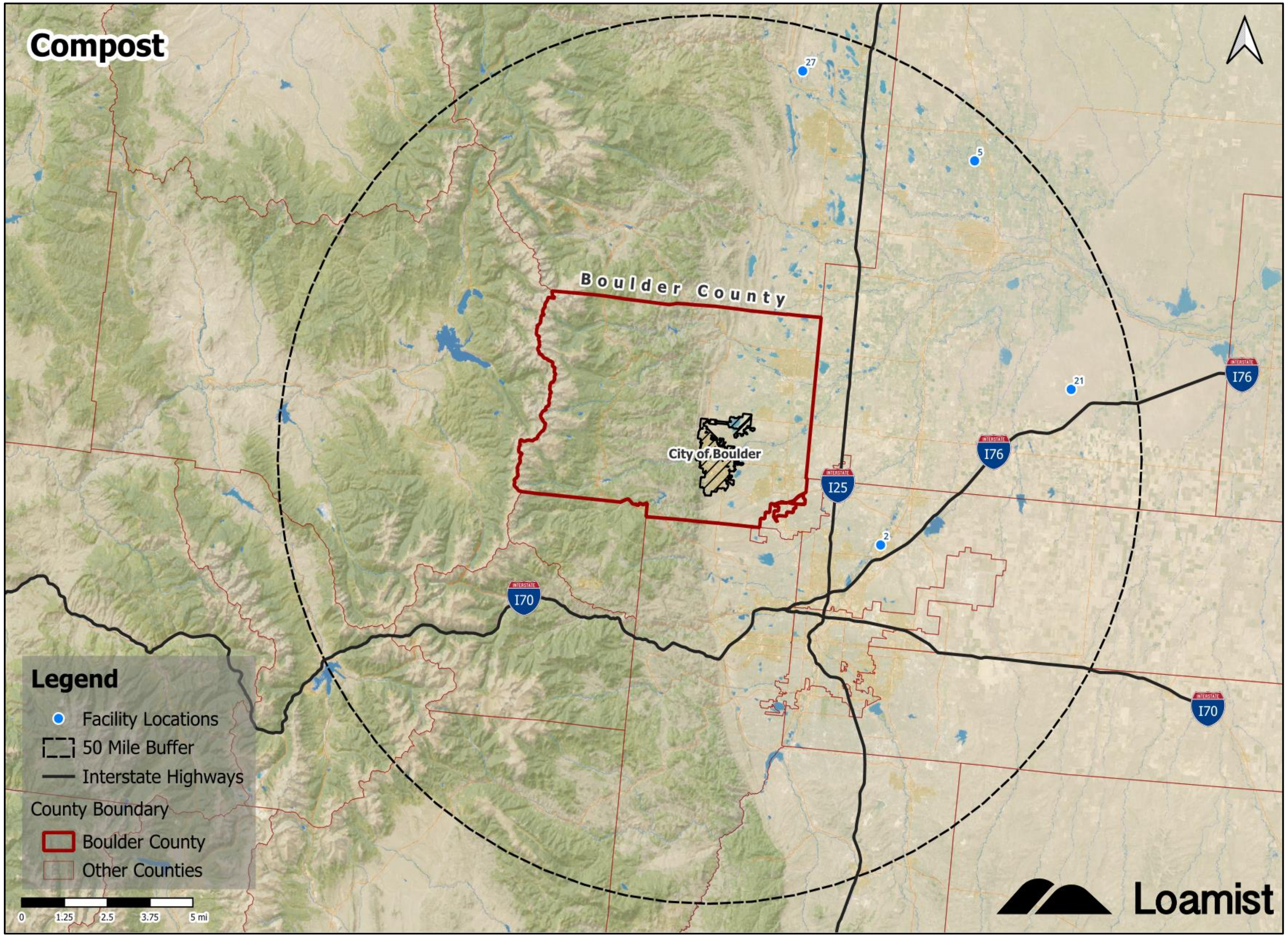


Table 3 - Boulder Region Wood Mulching Facilities

Mulch

Facilty Number	Name	Phone	Address	Total Distance (miles)	Estimate Delivery Cost	Est $/ton Delivered	Faciity Contact Notes	Facility Size
5	A1 Organics - Eaton	970-454-3492	16350 County Road 76 Eaton, CO 80615	70.6	$1,003.50	$50.20	One of the Largest producers that take waste biomass.	L
21	A1 Organics - Keenesburg	970-454-3492	12002 WCR 59, Keenesburg, CO 80643	54	$826.50	$41.30	One of the Largest producers that take waste biomass.	L
36	Morgan Timber Products	(970) 484-4065	2532 County Road 54G Fort Collins, CO 80524	69.8	$994.00	$49.70	The real Deal, Mill, Logging, sales of anything woody.	M

Figure 3 - Wood Mulching Facility Locations

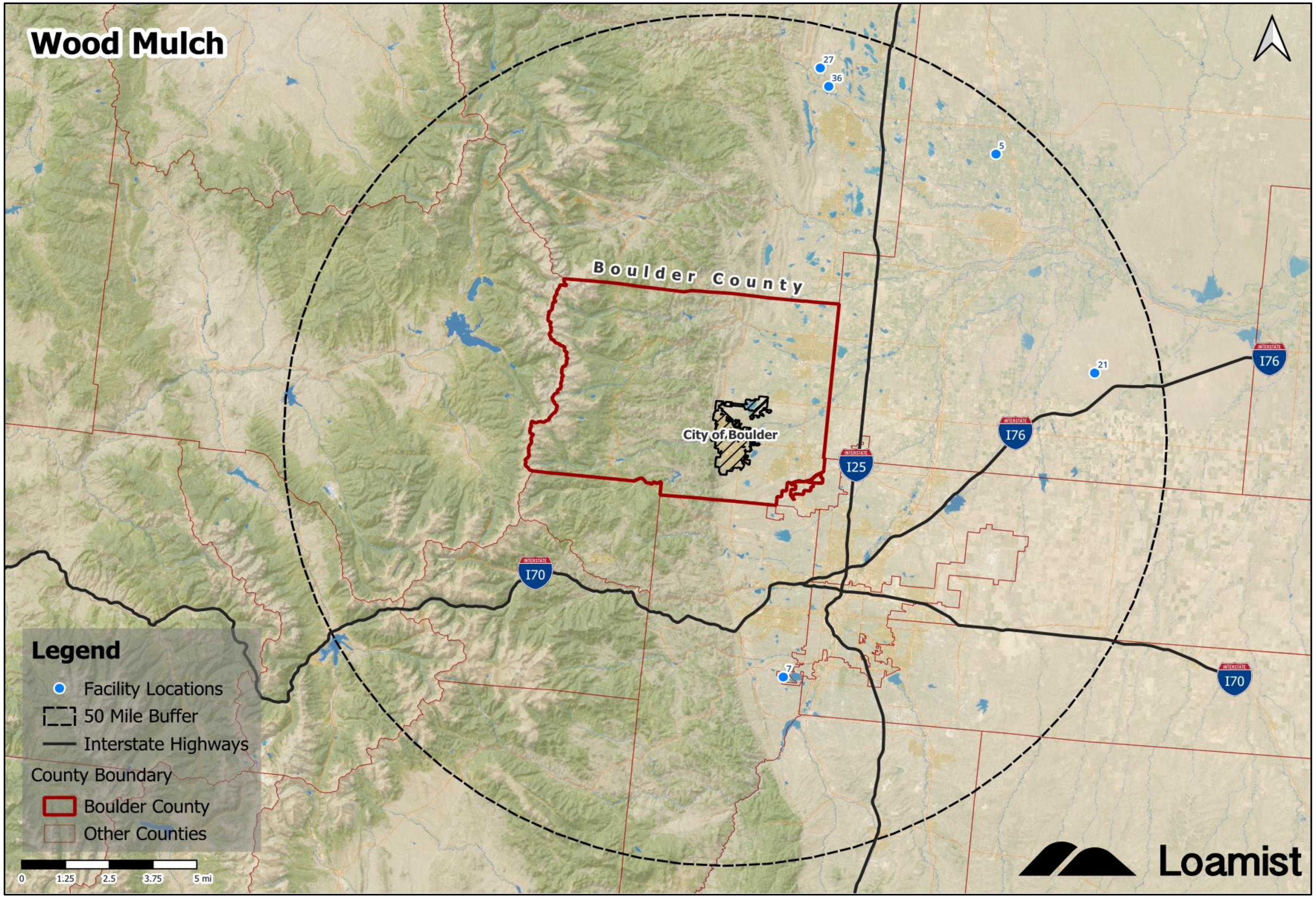


Table 4 - Boulder Region Wood Chipping Facilities

Wood Chips

Facilty Number	Name	Phone	Address	Total Distance (miles)	Estimate Delivery Cost	Est $/ton Delivered	Facility Contact Notes	Facility Size
29	TM Grand County Inc.	(970) 531-7071	400 CR 60 Granby, CO 80446	97.3	$1,287.70	$64.40	Ongoing operation in Grand county. Mostly firewood and fencir	S
36	Morgan Timber Products	(970) 484-4065	2532 County Road 54G Fort Collins, CO 80524	69.8	$994.00	$49.70	50 years of logging, firewoood, fencing.	M
40	United Wood Products Inc.	(303) 652-2872	7860 Diagonal Hwy. Longmont, CO 80503	11.8	$376.00	$18.80	Operational all info still accurate.	M
42	Wood Butcher Ltd.	(701) 720-0808	16 Tracy Trail Rd. Loveland, CO 80537	40.8	$685.40	$34.30	One man show, still cutting and selling products. Not buying.	S

Figure 4 - Wood Chip Facility Locations

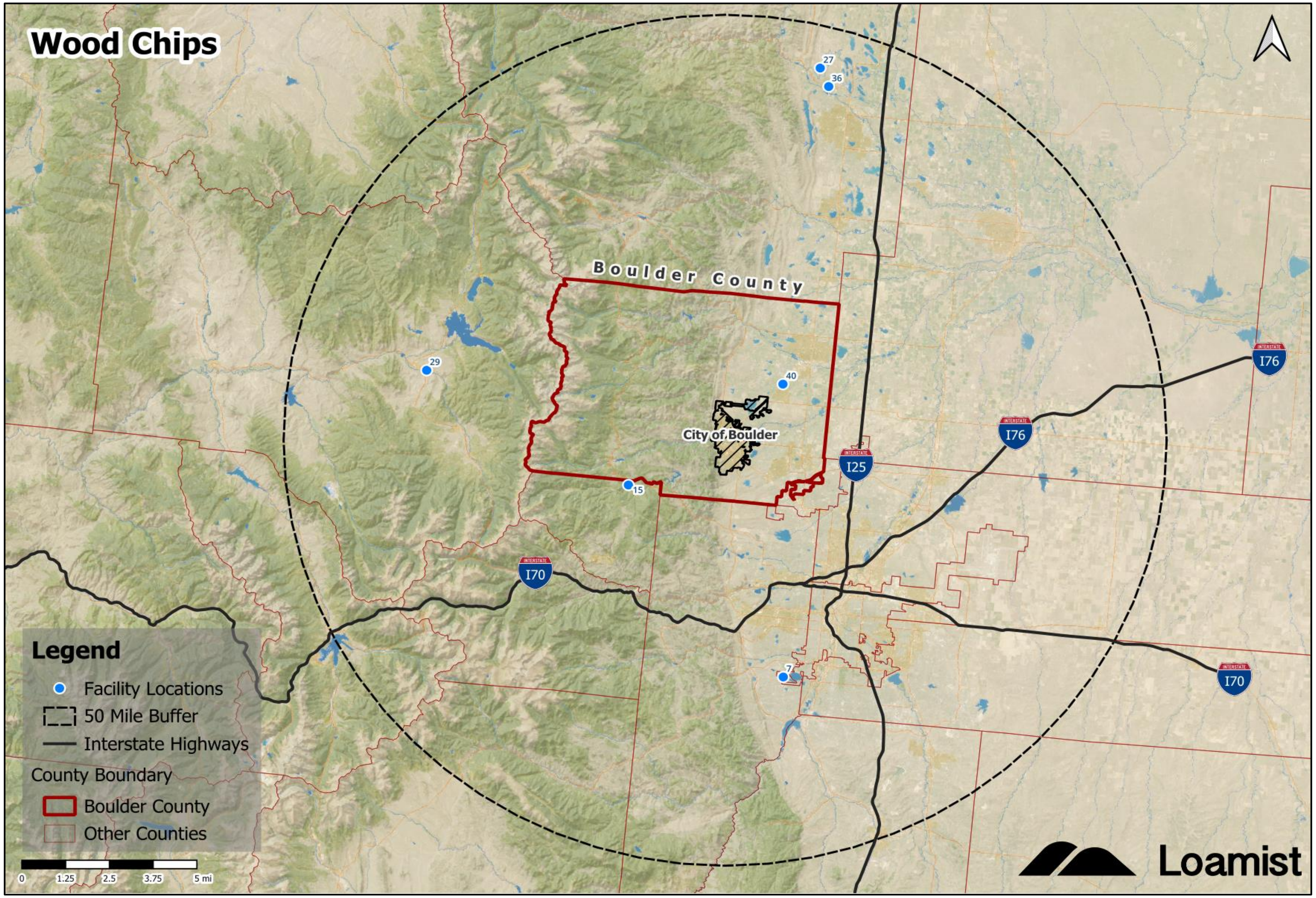


Table 5 - Boulder Region Animal Bedding Facilities

Animal Bedding

Facilty Number	Name	Phone	Address	Total Distance (miles)	Estimate Delivery Cost	Est $/ton Delivered	Facility Contact Notes	Facility Size
36	Morgan Timber Products	(970) 484-4065	2532 County Road 54G Fort Collins, CO 80524	69.8	$994.00	$49.70	50 years of logging lumber fencing and by-products	M
40	United Wood Products Inc.	(303) 652-2872	7860 Diagonal Hwy. Longmont, CO 80503	11.8	$376.00	$18.80	Operational all info still accurate.	M
42	Wood Butcher Ltd.	(701) 720-0808	16 Tracy Trail Rd. Loveland, CO 80537	40.8	$685.40	$34.30	One man show, still cutting and selling products. Not buying.	S

