

The Marin Biomass Study:

Pathways to Improved Utilization and
a Regenerative Biomass Economy



March 2026

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Executive Summary

Marin County faces a growing challenge. Its steps to improve wildfire safety are contributing flows of biomass into Marin's economy without ways to make productive use of them. Vegetation management around residences, schools, civic spaces, and places of commerce is increasing flows of biomass like foliage, branches, and trunks of smaller-diameter trees. Vegetation management on Marin's forested lands is likewise increasing flows of woody biomass. Currently, this biomass is largely being directed into waste management supply chains. Along with biomass from Marin's cities and towns, a majority of this biomass is being sent to landfills for disposal or transported over one hundred miles to power plants in the Central Valley. These options are expensive, offer little meaningful local benefit, increase Marin's environmental footprint, and fail to contribute to its long-term resilience.

There is an alternative. Marin has the opportunity to develop an economy for its biomass that helps achieve both wildfire safety and State and local goals to divert organic materials from landfill. This economy is focused on creating local, value-added products that make wildfire safety and landfill diversion more cost-effective over time. It prioritizes options that reduce the greenhouse gases driving climate change and our wildfire crisis and that support regeneration of the ecological resources that make Marin special.

The Marin Biomass Study offers a roadmap for this new biomass economy. Its findings and recommendations are based on a detailed assessment of Marin's biomass flows and a detailed evaluation of utilization "pathways" that can put them to productive use. The *Study* identifies the set of pathways that best supports Marin's needs and goals, and it offers detailed greenhouse gas and economic analyses that demonstrate their individual viability and synergistic potential.

Key Findings

- **Marin's Current System Is Inefficient and Insufficient.** More than half of Marin's discarded biomass is being landfilled or exported — an inefficient and insufficient outcome based on this Study's criteria. This does not position Marin well for growth, given that Marin is expected to generate 30% more green materials in the next decade. Its composting system, while robust, is not prepared to absorb them. In addition, only a small fraction of Marin's usable biomass is being directed into pathways that generate local, renewable electricity.
- **Alternative Pathways Can Boost Marin's Biomass Economy.** Marin could put its biomass to significantly better use, as well as reap meaningful economic and environmental benefits,

with better planning, better coordination, and targeted investments in the following pathways:

- **Bioenergy and Green Electricity.** Local gasification of woody debris and non-reusable construction materials can create a local supply of renewable electricity, even when the sun is down and the wind is not blowing. Alternatively, the syngas produced by gasification might be upgraded to create renewable fuels like biomethane, green hydrogen, or other biofuels — as markets for such products strengthen.
- **Soil Amendments.** Expanded composting will provide Marin with a sustainable management option for its flow of green materials, as well as provide significant opportunities to reduce its greenhouse gas footprint. Likewise, producing biochar from woody biomass from wildfire prevention with digestate (aka “biosolids”) from wastewater treatment plants can be done in a joint pyrolysis unit, and the biochar can be used to enhance soil health, sequester carbon, and support local agriculture.
- **Local Wood Products.** Small-scale milling can convert logs and branches into dimensional lumber, posts, poles, and artisanal wood products. This could create local jobs while reducing greenhouse gas emissions.
- **Coordination Can Create Meaningful Synergies.** Building a better biomass economy requires both physical infrastructure and coordinated institutional support. Representatives from wildfire agencies, wastewater districts, energy providers, and waste haulers, as well as planners, agricultural agencies, and municipal staff have jointly reviewed and discussed this Study throughout its development. These conversations are showing real opportunities for increased collaboration and system efficiency. By working together to improve the biomass economy, these groups can also advance Marin’s transition to a green energy economy and development of green job opportunities.
- **Better Pathways Can Reduce Greenhouse Gas and Environmental Impacts.** In addition to economic support for wildfire safety and resource regeneration, redirecting organic materials from landfills and from far-away power plants into local energy and resource pathways offers substantial GHG reductions. For example, expanded composting and local gasification each have the potential to reduce at least 11,000 metric tons of carbon dioxide equivalent (MTCO_{2e}) emissions per year. Local milling of logs and local biochar production can reduce several thousand more metric tons of greenhouse gases per year. Implementing all the biomass pathways proposed in this Study could reduce Marin’s countywide GHG emissions for the waste sector by almost three-quarters. This amount is equal to about three percent of Marin’s overall greenhouse gas emissions, and its reduction represents a tangible and achievable step toward the countywide goal of net zero emissions.

Key Recommendations

- **Develop Renewable Energy Projects.** Gasification and co-digestion projects have the potential to provide significant local, renewable electricity that increases power reliability on the electrical grid. These projects should be encouraged, and public investment should be provided. Funding of \$16M will spur development by reducing startup operational risks. It will also drive long-term GHG reductions and increase Marin's energy resilience.
- **Expand Composting Capacity.** Green materials are predicted to grow in the next decade and require additional composting capacity. Efforts now to expand local composting will help ensure infrastructure needed for SB 1383 compliance, as well as deliver significant GHG reductions, soil carbon sequestration, and agricultural resilience benefits. For these reasons, supportive funding on the order of \$7.5M should be invested to expand local infrastructure.
- **Develop Biochar Production:** Biochar production offers a missing economic pathway for both woody biomass from wildfire safety programs and for digestate (biosolids) from wastewater treatment plants. As a product, biochar can be used for a variety of industrial and agricultural purposes that reduce Marin's carbon footprint. The public entities considering this project need supportive funding on the order of \$5M to reduce risk and secure the capital needed to move this project forward.
- **Reinvest in Local Uses for Wood:** Small-scale milling is a better alternative for larger-diameter logs. Milling can turn them into lumber and artisanal slabs for local use. In addition to reducing transportation-related greenhouse gases, milling preserves carbon already sequestered in wood. Redevelopment of this pathway can be done with a modest supportive investment of \$0.5M.
- **Identify and Address Regulatory Barriers.** The development of better biomass pathways can run into a variety of non-financial, regulatory barriers. The County, cities and towns, and agencies in the county should consider and advocate for changes in zoning, permitting, procurement, and rates, with the goal of working together to bring about improved pathways for their discarded biomass.
- **Support Institutional Integration:** The Marin Biomass Project has undertaken analyses and provided a forum for providing insights and sharing understanding about Marin's biomass system. Ongoing engagement among stakeholders is needed to explore how business objectives, operating procedures, contracts, and capital plans can be synergized and lift ideas off the page. This ongoing institutional coordination and systems integration should be

encouraged. It is needed to achieve the multiple benefits of a more regenerative biomass economy.

The chapters in this Study offer analyses that build toward these recommendations and the unifying vision of a regenerative economy. Chapter 1 consolidates data about discarded biomass from across Marin to estimate the magnitude of these flows, to offer a composite picture of Marin's current biomass management system, and to identify what may be underutilized. Chapter 2 assesses a range of processing technologies and output products (i.e., what are called "pathways" in this Study) and identifies a set with the potential to put underutilized biomass to higher and better use. Chapter 3 offers a detailed comparison of Marin's current system and the alternative set identified in Chapter 3 to estimate the difference in greenhouse gas emissions and carbon sequestration potential between the two. Chapter 4 dives into the economics of the alternative set of pathways to identify their financial viability and supportive funding that could aid their development. These analyses roll up into a summary at the start of Chapter 5 before thirteen recommendations are offered for building a better biomass system in Marin.

Conclusion and Call to Action

Meeting the challenges of this century requires ingenuity, courage, and grit. Most of all, it requires a system that brings out the best in all of us. *The Marin Biomass Study* offers a framework for a biomass economy that brings parties together in an effort that manages surplus and discarded biomass not as waste but as a resource used to create value-added products. This shift in approach is meant to grow a biomass economy that, in the long run, offers affordable, sustainable ways to support wildfire safety, to reduce greenhouse gas emissions, and to increase Marin's energy resilience. The pathways analysis in this report lays out the building blocks of this regenerative biomass economy. This includes supportive funding — likely in the form of modest, near-term public investments — along with institutional collaboration and governance.

These pathways have the potential to position Marin as a model for other wildfire-prone, urban and suburban counties in California — demonstrating not just Marin's capacity to develop a more environmentally-conscious economy, but also how cross-sector collaboration and strategic infrastructure investments can scale solutions. Such leadership is needed to meet state wildfire safety and greenhouse gas reduction goals. Marin received funding for this work because of its potential to lead on climate, and it is the goal of the Study to deliver on this promise, both in Marin and beyond.

Preface

The Marin Biomass Project is motivated by two climate-related realities: the increasing risk of catastrophic wildfire, and a recognition that processing and landfilling biomass can emit large amounts of greenhouse gas, including methane — a particularly potent driver of climate change. The Project grew out of early discussions at MarinCAN, which later selected the Project as one of nine key Climate Solutions needed to reach zero net greenhouse gas emissions in Marin.

Work began in earnest when the Governor’s Office of Land Use and Climate Investments selected the Project for funding. As one of five pilots, the Project was funded to overcome barriers to biomass feedstock utilization and, in so doing, facilitate wildfire safety initiatives. Marin Resource Conservation District (MRCD) took on management of the grant and appointed a Steering Committee to guide development of a biomass utilization study.

The Study addresses increasing flows of organic materials generated by wildfire prevention activities and by landfill diversion efforts in the County required by Senate Bill 1383 (2016), California’s Short-Lived Climate Pollutants: Organic Waste Reduction Law. These biomass flows include woody materials resulting from woodland vegetation management, source separated green materials, and mixed organic streams arising from the collection of metropolitan landscape trimmings, wood debris, food scraps, yard materials, manures, and digestate from wastewater treatment.

The Study estimates the magnitudes of Marin’s biomass flows and traces them into Marin’s current utilization pathways. Then, based on the biomass flows expected in the next ten years, the Study identifies a system of biomass utilization pathways that offer improved economic prospects and greater capacity to reduce greenhouse gas emissions. Using a deeper comparative analysis, it estimates the potential greenhouse gas reductions of the alternative set of pathways. It also analyzes the economic viability of each alternative pathway and the investment support that will spur and speed their development.

The first chapter in the Study estimates Marin’s biomass flows and identifies its current utilization pathways. The second chapter surveys twenty-nine potential pathways to identify a set that offers the best potential economic and environmental opportunities for Marin. The third and fourth chapters scrutinize these pathways, respectively, to quantify their greenhouse gas savings and to establish their economic growth prospects.

The fifth and final chapter summarizes key findings from these detailed investigations. It also offers recommendations to facilitate the development of a better biomass system for Marin. Primary among them are these seven:

- Expand composting capacity for the expected growth in green material from wildfire safety programs, and support land application of compost to help Marin achieve its climate goals.
- Scale up co-digestion of food scraps at wastewater treatment plants to divert organics from landfill and increase generation of local renewable electricity.
- Develop a co-pyrolysis pathway that can convert digestate from wastewater treatment plants and recoverable biomass from wildfire safety programs to create a carbon-rich biochar to sequester carbon and improve soil health.
- Develop a gasification pathway to produce local, renewable electricity from woody biomass (including construction and demolition materials) and replace long-distance transport to combustion power plants in the Central Valley.
- Restart small-scale milling to turn large-diameter logs into durable wood products, rather than grinding them into chips and exporting them from Marin for combustion.
- Prioritize deconstruction of buildings and reuse of construction materials to retain their embodied energy and carbon, as well as to decrease lifecycle GHG emissions.
- Incentivize development of infrastructure to improve sorting, separation, and recovery of demolition materials, both to reduce waste and conserve resources (including landfill space).

Development and implementation of these recommendations depends on increased cooperation among existing institutions. Among others, these include public agencies like Marin Wildfire Prevention Authority, Zero Waste Marin, MCE, and their member jurisdictions; Marin Resource Conservation District and sanitation districts; and biomass haulers and processors like Marin Sanitary Services, Waste Management, and West Marin Compost. During the Study, a Marin Biomass Collaborative was formed to bring together these stakeholders and invite them to share observations about the Study framework, provide feedback on data and potential findings, and build recommendations that can spur cooperation and investment.

Through this partnership, the Project aims to accelerate development of a better system — one that sees the value in biomass otherwise treated as waste and that reduces greenhouse gas emissions, sequesters carbon in the landscape, and creates new, more sustainable economic opportunities.

Study Overview

The chapters in this Study offer analyses that build toward these recommendations. Chapter 1 consolidates data about discarded biomass from across Marin to estimate the magnitude of these flows, to offer a composite picture of Marin’s current biomass management system, and to identify what may be underutilized. Chapter 2 assesses a range of processing technologies and output

products (i.e., what are called “pathways” in this Study) and identifies a set with the potential to put underutilized biomass to higher and better use. Chapter 3 offers a detailed comparison of Marin’s current system and the alternative set identified in Chapter 3 to estimate the difference in greenhouse gas emissions and carbon sequestration potential between the two. Chapter 4 dives into the economics of the alternative set of pathways to identify their financial viability and supportive funding that could aid their development. These analyses roll up into a summary at the start of Chapter 5 before thirteen recommendations are offered for building a better biomass system in Marin.

This project has been approached as a collaborative effort from the outset, given the intersection of public and private and of individual and collective engagement with biomass. Accordingly, we hope that you will join us in reading this report, discussing its findings, and taking steps down the path towards a circular and regenerative biomass economy in Marin and beyond.

Chapter 1:

Marin's Current Biomass Pathways

The Marin Biomass Study is a comprehensive exploration of the biomass produced in Marin as part of its wildfire safety programs, as byproducts of agricultural activities, or as outflows from metropolitan life. The study asks a progressive series of questions about Marin's biomass system and these flows of "surplus" or "discarded" biomass:

- How much biomass is Marin expected to generate within the next decade? Where is it coming from, and where is it going?
- Which types of biomass conversion technologies best match Marin's biomass flows? Which processes and products look most likely to produce positive economic and environmental outcomes?
- How would an alternative set of pathways change the greenhouse gas footprint and sequestration of carbon for Marin's biomass management system, and thereby help reach the goals of Marin's climate action plans? How can it help Marin's jurisdictions support the goals and comply with the requirements of Senate Bill 1383 (i.e., California's Short-lived Climate Pollutant Reduction Strategy)?
- How capable is an alternative set of pathways to produce positive net revenues and overall better economic outcomes for Marin? And how much supportive funding is needed to catalyze development of this alternative system?

The chapters of this Study are organized to explore and answer these questions. This first chapter focuses on the first set of questions. It develops estimates for biomass flows generated in Marin County from the following activities and environments:

- Wildfire reduction-related vegetation management in forests and woodlands that aims to decrease the spread and severity of forest and woodland fires,
- Wildfire reduction-related vegetation management that aims to make Marin’s built environments more fire safe and decrease the potential for property damage and loss of life,
- Material collection programs like recycling and waste management that haul discarded organic materials from residences and commercial establishments, and
- Agricultural operations that generate biomass needing offsite processing.

The purpose of this assessment is to create a basis for analyzing how utilization of these kinds of biomass can sustainably support Marin’s wildfire management goals, contribute to countywide greenhouse gas reduction goals, and provide economic benefits. It asks, what kinds and how much biomass does Marin generate, and what is the fate of these materials?

The chapter assesses the types of biomass being handled and processed in Marin to estimate the quantities and character of biomass flows, both current and those expected in the future. The purpose of this survey of fuel reduction strategies, biomass handling practices, and utilization systems is to create a window into the factors and decisions shaping biomass generation, disposition, and utilization.

The chapter concludes with a summary of Marin’s current biomass generation and utilization system, with the goal of supporting an exploration of its potential improvement in the next chapter.

Assessment Approach

This assessment looks at the entire landscape across Marin County to estimate the amount of biomass flows being generated. Its scope is limited to biomass being cut, discarded, and hauled away in Marin. That means that flows passing through Marin or imported into the County are beyond the scope and, therefore, not included within the resource accounting estimate.

Marin County is located just north of the Golden Gate Bridge on the northwest side of the San Francisco Bay. Marin is one of the smaller Bay Area counties, both in geographic size and population. Located within the coast range, the county is known for its unique natural beauty with scenic areas including Muir Woods, Marin Headlands, Stinson Beach, Point Reyes National Seashore, and Mount Tamalpais. With a large rural area in West Marin, the

county is notable for its well-developed organic farming sector. Located primarily in West Marin, farms and ranches produce a range of products for local and regional markets.

This assessment draws on reports and interviews with key land owners and landscape managers to estimate flows that their forest and woodland fuel reduction strategies will generate over the next ten years and into the future. It draws on reports, interviews, and correspondence with staff from public agencies and private companies that plan, cut, haul, and process biomass. Data from these sources, as well as historical land management, are used to confirm fuel treatment scope and flows of materials through materials recovery, recycling, and waste management systems. These data are also used to distinguish where biomass is practically recoverable and where steep slopes or narrow roads make biomass from fuel treatment too difficult or expensive to remove.



This assessment takes account of California’s policies that encourage recycling. Starting with Assembly Bill 939 (1989), these policies have tried to stimulate the development of recycling systems to divert materials from landfill and recover resources. A summary of policies that discourage treatment of organic material as waste and encourage its diversion from landfills are summarized in Table 1-1. These policies indicate that many types of biomass, including those generated by wildfire safety work, need recycling outlets that, ideally, lead to value-added products as well as other social and environmental benefits.

Parallel to Table 1-1, Table 1-2 summarizes key wildfire policies and the accreting regulatory framework in California’s Public Resource Code that forms the basis for fire hazard mitigation-based vegetation management work in the State. This summary includes local Measure C (2020), which drives wildfire safety-based vegetation management in Marin. These policies, which authorize and require responsible parties to identify, plan, and implement fuel treatments and biomass management activities, generate biomass flows.

Table 1-1. Overview of California Recycling Policies

<p>Assembly Bill 939</p>	<p>Signed into law in 1989, this legislation created the California Integrated Waste Management Board (now CalRecycle). A disposal reporting system was created with CIWMB having oversight. AB 939 mandates a reduction of recyclable materials destined for landfills to meet diversion goals of 25% by 1995 and 50% by 2000.</p>
<p>Assembly Bill 1594</p>	<p>Signed into law in 2014 and effective by 2020, AB 1594 eliminates the landfill diversion credit for organics used as daily cover. Federal law requires landfills to be covered at the end of each workday to prevent odors, vermin, and insects, and landfills have historically utilized soil as daily cover. As part of their recycling policies, many states, including California, have allowed use of alternative materials as daily cover. After passage of AB 1594, organic materials like woody biomass and digestate may still be applied as daily cover at the open face of a landfill, but this usage no longer counts as recycling. Instead, it counts as disposal.</p>
<p>Assembly Bill 1826</p>	<p>Signed into law in 2014 and effective in 2016, this legislation requires commercial businesses to recycle their organic materials. In addition, this law requires local jurisdictions to implement local organic recycling programs to divert organic materials from landfills.</p>
<p>Assembly Bill 876</p>	<p>Signed into law in 2015 as a complement to AB 1826, AB 876 requires counties and regional agencies to forecast the amount of organic material that will be generated over a 15-year period and report this estimate annually to CalRecycle. In addition, reporting must include estimates of the additional organic material processing capacity needed to address the 15-year forecast, including potential locations for organics processing facilities.</p>
<p>Senate Bill 1383</p>	<p>Signed into law in 2016, this legislation seeks to mitigate short-lived climate pollutants (e.g., methane) by diverting organic materials (including wood) from landfills. Using a 2014 baseline, SB 1383 sets targets to achieve a 50% reduction of organic material disposal and a 75% reduction by 2025. It obliges cities and counties to set up organics recycling programs and to report progress on organics diversion.</p>
<p>Assembly Bill 901</p>	<p>Passed in 2015, AB 901 requires facilities, exporters, brokers, and transporters of recyclables or compostables to report types, quantities, and destinations of materials that are disposed of, sold, or transferred inside or outside of the state. These new requirements require data reporting to CalRecycle (rather than to counties) and are meant to create detailed information about material flows that can be used to calculate overall diversion rates from the jurisdictions with obligations under SB 1383.</p>
<p>Assembly Bill 2346</p>	<p>Passed in 2024, AB 2346 expands the kinds of recycled organic products, investments, and activities that California local jurisdictions may count toward their procurement targets under the state’s organics recycling regulations. Consequentially for Marin, it takes account of progress made so far to decrease the amount of compost procurement required each year.</p>

Table 1-2. Overview of Wildfire Safety Initiatives

Public Resource Code 4292, 4293	Adopted in 1965, PRC 4292 and 4293 require electric utilities to maintain specific vegetation clearances around power poles and lines along roadways in fire-prone areas, mandates a 10-foot firebreak around poles with equipment, enforces clearance distances for high-voltage lines.
Public Resource Code 4906	Adopted in 1965 and updated in 2021, PRC 4906 directs CalFIRE to establish and implement fire-resistant vegetation standards for areas within "High" and "Moderate" Fire Hazard Severity Zones and grants fire officials authority to require clearance of non-fire resistant vegetation with ten feet of highways, streets, and private roads.
Public Resource Code 51179	Passed in 1992 and periodically updated, PRC 51179 requires cities and counties to designate Very High Fire Hazard Severity Zones (VHFHSZ) based on State recommendations and may increase (but not reduce) the hazard classification. Once designated, properties in these zones are subject to wildfire safety requirements such as defensible space maintenance and other local fire-prevention regulations.
Public Resource Code 51182	Passed in 1992 and subsequently updated, PRC 51182 requires owners of structures in locally designated VHFHSZ areas to maintain vegetation and fuel conditions around buildings to reduce wildfire risk. Local governments typically enforce the requirements through inspections and vegetation management programs.
Public Resource Code 4201-4204	Adopted in 2007, PRC 4201-4204 maps wildfire hazard areas across State Responsibility Areas (SRA) and recommends maps for Local Responsibility Areas (LRA) to guide planning and regulation. These maps determine where wildfire-specific building codes, defensible-space requirements, and disclosure rules apply.
Public Utilities Code 8386	Adopted in 2019, PUC 8386 requires electrical utilities to prepare and implement Wildfire Mitigation Plans to reduce ignition risk from power infrastructure. Plans include vegetation management, grid hardening, inspections, and operational practices such as temporarily de-energizing lines during extreme fire weather.
Gov Code 51182.4	Adopted in 2020, GC 51182.4 directs regulators to develop rules for a 0-5 foot ember-resistant zone around buildings, reflecting evidence that most home ignitions occur from wind-blown embers near the structure. These rules will focus on specifying removal of combustible materials immediately adjacent to buildings and promoting non-flammable landscaping and surfaces.
Assembly Bill 38	Passed in 2019, AB 38 requires sellers of homes in designated wildfire hazard areas to provide buyers with disclosures about wildfire risk and property mitigation measures. The goal is to inform buyers and encourage home-hardening and defensible-space improvements before and after property transfers.
Marin Measure C	Passed by voters in 2020, Marin County Measure C establishes a 10-year parcel tax, creates the Marin Wildfire Prevention Authority (MWPA) to coordinate countywide wildfire prevention, and funds vegetation management, defensible-space inspections, evacuation planning, wildfire detection, and public education across most of Marin.

The observations and assessments in this chapter offer a starting point for analyzing the current and alternative disposition options for the following types of biomass:

- **Woody Materials** generated from wildfire mitigation activities (i.e., forest fuel treatment or defensible space clearing in the built environment), from roadway and power line maintenance, from building construction and demolition, and from landscape maintenance. Examples include logs, wood chips, and construction and demolition materials designated organic materials under California's biomass recycling law (Senate Bill 1383, 2016).
- **Green Materials** generated from landscape management, parkland maintenance, and commercial and residential materials collection. Examples include leaves, grasses, twigs, and other landscape trimmings that are designated organic materials in SB 1383. It may also include food residues when referring to materials from the curbside green carts used in municipal material collection programs.
- **Food Scraps** generated by commercial establishments, such as grocery stores and restaurants, that must be collected and diverted from landfill per AB 1826 (2014).
- **Agricultural Residues** from Marin's ranching, farming, and vineyard operations. Examples include any crop residues and manures that require off-farm management.
- **Digestate** from wastewater treatment operations, as included in material targeted for recycling under SB 1383.

The next section of this chapter estimates annual biomass flows that Marin is expected to generate in the next decade. The third section explores the current disposition of these materials. The fourth section synthesizes this information and provides a composite picture of Marin's current biomass system and baseline conditions, as the basis for evaluating alternatives in the next chapter.

Biomass Flow Estimates

This section surveys quantities and types of biomass based on the landscapes and activities that generate them. It begins with a review of land cover and ownership in Marin. These factors are foundational to the biomass assessment in this chapter. Land cover provides a basis for predicting the types of biomass that a landscape generates. Ownership provides a basis for analyzing land management practices and estimating the flow of material.

Based on vegetation type, Marin’s lands can be distinguished using the eight landcover categories defined in Table 1-3, as illustrated in Figures 1-1 and 1-2.¹

Table 1-3. Vegetation Types Used to Estimate Biomass Flows

Forest	Land with an even distribution of overstory conifer trees. In Marin, these are primarily coast redwood, Douglas fir, and bishop pine.
Woodland	Land with an even distribution of overstory broadleaf trees. In Marin, these are primarily California bay, tanoak, live oak, and sycamore.
Herbaceous	Land with vegetation that is non-woody, including grasses, graminoids, and broad-leaved herbaceous species.
Shrub	Land dominated by small- to medium-sized perennial woody plants.
Agriculture	Land used for crops and ranching, including pasturelands, orchards, and vineyards, that produce dairy products, vegetables, fruits, nuts, grains, hay or silage.
Urban	Land developed for human residence and commerce.
Other Forest	Riparian forest, forest fragment, or non-native forest in Marin Fine Scale Vegetation Data Set. (Eucalyptus canopies are included in this category.)
Barren	Land with little or no vegetation.

¹ Sources: Vegetation Classification of Alliances and Associations in Marin from the California Native Plant Society (2021) and the US Department of Agriculture, National Agriculture Statistics Service.

Figure 1-1. Land Cover in Marin (% Acreage)

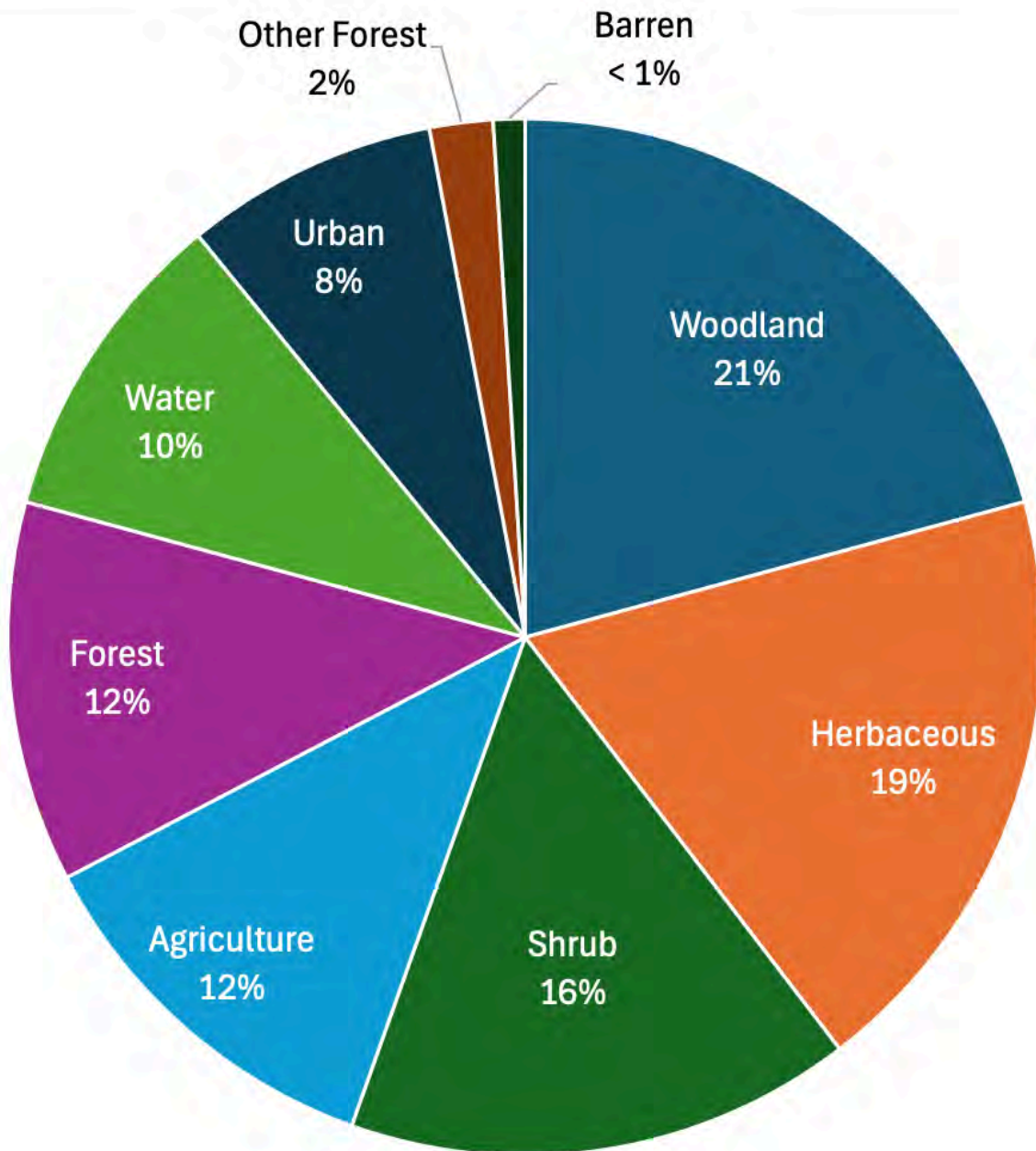
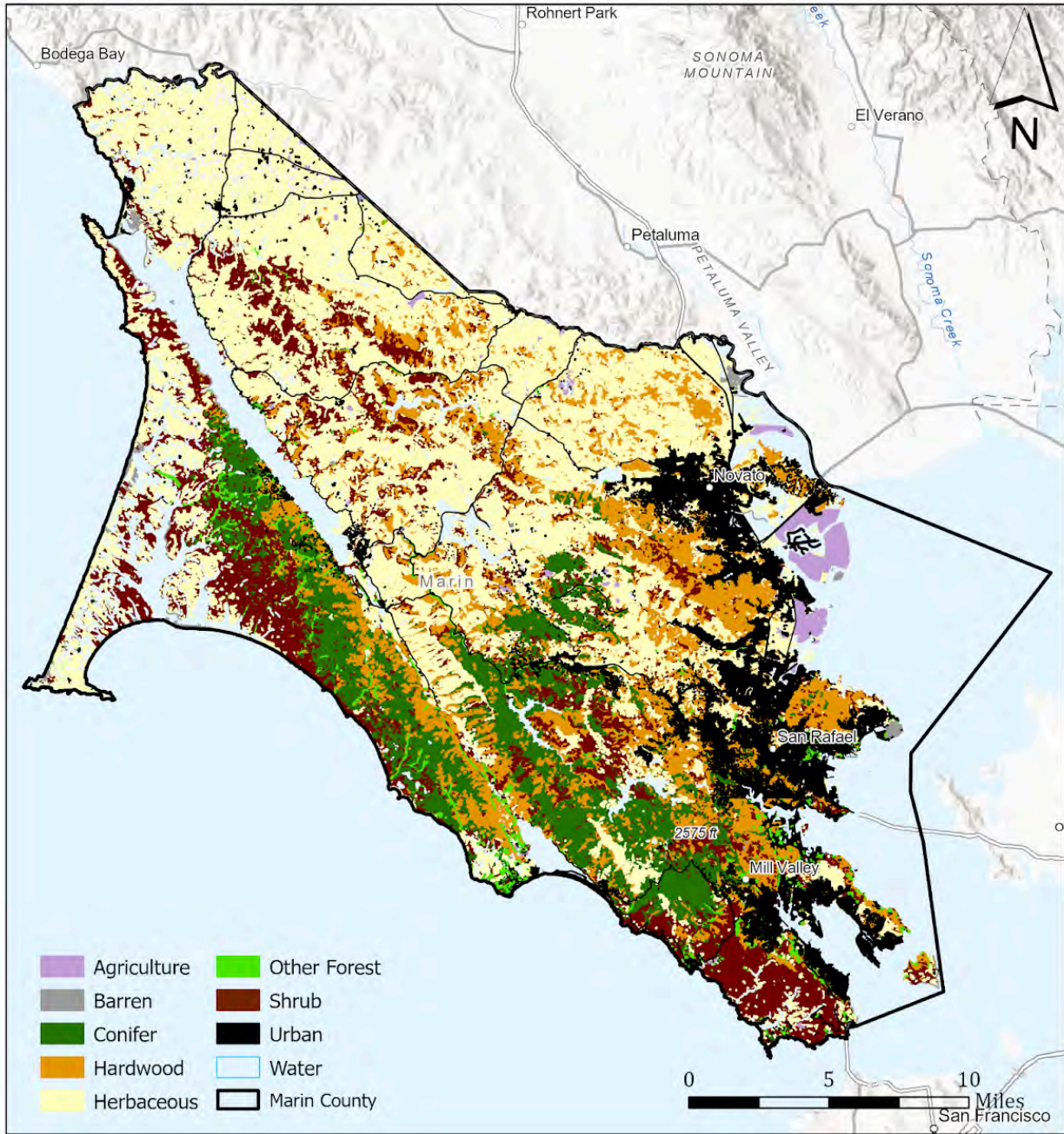


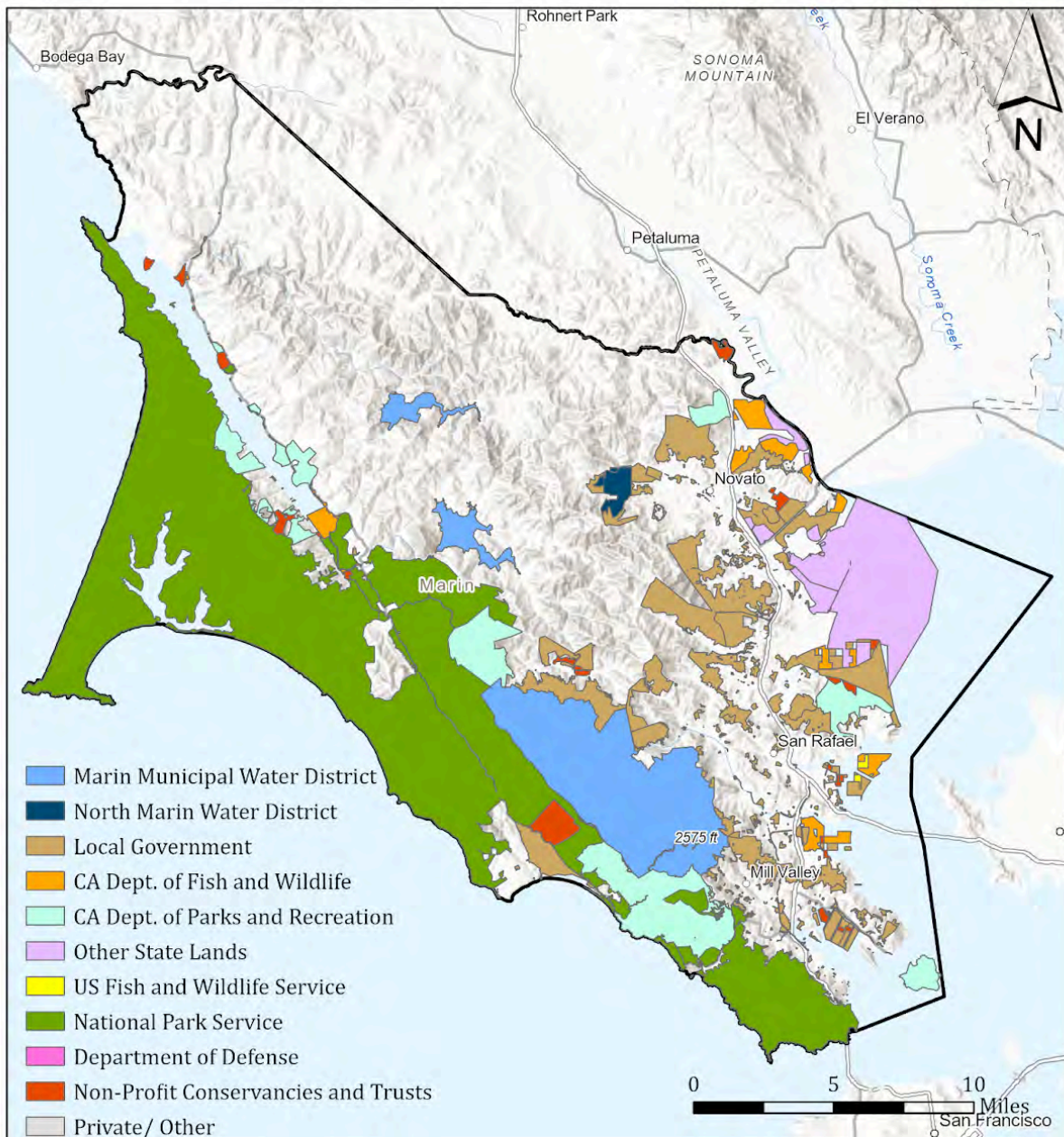
Figure 1-2. Land Cover in Marin County²



² Maps in this chapter use geographic information systems data from the Marin County Fine Scale Vegetation Analysis provided by the Golden Gate National Parks Conservancy and from data from the National Agricultural Statistics Service at the United States Department of Agriculture. Spatial Informatics Group conducted the GIS data analysis and generated maps used in Figure 1-2 and 1-3.

Biomass generation is also shaped by land ownership. Ownership shapes land management objectives and activities, and these, in turn, determine the type and amount of biomass generated. Figure 1-3 maps public and private land ownership in Marin. (Appendix C contains supplemental data about lands and land ownership.)

Figure 1-3. Land Ownership in Marin



In the following subsections, biomass flows are explored across the following landscape types: (i) forest and woodland, (ii) metropolitan, and (iii) agricultural. This breakdown

reflects, in part, the different economic activities associated with each land use type and their role in generating biomass.

Biomass from Forest and Woodland Landscapes

Biomass flows generated from forests and woodlands are estimated based on an analysis of wildfire mitigation initiatives, beginning with an introduction to fuel treatments and then analyzing the fuel treatment plans of land owners and landscape managers.

The initial assessment also included open space shrub and grasslands in Marin as potential sources of biomass flows. Based on a preliminary assessment of those landscapes, only a small amount of biomass is likely to be collected, removed, and utilized. For this reason, biomass flows from these lands are considered negligible in this analysis. Therefore, the remainder of this subsection focuses on biomass flows generated by wildfire management-related fuel treatments on Marin's forests and woodlands.

Overview of Fuel Treatments

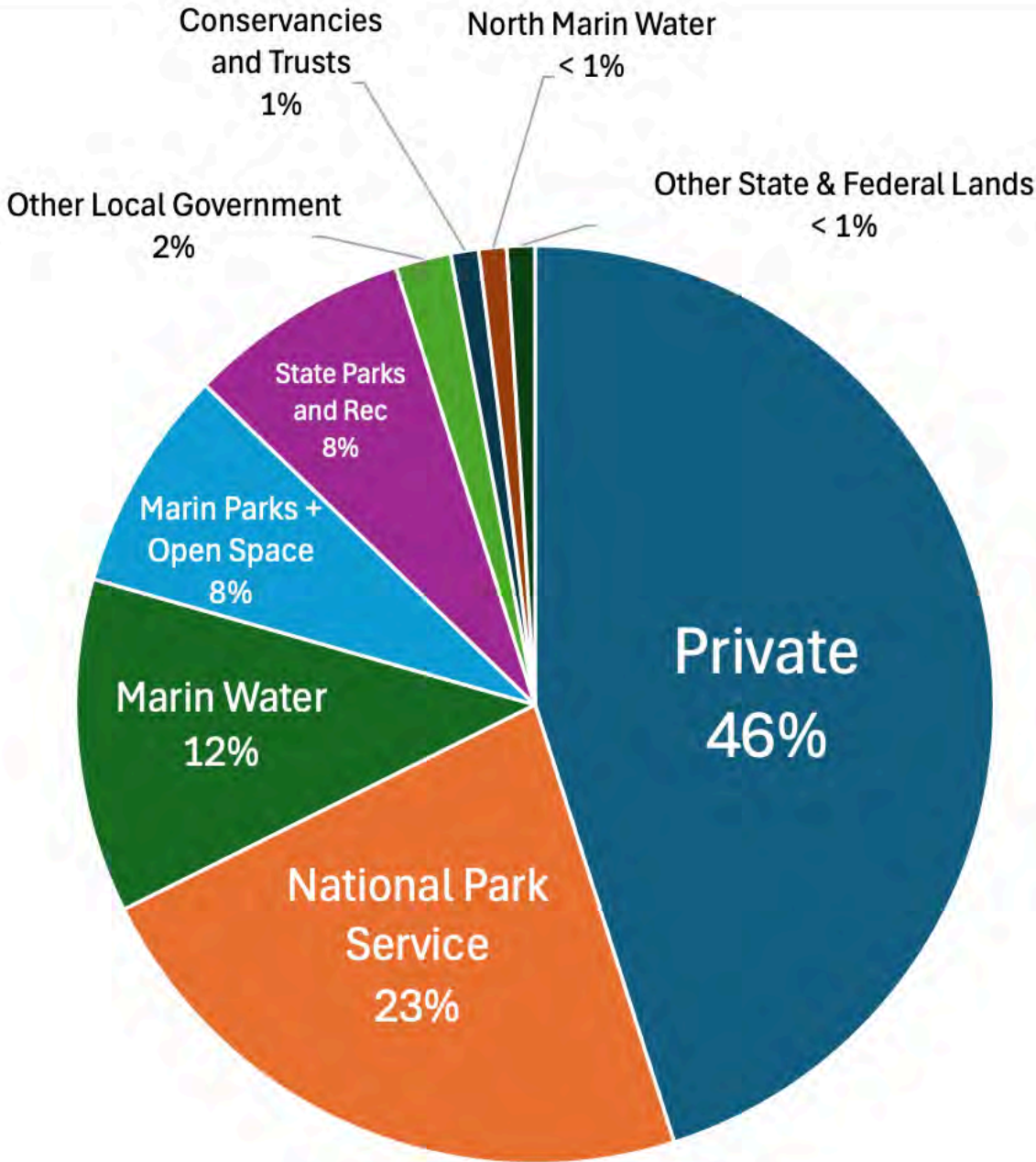
Over the last century, wildfire suppression has been a core practice in forest management. This practice has led to forest and woodland landscapes with denser vegetation than historical averages and, consequently, greater risk of high-severity wildfire, now further exacerbated by climate change. A remedy is the process called “fuel treatment.” This selective removal of vegetation aims to break up the path of fire spread, reduce the “fire ladder” created by an abundance of small stems and lower tree limbs, and decrease the intensity and severity of wildfire. In addition to mitigating wildfire, these practices can strive to increase forest resilience and reduce greenhouse gas emissions from wildfire.

A “fuel treatment” is an effort to change the availability and combustibility of biomass on a landscape. By reducing this “fuel,” a treatment reduces wildfire spread and intensity.

Fuel treatments funded by Marin County Measure C (2020)³ are now underway. Land owners and landscape managers are managing forest and woodland density toward the historical average and, thereby, mitigating the potential impacts of wildfire. This section explores their plans and practices as a basis for estimating the biomass flows that they may produce.

³ In March of 2020 Marin voters passed Measure C to fund a proactive, state-of-the-art wildfire prevention and preparedness program with a new parcel tax. The revenues raised by this tax total roughly \$20 million a year for ten years. These funds are used solely to finance, plan, implement, and manage the wildfire prevention system and the multi-jurisdictional agency that administers it.

Figure 1-4. Ownership of Forests and Woodlands in Marin



Nearly half (46%) of Marin’s forests and woodlands are privately owned. A sizable fraction (39%) is parkland held by the National Park Service, Marin County Parks and Recreation, and California State Parks. The other significant portion (12%) are watershed lands owned by Marin Water.

Land ownership can be a significant factor shaping whether and how fuel reduction is undertaken in addition to the timing and type of material generated. For example, a large amount of Marin’s forest and woodland acreage is managed as preserves. Resource conservation objectives for these lands means that fuel reduction is more likely to involve cutting and retention of biomass on the landscape, rather than collecting and transporting it offsite for processing and potential utilization. Further, the nature of the wildfire mitigation activities can have a significant effect on the form of the biomass removed. For example, trees cut along roadways to ensure safe ingress and egress may be more likely retained as logs. By comparison, biomass cut and hand carried to roadways is more likely to be chipped before being transported offsite.

Figure 1-5. Before and After Fuel Treatment
(Location: Terra Linda / Sleepy Hollow)



The images in Figures 1-5 and 1-6 depict fuel treatment techniques focused on removal of small stems, lower limbs, and brush making up the understory. This type of treatment reduces ladder fuels while retaining larger, more fire-resilient trees.

Figure 1-6. Before and After Fuel Treatment

(Location: Baywood Canyon / Fairfax)



Shaded Fuel Breaks

Shaded fuel breaks are landscape-level fuel treatments that involve carefully planned thinning of dense tree cover and the removal of underlying brush. Shaded fuel breaks not only reduce fuel, but can also reduce the potential spread of wildfire. The two largest, planned, and partially implemented shaded fuel breaks in Marin are the Greater Ross Valley Shaded Fuel Break and the Greater Novato Shaded Fuel Break. The Greater Ross Valley Shaded Fuel Break stretches over 38 miles of wildland-urban interface and borders the communities of Corte Madera, Larkspur, San Anselmo, and Fairfax. This project began in 2022, with the initial 12 miles of fuel break completed in 2023. Current plans are to complete the initial installation phase in 2026. The Greater Novato Shaded Fuel Break covers about 60 miles and borders Ignacio, Loma Verde, Pacheco Valley, Marinwood, and Novato. This fuel break was started in 2023 and will require about five years to complete. Installation of the Greater Ross Valley Shaded Fuel Break has generated almost 3 wet short tons⁴ per acre of woody biomass requiring disposition. All planned shaded fuel breaks are shown in Figure 1-7.

⁴ A short ton is the same as one imperial ton or 2,000 pounds. The term “wet” refers to biomass inclusive of its moisture content. Recently cut biomass is assumed to be 40% moisture by weight. (See Appendix A.)

Figure 1-7. Planned Shaded Fuel Breaks



Survey of Land Owner and Landscape Manager Plans

Significant volumes of woody materials are generated during fuel treatment projects. A survey of landowners and landscape managers is used to estimate biomass flows from fuel treatments in Marin's forest and woodlands.⁵

Marin Wildfire Prevention Authority

Marin Wildfire Prevention Authority (MWPA) is a landscape-level manager and joint powers authority for 17 member agencies. In its role as a leading wildfire safety agency, MWPA serves as a principal planner and funder of fuel treatments in Marin, as well as a central agent in some of Marin's largest and most ambitious vegetation management projects.

MWPA plans and supports a variety of work to slow the severity and spread of fire that can damage property. (Examples include fuel reduction projects, home preparation or "hardening," or the creation of defensible space around buildings in the wildland-urban interface.⁶) The Marin County Community Wildfire Protection Plan is a guiding document for this work and provides a basis for selecting strategic areas for fuel break installation. Major fuel reduction projects sponsored and managed by the agency include the 38-mile Greater Ross Valley Shaded Fuel Break and the 60-mile Greater Novato Shaded Fuel Break, mentioned above. In addition, MWPA supports fuel reduction activities throughout Marin including fuel break installations at Stinson Beach, Mill Valley, Ridgecrest, Ignacio Valley, and Marin Headlands, as well as roadside vegetation management along Marin's roadways to maintain safe egress in the event of an emergency.

Marin County Parks and Open Space⁷

Marin County Parks and Open Space manages a significant portion of local lands that contribute to the county's biomass stream through defensible space treatments near residential areas. Its approach reflects the logistical and financial challenges agencies face in removing or repurposing biomass. Marin County Parks and Open Space is tasked with managing approximately 16,000 acres of open space. A key issue is the creation of defensible space adjacent to the roughly 3,600 neighboring private properties. Typically, 100- to 1500-foot treatment zones are used to create this defensible space.

⁵ A list of enterprises involved in vegetation management and biomass hauling are included in Appendix D.