Figure 5 - Animal Bedding Facility Locations

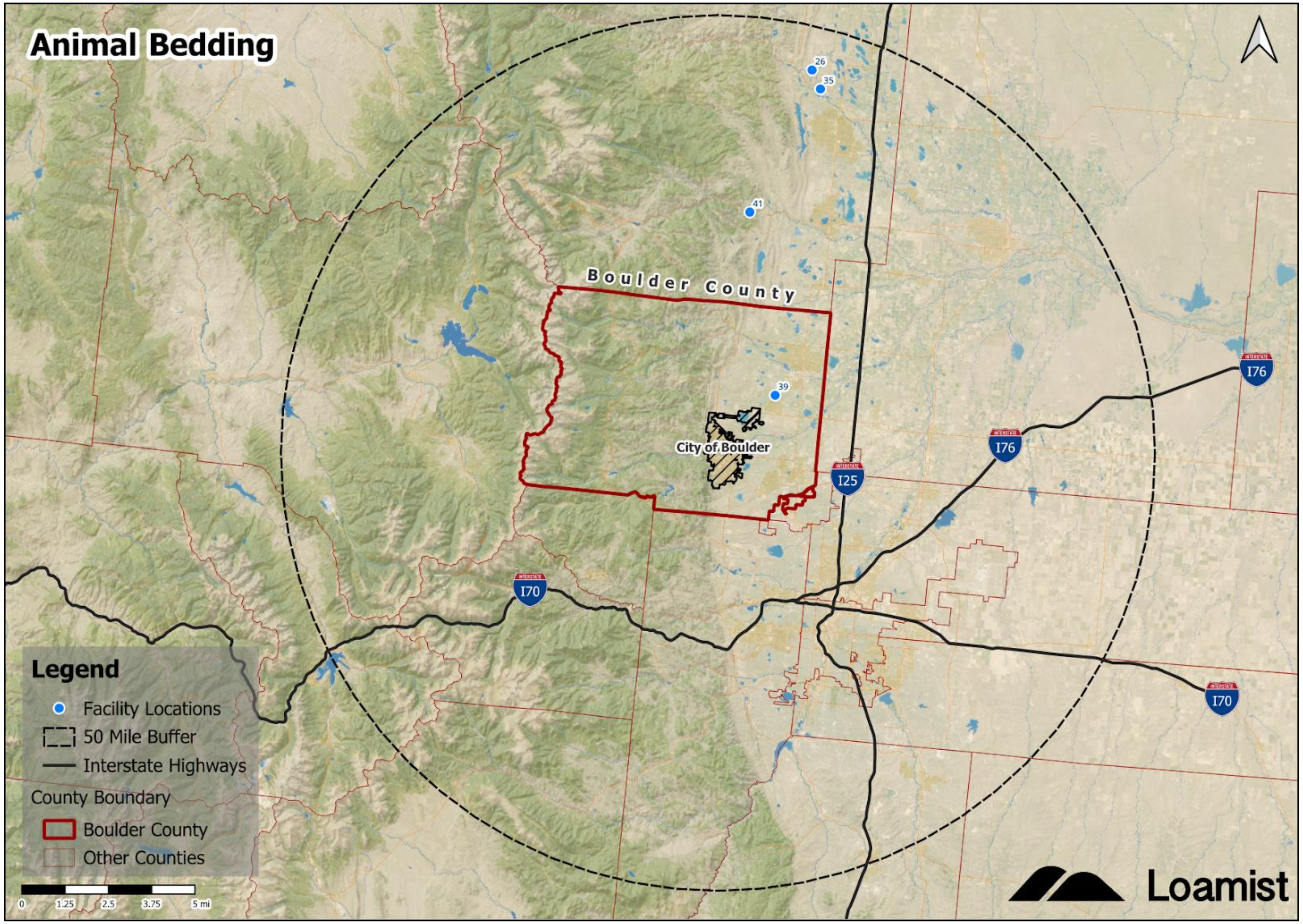


Table 6 - Boulder Region Lumber Production Facilities

Lumber Products								
Facilty Number	**Name**	**Phone**	**Address**	**Total Distance (miles)**	**Estimate Delivery Cost**	**Est $/ton Delivered**	**Facility Contact Notes**	**Facility Size**
1	J.C. Custom Design Works	(303) 594-8644	23500 E. Portland Way Aurora, CO 80016	56.3	$850.16	$42.51	In Business. Not listed by Colorado SOS	M
3	Jeremiah Johnson Log Homes Inc.	(303) 567-2202	1501 County Road 308 Dumont, CO 80406	50.0	$782.79	$39.14	In Business expired and deliquent on SOS website.	S
7	Clear Creek Service Company LLC	(270) 375-6791	4899 S. Dudley St., E8 Denver, CO 80123	34.4	$616.51	$30.83	Operational logging company hand sawyers and some equipt.	S
11	Denver Wood Slabs	(720) 780-7752	4903 Washington St. Denver, CO 80216	24.6	$512.39	$25.62	Custom Urban Mill. Buys timber	M
13	Golden West Pine Mills LLC	(970) 590-8351	219 E. 4th St. Ault, CO 80610	65	$943.70	$47.20	Full scale logging mill. Buys and sells.	L
14	Hard Up Lumber	(970) 726-9241	PO Box 366 Tabernash, CO 80478	86.4	$1,172.10	$58.60	Small scale, 1-2 guys loggers	M
15	LumberJacks Logging & Firewood	(720) 212-1875	5324 Highway 72 Black Hawk, CO 80422	22.8	$492.90	$24.60	Open and as stated	S
17	Moose Haven Milling Ltd.	(303) 944-7740	591 S. Field Ct. Lakewood, CO 80226	29.7	$566.90	$28.30	Open for business	S
20	Reclaimed West	(303) 775-0349	10475 Bountiful St. Firestone, CO 80504	11.2	$369.40	$18.50	Small company Colorado and California	L
22	TimberScapes	(970) 819-9767	1543 Walnut St. Windsor, CO 80550	47.3	$754.60	$37.70	Buys logs and beams.	M
23	TJ's Wood Products	(303) 838-5779	P.O. Box 437 Bailey, CO 80421	57.4	$862.80	$43.10	Buys logs and beams.	L
26	Sears Trostel Lumber CO	(970) 482-0222	125 Airpark Dr. Fort Collins, CO 80524	63.3	$925.20	$46.30	Large Millwork and timber retail/wholesale.	L
27	Shreiner Enterprises	(970) 689-8788	4719 Arthur Mae Ln. Laporte, CO 80535	71.9	$1,017.20	$50.90	Mitigation Logging, firewood Small	S
28	Timberline Log Exteriors	(303) 514-9192	19240 U.S. 85 Gilcrest, Colorado 80623	49	$772.50	$38.60	Ongoing operation buys logs	S
30	Western Log Creations	(720) 331-4673	10459 Cheetah Winds Littleton, CO 80124	49	$773.10	$38.70	Ongoing furniture manufactuer uses Colorado logs	S
36	Morgan Timber Products	(970) 484-4065	2532 County Road 54G Fort Collins, CO 80524	69.8	$994.00	$49.70	50 years of logging, lumber, firewood and fencing	M
38	T & G Hardwood Flooring Specialists	(303) 293-8600	5690 Logan St. Denver, CO 80216	23.4	$499.40	$25.00	Large retailer of recycled wood procucts, wood flooring, mill	M
39	TC Woods, Tree Recycling Center	(303) 666-8989	9850 Arapahoe Lafayette, CO 80026	7.9	$333.80	$16.70	Operational. Noinfo changed.	M
40	United Wood Products Inc.	(303) 652-2872	7860 Diagonal Hwy. Longmont, CO 80503	11.8	$376.00	$18.80	Operational all info still accurate.	M
41	Where Wood Meets Steel	(720) 780-7752	4903 Washington St. Denver, CO 80216	24.6	$512.40	$25.60	Mid sized lumber recycler and slabb miller	S
43	Wood Source	(303) 297-8310	8321 Steele St. Thornton, CO 80229	24.8	$515.10	$25.80	Large company, mills are out of state	M

Figure 6 - Lumber Production Facility Locations

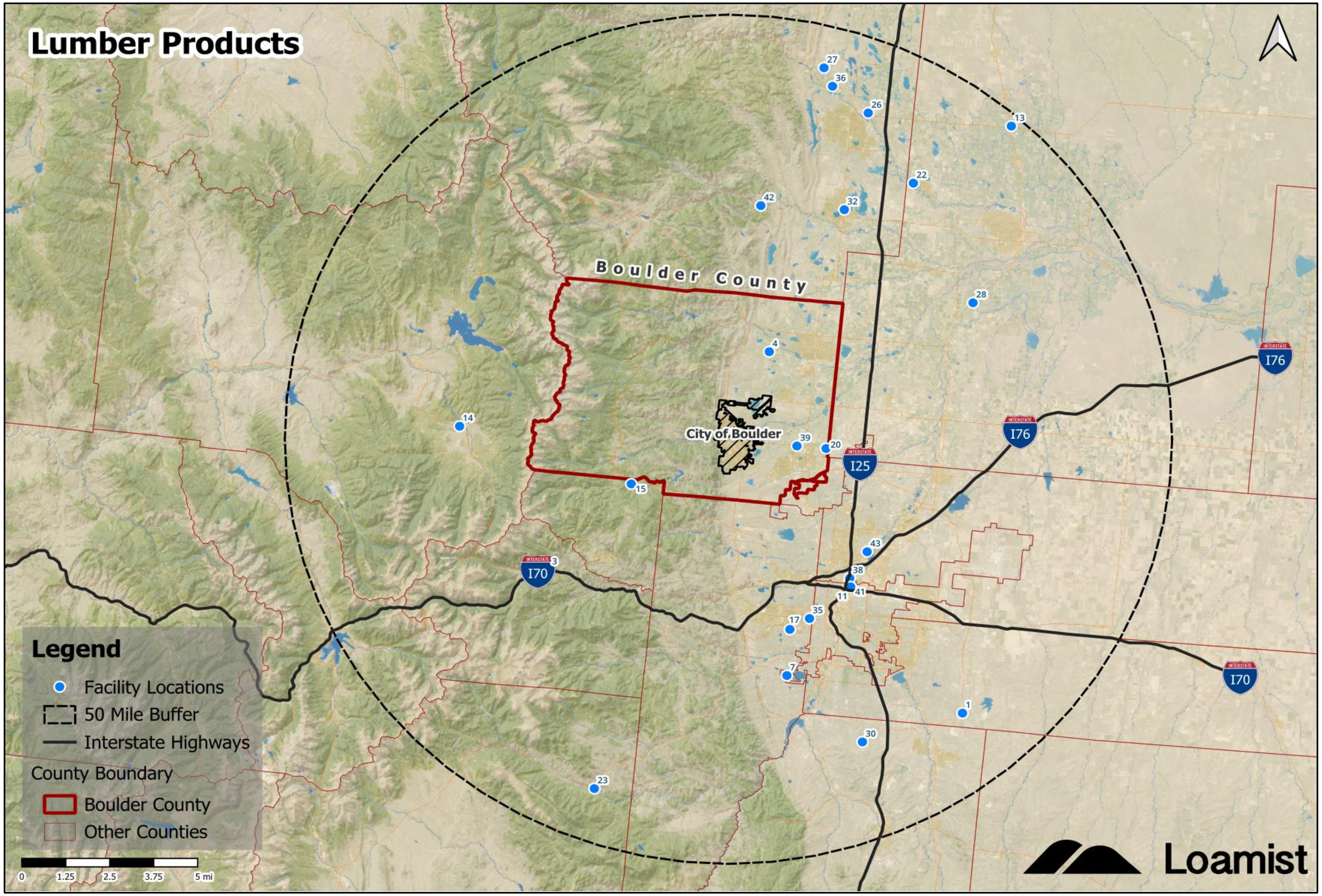


Table 7 - Boulder Region Wood Beams Production Facilities

Beams								
Facilty Number	Name	Phone	Address	Total Distance (miles)	Estimate Delivery Cost	Est $/ton Delivered	Facility Contact Size	Facility Size
11	Denver Wood Slabs	(720) 780-7752	4903 Washington St. Denver, CO 80216	24.6	$512.40	$25.60	Custom Urban Mill. Buys timber	M
12	Frameworks Timber	(970) 568-4900	208 Racquette Dr., Unit B Fort Collins, CO 80524	63.7	$929.10	$46.40	N/A	S
13	Golden West Pine Mills LLC	(970) 590-8351	219 E. 4th St. Ault, CO 80610	65	$943.70	$47.20	Full scale logging mill. Buys and sells.	L
14	Hard Up Lumber	(970) 726-9241	PO Box 366 Tabernash, CO 80478	86.4	$1,172.10	$58.60	Small scale, 1-2 guys loggers	M
17	Moose Haven Milling Ltd.	(303) 944-7740	591 S. Field Ct. Lakewood, CO 80226	29.7	$566.90	$28.30	Open for business	S
20	Reclaimed West	(303) 775-0349	10475 Bountiful St. Firestone, CO 80504	11.2	$369.40	$18.50	Moderate company, olorado and Cali	M
23	TJ's Wood Products	(303) 838-5779	P.O. Box 437 Bailey, CO 80421	57.4	$862.80	$43.10	Buys logs and beams.	L
36	Morgan Timber Products	(970) 484-4065	2532 County Road 54G Fort Collins, CO 80524	69.8	$994.00	$49.70	50 years of logging, firewoood, fencing.	M
43	Wood Source	(303) 297-8310	8321 Steele St. Thornton, CO 80229	24.8	$515.10	$25.80	Large compnay, mills are out of state	M

Figure 7 - Wooden Beam Production Facility Locations

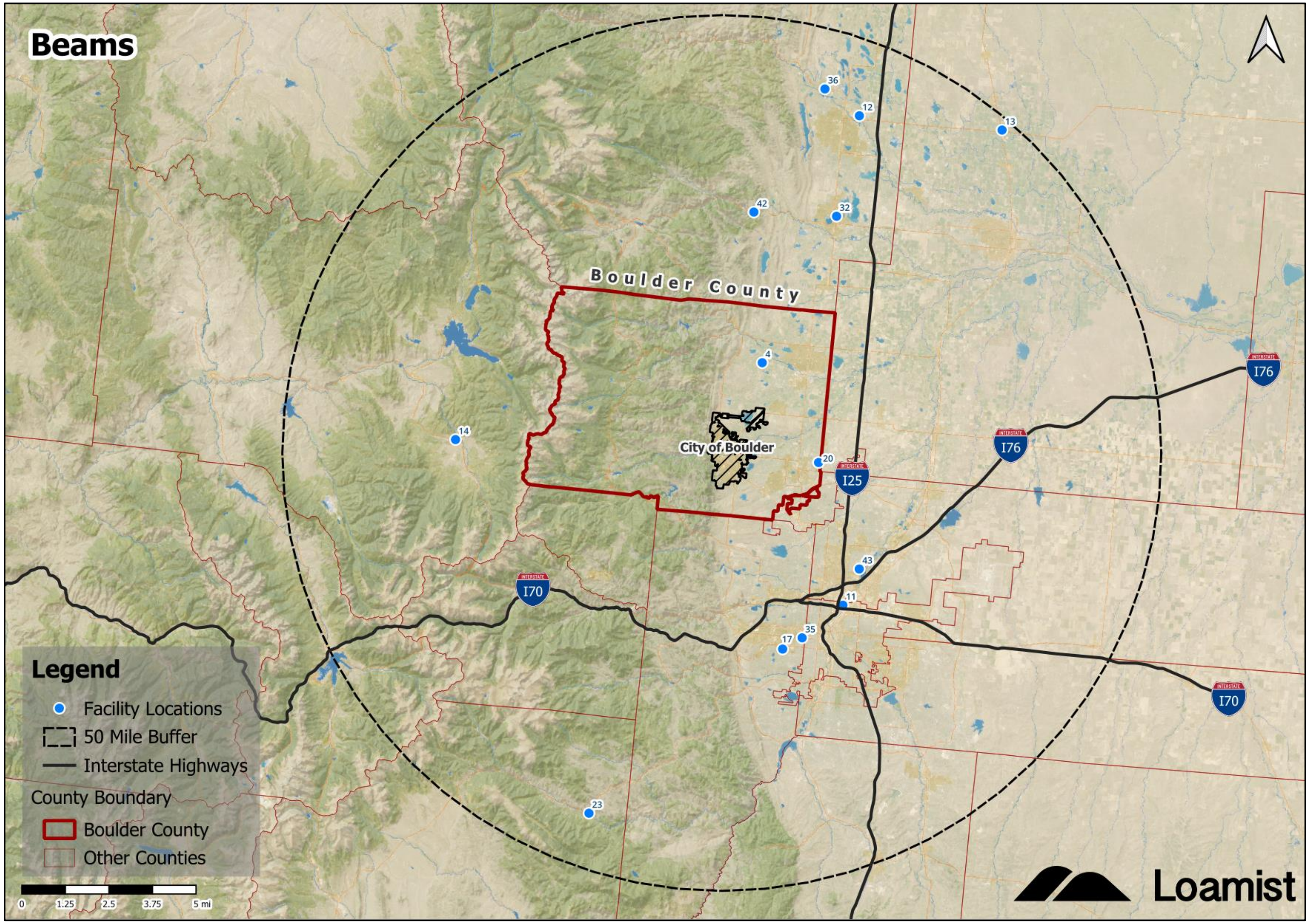


Table 8 - Boulder Region Pellet Production Facilities

Pellets

Facilty Number	Name	Phone	Address	Total Distance (miles)	Estimate Delivery Cost	Est $/ton Delivered	Facility Contact Notes	Facility Size
27	Shreiner Enterprises	(970) 689-8788	4719 Arthur Mae Ln. Laporte, CO 80535	71.9	$1,017.20	$50.90	Mitigation, Logging, Firewood.	S