⁶ Defensible space refers to the vegetation-managed buffer zone that makes a property more resistant to wildfire and increases the chances of it surviving a fire event. Creating defensible spaces can include clearing dead or flammable material, spacing and trimming vegetation, and creating noncombustible zones near the built environment that slow or stop wildfire spread, as well as create safe space for firefighting.

⁷ Data provided by Parks and Open Space Superintendent Jim Chayka and Biodiversity Monitor Nate Clark

Fuel reduction work is carried out by hand crews, including the Mount Tam Crew and the Fire Foundry Crew. Most woody vegetation is piled and burned or chipped and scattered due to very limited access for woody vegetation removal. In addition, Marin County Parks and Open Space is concerned about high disposal fees at landfills or transfer stations. The agency also uses goats from time to time as grazers and uses mechanical mastication where appropriate. A key objective of its vegetation management is to create and maintain defensible space near communities and to remove invasive plant species. Once shaded fuel breaks are installed, follow-up vegetation management will be undertaken to maintain them. Marin County Parks and Open Space is still working through what their maintenance activities will include.

*Marin Water*⁸

As the public water supply manager, Marin Water is another major land owner and landscape-level manager generating woody biomass flows. Marin Water manages approximately 22,000 acres of land with seven water storage reservoirs that serve 191,000 customers. They have been steadily planning and implementing fuel treatment projects, including fuel breaks and roadway improvements, on watershed lands.

The October 2019 Biodiversity, Fire, and Fuels Integration Plan is the basis for Marin Water's work plan. Treatment methods include removal of small stems and lower limbs, tree spacing, and removal of invasive species. In addition, small Douglas fir and tanoak stems are removed to meet tree spacing specifications. Some dead, standing trees are left intact to serve as wildlife habitat. Marin Water staff⁹ confirmed that fuel reduction techniques used in the watershed include mastication, pile and burn, lop and scatter, and chip and scatter. Marin Water has averaged about 100 acres of fuels treatment per year, with a target of 2,079 total acres of initial treatment. The goal is to complete most of the shaded fuel breaks planned for the watershed by 2029. After all fuel treatments are installed, Marin Water will transition to fuel maintenance treatments.

Initial treatments average about 30 wet short tons of woody biomass per acre. Maintenance treatments using primarily lop and scatter techniques are planned for three-to-five-year intervals and for treatments generating less than 1 wet short ton per acre. Marin Water staff estimate that average pile size is five cubic yards, which amounts to about 1.2 wet short tons per pile of vegetation, for a total of about 12,000 wet short tons

⁸ Additionally, the March 2022 Marin Municipal Water District Hazard Mitigation Plan addresses a multitude of hazards, including wildfire. Marin Water prepares an annual Vegetation Management Report, which summarizes accomplishments and plans for each year.

⁹ Data from Carl Sanders (natural resources manager) and Loren Jenkins (project coordinator) at Marin Water.

annually. Fiscal cost to burn piles is estimated to be \$106 per pile. Assuming 29 piles per acre, total burn cost comes to about \$3,000 per acre and about 30 to 35 wet short tons per acre of woody biomass material treated.

Figure 1-8. Examples of Fuel Treatment, Fuel Breaks, and Roadway Work



Marin Water’s shaded fuel breaks will generate some of the largest flows of woody biomass, both during initial installation and then ongoing through maintenance. With roughly 30 wet short tons of biomass produced per treated acre, removal of loose biomass, rather than lopping and scattering in place, is appealing. However, steep terrain and narrow road systems do not provide much support for either chip or log truck transport.

Marin Water is committed to vegetation management to reduce wildfire fuels. However, the lands it manages present unique topographic and logistical challenges which impact how much material can be processed or removed from treatment sites. A significant challenge is finding opportunities to burn piles due to air quality constraints. Approximately 10,000 piles have accumulated within the watershed. While Marin Water is currently in the process of burning many of these piles, a process that typically begins after rains in the fall, neighbors are pushing back on pile burning because of its air quality impacts. In addition to steep terrain and road systems constraints, there are also concerns regarding offsite movement of potential pathogen-infected woody material.¹⁰

National Park Service¹¹

The National Park Service (NPS) oversees 18,059 acres of forest and 8,752 acres of woodland in Marin — the largest share of each within the County. For this reason, its fuel treatment initiatives could generate significant flows of biomass. NPS land management jurisdictions include Golden Gate National Recreation Area (which includes Muir Woods National Monument) and Point Reyes National Seashore.

¹⁰ The primary pathogens is *Phytophthora ramorum*, and cinnamomyc species are those primarily infected.

¹¹ Data from Fire Management Officer Greg Jones.

The NPS [2005 Fire Management Plan Final Environmental Impact Statement](#) guides its fuels management program, with Alternative C in that plan (i.e., “Increased Natural Resource Enhancement and Expanded Hazardous Fuel Reduction”) selected as the preferred approach. Alternative C calls for marked increase in efforts to reduce wildfire fuels. Up to 3,500 acres could be treated per year, using prescribed fire and mechanical treatments. A current focus is creating defensible space near communities and on roadsides that ensure safe evacuation corridors. Emphasis is on fuel reduction within 100 to 200 feet of the NPS boundary and adjacent to private residential properties. No landscape-level mechanical treatments are planned. A major limiting factor is available staff to plan, design, and implement fuel reduction projects. However, individual project funding and community support are generally not an issue.

Currently, 90% of NPS fuel reduction work uses hand crews, and 10% relies on chopping or masticating (i.e., shredding) vegetation to reduce fire hazard. The primary focus is on removing small stems (i.e., less than 12 inches in diameter at breast height) along with brush/shrub removal. Material is chipped to less than six inches and scattered on-site. Occasionally, it may be chipped and removed, typically with box trucks with 10 cubic yards of capacity. Sometimes a pile and burn method is used, but neighbors are generally not supportive of that effort due to air quality impacts.

California State Parks¹²

The State Parks manages about 4,984 acres of forest and 3,850 acres of woodland within Marin. Most fuel reduction efforts focus on decreasing ladder fuels.¹³ Pile burning remains the default management technique, but alternatives like air curtain burners and prescribed fire projects are being considered to reduce emissions and in light of infrastructure constraints. Other techniques include chipping and lop-scatter. Chipped material is transported offsite or broadcast to specified depths on-site.¹⁴

California State Parks allows homeowners to treat fuel on park lands within 130 feet of residential structures following the agency’s defensible space prescriptions and through the issuance of a Boundary Vegetation Modification Right of Entry permit. Some invasive species removals are conducted as part of ongoing maintenance of historic fuel reduction projects and vegetation management zones. Plans are in place to conduct more prescribed fire projects, working closely with Marin County Fire.

¹² Data from environmental scientist Bree Hardcastle.

¹³ The term “ladder fuel” refers to vegetation that enables fire to climb from ground level into a tree canopy.

¹⁴ These efforts may also make use of an air curtain burner to mitigate air quality impacts.

Pacific Gas and Electric¹⁵

Pacific Gas and Electric (PG&E) provides electricity and natural gas delivery services throughout Marin. Hundreds of miles of distribution and transmission powerlines are managed by this utility. PG&E employs foresters and arborists who monitor and prevent contact between vegetation and these powerlines, as well as ensure regulatory compliance with California Public Utility Commission vegetation removal mandates. Public safety and wildfire mitigation are key objectives that guide PG&E's Vegetation Management Program.

Through this program, PG&E removes hundreds of tons of woody material annually. PG&E states that it tries to channel this material into commercial reuse pathways, such as composting, firewood, or biomass power. Tree service contractors are regularly hired to trim trees and remove dead or dying trees that pose a potential hazard to PG&E powerlines. Typically, these contractors assume ownership of woody material removed. Due to relatively high tipping fees at landfills and transfer stations, tree service companies seek out value-added uses for this material such as compost or biomass fuel for biomass power plants. For example, woody biomass received at Green Waste Recycle Yard in Richmond and West Marin Compost in Nicasio may come from these sources. PG&E estimates that approximately 1,250 wet short tons per year of woody material is removed as part of the vegetation management process within Marin. However, recordkeeping is limited, as are data about the size, timing, and disposition of PG&E's biomass flows.

Other Public Land Owners or Landscape Managers

A smaller but relevant contributor to Marin's biomass stream is land managed by local governments and municipalities. Though these properties represent only a small share of forested land, they are forecasted to generate consistent biomass through routine fuel treatment activities. Twenty acres per year of forecasted fuel treatments are assigned to this category based on discussions with fire district staff.

Other Private Land Owners

Privately owned land makes up nearly half of Marin's forest and woodland areas (Figure 1-4). Although data are limited, private landowners are actively engaged in vegetation management, largely driven by regulations, insurance requirements, and personal safety concerns. As treatment activity expands, this sector is expected to generate increasing volumes of woody biomass. Some private land is treated during installation of landscape-scale fuel breaks such as the Greater Ross Valley Shaded Fuel Break and the

¹⁵ Data from Wood Management Manager Joel Smith and Principal Kevin O'Brien.

Greater Novato Shaded Fuel Break. However, additional fuel treatment activities are being conducted by private landowners.

Marin County Fire Department, Novato Fire District, and San Rafael Fire Department report that significant efforts are underway on private property outside of the shaded fuel break initiatives.¹⁶ There is no exact count for the acreage of private land treated. Fire district personnel believe that private landowners are engaging in regular fuel reduction activities near structures and road systems. Based on this information, the forecast for fuel treatment on private land in 2023 is 20 acres per year and 50 acres per year from 2025 onward.

Insights from Survey of Land Owner and Landscape Manager Plans

The survey of fuel treatments above reveals the scope and variety of vegetation management efforts underway across Marin. To better understand the implications for biomass management, this section summarizes key insights shared by landowners and landscape managers regarding recent and planned fuel reduction projects. The following observations are used in this analysis to quantify the expected biomass volumes, to identify operational challenges, and to explain the need for scalable infrastructure solutions:

- Due to successful fire suppression activities in the past 120-plus years, many of the forest and woodland ecosystems within Marin have unnaturally high stocking (stems per acre) and brush/shrub densities.
- Fuel reduction efforts across landowners and landscape managers are increasing the flow of woody biomass from forests and woodlands — based on both the acreage treated and nature of vegetation treatments.
- The primary focus of vegetation management is wildfire mitigation in support of defensible communities. In addition, improving forest and woodland conditions within the upland watersheds is a top priority.
- Topography is frequently too steep to allow for mechanical fuel reduction treatments that use equipment to grind, chip, or break apart vegetation. Use of hand crews is the most common technique.
- Road systems near forest and woodland ecosystems were not designed to allow for large commercial vehicle access. Woody biomass removal will require use of smaller commercial vehicles that can navigate tight radius turns and steep roads.

¹⁶ Data provided by Vegetation Management Battalion Chief Jordan Reeser at the Marin County Fire Department, Vegetation Management Program Manager Mike Swezy at the Novato Fire Protection District, and Hazard Mitigation Coordinator Kate Anderson at the San Rafael Fire Department. These sources report that Public Resources Code 4291, which requires defensible space near structures, is motivating much of this work.

- Estimates for the amount of biomass generated by the creation of shaded fuel breaks vary significantly across agencies. MWPA estimates 2.8 tons per acre, and Marin Water estimates 35 tons per acre.
- Fuel break maintenance (i.e., regular inspection and additional vegetation management in areas where fuel breaks are planned and installed), is planned to take place at three- to five-year intervals. Maintenance generates significantly less woody biomass than initial thinning efforts.

In short, plans to reduce forest and woodland fuels have expanded significantly after the passage of Measure C in 2020, the subsequent creation of MWPA, and the funding of fuel reduction activities across Marin. Estimation of the biomass flows from fuel reduction initiatives is based on a detailed survey of the vegetation management plans. Using a five-year time horizon, Table 1-4 summarizes the fuel treatment plans in acres per year for major land owners and managers. (Additional data about fuel treatments is in Appendix C.)

Table 1-4. Planned Fuel Reduction Acreage
(Five-year Time Horizon)

Land Owner or Landscape Manager	Acres Treated per Year					Annual Avg
	2023	2024	2025	2026	2027	
Marin County Parks and Rec	28	28	28	28	28	28
Marin Water	220	316	316	316	316	297
MWPA (Greater Novato Shaded Fuel Break)	425	425	425	425	425	425
MWPA (Greater Ross Valley Shaded Fuel Break)	200	200	100	0	0	100
MWPA (other treatments, including roadside)	600	400	300	200	100	320
MWPA (maintenance of fuel treatments)	100	300	500	600	700	440
National Park Service	35	50	75	100	100	72
California State Parks	30	30	40	40	40	36
Other Public Land Owners or Managers	20	30	50	50	50	40
Other Private Land Owners	20	20	20	20	20	20
Totals	1,678	1,799	1,854	1,779	1,779	1,778

Biomass Flow Estimate from Forest & Woodland Landscapes

The purpose of this section is to estimate the expected biomass flow from forests and woodlands. Table 1-5 contains estimates of woody biomass flows generated as part of wildfire-related vegetation management that are also logistically and economically practical to remove from forests and woodlands in Marin.

Table 1-5. Estimate of Practically Available Biomass from Forests and Woodlands¹⁷

Land Owner or Landscape Manager	Wet Short Tons Per Year					Annual Avg
	2023	2024	2025	2026	2027	
Marin County Parks and Rec	70	70	70	70	70	70
Marin Water	1,320	1,896	1,896	1,896	1,896	1,781
MWPA (Greater Novato Shaded Fuel Break)	797	797	797	797	797	797
MWPA (Greater Ross Valley Shaded Fuel Break)	336	336	168	0	0	168
MWPA (other treatments, including roadside)	1,008	672	504	336	168	538
MWPA (maintenance of fuel treatments)	60	180	300	360	420	264
National Park Service	88	125	188	250	250	180
California State Parks	75	75	100	100	100	90
Other Public Land Owners or Managers	50	75	125	125	125	100
Other Private Land Owners	50	50	50	50	50	50
Totals	3,854	4,276	4,198	3,984	3,876	4,038

Not all biomass generated as part of fuel treatments is easily removable. Steep slopes, challenging road systems, and general accessibility limit the amount of biomass that is practical to remove from forests and woodlands. Drawing on observations and data from land managers, an estimate of the total biomass generated each year from vegetation management is available in Appendix C.

Biomass from Metropolitan Landscapes

Marin’s metropolitan landscapes can produce a variety of biomass flows. Some of these are the result of landscaping work at residences and commercial establishments, including defensible space treatments such as those described in the previous section. Many of them are discards from economic activity that are collected and hauled away to protect public health. Historically, hauling these materials away could mean using practices, like landfilling, that moved materials away and that appeared to be low cost, but that also produced substantial environmental consequences. Primary among these impacts are potent greenhouse gases — specifically methane — when organic material decomposes in landfills under anaerobic conditions.

Over the last forty years California has implemented policies that discourage landfilling and encourage recycling. The most recent of these policies is Senate Bill 1383 (2016). SB 1383 establishes a statewide goal to divert 75% of biomass flows away from landfills, and it

¹⁷ Cut woody biomass from fuel treatment has a moisture content of 40%.

requires local governments to track and report discarded biomass flowing from metropolitan landscapes and to establish systems that enable residents and businesses to recover, recycle, and reuse biomass. It also sets targets for procurement of products made from recycled biomass. This means that Marin needs to establish collection systems and develop pathways that can redirect biomass into products like compost or energy resources like transportation fuels and electricity.

Some of these systems already exist. For example, jurisdictions in Marin already have contracts with material haulers who collect biomass from residences in green carts at the curbside. To comply with the law, material haulers also collect organic material from businesses to divert it from landfill and into different utilization pathways.

Senate Bill 1383 targets biomass from a wide range of materials originating from living organisms. This study focuses on food scraps, green materials (like grass and tree trimmings), construction and demolition materials, fuel reduction residuals, and biosolids.

The definition of organic material under SB 1383 is broad. This study focuses on woody materials (including byproducts of construction and demolition work), green materials (like grass, yard prunings, and fuel reduction residuals), food scraps, and digestate from sewage treatment. These major categories are discussed below, and flow estimates are summarized in Table 1-6.

Woody Materials

Within metropolitan landscapes, trees are trimmed or removed by local governments, residents, and businesses for aesthetic and safety reasons. The biomass from these activities is usually categorized as green materials. (See the next section.)

However, metropolitan landscapes do produce a large amount of woody biomass as a byproduct of construction and demolition work. This includes leftover lumber products or scraps from construction and building renovation, demolition, or deconstruction. These woody materials may be attached to or mixed with other materials like metals, concrete, plastics, ceramics, sheetrock, and glass. Some can be separated using hand or mechanical sorting processes, such as those at the Marin Resource Recovery Center operated by Marin Sanitary Services in San Rafael, Pacific Sanitation in Windsor, or the sorting yard that Waste Management had previously operated on the grounds next to Redwood Landfill in Novato.

These materials may be aggregated at a transfer station, sorted at a resource recovery facility, and then sent for reuse or active recycling. It can be hard to trace materials with variable outcomes and that change hands a number of times.¹⁸ Based on available records and interviews, in the next decade Marin is expected to generate roughly 105,000 wet short tons per year of woody construction and demolition materials.

Green Materials

After the passage of SB 1383, residential material collection of “green” materials in curbside green carts is increasing. Green materials include grasses, leaves, branches, other plant debris, and more recently, food and paper compostables. In Marin roughly 5% by weight of green cart materials are food scraps from residential kitchens.¹⁹ Together, these are considered green materials. The range of materials is on average higher in water content than the woody biomass stream from forests and woodlands. However, the residential stream may contain some woody biomass from horticultural and defensible space work.

For example, Marin has multiple programs that encourage businesses and homeowners to create no-burn or low-burn zones around buildings to protect them from wildfire. This defensible space work can involve cutting back or removing plants and trees, and the Marin Wildfire Prevention Authority runs a Chipper Day program that chips and hauls away trimmings at the curbside. This flow can be a mixture of green materials like leaves and needles and woody materials like chipped branches or smaller-diameter trunks.

Currently, Marin’s curbside collection and Chipper Day programs have been collecting about 60,000 wet short tons of material per year. Over the next decade this flow is expected to grow to 80,000 wet short tons per year, similar to the amounts of C&D wood. Like other types of biomass, green materials are defined as “organic” under SB 1383 and targeted for diversion from landfill.

¹⁸ As an example, Waste Management (WM) segregates roughly 31,000 wet short tons of woody construction and demolition debris from the roughly 100,000 wet short tons that it receives from Marin and Sonoma Counties. WM sends these 31,000 wet short tons to the Marin Resource Recovery Center (MRRC), which also sorts construction and demolition debris from Marin Sanitary Service. From these streams, sorted material is processed (i.e., cut into three-inch pieces) for sale to combustion power plants in the Central Valley. Construction and demolition debris made of wood fastened to other materials are logistically complicated to sort and prepare. Roughly 10,000 wet short tons of these are shipped from the MRRC received back to WM, where they are turned into daily cover or handled as regular inputs to landfill. The flow of these materials is not carefully recorded and, therefore, is hard to verify.

¹⁹ Estimate from Ramin Khany (operations manager) at Waste Management’s Redwood Landfill.

Food Scraps

Marin has programs that support recovery of food scraps generated at residences and at businesses like food wholesalers, grocery stores, restaurants, and hospitals. Curbside green carts accept food along with green materials. Businesses individually contract with commercial haulers for removal of their discarded materials.²⁰ Marin's business sector is expected to produce over 14,000 wet short tons of source-separable and, therefore, recoverable food scraps per year in the next decade. A portion of this flow is already available and being recycled, as discussed later in this chapter. The rest is predicted to become available in the next decade as food scrap recovery and recycling programs improve.

Digestate

Many wastewater treatment plants use anaerobic digestion to deactivate sewage as part of their effort to clean and recycle water. As byproducts of this process, two bio-materials are created: a semi-solid digestate (sometimes called "biosolids") and a gas called "biogas" that is largely methane and carbon dioxide.²¹ Marin County has six wastewater treatment districts, and they collectively produce 16,500 wet short tons (3,000 dry²² metric tons) of the semi-solid digestate that may require alternatives to land application (which can only occur during the dry months of the year) and landfilling (which is restricted by SB 1383). Most of the districts capture the biogas byproduct, clean it to acceptable standards for combustion, and burn it in engines or microturbines to generate electricity.

Biomass Flow Estimate from Metropolitan Landscapes

Table 1-6 offers a snapshot of past biomass flows and, more significantly, the annual flows that Marin is expected to generate in the next decade.

²⁰ Both SB 1383 and AB 1826 apply here. AB 1826 mandates that municipalities set up programs to recover and recycle their food scraps. SB 1383 establishes that a "generator" of organic materials is an entity that produces more than 10-20 gallons per week, depending on the overall service.

²¹ Digestate is a general term for the semi-solid output from an anaerobic digestion process. In the wastewater sector, digestate is often called just "biosolids." The term "digestate" is preferred in this report and is treated as interchangeable with "biosolids" in a co-digestion application.

²² The term "dry" refers to biomass exclusive of its moisture content. That is, it is the weight of material after the water or moisture content is subtracted. A metric ton is equal to 1,000 kilograms or 2,205 pounds.

Table 1-6. Estimated Biomass from Metropolitan Landscapes (wet short tons per year)

Biomass Type (moisture content)	moisture content	Past	Expected
Construction and Demolition Materials	20%	105,000	118,000
Green Materials, including food scraps in green carts	50%	61,000	81,000
Food Scraps from commercial businesses	70%	3,900	14,200
Digestate, aka biosolids from wastewater treatment	80%	16,500	16,500
Totals		186,400	230,500

Marin’s metropolitan landscapes stretch across the county but are concentrated in the east in the larger cities of San Rafael, Novato, Mill Valley, Corte Madera, Sausalito, and Tiburon that make up part of the 27,000 acres of the urbanized landscape. These cities, along with the rest of Marin’s metropolitan landscapes, currently produce an estimated 188,500 wet short tons of biomass per year. Considering the estimated increases, these biomass flows will grow to 230,500 in the next decade.

Biomass from Agricultural Landscapes

Marin has an active agriculture sector, with commercial agricultural operations covering roughly 44,000 acres or 11% of the land in the County.²³ As summarized in Table 1-7, most of Marin’s agricultural land is in use for pasture, silage, and hay crops, given that livestock operations are the most common form of agriculture in Marin. Field crops, vineyards, and orchards make up a small percentage of Marin’s agricultural production.

Table 1-7. Agricultural Land Uses²⁴

Commercial Crops	Acres (NASS Data)	Acres (Marin Crop Report)
Pasture	38,271	154,000*
Silage	3,093	1050
Hay	2,461	1030
Orchard	268	< 228
Fallow	93	no data
Grapes	69	143
Other Crops	38	ND
Total	44,293	156,451

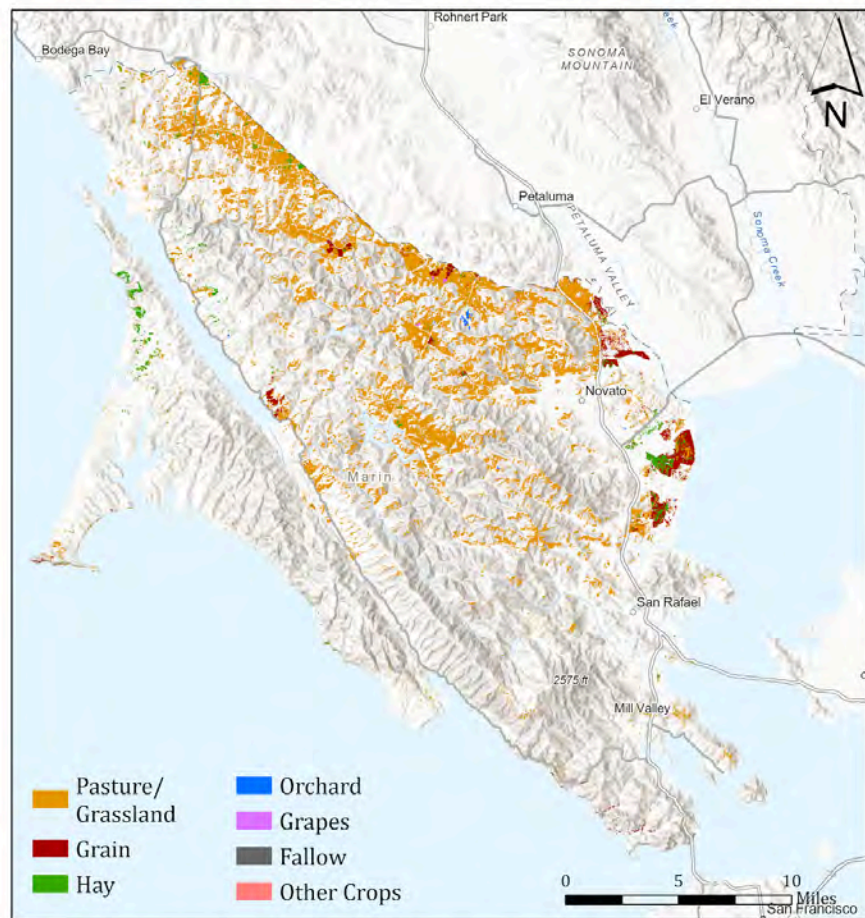
* Represents all rangeland acreage in Marin, not just pasture.