Figure 8 - Pellet Production Facility Locations

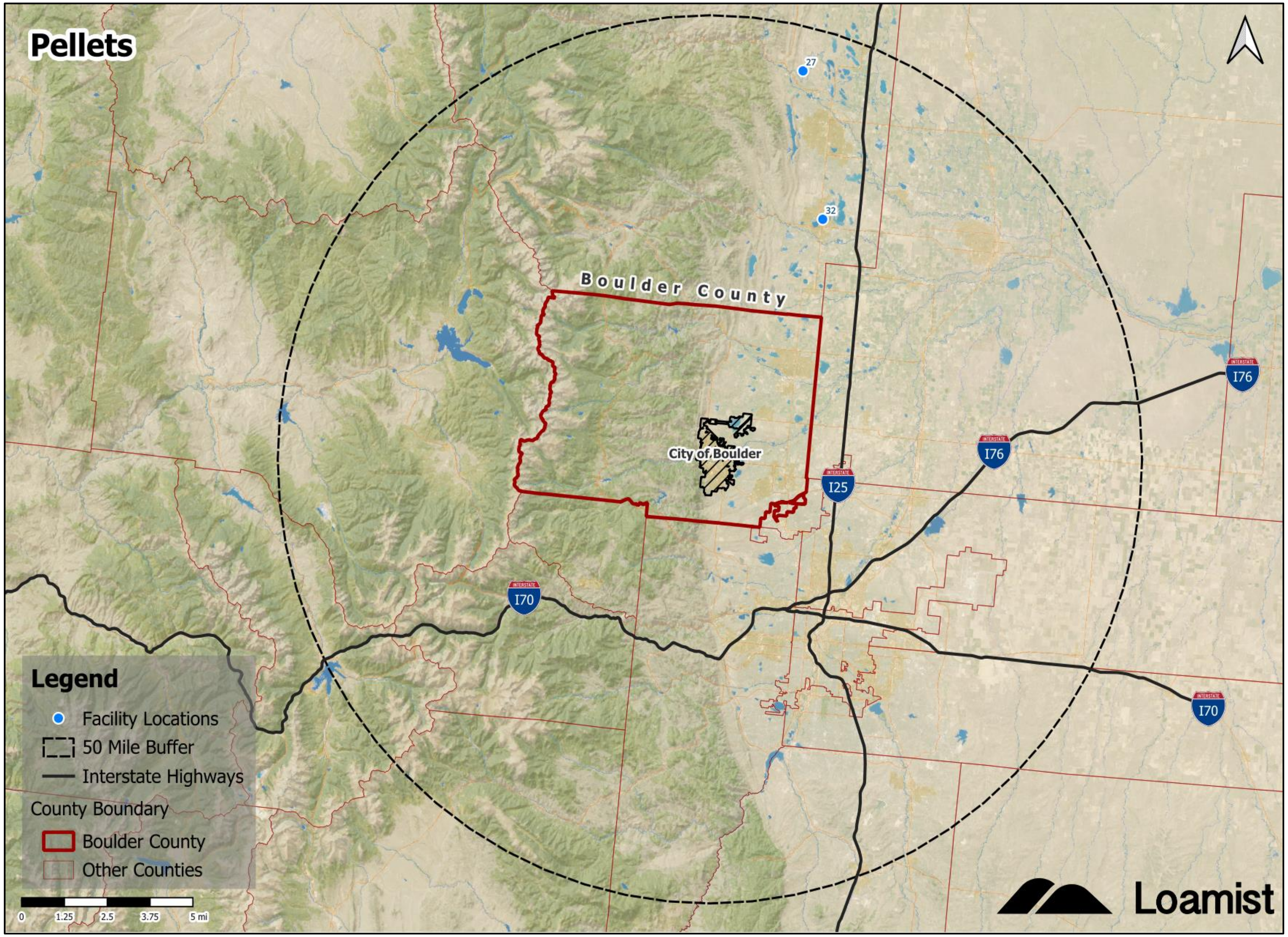


Table 9 - Boulder Region Post, Poles, and Fencing Materials Facilities

Post, Poles, and Fencing

Facilty Number	Name	Phone	Address	Total Distance (miles)	Estimate Delivery Cost	Est $/ton Delivered	Facility Contact Notes	Facility Size
13	Golden West Pine Mills LLC	(970) 590-8351	219 E. 4th St. Ault, CO 80610	65	$943.70	$47.20	Full scale logging mill. Buys and sells.	L
14	Hard Up Lumber	(970) 726-9241	PO Box 366 Tabernash, CO 80478	86.4	$1,172.10	$58.60	Small scale, 1-2 guys loggers	M
22	TimberScapes	(970) 819-9767	1543 Walnut St. Windsor, CO 80550	47.3	$754.60	$37.70	Small company log structures. Buys logs and beams.	M
23	TJ's Wood Products	(303) 838-5779	P.O. Box 437 Bailey, CO 80421	57.4	$862.80	$43.10	Buys logs and beams.	L
24	Rocky Mountain Log & Saw Co	(970) 482-3790	2318 W. County Road 54G Fort Collins, CO 80524	69.9	$992.00	$49.60	On going concern. Firewood rough cut, sells squared blank	M
27	Shreiner Enterprises	(970) 689-8788	4719 Arthur Mae Ln. Laporte, CO 80535	71.9	$1,017.20	$50.90	Mitigation Logging, firewood	S
29	TM Grand County Inc.	(970) 531-7071	400 CR 60 Granby, CO 80446	97.3	$1,287.70	$64.40	Firewood & Fuelwood, Posts, Poles & Fencing, Wood Chip	S
36	Morgan Timber Products	(970) 484-4065	2532 County Road 54G Fort Collins, CO 80524	69.8	$994.00	$49.70	50 years of logging, limber, firewood and fencing	M
40	United Wood Products Inc.	(303) 652-2872	7860 Diagonal Hwy. Longmont, CO 80503	11.8	$376.00	$18.80	Operational all info still accurate.	M
43	Wood Butcher Ltd.	(701) 720-0808	16 Tracy Trail Rd. Loveland, CO 80537	40.8	$685.40	$34.30	One man show, still cutting and selling products. Not buyi	S
43	Wood Source	(303) 297-8310	8321 Steele St. Thornton, CO 80229	24.8	$515.10	$25.80	Large compnay, mills are out of state	M

Figure 9 - Post, Pole, and Fencing Material Facility Locations

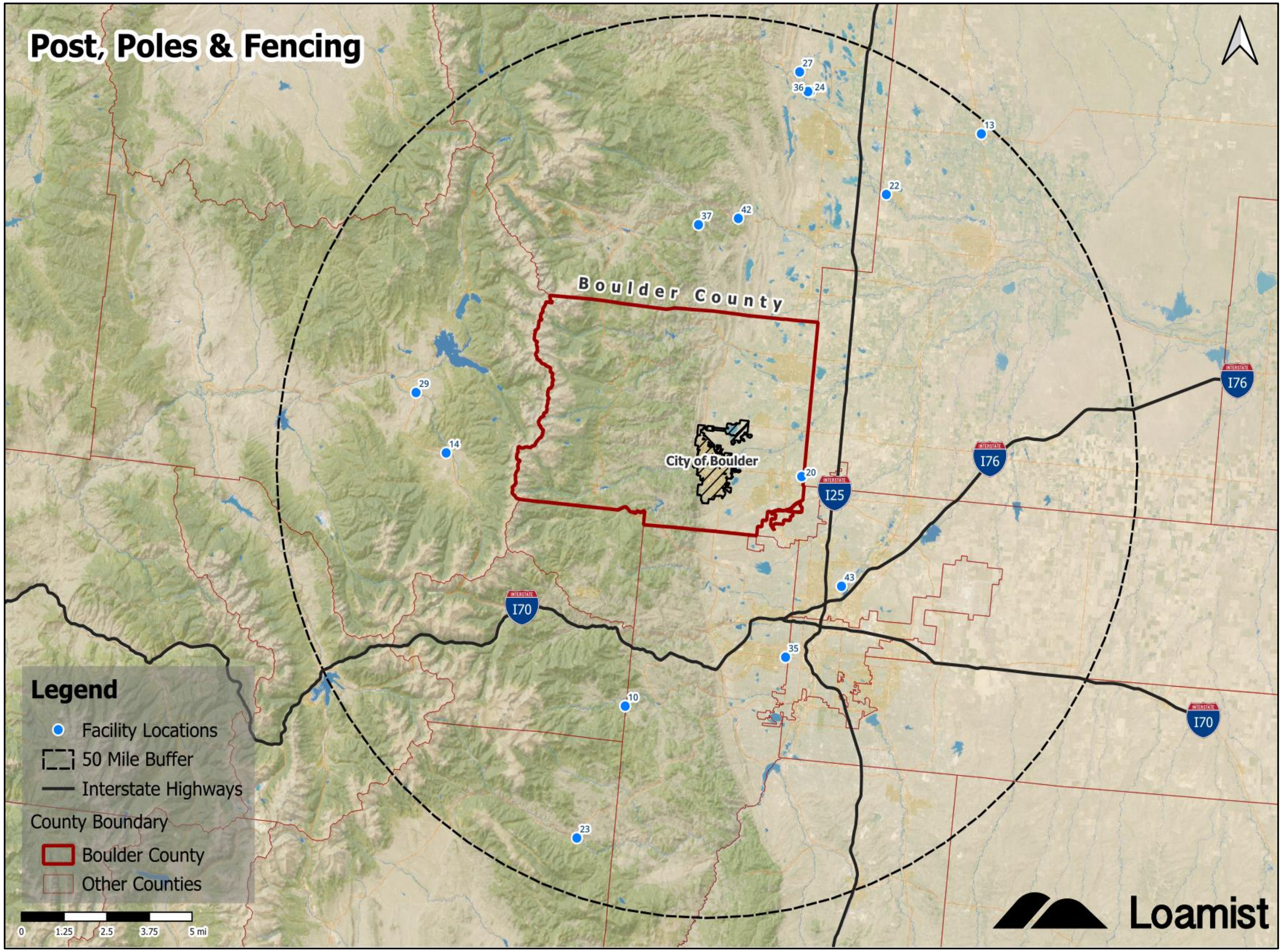


Table 10 - Boulder Region Wood Shavings Facilities

Shavings								
Facilty Number	**Name**	**Phone**	**Address**	**Total Distance (miles)**	**Estimate Delivery Cost**	**Est $/ton Delivered**	**Facility Contact Notes**	**Facility Size**
21	Renewable Fiber	(303) 857-0763	8395 U.S. 85 Fort Lupton, CO 80621	38.3	$658.70	$32.90	Ongoing concern	L
36	Morgan Timber Products	(970) 484-4065	2532 County Road 54G Fort Collins, CO 80524	69.8	$994.00	$49.70	50 years of logging, lumber, and by-products	M

Figure 10 - Wood Shavings Production Facility Locations

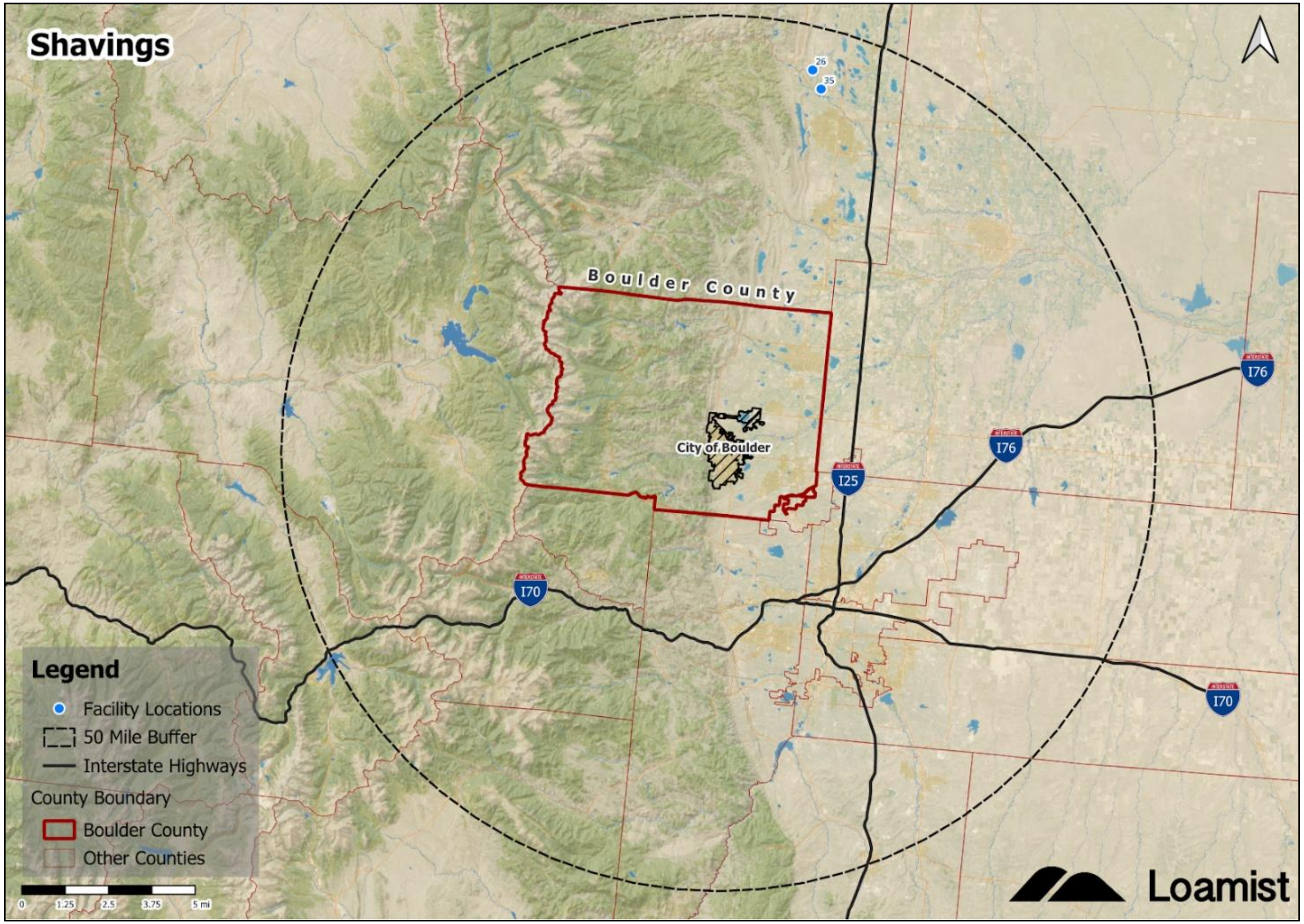


Table 11 - Boulder Region Logs and Log Homes Facilities

Log Homes & House Logs

Facilty Number	Name	Phone	Address	Total Distance (miles)	Estimate Delivery Cost	Est $/ton Delivered	Facility Contact Notes	Facility Size
3	Jeremiah Johnson Log Homes Inc.	(303) 567-2202	1501 County Road 308 Dumont, CO 80406	50	$782.80	$39.10	Successful log home builder	L
14	Hard Up Lumber	(970) 726-9241	PO Box 366 Tabernash, CO 80478	86.4	$1,172.10	$58.60	Logging company and log home builder. Small 1-2 guys	S
23	TJ's Wood Products	(303) 838-5779	P.O. Box 437 Bailey, CO 80421	57.4	$862.80	$43.10	Well established moderate to large company.	L
27	Shreiner Enterprises	(970) 689-8788	4719 Arthur Mae Ln. Laporte, CO 80535	71.9	$1,017.20	$50.90	Mitigation logging, specialty products.	S
28	Timberline Log Exteriors	(303) 514-9192	19240 U.S. 85 Gilcrest, Colorado 80623	49	$772.50	$38.60	Small lumber/mill company	S
35	GreenWay Building Products LLC	(720) 515-5189	5707 West 6th Ave., #100-105 Lakewood, CO 8021	31.6	$587.00	$29.40	Small outfit	S
36	Morgan Timber Products	(970) 484-4065	2532 County Road 54G Fort Collins, CO 80524	69.8	$994.00	$49.70	Small milling and logging capactiy works on own property soley.	M
42	Wood Butcher Ltd.	(701) 720-0808	16 Tracy Trail Rd. Loveland, CO 80537	40.8	$685.40	$34.30	One man show, still cutting and selling products. Not buying.	S