²³ Commercial crop data are available from databases managed by the National Agricultural Statistics Service (NASS) of the US Department of Agriculture. The NASS databases provide location, commercial crop type, and acreage. Data were collected from the NASS in 2023.

²⁴ Data were referenced from NASS in 2023. Marin Crop report data is from 2024. The analysis in this chapter relies on NASS data.

The map in Figure 1-9 shows these agricultural operations using data from the National Agricultural Statistics Service (NASS).²⁵

Figure 1-9. Commercial Crops within Marin



Commercial agriculture can produce biomass byproducts, such as nutshells, pits, prunings, crop tree removal, windbreak maintenance materials, crop residue, and manure. These types of biomass can be resources for other economic uses. For example, nuts and orchard prunings can be sold as a fuel for power production, and intensive cattle operations, such as feedlots in the Central Valley, may send their manure to anaerobic digesters that produce a methane-rich gas (biogas) that can be used in power production. Marin dairy

²⁵ Numbers vary for the acreage of agricultural land in Marin. The 2024 Marin Crop and Livestock Report from the Marin County Department of Agriculture Weights and Measures estimates 155,000 acres of pasture in Marin. When the USDA definition is applied, Marin has roughly 38,000 acres of pasture/grassland. For the purposes of this chapter and as included in Table 1-7, roughly 44,000 acres is used for the amount of agricultural land in Marin. In the greenhouse gas analysis in Chapter 3, the acreage from the [Marin County Climate Action Plan 2030](#) (published December 2020) is used. That estimate is for just over 60,000 acres of grassland suitable for compost and biochar application.

operators have been active in the development of anaerobic digesters for on-farm manure management and for on-farm use of biogas (e.g., for engines or heating).

Based on the 2024 Marin County Crop and Livestock report, Marin's primary agricultural outputs are livestock, livestock products (including milk and cheese), field crops, aquaculture (e.g., oysters, mussels, and clams), fruits, vegetables, and nursery crops. None of these produce significant volumes of prunings, crop residue, or other residual biomass.²⁶ Orchards and vineyards produce some woody biomass, but the little that is produced is generally chipped and spread on farms as mulch, used as firewood, or managed using controlled pile burning.

By contrast, Marin produces relatively large amounts of manure from its twenty active dairies. The 2024 Marin Crop Report estimates that the countywide cattle and calves population totals around 10,000 heads. About 6,500 spend most of their time on pasture, while the other 3,500 are milking cows that are on pasture only about a third of their time (i.e., 8 hours per day, 300 days of the year), where there is little practical opportunity to collect manure, and the other 70% of their time in corrals and barns.²⁷ On average each milking cow generates roughly 19 wet short tons of collectable manure per year.

As part of a pilot project at West Marin Compost, green materials and woody biomass are co-composted with roughly 1,800 wet short tons per year of separated dairy manure solids.²⁸ This pilot project was designed to offer a manure management solution for dairies and to produce compost for local agriculture and horticulture. As a practical matter, West Marin Compost is co-located with the dairy supplying the manure — thereby avoiding transport costs. Given the expense of moving wet manure and its value as an on-farm resource, very little dairy manure is currently available for off-farm management in Marin.

²⁶ Many dairies and ranches in Marin historically planted windbreaks or shelterbelts that provide shade and shelter. These agroforestry plantings are composed predominantly of eucalyptus and Monterey cypress. Many were planted 150 years ago or more, following European migration to California. These windbreaks require maintenance, including coppicing, pollarding, hedging, and complete tree removal. Annual maintenance and projected die-off for these windbreaks from old age is estimated at 5% of total trees over the next 20 years or 1,000 wet short tons per year. However, this windbreak and shelterbelt maintenance is episodic and unpredictable. For this reason as well as the relatively small volume and on-site management conventions typical for this material, this flow was omitted from this analysis.

²⁷ In these two settings, Marin's milking herds produce roughly 65,000 wet short tons of manure per year. Manure production in the corrals is estimated as 14,700 wet short tons per year (assuming 40% moisture content), and is typically composted and/or directly land applied. In the barns, it is estimated at 51,675 wet tons/year (88% moisture content, using lagoon storage and land application).

²⁸ Estimate from Dr. Jeff Creque at the Carbon Cycle Institute

Marin’s equestrian operations include roughly 4,000 horses producing about two cubic feet of manure and bedding per horse per day.²⁹ Assuming that there are three cubic yards of manure and bedding in a ton, Marin’s equestrian sector produces 100 wet short tons per day or about 36,500 tons per year. Most of this material is applied to land either directly or after composting. Very little is moved offsite for disposition, including being sent to landfill.

Biomass Flow Estimate from Agricultural Landscapes

In sum, Marin has a significant agricultural sector and meaningful streams of byproduct biomass. However, most of this material is managed on farms using accepted practices. For the purposes of this study, only the 1,800 wet short tons of manure being co-composted at West Marin Compost is considered available or ready for off-farm use.

Biomass Total Across Marin’s Landscapes

The previous sections developed estimates for biomass flows from forest and woodland management, from metropolitan residences and businesses, and from agricultural operations. Table 1-8 consolidates these estimates to describe the total current biomass flows and the flows Marin is expected to generate in the next decade.

Table 1-8. Total Biomass Flows (wet short tons per year)

Biomass Type	Past	Expected
Woody Materials (<i>from construction and demolition</i>)	105,000	118,000
Woody Materials from fuel treatment (<i>likely unrecoverable</i>) ³⁰	8,600	5,400
Woody Materials from fuel treatment (<i>potentially recoverable</i>)	4,000	2,500
Woody Materials (<i>self-hauled wood chips</i>)	6,700	7,100
Woody Materials (<i>logs</i>)	700	700
Wood Products (<i>from deconstruction and reuse</i>)	200	1,000
Green Materials (<i>including food scraps in green carts</i>)	61,000	81,000
Food Scraps (<i>source separated from commercial businesses</i>)	3,900	14,200
Digestate (<i>aka biosolids from wastewater treatment</i>)	16,500	16,500
Off-farm Manure (<i>bovine and equine</i>)	1,800	1,800
Totals	210,500	248,200

²⁹ Robert Rynk, 1992. *On-farm Composting Handbook*. Northeast Regional Agricultural Engineering Service NRAES-54. Cornell University.

³⁰ Steep slopes and challenging road systems can limit accessibility and removability. Biomass cut during fuel treatment may be managed onsite, as described in Chapter 2. Other biomass deemed potentially recoverable may be transported offsite if there are economic opportunities for doing so.

As the data in Table 1-8 show, flows for different biomass types are expected to increase, decrease, or remain constant in the next decade. For example, installation of shaded fuel breaks as part of wildfire risk reduction have produced 12,600 wet short tons per year of woody materials, two thirds of which (i.e., 8,600 wet short tons) is likely unrecoverable because of steep slopes or low road quality and approximately one third of which (i.e., 4,200 wet short tons) is potentially recoverable if there is an economic opportunity to do so. After shaded fuel break installation, maintenance is expected to produce only 7,900 wet short tons, 5,400 of which is likely unrecoverable and only 2,500 of which is estimated to be potentially recoverable.

The flow of green materials is currently estimated at 61,000 wet short tons per year. This flow is expected to grow another 20,000 wet short tons per year as homeowners create and maintain defensible space around their homes and as local ordinances requiring green cart use take hold. The flow of source-separated food scraps is expected to grow from 3,900 wet short tons per year to over 14,000 wet short tons per year as Marin and its commercial enterprises recover more food scraps to meet the requirements of AB 1826 and SB 1383. Marin currently generates 105,000 wet short tons of recoverable woody construction and demolition materials and is expected to generate 118,000 wet short tons per year by the end of the coming decade. The flows of biosolids and manure available for off-farm management are, respectively, 16,500 wet short tons and 1,800 wet short tons per year and expected to remain roughly the same into the next decade.

Biomass Pathways and Fates

The previous section characterizes the types and amount of biomass discards that Marin generates from fuel treatments, from metropolitan activities, and from agricultural operations. This section explores the current disposition or fate of these materials.

Current Biomass Pathways

Marin's biomass flows through a mix of channels. For example, biomass generated as part of vegetation management (including fuel treatments in forests and woodlands) is often left on-site, but some is transported by public agencies and contractors. For biomass discarded from metropolitan landscapes, collection and transport is a much broader system, often involving local governments who contract with material haulers to collect materials in green carts at residential curbsides. These activities are discussed below,

loosely in the order from reuse to disposal per the “waste management hierarchy” as defined by the US EPA.³¹

Deconstruction and Reuse

Marin has a handful of companies (see Appendix D) engaged in building material reuse. Rather than knocking a building down into a pile, these businesses use deconstruction techniques to disassemble a building to recover its components intact. This enables the building materials to be source separated on site and transported to reuse facilities, or directly to the end reuser. This is in comparison to demolition, where materials are sorted downstream and often commingled in a way that limits their reuse potential. This results in low recycling rates and more disposal.

[Hurricane Hauling](#)

Hurricane Hauling offers deconstruction, site cleanup, material hauling, and tree and yard services across six Bay Area counties. Their suite of equipment allows them to scale between large and small jobs.

[GreenLynx](#)

GreenLynx helps clients turn the end of a building’s life into the beginning of something new by reclaiming, reusing, and reintegrating valuable construction materials. Through careful deconstruction and material recovery, the company diverts wood, fixtures, and architectural elements from landfill while preserving their economic and environmental value. GreenLynx pairs hands-on salvage expertise with smart project coordination to deliver practical, circular solutions for the built environment.

[V’s Demolition](#)

V’s Demolition offers deconstruction services, including green salvage and material recovery. V’s emphasizes reclaiming, recycling, and repurposing and strives to recover 80 % of building materials — from lumber and windows to fixtures and hardware — diverting them from landfills and reintroducing them into the reuse market.

[The Reuse People](#)

The Reuse People is a nonprofit organization dedicated to building material reclamation and reuse through professional deconstruction, salvage, and resale services. While they no longer offer deconstruction services, they still operate reuse warehouses, partner with

³¹ www.epa.gov/smm/sustainable-materials-management-non-hazardous-materials-and-waste-management-hierarchy

contractors, and support community programs — all with the objective of advancing a circular-economy approach to construction and delivering environmental benefits that increase local reuse and economic opportunities.

While no significant reuse retail facility is operating in Marin, there are several operating nearby. These include Heritage Salvage in Petaluma, Recycletown in Petaluma, GreenLynx in Santa Rosa, ReStore in Santa Rosa, Urban Ore in Berkeley, The Reuse People in Oakland, and Building Resources in San Francisco.

Hauling

Marin has five companies that haul materials from its metropolitan environments. Many of these contracts and franchise agreements are written for five-year or longer terms. Businesses and residents may also contract on their own for collection and transport of additional material, or haul it themselves. Materials that flow outside of public franchise agreements are referred to in the materials handling industry as “self-haul” flows. A detailed analysis of franchise agreements and self-hauling habits is outside the scope of this study. However, this section offers a brief profile of the largest material collection companies operating in Marin because their business decisions (as well as the priorities of the public jurisdictions hiring them) shape where materials go.

Marin Sanitary Service

Marin Sanitary Service is a privately owned, local solid waste and recycling company that collects residential and commercial solid waste and recoverable materials. Located on 103 acres in east San Rafael, Marin Sanitary Service provides weekly collection services to approximately one-third of Marin’s residents.³²

Recology Sonoma-Marin

Recology Sonoma Marin is an employee-owned hauling and recycling company that collects residential and commercial solid waste and recoverable materials from communities in Unincorporated West Marin and the City limits of Novato. Additionally, they operate a buyback center in Novato for plastics with a California Redemption Value (CRV).

³² In addition to being a hauler that collects and transports materials, Marin Sanitary Service operates downstream components of Marin’s materials management system, including a material recovery facility that processes dry recyclables, the Marin Resource Recovery Center, the Marin Sanitary Service Transfer Station, and the Marin Household Hazardous Waste Facility, the last of which is funded as a regional program by the Marin County Hazardous and Solid Waste Management Joint Powers Authority (Zero Waste Marin).

Mill Valley Refuse Service

Mill Valley Refuse Service is a privately-held hauling service that services the cities of Belvedere, Mill Valley, the Town of Corte Madera, and other surrounding areas. As an example of the interconnection of Marin's material handling system, Mill Valley Refuse Service contracts with the Marin Resource Recovery Center to manage the recyclables and commercial food scraps that it collects.

Bay Cities Refuse

Bay Cities Refuse Service is a privately-held hauling company that services Sausalito, Marin City, and the surrounding unincorporated areas of Marin County.

Tamalpais Community Services District

Tamalpais Community Services District is a public community services district that operates its own hauling service. They contract with other firms like Mill Valley Refuse or Marin Sanitary Services to provide their services.

Transfer and Sorting

Materials collected from businesses and residences typically get consolidated and sorted at two kinds of facilities. One is called a transfer station, where materials collected at curbside by short-run vehicles like garbage trucks are consolidated into longer-haul vehicles like tractor trailers. Some material segregation can happen at transfer stations, but the sorting facilities that are set up to segment materials into value-added streams are called material recovery facilities (MRF). Three MRFs receive materials from Marin: the Marin Resource Recovery Center in San Rafael, a MRF operated by Republic Services in Richmond, and a MRF operated by Recology Sonoma-Marín in Santa Rosa. Marin's residents and business have access to these MRFs through franchise agreements for hauling. For example, materials collected in southern Marin by Bay Cities Refuse Service are dropped off at the Republic Services MRF in Richmond.

Marin Resource Recovery Center

The Marin Resource Recovery Center (MRRC) is a transfer and sorting facility. It is a sister company to Marin Sanitary Service. It serves as a transfer station for unsorted material from multiple collection and transport companies, including Marin Sanitary Service, the Tamalpais Community Service District, and Mill Valley Refuse Service. It also serves as a primary material sorting facility within Marin for recyclables and as a transfer station for materials sent to landfill or organics processing.

The Marin Resource Recovery Center receives, sorts, and ships a variety of biomass flows. Approximately 25,000 wet short tons per year of green materials are aggregated at the facility and shipped to the EarthCare composting operations that Waste Management has colocated with Redwood Landfill. Approximately 34,000 wet short tons of woody biomass per year is consolidated at the Marin Resource Recovery Center before being sold to DTE biopower combustion facilities in the Central Valley. At the Marin Resource Recovery Center, MSS also processes logs into firewood for local purchase. In recent years, demand for firewood has dropped as homes have removed wood-burning fireplaces and tightening air quality regulations have restricted hours of use.

The Marin Resource Recovery Center receives between seven and ten wet short tons of commercial food scraps per day. Some of this food comes in packages, and MRRC recently installed a centrifugal food depackaging system that can separate food scraps and food packaging. Some of the food scraps from this facility are sent to a hog farm as feed. Most is sorted and processed into a slurry that can be co-digested with sewage at the wastewater treatment plant in San Rafael operated by the Central Marin Sanitary Agency. (See the section below on co-digestion.)

Marin Sanitary Service staff³³ have observed trends in materials flow through the Marin Resource Recovery Center:

- *Increased* curbside green materials, likely the result of new ordinances requiring green cart use, along with more people working from home and increased yard maintenance, whether as part of household landscaping or from trimming of trees and shrubs to reduce wildfire threat.
- *Increased* woody construction and demolition materials, perhaps from remodeling during the pandemic and investments in home offices. However, this trend slowed as inflation increased the cost of construction materials and as home prices initially softened when mortgage rates increased.
- *Increased* green materials delivered through self-haul by tree service companies hired by homeowners or through MWPA's Chipper Day program.
- *Increased* cardboard from increased e-commerce and home delivery.
- *Rebounded* food scraps from the commercial sector, which went down during the pandemic when dining out was not an option. After dining out resumed, food scraps from restaurants have returned and now surpass pre-pandemic flow rates.

³³ Details provided by Director of General Operations Justin Wilcock, Marin Sanitary Service.

Republic Services

Republic Services is a large corporation with a diversified portfolio of waste management and recycling services. Among their operations are material collection, transport, and recycling services in Richmond, California. They operate the Golden Bear Transfer Station in Richmond. This facility receives materials from Marin. The large site they operate at the West Contra Costa County landfill also includes their composting facility. One of their tenants is Raven SR, a company seeking approval to build a new facility that can produce green hydrogen from woody biomass.³⁴

Composting and Mulching

As profiled below, there are three significant composting and mulching facilities in Marin and one in Richmond that receives biomass generated in Marin.³⁵

EarthCare

Waste Management owns and operates a composting facility called EarthCare. This facility is collocated with Redwood Landfill and is by far the largest composting operation in Marin. Launched in 2014, this facility is permitted to process 160,000 wet short tons per year of source-separated green materials, including food scraps and food-soiled paper. The current throughput of the facility is roughly 140,000 wet short tons per year.³⁶ Roughly 98% of the throughput consists of plant debris. The remaining 2% is classified as food or food-soiled paper. The facility uses covered, aerated, static pile (CASP) composting technology. It sells the compost it produces at the on-site EarthCare Landscape Center for residential, commercial, and municipal customers. The facility has been able to achieve organic certification from the Organic Materials Review Institute (OMRI) for its compost. Vineyards growing organic grapes are a primary customer segment. Some compost is also sold back to local governments to satisfy their procurement requirements under SB 1383.

West Marin Compost

The second largest composting operation in Marin is [West Marin Compost](#). It was developed through a partnership that includes the Marin County Resource Conservation

³⁴ This project was approved by the Richmond City Council for development at this site. See Richmond City Council meeting [minutes for May 16, 2023](#). See also *Richmond Standard*, "[Richmond green lights Raven SR's CEQA permit for renewable hydrogen project](#)," May 25, 2023.

³⁵ While on-farm, backyard, and neighborhood-scale composting are valuable, estimating their size and flow is beyond the scope of this study. As such, green materials, food scraps, and manure composted on-farm or in residential backyards are not included in this analysis.

³⁶ The 160,000 ton per year capacity translates to 525 tons per operating day, assuming roughly 300 operating days per year. The 140,000 ton per year average translates to 514 tons per operating day.

District and Lunny Grading and Paving. It is located in Nicasio and began operations in 2011. At its drop-off site it accepts logs, green materials, and stumps from public agencies as well as from homeowners, landscapers, ranches, and tree service companies operating in the area. Incoming materials are received at a drop-off site. Materials prepared for composting travel about a half mile to composting operations co-located with a local dairy.

Woody biomass, such as logs dropped off by the County's roadway maintenance crews, are initially sorted and processed at the drop-off site. When a small-scale sawmill was in operation next to the drop-off operations, logs of suitable dimension were cut into artisanal slabs for furniture making, architectural installation, or other artistic uses. When milling stopped, logs and stumps were chipped and shipped to combustion power plants in the Central Valley. A smaller amount of woody materials was ground up for mulch. Using turned windrow technology, West Marin Compost co-composts 5,000 wet short tons of green materials and 1,800 wet short tons of dairy and equestrian manure per year.

West Marin Compost sells mulch, compost, compost-soil, and compost-biochar mixes at its drop-off site in Nicasio. Some are certified organic by the California Department of Food and Agriculture (CDFA) and are purchased for use on ranches, vineyards, and local parks or for local residential, commercial, or municipal landscaping.

[Green Waste Recycle Yard](#)

The Professional Tree Company (website [here](#)) developed the Green Waste Recycle Yard to process logs and wood from local tree service companies into value-added products. Located in Richmond near the West Contra Costa County Landfill operated by Republic Services and by the West County Wastewater facility, the facility receives roughly 20,000 wet short tons of woody and green materials per year, an estimated 20% of which comes from Marin. Their primary products are mulch and woody fuel sold to combustion power plants in the Central Valley.³⁷ The Green Waste Recycle Yard is also capable of producing value-added building products like flooring and paneling for indoor use and boards suitable for decking.

[Bolinás Compost](#)

This facility, initiated in 1997, is operated by the Bolinas Public Utility District and Bolinas Fire. Staffed by two paid employees, this small compost operation yard accepts green material mostly from local homeowners and landscapers. In recent years, Bolinas Compost processed about 2,000 wet short tons of green materials per year. A local tree service

³⁷ These facilities include Sustainable Resource Management in Anderson, DTE Energy Services in Woodland and Stockton, and Pacific Ultrapower Chinese Station in Jamestown.

contracts to grind green material and logs prior to composting. All compost is given away to local agricultural producers, homeowners, and landscapers. It is certified by CDFA as organic input material.

In summary, Marin is expected to generate 81,000 wet short tons of green materials per year in the next decade as wildfire safety becomes a more routine part of landscape management. Currently, 61,000 wet short tons of green materials being generated in Marin are being composted, with a breakdown across the four facilities above included in Table 1-9. The other 20,000 wet short tons expected per year have no clear destination.

Table 1-9. Current Flows of Marin’s Biomass to Composting Facilities

Facility	Location	Green Materials (wet short tons per year)	Moisture Content
EarthCare (Waste Management)	Novato	50,100	50%
West Marin Compost	Nicasio	5,000	50%
Republic Services	Richmond	4,000	50%
Bolinas Compost	Bolinas	1,900	50%
As-yet Undetermined	---	20,000	50%
Total		81,000	

All of the compost facilities appear to have ready markets for compost produced, although Waste Management has reported that they have run out of customers willing to pay at their current price. However, Marin’s cities and county government need to purchase compost to meet their SB 1383 bioproduct procurement requirements. Current estimates are that jurisdictions in Marin County will be required to procure about 5,900 tons of compost per year, and this obligation could increase demand.³⁸ (See Appendix F.)

Co-Digestion

Some wastewater treatment plants deploy large anaerobic digesters that use microorganisms to deactivate sewage as a step in cleaning water. If permitted, non-sewage organic materials can be added to the digester and processed along with the sewage. This process is typically called co-digestion.

Marin has one wastewater treatment plant that has been co-digesting food scraps with its sewage. That facility is Central Marin Sanitation Agency (CMSA) in San Rafael. In 2014,

³⁸ Under SB 1383 until August 2025, Marin was obliged to procure roughly 20,000 wet short tons of recycled organic waste product (ROWP). Using the accepted conversion factor (i.e., 0.58 for compost), this obligation is equal to 12,000 tons of compost. However, after the passage of AB 2364 (2024), the obligation was changed for Marin to 10,100 tons of ROWP and roughly 5,900 tons of compost.

CMSA, in partnership with Marin Sanitary Service (MSS), launched a pilot program called Food2Energy that adds slurried food scraps to its digesters. MSS collects commercial food waste, processes it into a cake batter-like consistency, and transports it to CMSA. CMSA then adds this material to its digesters and co-digests it with sewage. As part of the pilot program, CMSA co-digests 3,100 wet short tons of food scraps per year (between 7 and 10 wet short tons per day). At full capacity their digesters could co-digest 14,200 wet short tons of food scraps per year (up to 40 wet short tons per day).

CMSA uses the biogas output from this co-digestion to generate electricity. A portion of this power is used onsite, and a portion is sold to MCE (formerly Marin Clean Energy).

Combustion Power

Combustion power plants (aka biopower or bioenergy plants) are a traditional user of biomass. Existing facilities were principally developed in the late 1980s and early 1990s in response to state and federal policies that mandated growth of renewable power and incentivized the creation of biopower facilities. Many of these facilities are reaching the end of their commercial service life of thirty to forty years, with limited replacement facilities being commissioned. As a result, biomass-based combustion power facilities are increasingly less common in California. There are no plants in Marin, although smaller direct combustion bioenergy facilities with more advanced emissions control equipment are being planned and developed elsewhere in the state.

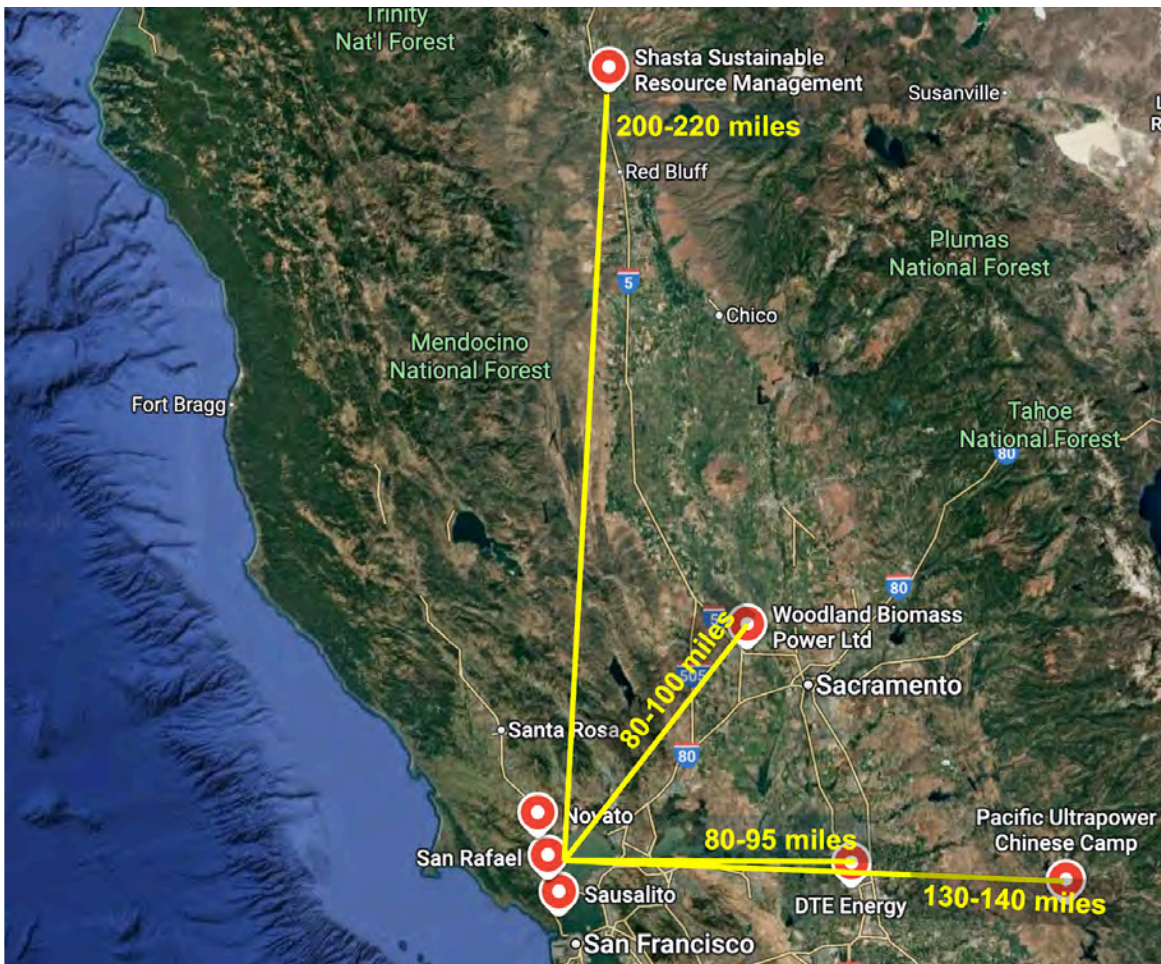
The Marin Resource Recovery Center, West Marin Compost, and Green Waste Recycle Yard are currently selling woody biomass generated in Marin to four power plants (Table 1-10). As illustrated in Figure 1-10, the distance from Marin to these power plants ranges from 80 to 220 miles. (In this study 100 miles is used as the average one-way shipment distance.) Sending biomass this distance results in a significant transportation cost for its sellers and buyers. It also is a significant source of greenhouse gas emissions in the biomass sector.

Sending woody materials to combustion power plants can also be logistically challenging. While the facilities listed in Table 1-10 deliver baseline power to the electrical grid, they have scheduled maintenance outages that can range from seven to thirty days. Like other power sources, the marketplace for biopower can fluctuate based on when electricity from these facilities is needed and sold into the electrical grid. As a result, the purchasing of woody materials by combustion power plants can create uncertainties for organizations who need reliable outlets for the biomass that Marin generates. Lastly, California may well face an oversupply of woody biofuels under the emerging wildfire safety regime and create more competition to be a supplier of fuels to these facilities.

Table 1-10. Power Generation using Biomass from Marin (flows in wet short tons per year)

Power Generation Facility	Generation Capacity (MW)	Woody Materials (all origins)	Woody Materials Generated in Marin		
			Metro Landscapes	Forested or Wooded	Both Landscapes
DTE Energy - Woodland, CA	24	320,000	30,000	3,000	33,000
DTE Energy - Stockton, CA	44	588,000	4,000	0	4,000
Jamestown Energy ³⁹ - Jamestown, CA	18	240,000	0	700	700
Sustainable Resource Management - Anderson, CA	35	467,000	0	1,500	1,500
Total	121	1,615,000	34,000	5,200	39,200

Figure 1-10. Location of Biomass Power Generation Facilities



³⁹ Previously, Pacific Ultrapower Chinese Station — as labeled by Google Maps in Figure 1-10.

Landfilling

Based on data in the Recycling and Disposal and Reporting System (RDRS) administered by CalRecycle, Marin generated and landfilled nearly 227,000 wet short tons of solid materials in 2021.⁴⁰ Over a dozen landfills received a portion of this material, but 99% of it went to three: Redwood Landfill in Novato (115,000 tons or 51% of the material stream), Potrero Hills Landfill in Suisun City (102,000 wet short tons or 45%), and Keller Canyon Landfill in Pittsburg (9,000 tons or 4%).⁴¹

Redwood Landfill

Redwood Landfill is owned and operated by Waste Management, Inc. The entire 600 acres commonly referred to as Redwood Landfill is segmented for different activities. Roughly 222 acres is allocated for waste disposal or landfilling. Roughly 200 acres is allocated for a combination of materials and recycling support and for its large EarthCare commercial compost operations. Roughly 180 acres is being managed by the Audubon Society to restore tidal wetlands and to protect wildlife habitat.

Redwood Landfill receives roughly 600,000 wet short tons of materials per year.⁴² These materials come primarily from Marin and Sonoma Counties and include soil, concrete, asphalt, paper, cardboard, glass, aluminum, appliances, food scraps, green materials, woody materials, digestate, and mixed debris (aka “garbage”). Waste Management segments these materials onsite into different operations, with the goal of sending them to their best utilization option.

One of these operations is a rough sorting system that can separate woody materials from other construction and demolition

Per Waste Management, in 2021 roughly 40% of the biomass flows at its Novato facility were mixed materials that were immediately interred into Redwood Landfill. Another roughly 40% were construction and demolition debris that underwent initial assessment to determine what could undergo processing and being sorted for other use, including use as daily cover in the landfill. The remaining 20% consisted of separated green materials that were sent to the onsite EarthCare operation for composting.

⁴⁰ This flow total is for all types of materials, not just biomass.

⁴¹ Totals that do not sum are due to rounding.

⁴² Plans developed for Redwood Landfill propose to expand its landfill disposal capacity by 8.5 million cubic yards and extend the landfill service life another 30 to 40 years. As part of this planning, Waste Management is looking into increasing the green material processes capacity.

(C&D) debris.⁴³ This operation produces half of the estimated 60,000 wet short tons per year of processed woody C&D materials that Waste Management goes on to use as daily cover at Redwood Landfill.⁴⁴ A portion of the C&D debris is sent to the Marin Resource Recovery Center operated by Marin Sanitary Service and the Windsor Material Recovery Facility operated by Pacific Sanitation.

Redwood Landfill operates a landfill gas recovery system and bioenergy production facility onsite. This 3.9-Megawatt facility was commissioned in 2017 and provides baseload power to MCE under a long-term power purchase agreement. Waste Management has considered development of a small community-scale bioenergy production facility fueled by processed tree trimming material and woody construction and demolition materials.

Current Biomass Fates

The previous section describes utilization options for Marin's biomass. This section explores where the main types of biomass go within the current system.

Woody Materials from Forests and Woodlands

As land managers implement fuel reduction projects, the logistics of biomass transport become increasingly important. Many fuel reduction projects are located near road systems allowing box trucks and conventional tree service chippers to be brought close enough for hand crews to collect and carry materials for removal. This can enable woody biomass to be managed into offsite utilization pathways. The feasibility of moving material is critical to creating alternatives to leaving biomass onsite. It can also reduce reliance on pile burning, the likelihood for pile fires to escape, and the air quality and greenhouse gas emissions that open burning creates. However, the high cost of removal and the lack of local, value-adding utilization options limit current removal options.⁴⁵

⁴³ Waste Management's operations previously included a clean lumber processing facility that would sort construction materials. It could process colorized chipped wood for use as landscape mulch. However, Waste Management decided that local markets did not support the landscape mulch processing operation. So, they decommissioned the facility. Waste Management also previously considered developing an advanced construction and demolition recovery line that could process 125,000 tons a year of cardboard, pallets, concrete, asphalt, and wood materials. However, this was not developed.

⁴⁴ Federal law requires landfills to be covered at the end of each workday to prevent odors, vermin, and insects. While landfills have traditionally utilized soil as ADC, many states allow the use of alternative materials (including organics such as wood waste) for cover.

⁴⁵ As an example, one might estimate the cost for collection, processing, and transport of forest and woodland biomass as between \$2,500 and \$3,200 per day for a three-person chipping crew. This would mean that removing biomass from fuel treatment locations would cost roughly \$570 per ton. However, when the cost of

For example, although wood chips have uses like mulch for landscaping, we found no evidence that the fuel treatment process was tapping into these uses. Instead, woody biomass from fuel treatment appears either to be left on-site or taken to transfer stations. This material may be sorted and segregated, and the woody portion may be sold as a woody fuel for biopower combustion facilities. As discussed in the next chapter, one interesting option that may be emerging is to co-process woody biomass and digestate into biochar.

Woody Construction and Demolition Materials

A large amount of woody materials are generated by new construction, remodeling, and building demolition. Based on best available data, Marin is expected to generate 118,000 wet short tons (94,500 dry metric tons) of woody construction and demolition materials per year. This woody biomass is often commingled with other building materials and flows into waste management supply chains via a combination of franchise hauling and self-hauling.

At present, deconstruction and reuse practices are reclaiming an estimated 200 wet short tons (150 dry metric tons) of woody construction materials per year. The rest of the Marin's building materials leave construction and demolition sites as various forms of mixed debris and enter waste management supply chains.

Most of this material undergoes some level of sorting and processing before its fate is determined. For example, Waste Management receives 62,000 wet shorts tons per year of potentially sortable C&D material at Redwood Landfill. After it undergoes initial sorting and processing, half (31,000 wet short tons per year) of this C&D stream is retained for use as daily cover at the landfill open face.⁴⁶ The other half (31,000 wet short tons per year) is sent to a combination of Pacific Sanitation in Windsor and the Marin Resource Recovery Center (MRRC) in San Rafael. At Pacific Sanitation, the C&D materials are sorting and processed for a variety

In 2022, Marin commissioned a study of its discard streams, in part to develop new strategies for managing them. This study determined that food scraps make up 16.3% by weight of Marin's total discard stream. A combination of yard waste, wood, and compostable paper products make up another 18.7% by weight.

burning and air impacts from pile burning are accounted for and internalized, biomass collection, processing, and transport may be less expensive than onsite burning.

⁴⁶ In recent years, Waste Management has explored options for more advanced on-site sorting and processing of woody construction and demolition materials. However, they have not developed a viable business model that has motivated investment in this infrastructure.

of uses, including daily cover back at Redwood Landfill. At MRRC recoverable woody C&D materials — both those that they receive directly and those received from Waste Management — are separated from the broader C&D stream. Those deemed suitable for use at combustion power plants are cut into 3" pieces and sold as fuel. (As illustrated in Figure 1-10, the MRRC transports 34,000 wet short tons of these materials to facilities in the Central Valley.) Other materials suitable for use as daily cover are cut into 6" pieces and sent back to Waste Management. Materials that cannot be processed and sold are sent back to Redwood Landfill for disposal.

Based on this series of flows and best available information about the level of sorting and recovery of construction and demolition materials, Marin sends 34,000 wet short tons (24,600 dry metric tons) to combustion power plants in the Central Valley. An estimated 200 wet short tons per year is reclaimed and reused through deconstruction practices. The remaining 84,000 wet short tons (61,000 dry metric tons) per year of woody construction and demolition materials, either as daily cover or waste.

Green Materials

Green Materials refers to grass clippings, leaves, and small branches, generally from management of parks, gardens, yards, and commercial landscaping. Sources of these materials include municipal material collection programs (i.e., green carts), self-haul by professional landscapers, municipal tree management, and the Chipper Day program run by the Marin Wildfire Prevention Authority. Marin has been generating 61,000 wet short tons of these materials per year. These all appear to make their way into composting operations, either in Marin or nearby. Over the next decade, Marin is expected to generate an additional 20,000 wet short tons per year of green materials.

Food Scraps

Marin Sanitary Service collects 3,100 wet short tons per year of source-separated, pre-consumer food scraps from businesses in Marin. These materials are depackaged, ground, and turned into a slurry with a consistency that allows it to be co-digested with sewage as part of the "Food2Energy" pilot project between Central Marin Sanitary Agency and Marin Sanitary Services. Separately, Recology Sonoma-Marin also collects 800 wet short tons per year of source-separated commercial food scraps. These are being sent to Napa Recycling for composting.⁴⁷

⁴⁷ The combined 3,900 wet short tons of food scraps going to co-digestion and composting are a fraction of the potentially recoverable food scraps from Marin's businesses. No food from residences are included in this number. Estimating that total and imagining its separation and recovery is beyond the scope of this study.

Digestate

Although Marin’s six wastewater treatment districts use different technologies to process sewage, all of the 16,500 wet short tons of biosolids that they produce each year are part of the definition of organic materials targeted for landfill diversion under SB 1383. More than half of Marin’s biosolids are currently sent to landfill. During dry periods of the year, some of Marin’s wastewater districts have contracts with commercial agricultural operations to apply biosolids as a soil amendment. A small portion of biosolids have also been sent to a thermal hydrolysis facility operated by Lystek in Fairfield, where they are an input to fertilizer manufacturing.

Summary of Marin’s Current System

Activities across Marin’s landscapes are generating flows of biomass. This chapter focuses on flows from the following types of activities and environments: fuel treatments in forests and woodlands to reduce wildfire spread and severity; vegetation management around Marin’s buildings that strive to reduce combustion risk and prevent property damage from wildfire; material collection systems that haul discarded organic materials away from Marin’s residences and businesses; off-farm processing of dairy and equestrian manure; and options for digestate (aka “biosolids”) from wastewater treatment.

In the past, Marin generated just under 210,000 wet short tons of biomass from these activities. In the next decade, Marin is expected to generate 248,200 wet short tons (roughly 139,150 dry metric tons). These biomass flows include woody materials — such as logs and stumps from roadway maintenance, wood chips from fuel treatments in forests and woodlands, and discarded wood products from construction and demolition. They include green materials generated from the work of commercial landscapers, nurseries, park managers, and homeowners. They include food scraps separately collected from businesses as part of programs to divert them from disposal in landfill. And they include dairy and equestrian manure sent off-farm and digested sewage from Marin’s wastewater treatment plants.

Figure 1-11 offers a composite picture of Marin’s current system for managing the combination of these materials. It illustrates how biomass flows through Marin’s economy and the fates or disposition of these materials. The left side of the diagram contains labels and vertical bars for the categories of biomass materials explored and assessed in this chapter. The colored bands extending to the right trace the management path of these materials. For example, the green band extending to the right from Green Materials at the

top of the diagram represents the flow of green materials that make their way into composting operations in or near Marin. The gray band flowing from Green Materials represents a flow of green materials into local landfills.

Figure 1-11. Projected Biomass Flows through Marin’s Current System
 (diagram read inputs on left to final products on right; width of line represents flow magnitude)

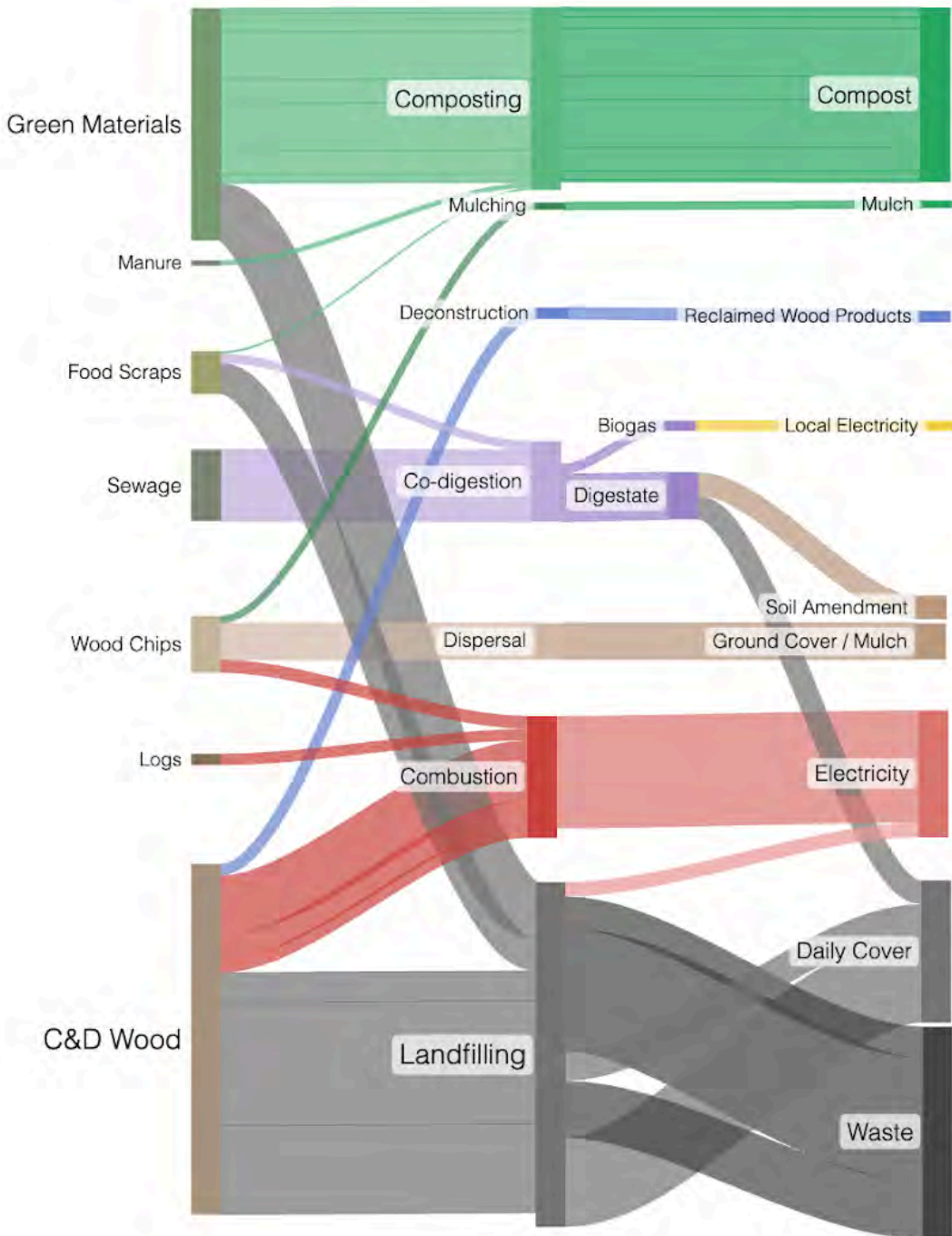


Table 1-11. Projected Biomass Flows through Marin’s Current System
(the categories and colors match the flows in Figure 1-11)

Biomass Type	Utilization Pathway	Annual Input		Product	Annual Output	
		wet short tons	dry metric tons		wet short tons	dry metric tons
Green Materials	Composting	61,000	27,500	Compost	31,800	14,000
Manure	Composting	1,800	360			
Food Scraps	Composting	800	240			
Wood Chips	Mulching	2,600	1,400	Mulch	2,600	1,400
Wood Chips	Dispersion	5,400	2,900	Ground Cover	7,900	4,300
Wood Chips	Dispersion	2,500	1,400			
Digestate	Dispersion	8,000	1,450	Soil Amendment	8,000	1,450
C&D Wood	Reclamation	200	150	Wood Products	200	150
Food Scraps	Co-digestion	3,100	800	Local Electricity	400 MWh per year	
Logs	Combustion	700	400	Electricity ⁴⁸	21,900 MWh per year	
Wood Chips	Combustion	4,500	3,300			
C&D Wood	Combustion	34,000	24,600			
Green Materials	Landfill	20,000	9,000	Electricity ⁴⁹	1,000 MWh per yr	
Digestate	Landfill	8,500	1,550	Waste and Daily Cover	123,600	74,650
Food Scraps	Landfill	11,100	3,000			
C&D Wood	Landfill	84,000	61,000			
TOTAL		248,200	139,150			

⁴⁸ Estimate calculated based on typical electricity production rate for biopower plants.

⁴⁹ Estimate based on assumptions about studied food scrap contribution to produced biogas.

Each of the colored bands in Figure 1-11 represents a different pathway for biomass materials. The wider the band, the larger the material flow. For example, Marin generates more woody construction and demolition materials than any other category. The largest share of this material currently flows into landfills. A good portion is sorted and chipped before being shipped to combustion power plants in the Central Valley. By contrast, the flow of wood chips from fuel treatment and roadway maintenance is smaller and has a more local fate. Much of the biomass generated during vegetation management in forests and woodlands is chipped and spread on-site or pile-burned. A small portion may be hauled offsite and may be mixed with the stream shipped to combustion power plants, absorbed into composting operations, or sent to landfill. Figure 1-11 also illustrates how materials converge and are intertwined. For example, a pilot co-digestion project at CMSA draws together raw sewage and source-separated food scraps in a process that converts them into a biogas used to generate electricity. Another pilot project called West Marin Compost receives a mixture of biomass types and its drop-off site and serves as a hub for directing them into pathways like composting, milling, or combustion power.

The biomass fates or dispositions are on the right side of the diagram. The fate for the largest percentage of biomass is waste in landfill or daily cover applied at the landfill working face at the end of each work day. Compost is the second most common fate, followed by use as fuel at combustion power plants. Next is dispersion on the landscape, either as wood chips and mulch left on forest and woodland floors or digestate applied to agricultural lands. The other current fate is biogas, the product of co-digestion, which is subsequently used as a fuel for producing local, renewable electricity.

Table 1-11 summarizes the flows and fates illustrated in Figure 1-11. Together, they depict how biomass flows in Marin's current system and how the biomass Marin is expected to generate in the next decade would flow if the system continues on its current path.

Interpretation of Marin's Current System

One objective of this study is to make the flows and disposition of biomass materials more visible, in order to facilitate evaluation of Marin's current system. The data in Figure 1-11 and Table 1-11 create a foundation for understanding the types of biomass flows that Marin is producing, how they are being processed, and where they end up. The following insights derive from these data:

- **Reliance on Landfilling and Combustion.** Over half of Marin's discarded biomass, particularly its woody biomass, is currently flowing to regional landfills or being transported considerable distances before being burned to produce electricity.

Landfill treats biomass as waste that truncates a cycle of regeneration, and it creates powerful greenhouse gases. Chipping and shipping biomass for combustion is expensive and exports a natural resource rather than growing local economic opportunities for its (re)use. Long-distance shipment also generates considerable greenhouse gas emissions.

- **Solid Start for Composting.** Marin is home to robust composting operations, and a very large portion of Marin’s source-separated green materials is being composted. This puts Marin in a potentially strong position to compost the expected growth in its flow of green materials, but systems and behaviors need to be expanded for this to happen. In the absence of such expansion, more green materials are likely to end up in landfills.
- **Limited Other Pathways.** Marin has successfully piloted a system for source-separating and co-digesting some of the most readily available commercial food scraps with sewage biosolids to produce electricity. There is room to expand this system. There are also other technologies and products that could be a good match for Marin’s biomass flows but are not currently available in Marin or readily accessible nearby, such as gasification, pyrolysis, and milling.