Figure 11 - Log and Log Home Facility Locations

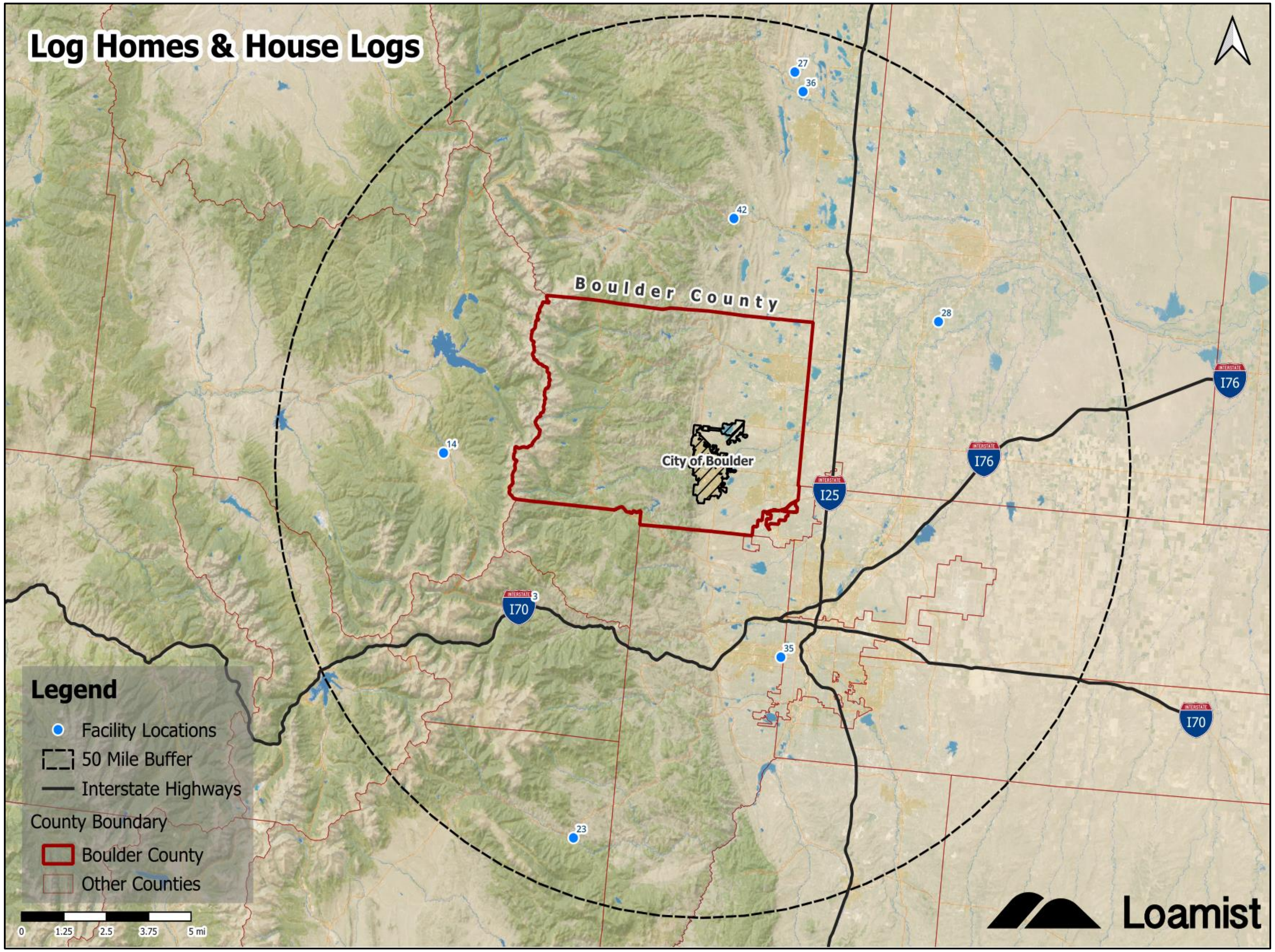


Table 12 - Boulder Region Wood Furniture Facilities

Furniture								
Facilty Number	**Name**	**Phone**	**Address**	**Total Distance (miles)**	**Estimate Delivery Cost**	**Est $/ton Delivered**	**Facility Contact Notes**	**Facility Size**
2	JKC Woods LLC	(720) 453-3138	10713 N. 65th St. Longmont, CO 80503	13.4	$392.60	$19.60	Ongoing small concern	S
6	Blue Pine Woodworks	(303) 502-6134	1550 Larimer Street, No. 761 Denver, CO 80202	28.2	$551.30	$27.60	Small company, as described	S
8	Cleveland Creek Log & Lodge Furniture	(303) 582-5802	221 Gap Rd. Black Hawk, CO 80422	26.9	$537.30	$26.90	Large for a funiture company 3 locations	L
11	Denver Wood Slabs	(720) 780-7752	4903 Washington St. Denver, CO 80216 Denver, CO	24.6	$512.40	$25.60	Medium sized furniture company large planer/mill	M
20	Reclaimed West	(303) 775-0349	10475 Bountiful St. Firestone, CO 80504	11.2	$369.40	$18.50	N/A	M
25	Ryan Schlaefer Fine Furniture Inc.	(970) 213-2353	518 C S. Lincoln Ave. Loveland, CO 80537	32.5	$596.20	$29.80	On going medium sized 3 showrooms	M
31	Mountain Woodworks	(303) 582-5076	51 Wolf Rd. Black Hawk, CO 80422	31.5	$586.00	$29.30	Small custom shop	S
32	Mourning Reclaimed Wood	(303) 921-8117	2650 North Lincoln Loveland, CO 80537	34.8	$620.80	$31.00	Small custom woodworking	S
33	Naked Aspen Designs	(970) 726-1373	208 Eisenhower Dr. Fraser, CO 80442	82.5	$1,130.40	$56.50	Small custom woodworking	S
34	Andersons Adirondacks	303-817-1618	Englewood, CO 80110	35.9	$632.60	$31.60	One man show	S
39	TC Woods, Tree Recycling Center	(303) 666-8989	9850 Arapahoe Lafayette, CO 80026	7.9	$333.80	$16.70	Ongoing medium sized company	M
41	Where Wood Meets Steel	(720) 780-7752	4903 Washington St. Denver, CO 80216	24.6	$512.40	$25.60	Medium sized business	M
42	Wood Butcher Ltd.	(701) 720-0808	16 Tracy Trail Rd. Loveland, CO 80537	40.8	$685.40	$34.30	One man show, still cutting and selling products. Not buying.	S

Figure 12 - Wooden Furniture Production Facility Locations

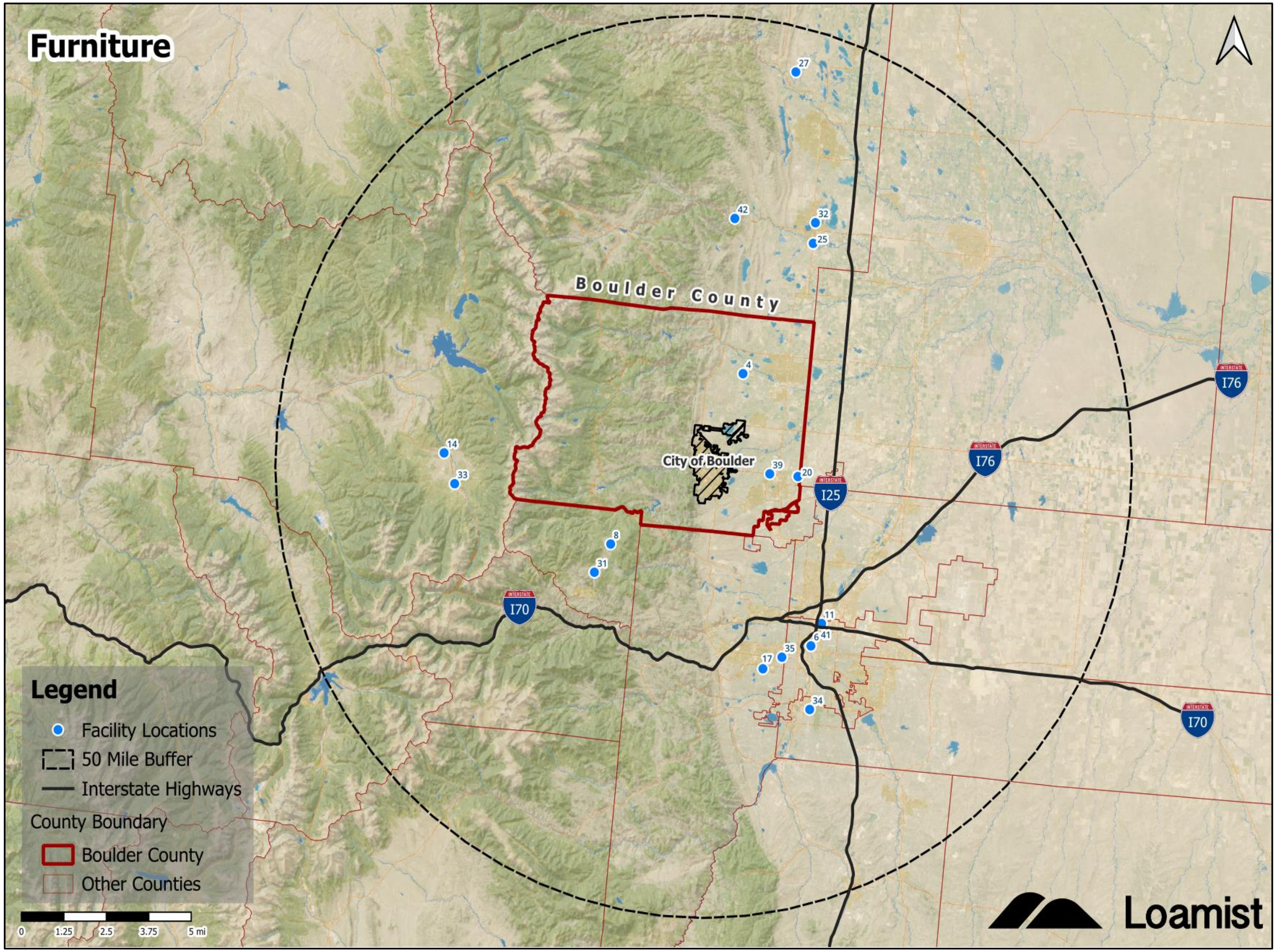
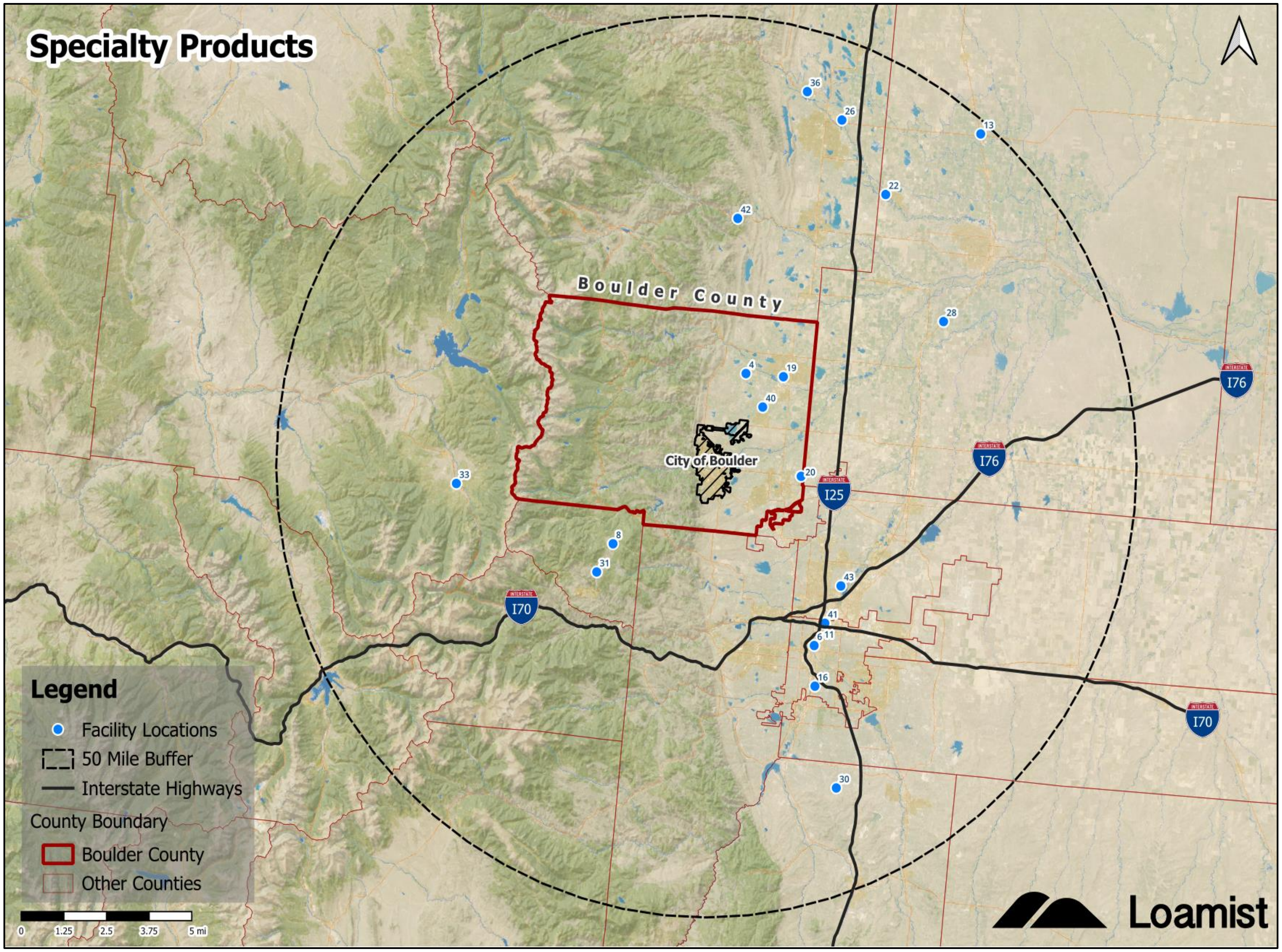


Table 13 - Boulder Region Wood Specialty Products Facilities

Specialty Products								
Facilty Number	Name	Phone	Address	Total Distance (miles)	Estimate Delivery Cost	Est $/ton Delivered	Facility Contact Notes	Faciiity Size
5	JKC Woods LLC	(720) 453-3138	10713 N. 65th St. Longmont, CO 80503	13.4	$392.60	$19.60	Ongoing small concern	S
13	Bouillez Acoustics	(970) 231-8776	126 Lori Dr. Loveland, CO 80537	32.7	$598.60	$29.90	Small Custom woodworking specializing in guitars	S
19	Cleveland Creek Log & Lodge Furniture	(303) 582-5802	221 Gap Rd. Black Hawk, CO 80422	26.9	$537.30	$26.90	Established furniture company 3 locations	M
11	Denver Wood Slabs	(720) 780-7752	4903 Washington St. Denver, CO 80216	24.6	$512.40	$25.60	Medium sized furniture company large planer/mill	M
13	Golden West Pine Mills LLC	(970) 590-8351	219 E. 4th St. Ault, CO 80610	65	$943.70	$47.20	Growing lumber mill in northern Colorado	L
16	Meier Skis	(844) 966-3754	1775 S. Broadway Denver, CO 80210	32.5	$596.40	$29.80	Custom hand-made ski manufacturer	S
19	Nature's Casket	(720) 343-0912	437 Vivian St. Longmont, CO 80501	15.1	$411.10	$20.60	Small casket company	S
20	Reclaimed West	(303) 775-0349	10475 Bountiful St. Firestone, CO 80504	11.2	$369.40	$18.50	Small company log structures	S
22	TimberScapes	(970) 819-9767	1543 Walnut St. Windsor, CO 80550	47.3	$754.60	$37.70	Med-large company	M
26	Sears Trostel Lumber CO	(970) 482-0222	125 Airpark Dr. Fort Collins, CO 80524	63.3	$925.20	$46.30	Large yard and selection	M
28	Timberline Log Exteriors	(303) 514-9192	19240 U.S. 85 Gilcrest, Colorado 80623	49	$772.50	$38.60	Small log milling company	S
30	Western Log Creations	(720) 331-4673	10459 Cheetah Winds Littleton, CO 80124	49	$773.10	$38.70	Small company. Small wood furnishings	S
31	Mountain Woodworks	(303) 582-5076	51 Wolf Rd. Black Hawk, CO 80422	31.5	$586.00	$29.30	Small custom shop.	S
33	Naked Aspen Designs	(970) 726-1373	208 Eisenhower Dr. Fraser, CO 80442	82.5	$1,130.40	$56.50	Small custom woodworking	S
41	Where Wood Meets Steel	(720) 780-7752	4903 Washington St. Denver, CO 80216	24.6	$512.40	$25.60	Medium sized business	M
42	Wood Butcher Ltd.	(701) 720-0808	16 Tracy Trail Rd. Loveland, CO 80537	40.8	$685.40	$34.30	One man show, still cutting and selling products. Not buying.	S
43	Wood Source	(303) 297-8310	8321 Steele St. Thornton, CO 80229	24.8	$515.10	$25.80	Large company, mills are out of state	L