Marin’s current system contains some elements that can support transition to a more circular and regenerative biomass economy. However, this system is not on track to grow fast enough to manage Marin’s expected biomass flow increases. The large amount of material being exported or landfilled should be a concern. It demonstrates that Marin lacks access to optimal biomass utilization infrastructure. This means that Marin is not putting biomass to its highest and best use. It also means that Marin may struggle to meet its SB 1383 obligations and is missing opportunities to reduce greenhouse gas emissions enough to meet targets in its Climate Action Plan(s).

The next chapter identifies ways to improve the economic and environmental aspects of Marin’s current system. It does so by surveying readily available technologies for converting biomass into value-added products. It considers the potential of these conversion technologies and products to complement or amend the current system, with an eye toward growth of Marin’s biomass economy and local development opportunities, while reducing the county’s GHG footprint. It looks for ways to move biomass flows in Figure 1-11 out of the landfill (gray) and far-away combustion (red) pathways and to grow a system that produces higher and better value over the next decade and beyond.

Chapter 2:

Promising Alternative Pathways

Over half of Marin's biomass discards are currently ending up in landfills or being shipped out of the county at some expense and then burned to produce electricity sold into the grid. While Marin has a robust system for composting its green materials in the county or nearby, this flow is expected to increase thirty percent over the next decade as more businesses and homeowners cut vegetation to reduce wildfire spread and property damage. The current system is not prepared to absorb this growth. A fraction of Marin's food scraps is being diverted from landfill into a successful co-digestion pilot that produces renewable and locally used electricity. However, most commercial food scraps are still going to landfill. And while some of the remaining biomass is returned to the land in some fashion,⁵⁰ current practices do not maximize the economic and environmental potential of these materials.

The previous chapter describes the volumes and processing of Marin's current biomass flows. This chapter explores whether there are higher and better uses for these materials. It raises the question, are there alternative ways of managing these biomass flows with fewer downsides than the current system and with more potential economic and environmental benefits?

To develop an answer, this chapter surveys readily available technologies and evaluates their potential match for Marin's current and expected biomass flows. It also considers their potential to convert Marin's biomass into value-added products and their ability to improve Marin's existing biomass infrastructure. As it reviews different pathways, the chapter suggests a system with the potential to fit Marin's needs and improve system outcomes. This overall system is summarized at the end of the chapter and then carried

⁵⁰ Most of the biomass fuel treatments is being managed onsite in forests and woodlands. Some digested sewage from wastewater treatment is being applied or injected on agricultural lands for part of the year.

forward for more detailed environmental and economic analyses in the third and fourth chapters, respectively.

Assessment Approach

The survey in this chapter uses the concept of a disposition “pathway” to assess the match between Marin’s biomass flows and available conversion technologies. It is also used to assess the potential of a technology and its output product to be an economic engine for the collection, transport, and (re)use of biomass. That is, each pathway is screened not only for its ability to manage “away” biomass discards, but also its ability to finance better outcomes. In this sense, this assessment explores how well-chosen pathways can help offset the public costs of fuel treatment in forest and woodlands or landfill diversion.

The “pathway” concept is offered in this study as a way to compare a range of biomass disposition options. It is meant to serve as a way to talk about a single-step process (such as chipping and broadcasting biomass in a forest) or a value chain with multiple hand-offs, such as a series of actors who do some portion of biomass cutting, hauling, milling, manufacturing, and selling to create advanced wood products. The key point is that a pathway drives and shapes the flow of biomass, whether it is seen as a diversion option, recovery route, market channel or supply chain.

A pathway is a route and driver for moving biomass through the economy. It is the combination of a processing technology that converts biomass into something usable and a value-added product that makes it useful.

The objective of this chapter’s pathways assessment is to look beyond Marin’s current system dominated by landfilling and combustion. The survey of biomass pathways is meant to help Marin identify better matches for its expected biomass flows and to improve the economic and environmental outcomes of its biomass management system. This survey includes technologies that can create higher-value products, such as bio-feedstocks for advanced-technology industries. It includes technologies that give Marin access to next-generation fuels like hydrogen, that could create new local jobs, or that can help finance Marin’s wildfire prevention programs. The ultimate premise of this study is that a smart combination of pathways can help grow an economy that reduces and prevents wildfires, creates value-added products that can be used locally, provides local governments with operations for meeting their SB 1383 obligations, helps achieve greenhouse gas (GHG) reductions, and aids regeneration of Marin’s resources.

Survey of Pathways

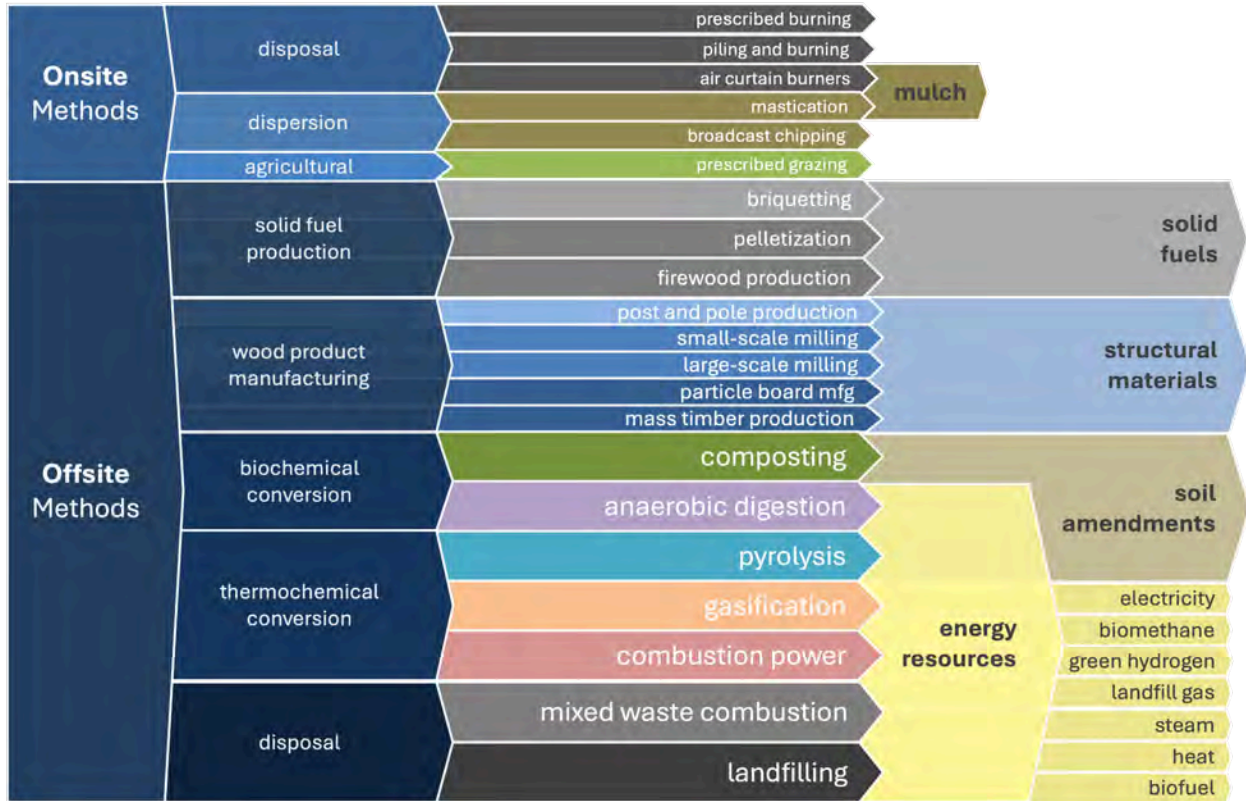
This section surveys management options and processing technologies that could be used to manage the kinds and amounts of biomass that Marin is expected to generate. The purpose of this survey is to explore options for turning these biomass flows into usable and useful products. It also lays a foundation for the analysis in the next section, which screens the potential of these pathways to synergize with Marin’s existing infrastructure and to provide economic, social, and environmental benefits.

The surveyed pathways vary in the types of biomass that they can absorb and in the kinds of products that they generate — i.e., from simple products like mulch and firewood to more complex manufactured wood products and bioenergy resources. The conversion technologies included are those deemed technologically ready enough for commercial use and feasible for near-term investment and implementation. (By comparison, technologies that have limited or no demonstration at a commercial scale are deemed more theoretical and not included.) The survey is loosely ordered from pathways using less complex or smaller equipment to those using more potentially more complex and capital-intensive processing equipment.⁵¹

The survey of pathways begins with technologies and methods used to manage biomass onsite (i.e., where it is first generated or mobilized). These do not transport biomass off the landscape or produce salable products. The survey then explores pathways that transport biomass to an offsite processing facility. Loosely speaking, this survey explores pathways that require smaller or less involved equipment before those that are large, more complex, or more capital intensive. For example, the pathways grouped under “Solid Fuel Production” use physical processes and relatively simple machines to convert biomass into energy resources. By comparison, those explored as “Wood Product Pathways” use both physical and thermal methods to convert biomass into building materials. The pathways considered “Biochemical” rely on biological and chemical techniques (e.g., management of microorganisms to decompose biomass) to produce materials and energy resources. The pathways categorized as “Thermochemical” use high-temperature processes to chemically change biomass into a mix of solid, liquid, and gaseous products. The final category of “Disposal” refers to pathways that treat biomass as “waste,” rather than a feedstock. (Figure 2-1 provides an illustration of these groupings, using a subset of surveyed pathways.)

⁵¹ Illustrations of pathway technologies are generated using AI and considered to be in the public domain.

Figure 2-1. Overview of Pathways Surveyed



Onsite Management

Marin is working to change the density and structure of vegetation in forests and woodlands to increase wildfire safety. Efforts to reduce wildfire fuel creates flows of woody biomass, not all of which can be easily removed from its point of origin. Hilly terrain and poor road quality can make biomass removal impossible or prohibitively costly. In those cases, fuel treatment programs may benefit from techniques for managing and leaving biomass on site. As described below, managed burning, dispersion, and grazing methods are components of such onsite management pathways.

Burning Methods

Several fire-based methods are used to manage forest and woodland residues, each with distinct benefits, limitations, and ecological impacts. These practices aim to reduce hazardous fuels, lower wildfire risk, and recycle nutrients, while also requiring careful attention to smoke, safety, and emissions. The following sections outline three common approaches — prescribed burning, pile burning, and air curtain burners — highlighting how each technique works and the considerations that guide its use.

Prescribed Burning

Intentionally setting fire can mimic ecological fire behavior on a western forest or woodland landscape. A managed fire can reduce ground litter, low branches, and the overall forest understory that enables wildfires to become more intense and destructive. In addition to reducing fuels, prescribed burns can promote growth of new vegetation, stimulate nutrient cycling in soils, and produce a landscape mosaic that enhances biodiversity. However, smoke from prescribed burns can be a danger to wildlife and humans and contributes to atmospheric greenhouse gases and black carbon particulates. Careful planning is needed to ensure that a fire does not alarm surrounding communities or burn beyond the planned area, or grow into a wildfire. Weather conditions, fuel moisture, and other factors must be carefully monitored to ensure that a fire is safe and can be contained. (For this reason, prescribed fires need to be carefully timed during the year.) Although prescribed burning releases greenhouse gases, and black carbon, models assume that controlled fires will produce fewer such emissions than wildfire.



Piling and Burning

Pile burning is the practice of collecting cut vegetation or logging slash into concentrated piles and igniting them under controlled conditions. This approach reduces residual biomass, lowers the risk of wildfire, and clears the forest or woodland floor for regeneration. By concentrating material, pile burning allows managers to more precisely control the intensity and extent of fire compared to broad-scale prescribed burning. However, smoke from piles can still affect local air quality and create visibility hazards, and poorly managed piles may leave behind scorched soil or damage nearby trees. To reduce risks, pile burning is generally conducted in winter or early spring when fuel moisture is high, and fire spread is unlikely. Even then, strict



monitoring, weather checks, and contingency planning are required to ensure piles burn completely and safely. Like other combustion-based practices, pile burning emits greenhouse gases and black carbon, though significantly less than the uncontrolled emissions from large wildfires. [Conservation burns](#) offer an additional strategy for reducing emissions from pile burning, while also producing biochar as a by-product.

Air Curtain Burners

Air curtain burners are portable devices that burn biomass under more controlled conditions than prescribed burns or pile burns. The main difference is that these devices blow a high-velocity stream of air across the opening of a combustion chamber and this airflow creates a barrier or "curtain" that reduces smoke and particulate matter. It also facilitates oxygen flow into the combustion chamber to facilitate more complete combustion of materials. The combustion chamber operates at temperatures between 1,200 to 1,800 degrees Fahrenheit and is considered hot enough for combustion of biomass into mostly carbon dioxide, water vapor, and ash although there is some emission of criteria air pollutants, but generally at levels below simple pile burning.



Air curtain burners can be used for a range of biomass — i.e., from tree limbs and brush to sawdust, agricultural residues, and digestate. The advantages of an air curtain burner is its ability to significantly reduce biomass volume, the ability to transport the device onsite (rather than transport biomass offsite), and an estimated 80-90% reduction in particulate matter emissions over open burning or pile burning. Because of their airflow management, air curtain burners can also be operated to produce biochar with quality depending on how the combustion and emissions are managed.



Dispersion Methods

Vegetation management that involves cutting trees, branches, and understory generates biomass in need of disposition. After it is cut, reducing the size and height of bulky materials can reduce its combustibility as well as make the landscape more traversable for fire and safety crews. This section describes techniques for size reduction and dispersion of biomass left on the landscape.

Mulching

Mulching is a general term for shredding biomass and applying it in a layer on top of soil. Applying mulch to land can have a variety of benefits: improved growing conditions, greater retention of soil moisture, moderated soil temperatures, reduced erosion, and suppression of weeds or invasive plants, as well as shielding the soil surface from wind, sun and rain. As mulch breaks down, it can also release nutrients and carbon to soil, increase fertility, and facilitate growth. In addition to reducing labor and irrigation needs, mulching can aid soil health by improving structure, encouraging beneficial soil organisms, and buffering against compaction. The use of mulch in a forest or woodland setting typically involves shredding and spreading biomass on site.

Figure 2-2. Production of Mulch with Mulching Technologies



The inputs are **woody biomass and green materials**. The output product is **mulch**. Two ways of generating mulch from woodland biomass are mastication and broadcast chipping, as described below.

Mastication

Mastication brings machinery to the landscape to grind and shred small trees, branches, and other forest debris into small enough pieces to leave behind as litter. Masticating biomass also makes it easier for firefighters to traverse the



landscape. There are arguments that masticating biomass improves forest health by speeding nutrient and carbon return to soil, helping to decrease erosion potential, and reducing competition between trees and their understory vegetation. That said, mastication can also disrupt habitat.

Broadcast Chipping

Like mastication, broadcast chipping is used to reduce the size of cut biomass and spread the resulting pieces on the forest floor. This option can be used when a portable chipper can be brought to a site to grind materials and spray chips. Benefits are similar to mastication — i.e., potential to return nutrients and carbon to soil, decrease erosion potential, and reduce competition for remaining vegetation. An even layer of wood chips can also help retain moisture in soil. Its downsides are that a significant layer of chips can reduce the amount of light that reaches the forest soil and inhibit the germination and early growth of some understory plants. The process of generating and distributing the wood chips can cause soil compaction and damage to the forest floor.



Grazing

Careful deployment of herbivores on a landscape can be used to control the growth of invasive plants, promote the growth of desired vegetation, and help restore native habitat. As part of a wildfire management plan, grazing planned with specific timing, duration, and intensity can help reduce fuel loads on the landscape and burn risk. Prescribed grazing can also help stimulate growth of new vegetation, improve soil health, and increase biodiversity by creating a more varied vegetation mosaic. This management approach can be a cost-effective and environmentally friendly alternative to mechanical or chemical controls, particularly for remote, steep, or sensitive areas.



Offsite Management

When movement of biomass off a landscape is feasible, it is possible to expand its economic uses by manipulating it physically, biologically, chemically, and thermally. The processing options can create fuels, electricity, wood products, and soil amendments, as well as other chemical and material feedstocks. This section surveys products made from a range of conversion technologies that are technologically mature, commercially available, and already in use.

Offsite management pathways differ from onsite management because they involve transportation. Without care, movement of biomass from one landscape to another can inadvertently transport pathogens or pests. In some cases, this becomes a barrier to offsite options altogether. In others, it can mean taking care to ensure that pathogens or pests are not tracked out, that none are released during transport, and that they are destroyed by the conversion process.

Offsite pathways can also aggregate biomass from different locations — either because a particular processing location provides common processing infrastructure for a particular kind of biomass or because its capital and operating plan depends on the sourcing and aggregation of materials that come from different locations and may benefit from economies of scale. This aggregation of materials from different locations raises two more issues for biomass pathways. One is the need for consistency of supply. Some processes, such as the biochemical and thermochemical processes discussed later in this chapter, are designed for biomass feedstocks of a particular type, size, moisture content, and inherent chemical composition. Assuring a stable supply is critical to ensuring operational stability, financial and economic viability, and output quality for bioproducts and biofuels. Seasonality of material flows (e.g., generation of biomass from wildfire safety programs primarily during dry months because of soil conditions, bird nesting periods, and other site access limitations) can make it more complicated to assure a consistent supply. Due to these and other potential supply interruptions, biomass utilization facilities typically need some feedstock storage, either onsite at the conversion facility or in satellite storage locations with convenient transfer, to enable continued operations until regular feedstock supplies can be restored.

Another way of looking at supply consistency is tolerance for heterogeneity or “contamination.” Contaminants can reduce processing efficiency by causing equipment wear, processing failures, and undesirable residues that lead to higher costs and inconsistent, lower-value products. When a facility receives inconsistent materials, it must

either tolerate variation in its process and products or sort and pre-process them at considerable expense. In some cases, physical conditioning or pretreatment of feedstocks, including several techniques mentioned here, may be needed to provide feedstock in appropriate quality and form for conversion to other products. Collection, handling, and processing systems should also avoid or reduce contamination of feedstocks — by plastics, soil, and other adventitious materials — to reduce the need for or required capacity of front-end separation technologies accompanying the primary utilization pathways at added expense. Pretreatment to improve feedstock quality can also be considered to alter inherent properties of feedstock, such as chemical or structural compositions, and to improve subsequent processing or conversion.

Among others, this chapter surveys a number of pathways focused on improving supply consistency, including several types of physical, biological, chemical and thermal processing. For example, deconstruction of buildings or other facilities instead of demolition, with manual or advanced sorting and separation, can substantially improve materials recovery and environmental performance over what is commonly possible from construction and demolition (C&D) materials, although costs may differ.

On balance, though, supply aggregation and consistency is largely beyond the scope of this chapter. It does underlie assumptions in the economic analysis in Chapter 4, but this study largely treats feedstock properties and qualities as something to be evaluated and considered during more detailed planning and engineering processes for a specific biomass project.

Densification Pathways

Densification refers to processes that compress wood fibers to reduce the overall volume and to cause pieces to cohere. When starting with larger biomass pieces, a densification pathway may involve grinding or shredding materials into smaller pieces, compressing them under high pressure into a desired shape (such as a bale, pellet, or briquette), and a drying step that decreases its transport weight and improves combustibility. The smaller size of densified biomass products makes their transport more economical. A higher energy density and lower water content can increase the efficiency of biomass combustion and decrease pollutant emissions. Densification can also produce more uniform and consistent particle size and distribution. It can produce feedstock characteristics important to other pathways like gasification and pyrolysis.

Densification pathways include the following technologies that change the size or density of the material but not its chemical composition.

Baling

Baling involves compressing biomass into large, rectangular bales using a baler machine. Baling is a simpler and lower-cost way to densify biomass than other forms of compaction like briquetting and pelletization, which require more complex machinery. Even though it produces less uniform shapes than these other technologies, bales are still easier to handle and transport offsite than loose biomass. Bales are also easier to stack and store when immediate use is not possible or when baling is an interim process step in a longer biomass pathway.



Figure 2-3. Production of Bales with Baling Technologies



The inputs for baling are **woody biomass and green materials**. The product output of baling is **bales**.

Compaction

Compaction uses machinery to press biomass into dense, uniform shapes. This process often involves grinding or shredding the biomass to create small particles, which are then compressed under high pressure and temperature to create pellets or briquettes. To make it more useful a fuel for heating or electricity generation, compacted biomass is often dried to reduce its moisture content and improve its combustion efficiency. Compaction requires more specialized and expensive equipment than baling. It also produces denser, more uniform products that are easier to handle and transport.

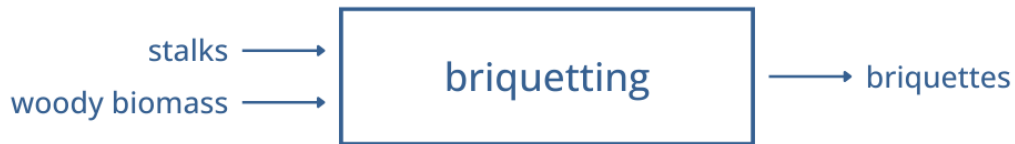
Briquetting

Chipped or shredded biomass from woody and agricultural sources can be densified into solid briquettes for more efficient storage, transportation, and utilization of its energy

content. Briquettes are formed by pressing the feedstock material under very high hydraulic pressure into small blocks, typically ranging from 2" to 4" in diameter and 4" to 6" in length. No binding agents are required to form briquettes. Therefore, they can be used as a direct substitute for firewood or other biomass fuels without any additional air pollution control requirements. Briquetting presses are available in a wide range of sizes, with throughputs ranging from as little as 60 pounds per hour (0.72 tons per day) up to 6,000 pounds per hour (72 tons per day).



Figure 2-4. Production of Briquettes with a Briquetting Press



The input materials for briquetting are **stalks and woody biomass**. The product output is **briquettes (an energy resource)**.

Pelletization

Similar to briquetting, pelletization can convert chipped woody biomass, shredded agricultural biomass, and sawdust into small cylindrical pellets using a mill. The difference is the smaller size of pellets, which make transportation and storage more efficient. The higher bulk density of pellets can also make them a more uniform and efficient fuel for gasifiers and combustion boilers. Pellets are typically less than 1" in diameter and range from 1/4" to 1-1/2" in length. Different from briquettes, they may use an additional binding agent. Moisture content must remain low (i.e., below 10% by weight) for the pellets to maintain their form. Wood pellet markets in particular are



well-established for both residential and commercial heating as well as utility-scale power generation, where they may be either co-fired with or used as a substitute for coal. Pellet mills generally benefit from economies of scale, with the largest systems having throughputs of more than 100 tons per hour. More commonly, pellet mills sized to handle local or regional residual biomass streams have throughputs of less than 10 tons per hour.

Figure 2-5. Production of Pellets with a Pellet Press



A wide variety of biomass types can be pelletized including crop residues, woody biomass, manures, biosolids and related materials when moisture and particle size are properly managed. The product output is **pellets** with a number of applications, principally as an energy resource.

Wood Product Pathways

Woody biomass like logs and branches can be transformed into fuels, structural materials, and value-added wood products that support both local use and industrial markets. The milling and processing technologies at the core of these pathways vary in scale, purpose, and complexity, as described below.

Milling Pathways

Physical manipulation techniques (like compaction, pelletization, and briquetting) process biomass primarily to make it usable as an energy resource. When the sought use is structural materials, these “manufacturing” techniques may be desirable:

Firewood Production

Firewood is woody biomass cut and prepared for use as fuel for heating or cooking. A consideration when choosing firewood is the burn characteristics of the wood. Hardwoods tend to burn hotter and longer than softwoods, but they may be more difficult to ignite. Softwoods are easier to ignite but burn faster and may



produce more smoke and less heat. Portable splitters are the equipment commonly used to make firewood.

The input for firewood production is **logs** from hardwoods like oak and eucalyptus or softwoods like pine and fir. The output product is **firewood**.

Post and Pole Production

Post and pole production turns woody biomass into timbers used in construction, agriculture, and landscaping for a variety of purposes, such as fence posts, utility poles, and signposts. Softwood species like pine and fir are the common source materials for posts and poles.

The starting point for post and pole production is the availability of logs that are suitably straight, large, and capable of having any knots and defects removed. Suitable logs are cut to the desired length and diameter using a saw or lathe, respectively. Ends may be chamfered or pointed, depending on the intended end use. To increase durability and resistance of wood to decay and insects, posts and poles may be treated with preservatives using a pressure treatment process before being dried to stabilize the wood. They may be further finished by sanding, staining, or painting for a desired appearance and increase resistance to weathering.



The inputs for post and pole production are **small diameter logs** (typically less than eight inches in diameter). The product outputs are **posts and poles**.

Small-scale Milling

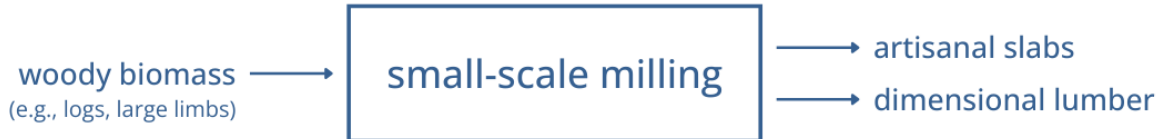
Small-scale milling cuts logs into wood products, typically at a lower volume and from smaller-diameter logs than an industrial sawmill. A small-scale mill can still be used to make common dimensional lumber, like 2x4s, 2x6s, and 4x4s that can be used to frame walls, floors or roofs or to build decks, fences, or other outdoor structures.



The timbers might alternatively be used to produce interior finish products like trim or moulding. Some small-scale mills may be portable. Redwood, pine, cypress, bay and fir are common input species in Marin.

At a small-scale mill, logs are cut into slabs that may then be cut to desired dimensions. When a wood kiln is available, wood may also be dried to remove moisture and improve strength and durability. In short, the product output of small-scale milling varies. It may include small dimensional wood pieces for furniture production or for manufacturing of composite wood products. At West Marin Compost in Nicasio, an electric band saw was used to cut a small volume of medium-diameter logs into artisanal slabs for architectural display or furniture production.

Figure 2-6. Production of Artisanal Slabs and Lumber via Small-scale Milling



The inputs for small-scale milling are **larger-diameter branches and medium-diameter logs**. The product outputs are **dimensional lumber and artisanal wood pieces**.

Large-scale Milling

Large-scale milling refers to the industrial process of converting logs into lumber and other wood products at high volumes, typically using larger-diameter logs and more advanced machinery than a small-scale mill. Larger mills are designed to produce a consistent, standardized output that meets the demands of construction, furniture manufacturing, and other wood-based industries. They often process softwoods such as redwood, pine, and fir, although hardwoods may also be milled depending on regional supply and market needs. The process involves debarking logs, sawing them into boards, and then planing, grading, and drying the lumber to meet commercial specifications. Kiln-drying is widely employed to reduce moisture content, which improves strength, stability, and resistance to decay. In addition to



dimensional lumber such as 2x4s, 2x6s, and 4x8s, large-scale mills may produce specialty products like engineered wood components, veneers, and wood chips for pulp or composite manufacturing. Because of their scale and efficiency, industrial sawmills play a central role in the modern wood products sector, supplying the raw material base for residential, commercial, and infrastructure construction while optimizing the use of available timber resources.

The input to large-scale milling is **logs**. The product output is **dimensional lumber and other commodity wood products**.

Composite Wood Product Pathways

Wood fiber is a key component of many wood products, including engineered wood products such as particle board, medium-density fiberboard (MDF) and oriented strand board (OSB). Wood fiber is obtained by mechanically or chemically breaking down wood into small pieces or fibers. Mechanical methods of fiber production involve grinding or chipping wood into small pieces, which are then further processed to create fibers. In contrast, chemical methods involve using chemicals to break down the lignin and other components of the wood, leaving behind pure cellulose fibers.

Figure 2-7. Production of Particle Board and Mass Timbers via Composite Production



The type and quality of the wood fiber used in wood products can have a significant impact on the properties of the final product. For example, longer fibers tend to create stronger, more durable products, while shorter fibers may be more suitable for softer, more flexible materials. In addition to the length and quality of the fibers, other factors that can affect the properties of wood products include the type of wood used, the processing method, and the adhesive or resin used to bind the fibers together. By carefully selecting and processing the wood fiber, manufacturers can create a wide range of wood products with varying properties and characteristics.

Particle Board Manufacturing

The manufacturing of particle board is a way to add value to wood chips, wood shavings, and sawdust in an engineered wood product. The manufacturing process grades and blends small wood particles with synthetic resins or binders under heat and pressure to

produce panels of desired thickness and density. These panels can be further finished with laminates, veneers, or coatings to improve durability and aesthetics and to fit applications like furniture, cabinetry, or flooring underlayment.

While not as strong as solid wood or mass timber products, particle board offers significant economic and environmental advantages by repurposing materials that would otherwise go to waste and reducing the demand for virgin timber resources. The downside is the limited applications for this product.



The inputs to particle board manufacturing are **small wood pieces and particles**. The product output is **particle board**.

Mass Timber Production

Mass timber refers to a category of engineered wood products made from solid wood panels, rather than small dimensional lumber pieces. These products are designed to be strong enough to replace traditional building materials such as steel and concrete in large-scale construction projects, while also offering environmental benefits such as lower carbon emissions and improved sustainability.

There are several types of mass timber products. These include cross-laminated timber, laminated veneer lumber, glued laminated timber, and dowel laminated timber. These products are made by bonding layers of wood together in a variety of configurations, using adhesives or mechanical fasteners to create large, solid panels or beams that can be used for walls, floors, and roofs in buildings.



Mass timber products have several advantages over traditional building materials. Among them is a lower carbon footprint than traditional building materials, given that production

of wood products requires less energy and emits fewer greenhouse gases than the production of concrete and steel, and the carbon contained in mass timber is considered sequestered for the life of the product.

Deconstruction and Reuse

Deconstruction and reuse save wood products after a first generation of use, with the goal of recapturing their value, as well as retaining their embedded carbon and displacing another generation of harvesting, processing and transporting new lumber.⁵² Deconstruction refers to activities that reclaim dimensional lumber, beams, joists, decking, and other finished wood products using techniques that intentionally remove and sort materials by type, species, and dimension. Deconstruction can refer to a range of activities (e.g., cleaning, denailing) that help reclaim wood products for reuse or repurposing in secondary products (e.g., engineered wood beams, furniture, and architectural finishes). For pieces that can be recovered intact, reclamation may also include regrading for structural reuse.

As an intention, deconstruction is a significant facilitator of reuse.⁵³ Its more intentional disassembly of a building makes it easier to recover construction materials for reuse.



Compared to demolition (i.e., knocking down a structure and sending materials into waste management together, generally to landfill), deconstruction facilitates separation and segregating on site. By more systematically dismantling and disaggregating structures (e.g., removing its fixtures and detaching its framing members, flooring and architectural elements), contractors can sort woody materials in streams that would otherwise become so commingled with other materials to render reuse impractical and even recycling

⁵² Reclamation and reuse can displace demand for virgin timber by, for example, bringing high-quality, old-growth redwood and fir back into circulation. This can, in turn, conserve forest resources, lower upstream energy and carbon impacts, and avoid downstream GHG emissions in landfills.

⁵³ For example, a typical 2,000 square foot single family home on a perimeter foundation in Marin can yield between fifteen to twenty tons of dimensional lumber from deconstruction, plus other wood products like doors, windows, trim, flooring, and cabinets. According to Green Lynx, with careful deconstruction between 60-80% of the wood products in a building can be reclaimed for reuse. (The percentage fluctuates based on the experience of the deconstruction team, the condition and installation method of the materials, the diversion goal, budget and timing allotted for the project.)

difficult. Reclamation and reuse benefit from local markets for wood product salvage and reuse. Market development can include local aggregation and sorting yards, local retail facilities for reclaimed materials, and direct-to-vendor and -consumer marketing. Technology innovation (e.g., easier ways to fasten and unfasten wood and other materials) can also advance deconstruction and reclamation practices.⁵⁴

In short, reclamation through deconstruction can salvage woody materials and create green jobs. Reuse can divert wood products from landfill and displace virgin lumber.

Biochemical and Thermochemical Pathways

Some pathways use combinations of biological, chemical, and thermal processes to convert biomass into manufacturing feedstocks, energy resources, or soil amendments.

While some biomass conversion processes are relatively straightforward, others require more substantial investments in equipment, facilities, and operational expertise. Processes like anaerobic digestion, gasification, and pyrolysis can be paired with subsequent processes that “upgrade” their outputs to alternative, new, or enhanced products. For example, the digestate produced via anaerobic digestion can be further refined through a process called thermal hydrolysis into a Class A fertilizer. Similarly, syngas from gasification could be followed by refining it into green hydrogen. Adding an upgrade step can create higher-value products that generate more revenue, provide new routes for local economic development, greenhouse gas reduction, and regenerative land management.

Biochemical and thermochemical pathways are presented below, generally in an order from lower to higher capital requirements.

Composting

Composting is a managed process of microbial aerobic decomposition that converts green materials and food scraps into a dark, crumbly, and earthy-smelling substance suitable for beneficial use as a soil amendment. In the presence of oxygen microorganisms (i.e., bacteria or fungi) break down biomass and produce enough byproduct heat to kill pathogens and seeds. Composting can involve simple backyard piles, but managing biomass for a region typically involves more complex, commercial-scale systems. Commercial composting uses specialized equipment to sort materials (to remove

⁵⁴For example, in 2025 the Cornell University Circular Construction Lab developed an AI grading tool for reclaimed lumber, and is working on a second phase to bring it to scale for the sector (Shi et al, 2025). Urban Machine (<https://urbanmachine.build>), based in Oakland, developed a “denailing robot” to enable scaling denailing operations. Finally, Pacific Reclaimed Lumber & Supply (<https://pacificreclaimed.com>) has launched an online marketplace for reclaimed lumber and is rolling out its programs to assist sellers and buyers in 2026.

contaminants) and grinds materials into more readily compostable sizes. It also uses material-handling equipment to manage the compost pile. Regardless of compost design, success depends on balancing carbon-rich materials (such as leaves, straw, or shredded paper) and nitrogen-rich materials (such as food scraps, grass clippings, or manure), moisture, and oxygen (for aeration).



Compost can be used as a soil amendment to improve soil's fertility, structure, water retention capacity, and carbon content. In addition to providing an alternative to landfilling, composting biomass and applying compost to soil can improve soil health and fertility, increase carbon storage, and improve soil's water retention capacity. Composting can also reduce demand for synthetic fertilizers and pesticides and increase crop productivity. To accomplish these benefits, and to assure the marketability of compost for conscientious uses (e.g., organic farming), biomass feedstocks and products need to be free of non-decomposable contaminants like plastics and concrete. Maintaining contaminant-free feedstock benefits from traceability back to the generator and education about segregation of materials.

Figure 2-8. Production of Compost via Composting (managed aerobic decomposition)



For this analysis, inputs to composting are **green materials, food scraps, manures, and digestate**. The product output is **compost**.

Anaerobic Digestion (also Co-digestion)

Anaerobic digestion is a biological process that breaks down organic matter in the absence of added free oxygen (e.g., air). The process occurs naturally in wetlands, swamps, and other oxygen-deprived environments. Industrial applications of anaerobic digestion are

used to break down sewage and manure and other biomass to produce a methane-rich combustible gas commonly called “biogas” and a semi-solid material called digestate.

The conversion of biomass into biogas and digestate using anaerobic digestion requires careful management of four stages of biological decomposition: hydrolysis, acidogenesis, acetogenesis, and methanogenesis. During hydrolysis, a colony of microorganisms releases enzymes that break down large organic molecules like carbohydrates, proteins, and fats into smaller molecules. During acidogenesis, acid-forming microorganisms break these smaller molecules down into smaller organic acids like acetic acid, butyric acid, and propionic acid. During acetogenesis, acetogenic microorganisms break down organic acids into acetate, hydrogen, and carbon dioxide. During methanogenesis, methanogenic microorganisms convert acetate, carbon dioxide, and hydrogen into methane. The semi-solid material at the end of this process is digestate. The biogas is composed mostly of carbon dioxide and methane. While biogas is combustible, cleaning it to remove impurities (especially hydrogen sulfide and water) or upgrading it is typically needed to reduce corrosion and emissions in application, such as in engines to generate electricity, or to increase its heating value, particularly if intended for utility pipeline distribution as renewable natural gas where strict compositional standards are maintained. The semi-solid residual digestate is nutrient rich and can be used as a soil amendment, but further treatment or refinement may be needed before it can be used. Source separation, feedstock inspection, and pretreatment may widen the range of materials that could be included in an anaerobic digester — e.g., by removing sand, plastics, and other adventitious materials so that they do not accumulate in reactors, inhibit digester processes, affect biogas compositions, or appear in digestates. Control of potential emissions (e.g., leakage of biogas) is also considered in project design.

Anaerobic digestion systems are differentiated based on the wetness of the operating conditions and input materials. These, as well as a potential upgrade thermal hydrolysis step, are described below.

Wet Anaerobic Digestion

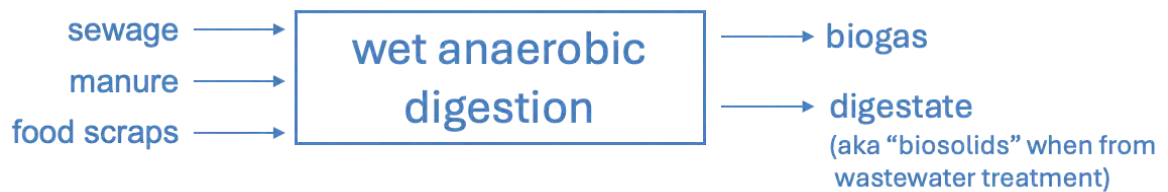
Wet anaerobic digestion is widely used to digest sewage, manure, food scraps, and wet agricultural residues. A wet anaerobic digester is a closed container capable of holding and mixing a viscous mixture of organic solids and water. A domed



diaphragm on top of a wet anaerobic digester is used to collect and hold the biogas generated during the digestion process.

The advantage of wet anaerobic digestion is its ability to process wet biomass (i.e., 85% water, 15% solids) like sewage. The disadvantage is its relative inability to break down the cellulose and lignins in woody biomass. Other considerations include its need for heat and a steady supply of water to maintain needed moisture levels to support the microorganism colonies to sustain digestion. Input biomass needs careful management as well as to ensure necessary biochemical conditions are sustained.

Figure 2-9. Production of Biogas and Digestate via Wet Anaerobic Digestion



The inputs to wet anaerobic digesting are typically wetter materials like **food scraps**, **sewage**, and **manure**. The output products are methane-rich **biogas** and **digestate**.

Dry Anaerobic Digestion

As its name implies, dry anaerobic digestion breaks down biomass that is not suspended in water. Instead, the agricultural residues, food scraps, and green material inputs are shredded or chopped into small pieces before being loaded into airtight chambers, where microorganism communities break them down. The system still uses water, but as a recirculating percolate for keeping the materials and microorganisms just wet enough to enable decomposition to proceed. The advantage of dry anaerobic digestion is this lower need for water and associated lower cost and complexity of the system. It also is better able to digest biomass with higher lignin and cellulose content than wet systems. The disadvantage of a dry anaerobic digester is its longer digestion time and a greater sensitivity to changes in input materials.



The inputs to dry anaerobic digestion are typically drier biomass types like **green materials** and **some woodier materials**. Like wet anaerobic digestion, the output products are methane-rich **biogas** and **digestate**.

Figure 2-10. Production of Biogas and Digestate via Dry Anaerobic Digestion



Gasification

Gasification is a thermochemical process for converting wood chips, agricultural residues, or other carbon-rich feedstocks into a combustible synthesis gas or “syngas.” At high temperatures and with limited oxygen present (e.g., from air or other oxidants such as steam), gasification breaks down the biomass into gas, solid, and liquid fractions with the gas serving as a fuel or synthesis gas (syngas). The gas contains hydrogen, carbon monoxide, methane, smaller amounts of other hydrocarbon gases, along with carbon dioxide, and, depending on the type of gasification system, nitrogen and other species. The resulting syngas can be burned directly for heat and electricity generation, cooled and cleaned for use in engines and other prime movers, or further refined into fuels and chemicals, offering a versatile energy carrier. The benefits of gasification are its ability to convert a range of biomass types into a useful energy resource and its potentially lower emissions of particulate matter and oxides of nitrogen (NO_x) than direct combustion (in well designed and managed systems). Depending on the type of gasification system, the solid product may be a biochar or ash, both potentially of economic value in downstream uses, including carbon sequestration and fertilizer, among others. Depending on the design of the reactor, feedstock quality, particularly feedstock size and form, as well as potential emission levels, need careful control and should be considered in system design and specification.



Figure 2-11. Production of Biochar and Syngas via Gasification



The inputs to gasification are drier types of biomass like **woody materials, nut shells, and some crop residues**. The output products are **syngas** and **biochar**.

Pyrolysis

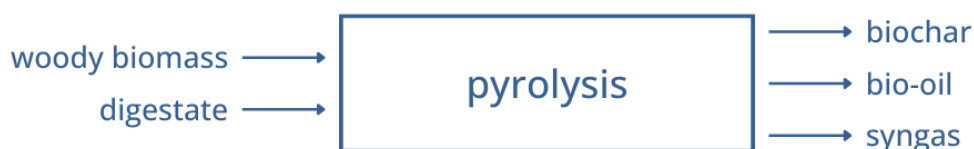
Pyrolysis is a moderate-temperature thermochemical technique for decomposing organic materials in the absence of added oxygen. Unlike combustors or gasifiers, pyrolysis reactors do not include direct addition of air or oxygen (or other oxidizers). Under heating alone, the feedstock decomposes into gas, liquid and solid fractions, typically with the intent to produce a majority of either liquids or solids depending on the reactor design and operating conditions. Pyrolysis is the principal method of producing biochars, although biochar of a different quality may also be produced in gasification. Pyrolysis is also used to produce bio-oils that can be further refined into useful biofuels. The gas, similar to the gas produced by gasification, may be used internally to supply energy for the pyrolysis, or cleaned and upgraded to a syngas for chemical synthesis or other fuel uses. The pyrolysis gas contains combustible gases including carbon monoxide, hydrogen, methane, and higher molecular weight species, the latter subject to condensation upon cooling of the gas. Carbon dioxide, carbon monoxide, and other oxygenated species also arise due to the oxygen in the biomass. The liquid product is called “bio-oil” that, generally after water removal, can be burned (e.g., as a heating oil alternative for an industrial or commercial boiler), upgraded to higher-grade liquid biofuels, or used for process heat in another industrial application. The solid product is called “biochar.” This carbon-rich material has multiple applications and may be further activated to improve utility and value (such as for activated carbon used in water purification and other applications). Biochar is also valued as a soil amendment, to increase soil carbon and enhance carbon sequestration.



Pyrolysis has been used for centuries to turn wood into charcoal for cooking and industrial uses. It is also used in metallurgical applications, such as converting coal into coke for steelmaking. Its use for managing forest and woodland biomass from wildfire prevention programs or for diverting biomass from landfill is relatively new.

The inputs to pyrolysis are similar to those for gasification and include drier types of biomass like **woody materials** or dry **digestate**. The output products are **biochar**, **bio-oil**, and **syngas**. Here again, feedstock characteristics may need careful consideration and control for proper reactor operations.

Figure 2-12. Production of Biochar and Syngas via Pyrolysis



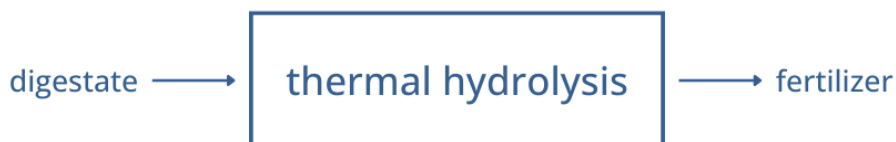
Upgrading Options for Biochemical and Thermochemical Pathways

Processes like anaerobic digestion, gasification, and pyrolysis can be paired with subsequent processes that “upgrade” their outputs to alternative, value-added products. This section describes these options.

Upgrade Option: Thermal Hydrolysis

Thermal hydrolysis is a high-pressure, high-temperature process that treats wastewater digestate to improve its suitability for use as fertilizer. In this method, digestate is heated with steam, typically at temperatures of 150–170°C, and held under pressure before being rapidly depressurized. This breaks down complex organic matter, destroys pathogens, and enhances the release of nutrients such as nitrogen and phosphorus, making them more bioavailable for plant uptake. The resulting product is a safer, more stable, and nutrient-rich material that can be applied to soils as a fertilizer, while also reducing odors and improving handling characteristics compared to untreated digestate.

Figure 2-13. Upgrading of Digestate to Fertilizer via Thermal Hydrolysis



The benefit of thermal hydrolysis is its ability to convert digestate into a higher-quality soil amendment.

Upgrade Option: Hydrogen Production

Syngas is principally composed of hydrogen, carbon monoxide, carbon dioxide, and methane. A process called reforming exposes biogas or syngas to steam in the presence of a catalyst to convert carbon monoxide and methane into carbon dioxide and hydrogen gas. Hydrogen can be separated for use as an energy resource. When biogas is used or when syngas is produced from a resource like biomass that is deemed renewable or “green,” the resulting product is called “green hydrogen.”

Figure 2-14. Upgrading of Syngas to Hydrogen via Steam Reforming



Hydrogen production facilities have significant economies of scale, and hydrogen production has been slow to expand into counties like Marin for this reason. However, a hydrogen production facility that uses biomass as a feedstock is being developed in Richmond on the grounds of the West Contra Costa Sanitary Landfill. In its initial phase, this facility is planned to process 100 wet short tons per day (or 36,500 wet short tons per year) of green materials and food scraps.

Upgrade Option: Renewable Natural Gas Production

Renewable natural gas is a term applied to methane that has been developed from renewable sources like biomass. In hydrogen production (see above), hydrogen is extracted from syngas and split off from hydrocarbons. Production of renewable gas is the opposite. It uses a high-pressure catalytic process called methanation to convert hydrogen, carbon monoxide and carbon dioxide to methane.

Figure 2-15. Upgrading of Syngas to Renewable Natural Gas via Methanation

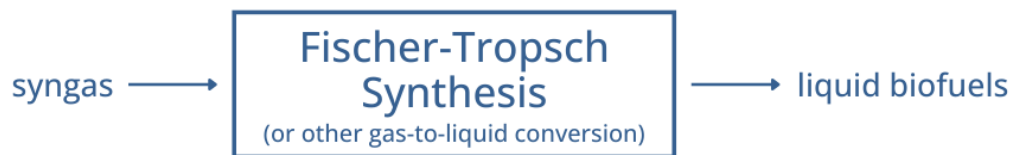


Although methanation technology has been demonstrated on a pilot scale as a way to make renewable natural gas from syngas, there are limited commercial-scale methanation plants that do so. Like hydrogen production, the capital costs and current market prices suggest that these projects require significant economies of scale to attract investment.

Upgrade Option: Biofuel Production

Syngas from gasification or pyrolysis can be converted to liquid products like gasoline, biodiesel, and aviation fuel. One well-established process is Fischer-Tropsch synthesis, a catalytic chemical reaction that can convert carbon monoxide and hydrogen to hydrocarbons. (The specific hydrocarbons produced are determined by the catalyst used and the temperature of the reaction.) One newer use of the Fischer-Tropsch process is the production of sustainable aviation fuel from biomass-based syngas.

Figure 2-16. Upgrading of Syngas to Biofuel



Upgrade Option: Electricity Generation

Biogas and syngas can be used to generate electricity. Each can be burned in an internal combustion engine or gas turbine connected to an electric generator. Generally, internal combustion engines are used for smaller generation projects, and gas turbines are used for projects at a utility scale (i.e., above 5 Megawatts of power production). Typically, upfront cleaning of the biogas or landfill gas or syngas is needed prior to combustion to remove impurities and to reduce air pollution.