Figure 13 - Wooden Specialty Facility Locations



Appendix 2B. Potential Woody Biomass Utilization Pathways for the Boulder County Region: Preliminary Evaluation List

Process or Product	Feedstock Specifications	Main Equipment	Market Potential	Comments
Biomass to Electricity (Direct Combustion)	Woody biomass chipped to 3"minus, 50% mc, 3% ash. Drier feedstock preferred.	Feedstock handling, boiler, steam cycle turbine-generator, emissions control, water-cooling and recovery.	Technology is evolving quickly and slowly becoming more cost effective.	More appropriate where electrical and thermal energy wholesale rates are high. Typically found in states with attractive Renewable Portfolio Standards or renewable energy incentives
Biomass to Electricity (Gasification)	Woody biomass chipped to 3"minus, 30% mc, 3% ash. Feedstock needs to be around 20% or lower moisture content.	Gasifier, gas cleanup, IC engine or turbine-generator.	Technology is evolving quickly and slowly becoming more cost effective.	Like bioelectricity via direct combustion, more appropriate where electrical and thermal energy wholesale and/or retail rates are high or in remote installations where power is not currently available.
Biomass to Heating (space and processes)	Woody biomass chipped to 3"minus, 50% mc, 3% ash.	Boiler system and hot water or steam delivery system.	Especially cost effective if replacing existing heating oil or propane heat. Can use for cooling also (using absorption chillers).	Feedstock sizing has been an issue with recently installed thermal energy facilities. Typical installations include schools, hospitals, community buildings, and commercial buildings. Could also work for district heating systems, but none are known in the U.S.
Biomass to Biofuels (liquid & gaseous)	Similar to gasification	Gasifier, gas cleanup, conversion equipment to liquid fuels, hydrogen, or RNG	Use as alternative transportation fuels (renewable diesel, jet fuel, RNG, Hydrogen). The gaseous fuels, RNG & H2 can be also used for space and industrial processes heating	Due to economies of scale, commercial facilities will need to be large with considerable feedstock needs. CAPEX and OPEX are relatively high. There are several vendors claiming that they can make smaller scale biofuels units but there are none at a commercial level yet in the U.S.
Biochar (Slow pyrolysis)	Wood pieces (flexible spec).	Biochar kiln or pyrolysis vessel. Systems can be stationary or portable depending on vendor	Soil amendment activated carbon (water filtration), and several other uses, but markets are still developing. Biochar for carbon dioxide removal credits is becoming a significant source of revenue	Carbon dioxide removal credit market currently creating a significant development boom in biochar production. Slow pyrolysis operates at longer residence times and temperatures of 350 to 600 C to maximize solid products such as biochar

Process or Product	Feedstock Specifications	Main Equipment	Market Potential	Comments
Bio-oil (Fast pyrolysis)	Wood pieces (flexible spec).	Fast pyrolysis vessel Systems can be stationary or portable depending on vendor	The current principal revenue source is carbon dioxide removal credits market.	Originally considered for direct use as fuel, or feedstock to be upgraded into fungible transportation fuel. Currently finding a niche market in carbon dioxide removal credit market. Charm Industrial is the current leader in this sector. Fast pyrolysis operates with a faster residence time and over 500+ C to produce more liquid products such as bio-oil.
Compost	Tree trimmings and grass clippings (greenwaste).	Grinder, screen and windrow turner.	Soil amendment market is seasonal. Typically sold in bulk or bagged. Compost is widely used in the agricultural sector.	Compost is a biologically active material that breaks down from organic material (which includes wood). Biochar can also be added to compost products to further enhance it.
Fungal Inoculation	Chip piles left in the forest with no dirt mixed in.	Fungal inoculate currently applied by hand equipment.	As this is a wood chip more rapid degradation process in the forest there is no external market per se.	Currently in the experimental phase of development. Piles of woody waste can take considerable time to degrade on their own. This fungal inoculation process shows promise to very significantly shorten the time it takes for the piles to degrade and return the nutrients to the forest soils.
Woody Biomass Burial	Whole logs and wood waste	Equipment to construct and place wood into burial site.	Current principal revenue source is carbon dioxide removal credits market.	This is a carbon sequestration pathway that consists of burying woody biomass under conditions that inhibit biomass decomposition and can maintain those conditions for containment of the stored carbon for at least 100+ years
Hog Fuel for Bioenergy	Whole logs and woody biomass waste, or sawmill residuals, generally reduced to 3”-minus	Chipper, grinder, or shredder to reduce wood to fuel feedstock size	Hog fuel is processed and generally sold to bioenergy facilities as fuel feedstock or used directly by facilities that may generate their own hog fuel	Hog fuel is the staple feedstock for bioenergy facilities and can be generated at various facilities for direct use at the facility (such as energy production at a sawmill) or at offsite facilities such as a biomass utilization facility to produce heat, electricity, biofuels, biochar, and bio-oil.
Chip for pulp and paper	Woody biomass chipped to 3"minus, 50% mc, bark free with few fines.	Debarking equipment (e.g., chain flail) chipper and screen.	No virgin pulp/paper operations in the region.	No virgin paper mills in CO, some secondary mills utilizing manufactured paper or recycled paper.

Process or Product	Feedstock Specifications	Main Equipment	Market Potential	Comments
Plastic/Wood Fiber Composites (WPC)	Clean, dry (2-12% mc) wood flour. Wood is ~55% of feedstock along with plastic and additives. Recycled wood use common.	Blender (compounder extruder), extrusion line, cooler, cut-off saw.	Landscape (bender board), decking, fencing, park furniture (picnic tables and seats), outdoor signage. Composite wood furniture market is growing due to interest in sustainability. Increasingly used in building, exterior siding.	Requires cost effective thermoplastic feedstock (HDPE, LDPE, PP, PVC). Utilize recycled plastics (milk jugs, plastic bags). Commercial facilities typically use pine, oak and maple. Commercial molding processes typically continuous extrusion or batch injection molding.
Firewood	Whole logs (bucked), larger branches	Log/branch saws, log splitter.	Primarily sold into space heating market.	Firewood has partially controlled emissions in work stoves, less in open fireplaces or fire pits (not unlike open pile burning). Air agencies try to discourage the use of firewood due to the generation of smoke (particulate matter entrained)
Drying kilns for Firewood	Firewood or hog fuel for biomass-fired heater	Equipment to load/stack firewood into kiln(s) and biomass heating system.	Drying firewood may add some small value to sales.	Dry firewood burns hotter and more efficiently than wood with higher moisture content. Less smoke and PM is generated.
Pellets	Clean, dry (<10% mc) chip, needs to be <1% ash.	Pellet mill, dryer, cooler, hammermill, packaging.	Domestic users now, but potential for biomass boilers. At the industrial scale can be co-fired with coal. Could also be marketed to international markets. Possible niche market for barbeque pellets (hardwoods).	Use of either roundwood or biomass from forest possible (e.g., small logs or chips low in bark). Key issue and expense is drying system. Larger scale facility may face challenges in gaining market share for domestic stoves. Large-scale export facility may have feedstock sourcing challenges and exposure to currency exchange rate risk.
Fuel Bricks	Chip, dry (<15% mc), needles, bark okay.	Brick machine, possible dryer, cooler, hammermill, packaging.	Substitute for firewood is the primary market. Domestic use or camping, lighter and more portable.	May use needles and bark. Also paper. Potential to use field-dried material as feedstock. Bricking machines can be small and portable.
Small-scale sawmill	Medium to large size roundwood.	Debarker, head rig, resaw, edger.	May need to target specialty markets to secure optimal value for products.	Tough to compete with large-scale sawmills for logs and lumber sales. Niche markets for lumber is important. Most lumber is low-value commodity product.

Process or Product	Feedstock Specifications	Main Equipment	Market Potential	Comments
Post and Pole	Straight, low taper softwood (lodgepole, ponderosa) is preferred.	Rosser head peeler and/or doweller. Sorting line. Bucking saw.	Market for fencing, landscaping, ag crop trellising, etc.	Typically sold without stripping bark or treating the wood. Small 2–5-inch diameter can be utilized.
Mass Timber	Smaller sections of wood as opposed to whole logs.	Mass timber products are made by taking smaller wood elements such as dimension lumber, veneers, or strands and connecting them with adhesives, dowels, nails, or screws to create larger structural building components.	Markets for replacement of steel and concrete for building construction. Because the wood stores carbon dioxide (CO_2) that was captured from the atmosphere via photosynthesis, mass timber construction can function as a form of carbon removal.	Mass timber, unlike Light Wood-Frame or Heavy Timber, uses a combination of smaller sections of wood and adhesives or fasteners to create larger sections to provide strength, dimensional stability, and fire resistance. Also, unlike currently produced steel and cement it has carbon sequestration status. Mass timber production facilities are generally larger facilities to meet economies of scale necessary for the CAPEX and OPEX.
Mulch	Tree trimmings and ground wood waste	Grinder, screen and windrow turner.	Soil cover for weed control and soil amendment. Sold in bulk and bagged similar to compost	Mulch differs from compost as it is basically ground or chipped material used to cover soil surfaces.
Decorative Chips	Bark free and sized (no fines) wood chip.	Debarker (flail, ring or rosser head), screen (trommel or flat).	Colorized landscape cover sold in bulk and/or bagged.	Colored landscape cover requires additional equipment (colorizer). Note that bark free chip has alternative markets such as pulp/paper or furnished for composite products (particleboard/hardboard/decking).
Decorative Bark	Roundwood that is easily de-barked. Raw bark from sawmills is common source.	Debarker (flail, ring or rosser head), screen (trommel or flat).	Higher value in urban communities.	As sawmill residuals become scarce, value of bark for landscape cover increases. Alternative use is hog fuel.
Animal Bedding (shavings)	Small roundwood (ponderosa pine preferred).	Shaver, screens, drying, packaging.	Can be sold in bulk and/or bagged.	Shavings are produced from roundwood, including small diameter material. Chipped biomass or mill sawdust can also be used for animal bedding, (but are not considered shavings). Local sawmills could add animal bedding systems to their operations.

Process or Product	Feedstock Specifications	Main Equipment	Market Potential	Comments
Open Burning	Piled wood waste	Logging and thinning equipment. Equipment to move wood waste to pile areas for burning.	Not a utilization pathway market	Currently a significant fate of liability forest biomass. Significant emissions with no emissions control.
Air Curtain Burning	Whole bucked logs, unchipped wood waste	Logging and thinning equipment. Equipment to move wood waste to pile areas for burning. ACBs can be stationary or portable depending on use needs	With burning only revenue only to owner/operator of ACB. With potential energy generation potential revenue from the substitution of fossil fuel use. If used to produce biochar, markets similar to that described above in biochar markets	Air curtain burners significantly reduce PM compared to open burning. Newer systems can produce biochar, heat for drying and other heat requiring processes, and electricity for system power and battery storage for electrified rolling stock charging. ACBs come in several sizes.
Masticate and/or Chip and Leave in Place	Woody biomass waste on site	Masticating and chipping/grinding equipment	Not a utilization pathway market	Currently a significant fate of liability forest biomass. Potential release of GHG due to decay in forest.
Landfilling as Waste	Woody biomass primarily from the urban environment	Rolling stock to collect wood waste and transport to landfills	Revenue received via waste collection fees, and tipping fees at landfill (or transfer/processing yards)	Wood waste in landfill will ultimately decay in landfill and contribute to GHG emissions from landfills

Appendix 2C. Biomass Pathway Evaluation Tables.

Table 1. Scoring Matrix - Primary Products, Feedstock Matches, Technology Considerations and Maturity

Pathway	Primary Products	Score	Feedstock Matches	Score	Technology Considerations and Maturity	Score
Biochar	Primary product - biochar, biocarbon. Secondary products - bio-oil, syngas, wood vinegar	4	The feedstocks for the pyrolysis of wood to produce biochar vary depending on the desired biochar properties, pyrolysis technology, and local availability of materials. Most types of woody biomass feedstocks - logs (to be chipped), woody chips, bark, shavings, and sawdust. Generally, woody biomass with low moisture content, low ash content, and high lignin and cellulose content is preferred	5	Pyrolysis of wood into biochar is a commercially viable and increasingly mature technology, with adoption seen in both developed and developing countries. A relatively sophisticated woody biomass pyrolysis to biochar operation already exists in the Boulder Region (Biochar Now). TRL is 8 to 9 for many pyrolysis to biochar systems.	4
Bio-Oil	Primary product - bio-oil. Secondary products - biochar, syngas, wood vinegar	2	Wood chips, forestry slash, and sawmill residues are the most common feedstocks for pyrolysis to bio-oil. Some pyrolysis systems refer to clean chips. Use of bark is not recommended.	4	Pyrolysis of wood into bio-oil is a relatively mature technology, however, commercial use of bio-oil is not widespread. Currently the most increasing active market for bio-oil is for carbon dioxide removal credits primary by injection of produced bio-oil into deep wells. A bio-oil production startup is in the Boulder Region (Charm Industrial) but is currently operating on a relatively small scale. TRL is 8.	4
Firewood/Kiln	Firewood (may need natural drying). Kiln dried firewood	4	The trunk of the tree is the best source of firewood because it provides thick, straight-grained, dense wood. Large branches that are thick and straight-grained are also good for firewood. Smaller branches can be used for kindling.	4	The technological maturity of firewood production varies depending on the region, resources, and scale of production. In the U.S. and other developed nations, advanced mechanized production of firewood is prevalent. This includes1) Fully Automated Equipment: Firewood processors can cut, split, and stack logs in one continuous process. 2) Hydraulic Splitters: High-efficiency machines that can handle large volumes. 3) Industrial-Scale Machinery: Includes log chippers, conveyors, and bundling equipment for large-scale operations. 4) Precision and Uniformity: Ensures consistent size and quality of firewood, suitable for commercial markets. 5) Integration with Forest Management: Often part of larger forestry operations, ensuring sustainable harvesting. 6) Efficient Drying Techniques: Solar drying or kilns for faster seasoning and improved combustion efficiency. TRL is 9	5

Pathway	Primary Products	Score	Feedstock Matches	Score	Technology Considerations and Maturity	Score
Biomass Heat	Structure heating in lieu of fossil fuel heating	4	Wood chips are the primary feedstock for biomass heating systems. Wood pellets can also be utilized if available.	5	The technology for **biomass heating** is **highly mature**, particularly for residential, commercial, and industrial applications using modern stoves, boilers, and district heating systems. While innovative technologies and hybrid systems are still under development, the core technologies are widely adopted and proven to be reliable, efficient, and environmentally beneficial when implemented with modern controls and emission management systems. TRL is 9	5
Compost/Mulch	Compost products as soil amendment. Mulch is used primarily as soil cover (not mixed into soil)	5	Wood feedstocks for composting include Wood chips, shredded bark, shredded branches and twigs, sawdust, a untreated wood products waste. However, there is a limit to the percentage of woody biomass that can be input into compost.	3	The technological maturity of compost and mulch lies in their well-established status as low-tech, proven, and widely adopted technologies for organic waste management and soil enhancement. Maturity level for compost is advanced and widely adopted with industrial scale facilities using advanced technologies such as: 1) Aerated Static Piles (ASP): To control temperature and oxygen levels, 2) In-Vessel Composting: For faster and odor-controlled decomposition. 3) Windrow Composting: For large-scale, outdoor applications. Mulch maturity is high and well-integrated in agriculture and landscaping. Both compost and mulch are TRL 9	5
Fungal Decomposition	In-field reduction of wood chips only, but with ecosystem benefits	3	Wood chips	3	The technological maturity of augmented fungal degradation of wood chips in the forest can be classified as moderate. Emerging innovations like inoculation and controlled conditions are promising but not widely applied. TRL is 6 to 7	3
Animal Bedding	Bedding for horses, some livestock and poultry. No secondary products	4	Wood chips, wood shavings, sawdust	4	Woody biomass, such as sawdust, wood shavings, and chips, is widely recognized as a viable material for animal bedding due to its absorbency, insulation properties, and ability to control odors Woody biomass products are commercially available and widely used in livestock farming (e.g., poultry, equine, and dairy industries. TRL is 9.	5

Pathway	Primary Products	Score	Feedstock Matches	Score	Technology Considerations and Maturity	Score
Pellets/Fuel Bricks	Pellets for heating, primarily residential and commercial use. Fuel bricks same.	4	Wood chips and sawdust particularly for residential and commercial building heating to have reduced ash. Bark can be blended in for industrial use heating.	4	Wood pellet production systems are well-developed and commercialized. Pelletizing technology, both small and large scale is standardized and widely available, making it a mature technology in the bioenergy sector. Fuel brick production systems are well developed but less standardized. Fuel bricks are widely used, particularly in developing regions, but production technology is less standardized compared to pellets. Pellet TRL is 9, with fuel brick 8 to 9.	4
Small Sawmill	Production of dimensional lumber, decorative wooden slabs for furniture,	5	Logs 6 inches or greater in diameter, up to 36 inches in diameter. Includes forest timber as well as urban timber.	3	Small sawmills in the United States exhibit a range of technological maturity, influenced by factors such as mill size, resource availability, and market demand. Small sawmills vary in their adoption of technology. Some utilize advanced machinery and optimization software, while others operate with traditional, less automated equipment. There is a very robust array of commercial small sawmill equipment, both for stationary and portable operation available in the marketplace. TRL is 9	5
Mass Timber	Layers of wood from logs that are laminated or mechanically fastened together to create large, strong panels or beams to be used primarily in building construction	5	Soft woods such as forest conifers are preferred due to their strength-to-weight ratio workability, and availability. Small diameter logs from thinning and sustainability forestry practices.	3	Mass timber products, such as cross-laminated timber (CLT) and glued laminated timber (glulam), have seen significant advancements in technological maturity within the United States. Mass timber products in the U.S. have achieved a high level of technological maturity, supported by expanded manufacturing, updated building codes, and growing market acceptance. Ongoing efforts address challenges related to supply chains, regulatory familiarity, and cost, positioning mass timber as a viable and sustainable alternative in modern construction. TRL is 9	5

Pathway	Primary Products	Score	Feedstock Matches	Score	Technology Considerations and Maturity	Score
Post&Pole	Cylindrical wood products from suitable trees are commonly used in fencing construction, agriculture and landscaping and utility applications.	4	Suitable smaller diameter tree for fencing, agricultural, and landscaping P&Ps. Medium diameter for utility poles (such as telephone poles	3	The post and pole production industry in the United States has achieved a notable level of technological maturity, characterized by the integration of advanced manufacturing processes and equipment. Modern facilities employ precision cutting machines, computer-aided design (CAD) technology, and specialized equipment for peeling, incising, and treating wood poles. Traditional post and pole production techniques involve manual or semi-mechanical processes to transform raw logs into usable posts and poles. These traditional techniques were widely used before the advent of industrial processes and are still practiced by small-scale operators focusing on rustic or environmentally conscious production. TRL for both advanced and traditional post and pole production is 9	5
Air Curtain Burner	Disposal of waste wood. Secondary products include ORC electricity if applicable equipment is used.	2	Whole logs (cut to fit in burn box). Forest thinning and slash. No wood chips	3	Air curtain burner technology, also known as air curtain destructors or air curtain incinerators, is employed in the United States to efficiently and environmentally dispose of wood waste. This method is particularly useful in forestry management, land clearing, and disaster recovery. Air curtain burners are utilized to dispose of forest slash, reducing wildfire risks and managing forest health. The U.S. Forest Service has evaluated and recommended their use as an efficient and environmentally friendly alternative for fuel reduction and disposal. TRL is 9	5

Table 2 - Scoring Matrix - Scalability, Transportation of Feedstock, Capital Expenditure, Operational Expenditure

	Scalability	Score	Transportation of Feedstock	Score	Capital Expenditure	Score	Operational Expenditure	Score
Biochar	Very scalable as there is a variety of sizes of pyrolysis systems that can be considered modular and additional units can be added at a biochar production facility. There are currently <1 ton to 5-7 tons per hour woody biomass input pyrolysis units commercially available.	4	Proportion of OPEX: 5%–15%. Typical Cost Range: $5–$15 per ton of biochar.	4	Small-Scale Facility 1–5 tons/hour of feedstock producing 0.25 to 1.25 tons/hour of biochar: $4–$8 million. Medium-Scale Facility 5–15 tons/hour of feedstock producing 1.25 to 3.75 tons/hour of biochar: $8–$15 million.	4	Small-Scale Facility (1–5 tons/hour): $700,000–$3 million. Medium-Scale Facility (5–15 tons/hour): $2 million–$8 million. Woody biomass feedstock cost can be as high as 2/3-plus the total annual OPEX.	3
Bio-Oil	Currently, bio-oil production-only systems are limited in commercial use, and these units are relatively small in woody biomass input - 2 to 10 tons per day. Like biochar production units they are modular and units can be added to increase biomass throughput.	2	Proportion of OPEX: 5%–15%. Typical Range: $5–$15 per ton of bio-oil.	4	Small-Scale Facility 1–5 tons/hour of feedstock producing up 75% by weight/hour of bio-oil: $4–$8 million. Medium-Scale Facility 5–15 tons/hour of feedstock producing up to 75% by weight/hour of biochar: $8–$15 million.	4	Small-Scale Facility (1–5 tons/hour): $700,000–$3 million. Medium-Scale Facility (5–15 tons/hour): $2 million–$8 million. Woody biomass feedstock cost can be as high as 2/3-plus the total annual OPEX.	3
Firewood/Kiln	Firewood production is scalable under the right conditions, particularly in regions with abundant resources, mechanized processes, and strong local demand. However, sustainability, environmental impacts, and economic considerations often limit the extent of scaling	5	Proportion of OPEX: 10%–20%. Typical Range: $10–$20 per ton of firewood.	3	Small Facility (5,000–10,000 cords/year): $300,000–$700,000. Medium Facility (10,000–25,000 cords/year): $700,000–$1.5 million. Large Facility (25,000+ cords/year with drying and packaging): $1.5–$3 million.	5	Small Facility (5,000–10,000 cords/year): $400,000–$1 million. Medium Facility (10,000–25,000 cords/year): $1 million–$2.5 million. Large Facility (25,000+ cords/year): $2.5 million–$5 million. Feedstock costs are approximately 50% of annual OPEX.	1

	Scalability	Score	Transportation of Feedstock	Score	Capital Expenditure	Score	Operational Expenditure	Score
Biomass Heat	Biomass heating systems range from small-scale residential units to large industrial systems. While small systems are easier to deploy widely, larger systems require significant capital investment and infrastructure, which can limit scalability. A reliable and efficient supply chain for biomass materials is essential. Transportation costs and logistics can limit scalability	3	Proportion of OPEX: 15%-25%. Typical Range: $10–$30 per ton using wood chips	2	The capital expenditure (CAPEX) for installing a biomass heating system in a large commercial building varies based on factors such as system capacity, technology type, and specific site requirements. The cost per kilowatt thermal (kWth) decreases as system size increases due to economies of scale. Smaller systems may have higher per kWth costs compared to larger installations. Biomass heating plants are reported to have installed costs averaging between $500 to $1,500 per kWth of installed heating capacity, with a 5 MWth cost at $2.5MM to $7.5MM. The biomass boiler typically accounts for about 55% of the total project cost. Other components, including the flue, thermal store, heat meter, pumps, valves, and pipework, make up around 30%, with the remaining 15% covering labor and delivery.	3	A 5MWth biomass heating system OPEX is approximately $1.8 MM per year, with approximately 50% of OPEX going to feedstock procurement costs.	3
Compost/Mulch	Composting is highly scalable, from small-scale household systems to large industrial facilities, but the level of scalability depends on waste availability, infrastructure, public participation, and market demand for finished compost. Large scale composting requires significant infrastructure, including large processing facilities, trucks for waste collection, and advanced monitoring equipment. Technologies like windrow composting, aerated static piles, or in-vessel systems enable processing at scale.	5	Proportion of OPEX: 10%–20%. Typical Range: $10–$20 per ton of compost.	3	Small-Scale Facility (5,000–10,000 tons/year): $500,000 to $1 million. Medium-Scale Facility (10,000–50,000 tons/year): $1 million to $5 million. Large-Scale Facility (50,000+ tons/year): $5 million to $20+ million	3	Small Facility (5,000–10,000 tons/year): $200,000–$800,000. Medium Facility (10,000–50,000 tons/year)**:** $800,000–$2 million. Large Facility (50,000+ tons/year)**:** $2 million–$5 million. Feedstock costs are in the 25% of OPEX range depending on tipping fees vs. Costs to acquire.	3

	Scalability	Score	Transportation of Feedstock	Score	Capital Expenditure	Score	Operational Expenditure	Score
Fungal Decomposition	Mechanical treatment (e.g. chipping and grinding) can enhance fungal access to lignin and cellulose, increasing scalability by reducing degradation time. Scalability improves if fungi can handle diverse feedstocks. Competing technologies (e.g., anaerobic digestion, pyrolysis) may offer lower-cost or faster solutions, potentially limiting fungal degradation's competitiveness	4	Fungal decomposition occurs at site and transportation costs of woody biomass are not incurred.	5	TBD	0	$25/BDT	3
Animal Bedding	The scalability of producing animal bedding from woody biomass waste depends on several factors, including the availability of raw materials, technology, market demand, and logistics. Animal bedding is widely used in: Livestock farming (e.g., cows, horses, poultry, pigs) and pet care (e.g., for rabbits, guinea pigs, and other small animals). Scalability potential: 1)small-scale - suitable for localized markets, particularly in rural areas or near forestry operations; 2) medium-scale - ideal for regions with moderate demand, supporting agricultural communities; and 3) large-scale - feasible with significant investment, high demand, and efficient logistics, targeting broader markets.	4	Proportion of OPEX: 15%–20%. Typical Range: $10–$20 per ton of bedding.	3	Small-Scale Facility (5,000–10,000 tons/year): $1–$3 million. Medium-Scale Facility (10,000–50,000 tons/year): $3–$7 million. Large-Scale Facility (50,000+ tons/year): $7–$15 million or more.	3	Small Facility (5,000–10,000 tons/year): $500,000–$1.5 million. Medium Facility (10,000–50,000 tons/year):$1.5 million–$4 million. Large facility (50,000+ tons/year): $3.5-$7 million or more	3
Pellets/Fuel Bricks	The scalability potential for converting woody biomass into fuel pellets and bricks is significant, driven by increasing demand for renewable energy, advancements in technology, and the abundant availability of biomass. Fuel pellets and bricks are produced using established technologies like drying, grinding, pelletizing, and compressing. Modular and large-scale systems are available, allowing scalability from local to industrial production.	4	Proportion of OPEX: 10%–20%. Typical Range: $10–$30 per ton of pellets.	3	Small-Scale Facility (10,000–50,000 tons/year): $3–$7 million. Medium-Scale Facility (50,000–100,000 tons/year): $7–$15 million. Large-Scale Facility (100,000+ tons/year): $15–$30+ million.	2	Small-Scale Facility (10,000–50,000 tons/year): $50–$100 per ton. Medium-Scale Facility (50,000–100,000 tons/year): $40–$80 per ton. Large-Scale Facility (100,000+ tons/year): $30–$60 per ton. Feedstock costs up to 60% of OPEX.	2

	Scalability	Score	Transportation of Feedstock	Score	Capital Expenditure	Score	Operational Expenditure	Score
Small Sawmill	The scalability potential of small sawmills depends on several factors, including market demand, available resources, and the operational strategies employed. Small sawmills can scale by expanding their reach within local or regional markets and targeting niche markets (e.g., custom wood products). Scalability depends on sustainable access to raw materials. Upgrading to more efficient sawmill machinery or implementing automated systems can increase production capacity without proportionately increasing labor costs.	4	Proportion of OPEX: 10%–20%. Typical Range: $10–$30 per ton of firewood	3	Small-Scale Facility (10,000–25,000 board feet/day): $1–$3 million. Medium-Scale Facility (25,000–50,000 board feet/day): $3–$7 million.	3	Small-Scale Facility (10,000–25,000 board feet/day): Annual OPEX: $700,000–$1.4 million. Medium-Scale Facility (25,000–50,000 board feet/day): Annual OPEX: $1.4 million–$3 million	3
Mass Timber	The potential scalability of using woody biomass wastes and logs for mass timber products is significant, given the increasing global demand for sustainable building materials and the push to reduce construction-related carbon footprints. However, Scaling production involves much larger investments in automated and large-scale machinery	4	Proportion of OPEX: 10%–20%. Typical Range: $15–$30 per ton of mass timber	2	Small Facility (10,000–30,000 m^3/year): $8–$15 million. Medium Facility (30,000–60,000 m^3/year): $15–$30 million.	2	Small Facility (10,000–30,000 m^3/year): $3.8–$9 million. Medium Facility (30,000–60,000 m^3/year): $10–$20 million. Woody biomass feedstock can be as high as 2/3 the total annual OPEX.	3
Post & Pole	The scaling potential of using woody biomass to produce wooden posts and poles is influenced by several factors, including the availability of biomass resources, market demand, processing technology, and sustainability considerations. Scaling is particularly viable in areas with abundant woody biomass and significant rural demand for agricultural fencing and construction materials.	5	Proportion of OPEX: 15%–25%. Typical Range: $10–$30 per ton of post and poles	0	Small Facility (up to 50,000 poles/year): $800,000–$1.5 million. Medium Facility (50,000–100,000 poles/year): $1.5–$3 million.	3	Small Facility (up to 50,000 poles/year): $500,000–$1.5 million. Medium Facility (50,000–100,000 poles/year): $1.5 million–$3 million.	2

	Scalability	Score	Transportation of Feedstock	Score	Capital Expenditure	Score	Operational Expenditure	Score
Air Curtain Burner	Current air curtain burners are basically modular in nature, which can dispose of 1 to 12+ tons per hour depending on size of unit. Additional units can be added to scale up waste biomass utilization. Operations are usually limited to daylight hours due to potential for fire escape	3	Air curtain burners brought to the site and transportation costs of woody biomass are not incurred. However, units must be brought to the source of wood incurring some transportation costs dependent on how often the unit is moved	3	Small Unit (up to 5 tons/hour):$80,000–$150,000. Medium Unit (5–15 tons/hour): $150,000–$300,000. Large Unit (15+ tons/hour): $300,000–$500,000.	5	The total OPEX can vary based on factors such as the specific ACB model, biomass characteristics, and operational scale. It is reported that the cost of disposing of forest residues using an air curtain burner that can burn up to 7 tons per hour ranges between $12 and $14.25 per green ton.	3

Table 3 - Scoring Matrix - Feedstock Specifications, Current Use in Region, Potential Co-Benefits Importance, Market Potential, Environmental & Permitting Issues

Pathway	Feedstock specifications	Score	Current use of technology in region	Score	Potential co-benefits importance[15]	Score	Market potential	Score	Environmental & permitting issues	Score
Biochar	Wood chips, generally 2 to 3 inch minus depending on specific pyrolysis reactor.	4	There is a medium size biochar production facility located in Berthoud (Biochar Now). Biochar has also been produced by the City of Boulder in a small scale.	4	The range of co-benefits include carbon sequestration and reduction, wildfire risk reduction, and improvements in forest and soil health. It also enhances air quality, mitigates pollution, and supports waste reduction. Economic benefits include job creation, market diversification, cost savings, and opportunities for value-added products and energy production. Additionally, it contributes to rural and community development, strengthens climate resilience, and promotes education and engagement.	5	Biochar markets have been undergoing growth as new applications are demonstrated. Biochar also has a ongoing revenue source from the voluntary Carbon Dioxide Removal credit market.	4	Small modular units are commonly used and can be designed or fitted with air emission control systems (primarily for particulate matter in CO). Air quality permits will be required along with land use entitlements. Local zoning laws may restrict industrial processes like pyrolysis in certain areas. The process may release odorous compounds, which can be a nuisance to nearby communities. There is associated truck traffic for incoming woody biomass feedstock and outgoing biochar product.	3
Bio-Oil	Wood chips, 1/2-inch to 3-inch minus depending on specific pyrolysis reactor. Bark no recommended	4	Charm Industrial is operating a woody biomass to bio-oil fast pyrolysis steam manufacturing facility in Fort Lupton and has been demonstrating their use in Front Range forests	3	The range of co-benefits include carbon sequestration and reduction, wildfire risk reduction, and improved forest and soil health. It also enhances air quality while creating job opportunities and fostering market diversification. The initiative supports energy security, promotes the development of value-added products, and contributes to energy production. Additionally, it plays a vital role in rural and community development, strengthening local	4	Although bio-oil can be potentially used to produce renewable biofuel primarily for aviation transportation, this is only slowing evolving. In Colorado, bio-oil production is used primarily to convert waste woody biomass into a carbon sequestration product that can be monetized by the voluntary carbon	3	Bio-oil is produced from woody biomass via pyrolysis like biochar so environmental and permitting issues could be similar.	3

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Pathway	Feedstock specifications	Score	Current use of technology in region	Score	Potential co-benefits importance[15]	Score	Market potential	Score	Environmental & permitting issues	Score
					economies and sustainability efforts.		dioxide removal credit market.			
Firewood/ Kiln	Whole logs and branches to produce final product of following dimensions: Length: Commonly 16 inches to fit standard fireplaces or stoves, but may vary by appliance. Diameter: Typically 3-6 inches for easy handling and effective burning	4	There are numerous firewood and fuelwood businesses in the Boulder Region (20+within 30 miles of Boulder). Firewood is well established woody biomass utilization pathway.	5	The range of co-benefits include carbon sequestration and reduction, wildfire risk reduction, and improved forest health. It enhances air quality while driving job creation and expanding market opportunities. The initiative strengthens energy security, supports the development of value-added products, and promotes cost savings. Additionally, it contributes to cultural preservation, ensuring sustainable practices that honor and maintain local heritage.	3	The firewood market in the Boulder Region has very robust potential, driven by the cold climate and a strong cultural affinity for wood-burning practices. The demand for firewood is substantial, particularly during the fall and winter seasons.	5	Producing firewood from woody biomass waste involves several environmental and permitting considerations to ensure sustainability and compliance with local, state, and national regulations. Firewood combustion releases particulate matter (PM), carbon monoxide (CO), and volatile organic compounds (VOCs), which can affect air quality. Non-residential Facilities that process and burn woody biomass may need permits for emissions under local, state, or federal air quality regulations. Ensure the site for processing biomass is zoned appropriately for industrial or agricultural use	3

Pathway	Feedstock specifications	Score	Current use of technology in region	Score	Potential co-benefits importance[15]	Score	Market potential	Score	Environmental & permitting issues	Score
Biomass Heat	Woody biomass chipped to 3"minus, 50% mc, 3% ash	4	Biomass heating systems in Boulder County are primarily the wood chip-fired heating systems at the Boulder County Open Space and Transportation Complex and the Boulder County Jail	4	The range of co-benefits include carbon sequestration and reduction, wildfire risk reduction, and improved forest health. It enhances air quality while mitigating pollution and promoting waste reduction and diversion. The initiative drives job creation, expands market opportunities, and strengthens energy security. Additionally, it supports cost savings, fosters rural and community development, and encourages education and engagement to promote sustainable practices.	4	Especially cost effective if replacing existing heating oil or propane heat.	4	Installing a wood chip heating system at commercial, institutional, or governmental facility will require building permits and zoning approval, ensuring the facility complies with local land-use regulations. Facilities must obtain permits for air emissions under local, state, or federal Clean Air Act (CAA) regulations. This can involve meeting specific thresholds for particulate matter, CO, and NOx emissions. And implement a robust system for monitoring emissions, fuel use, and environmental impacts, with regular reporting to regulatory authorities.	3
Compost/ Mulch	Tree trimmings (forest and urban green waste), wood chips	5	Composting and mulch operations are well established in the Region. A1 Organics has two large facilities in Eaton and Keenesburg, which reportedly can take considerable woody biomass if the cost is financially available.	5	The range of co-benefits include carbon sequestration and reduction, improved soil health, and enhanced air quality. It supports pollution mitigation, waste reduction, and diversion while driving job creation and the development of value-added products. The initiative also promotes cost savings, strengthens climate resilience, and fosters education and engagement in sustainable practices. Additionally, it contributes to food security and animal welfare, ensuring a more	4	The Boulder area presents a significant opportunity for producing compost from woody biomass, driven by local environmental initiatives and a strong demand for sustainable soil amendments	5	Composting facilities are subject to comprehensive environmental regulations and permitting requirements designed to protect public health and the environment. These regulations address various aspects of facility operation, including water quality, air quality, and overall environmental health. In Colorado, composting facilities are regulated by the Colorado	2

Pathway	Feedstock specifications	Score	Current use of technology in region	Score	Potential co-benefits importance[15]	Score	Market potential	Score	Environmental & permitting issues	Score
					resilient and sustainable future.				Department of Public Health and Environment (CDPHE) under the Solid Waste Regulations. These regulations classify composting facilities into three categories—Class I, Class II, and Class III. The CDPHE has revised composting regulations to address permitting challenges and promote organics diversion. These changes aim to streamline the permitting process and enhance environmental protections, reflecting Colorado's commitment to sustainable waste management practices In Boulder County, commercial composting facilities must obtain a Special Use Permit through the Community Planning & Permitting Department. These permits necessitate comprehensive site design, engineering reviews, operational assessments, traffic evaluations, and environmental impact studies, with mitigation measures required prior to permit issuance	

Pathway	Feedstock specifications	Score	Current use of technology in region	Score	Potential co-benefits importance[15]	Score	Market potential	Score	Environmental & permitting issues	Score
Fungal Decompositi on	Wood should be chipped to 1-inch minus increase surface area for fungal colonization. Moisture content ideal is 50%+ for optimal fungal activity, but not too high as to cause anaerobic conditions.	3	There is ongoing field research in the Boulder Region for augmented fungal decomposition of wood chips from forest thinning activities.	4	The range of co-benefits include carbon sequestration and reduction, improved soil health, and enhanced air quality. It supports pollution mitigation, waste reduction, and biodiversity conservation while fostering job creation and market diversification. The initiative drives the development of value-added products, promotes cost savings, and contributes to energy production. Additionally, it strengthens climate resilience and supports food security and animal welfare, ensuring a more sustainable and resilient future	3	In the Boulder area, the market for fungal degradation of woody biomass is emerging as an innovative approach to forest management and wildfire mitigation. Local organizations have been developing and demonstrating the use of native saprophytic fungi to manage excess wood biomass from forest health management and wildfire potential reduction activities. However, marketable products from onsite fungal degradation are lacking.	3	There's a risk of fungi spreading beyond targeted biomass, degrading standing trees or other non-targeted woody material. In the U.S., fungal use might be regulated under the Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA) or state-level environmental regulations. Forest management agencies (e.g., U.S. Forest Service) may require approval for activities impacting forest ecosystems. Permits may require ongoing monitoring of the fungi’s effects on the ecosystem and adherence to strict protocols.	4
Animal Bedding	Woody biomass feedstock should be dry (or dried) to absorb moisture effectively when used as bedding. The woody biomass must be processed to 0.5-inch minus for small animals and poultry, and 1-inch minus for larger animals (e.g. horses and livestock).	3	Animal bedding is produced by several wood products related facilities in the Boulder area.	4	The range of co-benefits include carbon sequestration and reduction, wildfire risk reduction, and improved forest and soil health. It supports pollution mitigation, waste reduction, and diversion while fostering job creation and market diversification. The initiative also promotes cost savings, encourages education and engagement in sustainable practices, and contributes to food security and animal welfare, ensuring long-term environmental and community benefits.	3	The Boulder region presents a promising yet developing market for The animal bedding products derived from woody biomass in Boulder area is a promising yet developing market. The area's active forest management and wildfire mitigation efforts could generate waste woody biomass, offering a potential resource for such	4	Animal bedding production facilities may emit particulate matter (PM), volatile organic compounds (VOCs), and other pollutants, especially if biomass is burned or dried on-site. Bedding processing facilities may need air quality permits to regulate emissions of PM, VOCs, and greenhouse gases. Used bedding may be regulated as part of manure management, with requirements for	4

Pathway	Feedstock specifications	Score	Current use of technology in region	Score	Potential co-benefits importance[15]	Score	Market potential	Score	Environmental & permitting issues	Score
							products. The agricultural sector in the region includes a diverse array of livestock, necessitating substantial use of animal bedding materials.		composting, spreading, or disposal to prevent nutrient pollution. Facility operations may require zoning permits, especially in residential or mixed-use area	
Pellets/Fuel Bricks	Pellets: Clean, dry (<10% mc) chip, needs to be <1% ash. Fuel Bricks: Chip, dry (<15% mc), needles, bark okay.	3	There are a few wood products businesses reportedly making some wood pellets. The large Confluence Energy pellet facility in Kremmling, CO is no longer operating	2	The range of co-benefits include carbon sequestration and reduction, wildfire risk reduction, and improved forest and soil health. It enhances air quality while supporting pollution mitigation, waste reduction, and diversion. The initiative drives job creation, fosters market diversification, and strengthens energy security. Additionally, it promotes cost savings and enhances climate resilience, contributing to a more sustainable and adaptive future.	4	With concern over air quality and reduction of particulate matter, pellet stove use is increasing with the growth potential for additional pellet production at the local and regional level. Wood pellets can also be used as animal bedding, and this is also becoming increasingly available in the Boulder area.	4	Dust generated during grinding, drying, and pelletizing can affect air quality and pose health risks to workers. VOCs are released during the drying of wood. Combustion of biomass for drying would further contribute to air quality impacts. Facilities will obtain permits under air quality regulations to control emissions of PM, VOCs, and CO_2. Facilities will need to comply with zoning regulations, especially if located near residential areas or environmentally sensitive zones.	4
Small Sawmill	Minimum small-end diameter: 6 inches for sawlogs. Larger diameters (e.g., over 12 inches or 30 cm) are ideal for maximizing lumber yield. Logs are typically cut to industry-standard lengths: 8, 10, 12, or 16 feet. Minimal taper (difference in diameter between the two ends of a log) is preferred.	3	There are several small sawmills and artisanal wood products facilities in the Boulder Region. There are no large industrial scale sawmills producing dimensional lumber or veneer	3	The range of co-benefits include carbon sequestration and reduction, wildfire risk reduction, and improved forest and soil health. It supports biodiversity conservation while driving job creation and expanding market opportunities. The initiative fosters the development of value-added products, promotes cost savings, and contributes to	4	The growing focus on forest management and the availability of woody biomass in Boulder County present opportunities for small sawmills. The region's emphasis on sustainable building practices and the presence of a vibrant construction industry	4	Sawmill operations can generate dust and particulate matter. Compliance with state and federal air quality standards is essential, which may involve installing dust control systems and obtaining air quality permits. Sawmills can produce significant noise, potentially impacting nearby	4

Pathway	Feedstock specifications	Score	Current use of technology in region	Score	Potential co-benefits importance[15]	Score	Market potential	Score	Environmental & permitting issues	Score
					energy production. Additionally, it plays a vital role in rural and community development and encourages education and engagement to support long-term sustainability.		create demand for locally sourced timber products. Small sawmills can cater to this market by providing custom-cut lumber, beams, and other wood materials. However, the sawmill industry in general can experience fluctuations, with factors like housing market trends influencing demand for wood products.		residents. The sawmill location must be zoned appropriately for industrial or commercial use and could require a special or conditional use permit.	
Mass Timber	Soft woods are best used as feedstock due to their strength to weight ratio and workability. Drying feedstock down to 10 to 15% moisture needed for optimal adhesive bonding and to prevent warping or shrinking after production	3	There are no mass timber production facilities in the Boulder Region. However, the Golden West Pine Mills is fabricated smaller mass timber panels at its facility in Ault, CO	2	The range of co-benefits include carbon sequestration and reduction, wildfire risk reduction, and improved forest and soil health. It supports biodiversity conservation while fostering job creation and expanding market opportunities. The initiative drives the development of value-added products and contributes to energy production. Additionally, it plays a crucial role in rural and community development and supports cultural preservation, ensuring sustainable practices that honor local heritage and traditions	4	There is a rising interest in mass timber construction within Colorado, including Boulder County. Developers and architects are increasingly recognizing the environmental benefits and aesthetic appeal of mass timber, leading to a surge in projects utilizing this material. The establishment of the Colorado Mass Timber Coalition underscores the state's commitment to advancing mass timber as a sustainable building material. The coalition aims to integrate mass	4	Processing wood into engineered products like CLT (Cross-Laminated Timber) involves significant energy use. The manufacturing process can release volatile organic compounds (VOCs), particulate matter, and formaldehyde from adhesives and resins used in production and air quality permits will be necessary. Facilities must comply with local zoning laws and land use regulations.	4

Pathway	Feedstock specifications	Score	Current use of technology in region	Score	Potential co-benefits importance[15]	Score	Market potential	Score	Environmental & permitting issues	Score
							timber into construction practices, promoting forest health and economic development.			
Post & Pole	Straight, low taper softwood	3	There are several businesses in the Boulder Region that produce and/or sell post & pole, mainly for fencing and landscaping.	3	The range of co-benefits include carbon sequestration and reduction, wildfire risk reduction, and improved forest health. It supports pollution mitigation, waste reduction, and biodiversity conservation while fostering job creation and expanding market opportunities. The initiative promotes the development of value-added products, strengthens rural and community development, and encourages education and engagement to enhance sustainability efforts.	3	The ongoing demand for housing and infrastructure development suggests potential market opportunities for poles and posts in the Boulder region. Suppliers focusing on sustainable and innovative products may find a receptive market in this area.	4	Emissions of volatile organic compounds (VOCs) and other pollutants can occur if the post and pole facility employs wood drying and chemical treatment (preservatives to inhibit decay). Permits may be required to regulate emissions from drying kilns, treatment processes, and dust production. Facilities must comply with local zoning laws and land use restrictions.	4
Air Curtain Burner	Tree trunks, branches, and limbs, large and small diameter. Wood chips are not recommended.	3	Within the Boulder Region, Larimer County has a small portable air curtain burner. Larimer County allows the use of air curtain burners under its open burning regulations. Air curtain burners are also allowed to operate at the Boulder County Forestry Processing and Sort Yards in Meeker Park and Nederland (Boulder County Resolution 2022-020).	3	The range of co-benefits include carbon sequestration and reduction, wildfire risk reduction, and improved forest and soil health. It enhances air quality while fostering job creation and promoting cost savings. Additionally, the initiative supports energy production, contributing to a more sustainable and resilient environmental and economic future.	3	Although air curtain burners offer a rapid and efficient method to dispose of forest slash and other vegetative debris, thereby reducing fuel loads and associated fire risks. They also can be rapidly deployed to forest use. Although they are primarily a disposal method with reduced emissions compared to open burning, they	4	Even in controlled combustion, air curtain burners release PM, CO, VOCs, and NOx. However, PM is significantly control by the air curtain burning process. Although some jurisdictions may regulate air curtain burners under their open burning rules (e.g. Larimer County) other jurisdictions may require an air quality permit. Although designed to contain fire, improper	4

Pathway	Feedstock specifications	Score	Current use of technology in region	Score	Potential co-benefits importance[15]	Score	Market potential	Score	Environmental & permitting issues	Score
							can produce biochar as a marketable commodity.		placement or high winds can lead to accidental fire spread in forested environments.	

Appendix 3.A. Forest Carbon Analysis Tool Modeling Process and Avoided Wildfire Emissions Evaluation Details

Step 1. Define project area and fire weather conditions. In this step we specified the project's geographic boundary (e.g., Boulder County) and treatment footprint. In addition, we established forest conditions at the start FCAT model run - including tree stands, species, height, diameter, and surface fuels. Weather conditions were also established for fire simulation during the project term.

For general landscape-level co-benefits assessment and avoided wildfire emission (AWE) accounting, we considered the best available vegetation datasets as well as weather data. For vegetation, we used 2016 TreeMap data from the US Forest Service Missoula Fire Lab (Riley et al., 2019). The TreeMap dataset has been approved by the California Air Resources Board for carbon modeling in support of applications related to their Greenhouse Gas Reduction Fund. The TreeMap dataset is a 30-m interpolated raster map, imputed from Forest Inventory and Analysis (FIA) plot data, that covers the entire contiguous United States and can be used to explore tree-level data as of 2016. We simulated wildfires and timber harvests that occurred between 2017 and 2022 with FVS to update the tree inventory to current conditions (in 2024).

TreeMap 2016: updating TreeMap with past wildfire layers

The information used to update the 2016 TreeMap inventory data is past wildfires. Spatial information about past wildfires is compiled but is saved as a raster rather than vector data. Fire perimeters come from MTBS (2013-2020; USDA, 2024) or NIFC (NIFC, 2022) and fire severity was calculated using a Google Earth Engine tool (Kearns et al., 2022). Every cell of the raster is assigned a code from which the time since wildfire (either one year or two-five years) and severity (unburned, low, medium, or high) can be extracted.

Currently, we include past wildfires covering the period 01 January 2017 - 31 October 2022 and wildfires covering 01 January 2017 - 30 June 2022. We consider anything before 01 January 2017 to be already represented by the latest TreeMap data. MTBS only reports on wildfires one year and older. This is driven by the fact that MTBS wildfire severity mapping relies on a one-year plus survival of trees which can only be recorded after the fact.

Set up FVS

Once the GIS past wildfire data have been formatted, we run a custom Python script that "flattens" the past wildfire and then extracts all unique combinations of TreeMap ID and wildfires. Flattening the overlapping vector features allows us to simulate repeated wildfire over the same area in different years.

Execute FVS

This list of unique combinations is then used by another Python script to build the FVS input database. Each unique combination is treated as an individually simulated forest stand in FVS. During the previous processing steps rasters are produced that spatially tie each stand to the landscape. Any given stand can occur in multiple locations across the landscape, so we produce a table that defines the total area represented by each stand. The 2016 TreeMap FIA-based tree inventory information is used as the basis for the FVS simulation. The previously developed past wildfire information is used during this process to assign appropriate FVS addfiles to any past burned stands. Each unique combination of wildfire severity and time since wildfire has its own addfile (e.g., moderate-severity wildfire one year ago). For example, a severe wildfire in 2017 would have the following FVS parameters within the automatic update of TreeMap data within FCAT:

- Year – 2017
- Wind speed (mi/hr) 20ft above the vegetation – 20
- Moisture – 1 (very dry)
- Temperature – 80
- Mortality – 100%
- Percentage of stand area burned – 100%
- Season of the burn – 3 (fall, after green-up)

Finally, we began an FVS simulation in 2016 and let it run until the year of interest. It simulates forest growth, fuel accretion, fuel decay, etc. along with the included past wildfires for each stand and then reports the results in various database tables which may be combined and queried later as needed.

Step 2. Management scenario development. This step includes defining fuel treatment details - including fuel reduction harvesting levels, procedures, location, timing, and fate of residuals.

In collaboration with stakeholders and a part of the biomass availability component of the project, we identified fuel treatment locations, types and schedules to be modeled. The kcps, or addfiles, used to model these treatments used in FVS are available below. These treatments are modeled in 2017, but in the modeling effort they were also implemented for years 2022 and 2027.

Lodgepole Pine Clearcut Treatment 2017

```
* remove all slash

YardLoss     2017          0      0      0

* Clearcut/Coppice:

ThinDBH      2017          0      999.0    1.0        LP     0      0

* Salvage for Boulder

FMIN

SalvSP       2017    All   0

Salvage      2017    0     999    999         0      0.9    0

END

Compute      0

SALV_VOL = SALVVOL(All,0,999)
```

```
END
```

OSMP Treatment 2017

```
* remove all slash
YardLoss    2017    0    0    0
* Thin from below
ThinBBA     2017  Parms(70,1,0,999,0,999)
* Salvage for Boulder
FMIN
SalvSP      2017    All    0
Salvage     2017    0    999    999    0    0.9    0
END
Compute     0
SALV_VOL = SALVVOL(All,0,999)
END
```

Ponderosa Pine Treatment 2017

```
* remove all slash
YardLoss    2017    0    0    0
* Thin from below
ThinBBA     2017  Parms(60,1,0,999,0,999)
* Salvage for Boulder
FMIN
SalvSP      2017    All    0
Salvage     2017    0    999    999    0    0.9    0
END
Compute     0
SALV_VOL = SALVVOL(All,0,999)
END
```

Step 3. Forest carbon and forest removals life cycle assessment. Forest growth and carbon fluxes were projected over the project term (40 years) at five-year intervals. Growth simulations used in the initial stand conditions are already established from TreeMap 2016 inputs (as described in Step 1), including individual tree characteristics (species, diameter at breast height (DBH), height, crown ratio, and tree class) and stand-level attributes (live and dead biomass, basal area, stand age, and canopy cover). Sequestration in wood products and avoided fossil fuel emissions from bioenergy were also assessed.

FVS Parameters: Site productivity was modeled using default site index values associated with species in the Central Rockies variant, based on FIA plot data. Forest growth and mortality dynamics were simulated using the default settings of the Central Rockies Forest Vegetation Simulator Fire and Fuels Extension (FVS-FFE; Rebain 2022) model without calibration or manual adjustments.

FVS-FFE calculates and tracks carbon in the following pools: total aboveground live (including merchantable and unmerchantable live stems, branches, and foliage), standing dead, understory (shrub and herbaceous layers), forest floor (litter and duff), down dead wood, and both live and dead belowground roots. FVS-FFE outputs include projected volume in live aboveground biomass and fire emissions. Additionally, FVS-FFE outputs were used to estimate non-CO_2 GHG emissions (e.g., N_20, CO, CH_4) through integration with the FOFEM model. Baseline FVS simulations assumed no project fuels treatment implementation in any stands. Regeneration was not modeled in this application. No natural or artificial regeneration events were included, and automatic regeneration was disabled.

Step 4. Wildfire modeling and emissions. Emissions from wildfire that burns the entire project area are determined in this step, at five-year intervals over the project term. Emissions are amortized by the statistical fire probability. We ran the GridFire[16] fire behavior model to determine a change in fire behavior due to fuel treatments to capture forest related and GHG-related benefits from a change in wildfire behavior in non-treated forested stands. For example, extreme wildfire weather conditions (97th percentile) were used to model wildfire behavior in GridFire as follows:

- Temperature – 94 F
- Relative Humidity – 13%
- Wind Speed – 18 mph
- Wind Direction – 270 degrees clockwise from north
- Model run time – 8 hours

Step 5. Aggregated emissions accounting. Determine the difference between the baseline (no treatment) and project scenario GHG emissions, for each five-year interval period over the project term.

In a last related step, we considered GHG flux consequences if high-severity wildfire occurrence decreases due to fuel treatments and a reduced acreage of stands would experience prolonged time scales of delayed regeneration (temporary or permanent vegetation type change from forests to grass or shrub dominated landscape) and therefore exhibit a forgone carbon sequestration potential. Wildfire-related emissions were discounted by the area's expected statistical fire probability over the project term. The final result are net climate impacts when implementing fuel treatments measured in metric tons of CO2e for the entire forested fireshed. Figure A1 shows the links between the FCAT run and the multiple products (microservices) produced along the process to contribute to specific outputs.

[16] https://github.com/pyregence/gridfire/

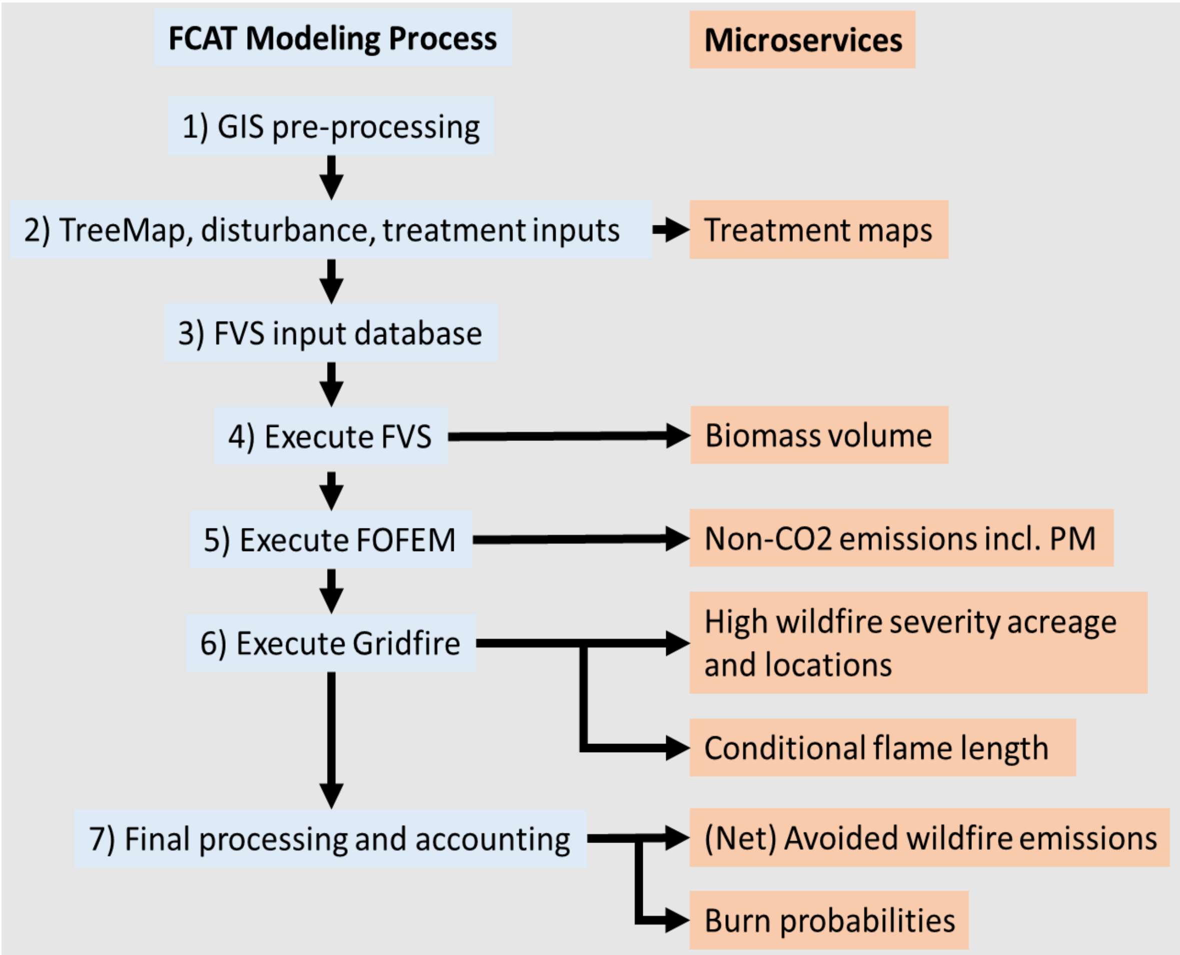

Figure A1: FCAT modeling steps and microservices provided at specific steps for producing specific outputs.

The FCAT modeling process consists of a series of semi-automated microservices:

1) GIS pre-processing to prepare the area of interest (AOI), baseline (e.g., let grow) and project conditions (e.g., implementing fuel treatments), as well as disturbances (e.g., burn scars). The only project-specific data input required in this context are treatment locations and prescriptions while all other inputs (e.g., vegetation and climate data, burn probabilities) are lookup based or derived from datasets in the public domain.
2) Identify every unique combination from TreeMap ID (a CONUS wide 30m resolution tree-level inventory database), past disturbance, and future treatment rasters.
3) Build an USFS Forest Vegetation Simulator (FVS) input database:
   a) Each unique combination is simulated as an individual forest stand,
   b) Instructions are embedded for simulating wildfires
4) Execute FVS:
   a) R script are used to automate building and executing FVS keyfiles for various FVS simulations in 5-year time steps over a 40-year time horizon,
   b) FVS post-processing,
   c) Compute the acreage represented by each FVS stand.
5) US Forest Service First Order Fire Effects Model (FOFEM):
   a) Automate data formatting and execution of FOFEM.

6) Run Pyregence's GridFire Wildfire Behavior Simulations:
   a) Automated data setup and execution of GridFire,
   b) Calculate conditional burn probability (CBP) ratio for each stand.

Final processing to produce carbon tables including GHG impacts, carbon stock trajectories, biomass removed, etc.

Metrics Evaluated

Reduced Emission from Wildfire/Avoided Wildfire Emission Specific Metrics and Input Parameters

Forecasted Mitigation Units (FMUs)

In the REM/AWE methodology, Forecasted Mitigation Units (FMUs) estimate net GHG reductions from a mitigation project, representing one metric ton of CO_2e expected to be reduced or sequestered. A positive value indicates emissions avoided or carbon sequestered, while a negative value indicates GHG emissions due to treatment. FMUs are calculated over time starting from the treatment's inception. Initially, they may be negative (climate liability) as carbon stocks decrease due to removals, and carbon accumulates slowly without wildfires because of reduced growing stock. Over time, FMUs can turn positive (climate benefit) as reduced wildfire severity leads to fewer emissions and lower risks for delayed reforestation, offsetting the initial 'carbon debt' (Pena & Bird, 2010).

Delayed reforestation

Delayed reforestation refers to the temporary or permanent loss of forest cover due to a high severity fire. Delayed reforestation is incorporated into the model by assuming that tree species that experience a high severity fire that 50% of the area will not experience the same forest type for 20 years (e.g., Buchholz et al., 2019).

Annual burn probability (ABP)

Based on the methodological steps outlined above, wildfire GHG emissions can be reported for wildfire events for each 5-year period over the timeline we looked at. An additional step towards more realistic projections of AWE can be the addition of a 'discount factor' to expected wildfire related GHG emissions due to fire risk. This discount factor can be expressed as the annual fire ignition probability or the Mean Fire Return Interval (MFRI) that describes the average time measured in years that pass between wildfires for a given area[17].

While empirical datasets on pre-European settlement MFRI abound, there is a significant departure of historically observed MFRI's over the last decades based on multiple factors such as climate change, fuel composition, recent fire suppression history and human population density (Mann et al., 2016). MFRIs are a crucial input metric to estimate avoided emissions from wildfires for a given study area. However, such spatial data are not available in a consistent format and methodology for regions as large as the western USA (e.g. Mann et al., 2016) and/or use very conservative assumptions (e.g., Kearns et al., 2022). To create applicable annual burn probability (ABP) input metrics, it is crucial to apply consistent methodology, at an appropriate resolution which considers

[17] MFRI can also be expressed as the inverse of the mean annual fire probability, i.e., MFRI= 1/mean annual fire probability.

latest fire history to provide maps that reflect modern or contemporary fire regimes in contrast to historic/pre-European settlement MFRIs.

For this project, FMUs were calculated with an ABP value found using Kearns et al., (2022) for the entire Boulder County which is equal to 0.46%. ABP acts as a discount factor in the amount of emissions avoided due to the fuel treatments and can exponentially affect these results. Since the ABP of 0.46% appears to potentially underestimate the risk of fire in Boulder County, due to more localized and high-resolution data (per Kearns et al., 2022), ABP were tested incrementally to identify a breakeven point in FMUs. Using ABP of ~3%, which resulted in the creation of FMUs, was considered a reasonable estimation of fire occurrence in the area based on trends in climate change. We consider this a very conservative estimate since it does not include a further increase in the annual fire probability over the next 40 years. There is increasing evidence that annually burnt acreage is currently increasing at an annual rate of over 4% in the western US (Westerling, 2016).

Carbon Stock Change

Carbon stock across different carbon pools was measured through FVS using the CARBCALC keyword. Carbon is represented by total stand carbon in metric tons across the treatment footprint.

Stand Metrics

Stand metrics such as canopy cover (CC), trees per acre (TPA), basal area (BA), stand density index (SDI, as calculated in), quadratic mean diameter (QMD), total cubic feet of wood (TCuFT), and merchantable cubic feet of wood (MCuFt) are represented as calculated by FVS-FEE within the FCAT tool.

Fire Behavior Metrics

FVS estimated fire behavior under high severity weather and fuel moisture conditions including surface flame length (in feet) (surf flame severity), probability of torching (PTorch Sev), percent of basal area mortality (Mortality BA Sev), potential smoke emissions (tons/acre) (Pot Smoke Sev), canopy base height (in feet) (CBH), canopy bulk density (in lbs/ft^3) (CBD), percent canopy cover (CC), and canopy height (in feet) (CHT).

GHG emissions

GHG emissions were modeled using FOFEM. Emissions were calculated for, Particulate Matter 2.5um ($PM_{2.5}$), Methane (CH_4), Carbon Dioxide (C_2O), and Nitrous Oxide (NO_X) are all represented in metric tons. Emissions are shown for each treatment within the project and then in total over the combined project area.