Figure 2-17. Upgrading of Biogas or Landfill Gas or Syngas to Electricity



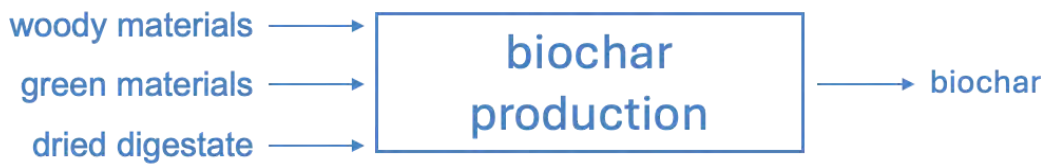
Upgrade Option: Biochar Production

Both gasification and pyrolysis produce a solid co-product called biochar. With an appearance similar to charcoal, this material output can be up to 90% carbon. In

gasification, about 5-10% of initial biomass is converted to biochar. For pyrolysis, yield of biochar from feedstock can range from 20-50%. The proportion and quality of biochar depends on the speed of the reaction, the temperature and oxygen levels in the reactor, and the physical and chemical characteristics of the feedstock used. So, the amount and quality of biochar depends on the way that gasification and pyrolysis systems are designed and operated. This means that an upgrade choice is to optimize these systems for biochar production.

Biochar has a wide range of potential applications, depending on its quality. Biochar contains carbon black, a material often used to darken materials like tires. It can be used as a water filtration medium to replace granular activated carbon, or as an additive to concrete mixes to improve both the compressive and flexural strength of structural elements. Some higher technology applications, such as creation of ultracapacitors as a form of energy storage, use high-quality carbon black produced through pyrolysis of plant residues. Biochar can also be applied to land, with a variety of benefits. Depending on production methodology and biochar quality, application of biochar to soil can sequester three metric tons of carbon dioxide equivalents per dry metric ton of biochar applied for decades to thousands of years. Biochar can also improve water and nutrient retention in soils and increase crop yields.

Figure 2-18. Biochar Production from Gasification and Pyrolysis



Combustion Pathways

Combustion or “burning” is the rapid combustion of biomass into heat and ash. It is the historically most common conversion technique for drawing energy from biomass. During combustion, oxygen and feedstock react exothermically. The theoretical outputs of combustion of biomass (and its carbohydrates, the principal organic components that burn) are carbon



dioxide and water. However, most combustion systems also produce a mixture of partially oxidized species such as carbon monoxide and hydrocarbons, oxides of nitrogen and sulfur (i.e., NO_x and SO_x), and particles of different sizes that, together, are called “smoke.” Simple combustion systems, like household stoves, provide localized energy. Larger-scale facilities use boilers and turbines to produce heat and electricity for industrial and utility applications. Efficiency and emissions vary depending on fuel quality and technology, with modern systems incorporating improved designs to reduce environmental pollutants and increase energy output. As with other conversion systems, feedstock quality needs to be considered in design and operation, and front-end processing is typically employed to remove oversized materials and adventitious metals.

A main advantage of combustion is its longstanding use and relative technical maturity. It can absorb a flexible range of biomass, such as wood, crop residues, compacted products, or even dried manures. It is a well-established application for heating and electricity generation. A major concern of combustion is pollution, although it is not alone in this regard and like other pathways, needs to meet environmental standards for permitting and operation when implemented. Even under controlled conditions, and like other conversion processes, it still releases air quality pollutants and greenhouse gases which may be offset, at least in part, through design of the feedstock production and conversion lifecycle. Carefully managed burning of vegetative feedstock from fuel treatment may, however, release fewer greenhouse gases than wildfire and uncontrolled anaerobic decomposition.

Inputs to combustion can be a **range of biomass types**. In industrial applications, common product outputs are **a heated fluid** and **ash**.

Figure 2-19. Production of Heat (and Steam) via Combustion



District Heating

District heating can support different uses of heated fluids from combustion. A district heating system moves a heated fluid like steam or hot water through an insulated piping network to support different uses. These could be space heating for a collection of buildings or a set of industrial processes that require heat to operate. The advantage of district heating is its economies of scale. A single, biomass-based boiler on a district heating

network can be an efficient and cost-effective way to provide heat for a variety of uses. District heating systems can accompany multiple types of thermal conversion systems including gasification and combustion, again with careful control of air emissions and other pollutants.

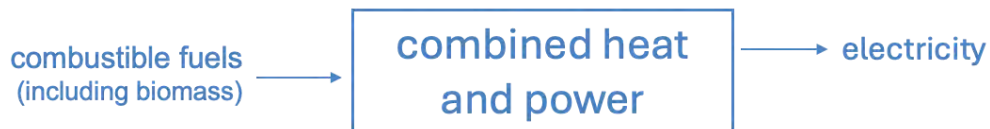
Figure 2-20. Production of District Heating via Combustion



Combined Heat and Power (also Cogeneration)

Electricity and process heat can be produced together in what is called combined heat and power. The hot fluid produced by burning biomass in a boiler can be used to drive a turbine connected to an electric generator. Gasification systems with heat recovery from turbines and engines can also operate in combined heat and power modes. Common "cogeneration" plants can produce 20-30 Megawatts of reliable power annually. The advantage of this approach is its ability to achieve efficiencies up to 80% through secondary use of the hot fluid (i.e., after production of electricity, including for district heating and industrial processing). Pollutant control is again essential to the design, although the higher overall efficiency means less pollution per unit of total output.

Figure 2-21. Co-production of Heat and Electricity via Combustion



Disposal Pathways

Disposal refers to the treatment of biomass as waste with limited/no further value. When unmanaged, these materials often end up in landfills, are openly burned, or decompose in ways that release methane and other greenhouse gases. Treating biomass simply as waste represents a missed opportunity for resource recovery, as it can instead be converted into energy, soil amendments, or other useful products.

Mixed Waste Combustion Systems

A “waste to energy” system is one designed for a complex, heterogenous input stream. Examples include mixed material discards from metropolitan landscapes (historically called “municipal solid waste”), agricultural residues, industrial byproducts, or hazardous substances that might be destroyed by burning. Biomass may be mixed into these material streams. That said, recovering materials from mixed material (aka “waste”) streams is beyond the scope of this study. The combustion of heterogeneous materials in a waste-to-energy system is generally complex and produces environmental impacts of considerable community concern. For this reason, it is mentioned but not considered a pathway that should be analyzed as a potential biomass utilization pathway for Marin.

Landfilling

Except those deemed hazardous (e.g., by contamination, chemical nature, or chemical treatment), **all types of biomass** are potential inputs to conventional sanitary landfill. As a disposal pathway, a landfill treats biomass as **waste** rather than a feedstock. However, modern sanitary landfills with vapor collection systems can also recover **landfill gas**, which can be upgraded to a fuel for transportation or electricity generation. Landfill gas is currently captured at Redwood Landfill and used to generate electricity, a portion of which is sold to MCE through a long-term power purchase agreement.



Findings from Pathways Analysis

The previous section lists biomass conversion technologies and their product outputs. In this section, these possibilities are evaluated to identify pathways that best match Marin’s expected biomass flows and that offer the most promising opportunities for advancing a functioning biomass economy and other benefits. The most promising pathways are then analyzed more thoroughly in subsequent chapters. The following screening categories are used:

- Pathway inputs and outputs,
- Technological factors,
- Greenhouse gas (GHG) emission or sequestration potential,
- Financial viability,
- Economic and social factors,
- Environmental factors, and
- Infrastructure readiness.

These categories contain eighteen individual criteria. Each of the thirty pathways and upgrade options explored is qualitatively scored on each criterion as positive (score = 2), neutral (score = 1), or negative (score = 0). Definitions and individual scores are detailed in [Appendix E](#). Each pathway is also given an overall score. This score is a simple summation of the eighteen individual scores. This overall score provides a basis for preliminarily ranking pathways based on Marin's existing infrastructure, expected biomass flows, and potential to create social, economic, and environmental benefits. (See Table 2-1.)

The scores in Table 2-1 showcase how pathways create different opportunities for Marin. Each pathway can transform biomass, but some offer better matches and show more promise as steps toward an improved biomass system. The eight top contenders (i.e., those with a score of 21 or higher) are Composting, Biochar Production, Wet Anaerobic Digestion, Gasification, Pyrolysis, Electricity Production, Dry Anaerobic Digestion, and Small-scale Milling. The capacity of these pathways to grow economic opportunity for Marin, reduce greenhouse gas, and produce other benefits is explored below.

The next section explores pathways that best match Marin's expected biomass flows and that offer the most promising economic and environmental potential based on known infrastructure in Marin, on public and private organizations working in the space, and on products and product uses. Each section concludes with a suggestion about ways to consider the pathway further.

Table 2-1. Overall Scores for Conversion Processes and Production Systems

Conversion Processes	Score	
Composting	29	pathways carried forward for further consideration in the section below
Biochar Production	26	
Wet Anaerobic Digestion	23	
Pyrolysis	23	
Electricity Generation	22	
Gasification	21	
Dry Anaerobic Digestion	21	
Small-scale Milling	21	
Reclamation and Reuse	21	
Prescribed Grazing	20	
District Heating	20	
Combined Heat and Power	20	
Reclamation and Reuse	19	
Broadcast Chipping	19	
Baling	19	
Post and Pole Production	19	
Biofuel Production	19	
Mastication	18	
Renewable Natural Gas Production	17	
Hydrogen Production	17	
Large-scale Milling	17	
Air Curtain Burners	17	
Briquetting	16	
Pelletization	16	
Firewood	16	
Mass Timber Production	16	
Particle Board Manufacturing	16	
Prescribed Burning	16	
Piling and Burning	16	
Landfilling	15	
Mixed Waste Combustion	10	

Composting and Land Application

Composting of green materials and food scraps is currently the most active and robust non-disposal pathway in Marin. There are four active composting facilities in or near Marin: (1) Waste Management's EarthCare operations on site at Redwood Landfill in Novato, which processes 140,000 wet short tons of green materials and food scraps per year, roughly 50,000 of which have historically been generated in Marin;⁵⁵ (2) West Marin Compost's biomass yard and co-composting system in Nicasio, which processes 5,000 wet short tons of green materials and 1,800 wet short tons of manure per year; (3) Green Waste Inc.'s recycle yard at the West Contra Costa Landfill in Richmond, which processes 4,000 wet shorts tons per year of green materials generated in Marin; and (4) Bolinas Compost's operation in Bolinas, CA, which processes 1,900 wet short tons per year. In total, these facilities currently process roughly 61,000 wet short tons of biomass generated in Marin.

Compost outputs are reported to CalRecycle on a quarterly basis and can also be estimated based on an assumption that 0.5 wet short tons of compost are produced for every ton of commingled feedstocks. Based on these numbers, Marin's current system produces around 70,000 wet short tons of compost per year. Just under 32,000 of which is from biomass generated in Marin. Waste Management sells its EarthCare compost into a variety of markets. Among them are vineyards growing organic grapes. West Marin Compost sells its compost to local businesses and residents, particularly those in the agricultural sector in west Marin.

Local jurisdictions represent an emerging market for compost purchase. Senate Bill 1383 includes an obligation for cities and counties not only to recycle biomass, but to procure outputs from biomass recycling operations. Compost is one of the product outputs that can satisfy this requirement.⁵⁶ Based on the formula that establishes the procurement target, Marin is obliged to procure roughly 9,500 wet short tons of compost per year. (See [Appendix F](#) for more detail.)

The current flows into compost, current compost sales, and procurement targets that can be met through compost purchase and placement are lenses for looking at composting's role for managing Marin's expected biomass flows. Over the next decade, Marin is expected to generate an additional 20,000 wet short tons of green materials (i.e., to grow from the 60,000 wet short tons it produced in 2023 to 80,000 wet short tons near the end

⁵⁵ The current 140,000 wet shorts tons per year of throughput for the EarthCare operations includes materials generated outside Marin County — mostly in Sonoma County.

⁵⁶ This requirement is in Section 18993.1 and is called the Recovered Organic Waste Product or "ROWP" procurement target.

of this decade). There is, theoretically, enough permitted capacity for EarthCare's composting operations to absorb the increase. However, at the current sale price for EarthCare compost, markets are currently saturated and diminish reason to invest in expanded operations.

This situation could change as local governments strive to meet their SB 1383 procurement targets. On behalf of all jurisdictions in the county, Zero Waste Marin has purchased and placed enough compost to satisfy the progressive procurement schedule that CalRecycle has established. A growth step is working with local producers so that all of this compost is purchased and placed locally, rather than elsewhere in California.⁵⁷ Local procurement may be attractive for a number of reasons. One is the ability to establish long-term contracts that support local producers and that assure ongoing access to compost. Another is the ability to work with other organizations in Marin to use procurement to build a more circular and regenerative biomass economy.⁵⁸ Such an economy would return carbon and other nutrients to soil through application of compost on local lands, such as degraded rangelands, croplands and urban park lands where social and environmental benefits may be maximized.

Give Further Consideration To:

- **Expansion of local composting**
- **Application of compost on local lands (e.g., rangelands)**

In sum, **additional investment in composting** should be considered. One way that composting should expand is in the processing capacity of composting operations. Without it, there are few outlets other than landfills that can absorb the expected increase of 20,000 wet shorts tons in green materials. Another avenue for expanding demand for compost is by explicitly linking the purchase of compost with the environmental benefits of its placement on agricultural and urban lands in Marin.

⁵⁷ One current barrier is the higher cost of local compost procurement and placement inside Marin, compared to sources and placement outside the county.

⁵⁸ A more circular economy means that biomass materials are managed within the county, rather than exported for disposal or management elsewhere. A more regenerative economy builds on the circular notion to place compost where it can help to nourish and rebuild Marin County soils.

Pyrolysis and Biochar Production

Marin has six wastewater treatment districts facing a similar challenge. They all need options for managing the digestate they produce, and they have limited utilization options. As discussed in Chapter 1, some digestate is applied to land during the dry months of the year. Most of the time, Marin's digestate is being sent to landfill. Co-composting digestate with woody and green materials is one possible alternative

Another option is co-pyrolysis of digestate with woody and green materials. In addition to providing a more resilient utilization option for digestate, this would produce a high-quality biochar — potentially for use as a carbon-rich soil amendment. As one of Marin's larger wastewater processors, Novato Sanitary District is exploring this option. They are considering repurposing land previously used for wastewater treatment and developing a system large enough to process all digestate produced in Marin. They have also expressed interest in designing the system to use biomass from fuel treatment as a co-feedstock. The imagined co-pyrolysis would process 16,500 wet short tons (3,000 dry metric tons) of digestate per year with 2,500 wet short tons (1,400 dry metric tons) of woody materials per year from shaded fuel break installation and maintenance.

Pyrolysis systems vary. For this application a slow pyrolysis design is imagined to maximize biochar production and economic feasibility — i.e., to yield up to 0.30 tons of biochar per input ton of biomass. This means that pyrolysis of 3,000 dry metric tons of digestate combined with 1,400 dry metric tons of woody materials (i.e., 4,400 dry metric tons together) would produce roughly 1,300 dry metric tons of biochar per year.

The biochar market is still nascent, and the price per ton of biochar fluctuates significantly. Prices for biochar used as a soil amendment in agriculture can rise as high as \$700 per ton and slide as low as \$90 per ton. Price support for biochar can come from carbon credits. Newer markets have supported carbon dioxide credits in the range of \$200-\$250 per metric ton. Applied to land, one metric ton of biochar can sequester between 2-3 metric tons of carbon dioxide equivalents (CO₂e). Carbon credits thus have the potential to provide considerable price support for pyrolysis, while also supporting biochar production and application as a carbon negative pathway.

Give Further Consideration To:

- **Development of co-pyrolysis for digestate and woody materials**
- **Application of biochar on rangelands**

In sum, **development of a co-pyrolysis and biochar production** system should be considered. This system would provide a sustainable solution for digestate from wastewater treatment, as well as provide a utilization option for woody biomass from fuel treatment. Further, it would provide a local source for the biochar that Marin is currently importing and another soil amendment that supports greenhouse gas solutions for the agriculture sector.

Additional Idea: Biochar Market Development

The last consideration is less of a pathway in its own right. It is more of an emphasis on facilitating the development of an economy that can make use of biochar.

Biochar is an increasingly valuable co-product of pyrolysis or gasification technologies. Along with sequestering a significant amount of carbon, biochar is increasingly being used as a soil amendment to aid in water and nutrient retention while increasing productive microbial activities in the soil.

Another promising application of biochar is as an amendment to compost and topsoil. As noted above, Marin County has developed a robust composting infrastructure composed of numerous green waste feedstock sources and multiple compost producers. Redwood Landfill, for example, has been producing certified organic compost (listed by the Organic Materials Review Institute or OMRI) through Waste Management's EarthCare operations for a number of years in order to serve various organic farms, orchards, and vineyards in Marin County and beyond. This mature composting infrastructure could be enhanced by greater availability of biochar-amended compost and topsoil.

The benefits of adding biochar to compost in particular have been extensively studied in recent years, and include the following:

- *Nutrient Conservation.* High surface area and porosity of biochar can help to conserve nutrients in compost through direct adsorption and by supporting beneficial microbial activity, reducing nitrogen losses by more than 50%.
- *Greenhouse Gas Reduction.* Ammonia (NH₃), the potent greenhouse gases nitrous oxide (N₂O), and methane (CH₄) can be substantially reduced via co-composting with biochar.
- *Odor Reduction.* Ammonia emissions are a contributor to undesirable odors from composting operations, which can be significantly reduced through application of 5-10% biochar by volume.

- *Compost Maturity and Stability.* The addition of biochar is reported to accelerate compost maturity, increase aeration, and reduce bulk density, thus reducing the processing costs associated with compost production.
- *Biochar Surface Functionality.* Compost improves the nutrient value of biochar as well as its ability to “lock up” various toxic compounds through increased adsorption.
- *Agronomic Benefits.* Recently published research demonstrates improved agricultural productivity from application of co-composted biochar compared with applying two soil amendments separately.

Along with the various types of compost and mulch it offers, West Marin Compost currently sells small quantities of biochar as a direct soil amendment, as well as biochar-amended compost and topsoil blended at 15% biochar. Sales of biochar and compost-amended biochar have been light to date; however, a more than tenfold increase in sales of biochar-amended topsoil between 2022 and the first half of 2023 were reported (from 35 cubic yards to 360 cubic yards). This amount is expected to increase as the benefits of this product as a soil amendment become better known and understood. Biochar for these products previously has been sourced from Pacific Biochar (located in Sonoma County). While this remains a potential source of biochar in the region, it could further benefit a local source for biochar using Marin’s expected flow of woody materials. This could include any of the pyrolysis or gasification pathways discussed in this chapter. Assuming a yield of 10%, gasification could produce 1,500 dry metric tons of biochar as a secondary product. This may be enough to meet the immediate market demand for biochar-amended topsoil.

In recent years, municipal uses for biochar have grown dramatically throughout the United States and Europe. Cities including Minneapolis, Minnesota; Boulder, Colorado; Stockholm, Sweden; and Helsinki, Finland are using biochar extensively in support of urban forestry, landscaping, and agriculture, stormwater filtration, and carbon drawdown.

As noted in the integrative work compiled by organizations such as the Center for Regenerative Solutions (CRS) , municipal applications of biochar offer a range of benefits touching on many of the fundamental goals of the Marin Biomass Project. These include: reducing GHG emissions and increasing long-term carbon sequestration, allowing

Give Further Consideration To:

- **Support for biochar production**
- **Growth of local biochar markets and uses**

productive reuse of organic waste generated through forestry, agriculture, and waste management operations in the county, and spurring the development of a sustainable bioeconomy in the Marin County region that can be replicated throughout California.

In sum, **development of biochar facilities and markets** should be considered. Biochar offers a practical way to sequester carbon, improve soil health, and reduce waste streams, making it a valuable tool for both climate resilience and sustainable land management. Supporting biochar market development helps public agencies unlock economic opportunities while advancing environmental goals such as emissions reduction, water quality, and soil restoration.

Wet Anaerobic Digestion and Electricity Generation

Marin already has a modest start on converting food scraps to electricity through combined wet anaerobic digestion and electricity generation systems. Marin Sanitary Service (MSS), the materials hauler and handler for much of eastern Marin, and Central Marin Sanitation Agency (CMSA) have partnered on a food recovery program. In this program MSS collects pre-consumer food scraps directly from restaurants, grocery stores, and other commercial food processors. After depackaging⁵⁹ and removing contaminants (e.g., plastics, paper, metals, etc), MSS grinds the food scraps and fats, oils, and grease (aka FOG⁶⁰) into a sludge that can be delivered by tanker truck to CMSA. At its wastewater treatment plant in San Rafael, CMSA further processes this biomass stream into a slurry that can be added to the anaerobic digesters it uses to process sewage.

Roughly 3,100 wet shorts tons of food scraps per year have been successfully co-digested with sewage as part of this system. The liquified food is added along with sewage to CMSA's 130,000 cubic foot anaerobic digesters. In this co-digestion system, food scraps are 11% by volume of the input stream. The co-digestion of sewage and food scraps produces a larger amount of biogas and digestate than the sewage would alone.

As is increasingly common in the wastewater sector, CMSA uses an internal combustion engine and electricity generator set on site to convert biogas to electricity. Using this system, CMSA is able to generate both heat and power to meet its onsite demand of roughly 600 kilowatts of electricity. Any electricity beyond that is excess, and MCE (formerly

⁵⁹ Depackaging is the process of separating food scraps from non-organic packaging, such as plastic and paper wrappings or metal and plastic containers.

⁶⁰ FOG is fats, oils, and grease generated by households and food service establishments, particularly from cooking and food preparation activities. Food service establishments generally have FOG containers that are serviced by companies that recycle the FOG for reuse or the production of energy in wastewater treatment facilities

Marin Clean Energy) purchases this electricity at a rate of between \$0.086 and \$0.105 per kilowatt-hour. Financial support for this project also comes from tipping fees. In addition to the avoided expenditure on electricity because of its onsite power generation and the revenue from sale of electricity to MCE, CMSA is paid \$24.50 per wet ton of food scraps received.

Previously, CMSA had only a 750-kilowatt generator on site. They now have a fully commissioned 995-kilowatt cogeneration system. This extra capacity means that CMSA could utilize more biogas and support additional electricity for sale to MCE. Thus, this pilot could potentially be scaled up to increase recovery of food going to landfill and generate more local, renewable electricity.

In sum, **additional investment in co-digestion and electricity production** of food and sewage beyond the pilot system should be considered. Assuming that the wet anaerobic digesters at CMSA can handle a 1:1 ratio of sewage and food, expansion of the pilot program could divert the remaining 11,100 wet short tons of commercial food scraps still going to landfill and produce a total of 3,100 MWh of renewable electricity per year.⁶¹

Gasification and Electricity Generation

Marin has no current outlets for using chipped, ground, or shredded woody materials as feedstocks for electricity generation. Instead, these materials are trucked to combined heat and power plants or independent power generators in the Central Valley, at distances up to 220 miles one way. Although this “export” of woody materials to bioenergy plants could be considered preferable to alternatives, such as landfilling, pile burning on the landscape, or leaving biomass to decay on the forest floor, chipping and shipping biomass has several drawbacks. One is the significant costs to transport biomass this distance. A second is the logistical headaches, given that large biopower plants can be inconsistent purchasers of biomass feedstocks. Based on demand on the power grid, biopower plants may run or shutter on short notice, may lower the purchase price of fuels, and may change fuel specifications based on their available feedstock supplies. This means that organizations

Give Further Consideration To:

- Scale up food scrap co-digestion pilot
- Sale of renewable electricity to local community choice energy program

⁶¹ CMSA believes that up to 40 tons per day of liquified food could be introduced into their digesters.

like Waste Management and Marin Sanitary Service must grapple with cost uncertainties and potential flow disruptions. A third is the opportunity cost. By exporting material, Marin is foregoing a potential annual revenue on the order of \$1 million per year from generation and sale of electricity.⁶²

Another drawback is the GHG impact of this approach. Assuming that trucks with combustion engines are used to transport the materials, shipping 34,000 wet short tons of woody materials per year to the Central Valley requires 2,000 trucking roundtrips and 320,000 heavy duty truck road miles.

Local gasification combined with electricity production is an alternative that local biomass handlers have been exploring. MSS has been exploring development of a biomass 2-Megawatt gasification system that would make local use of woody construction and demolition materials instead of sending them to biopower plants in the Central Valley.⁶³ The imagined project has already completed a required interconnection study with PG&E, has received a conditional use permit from the City of San Rafael, and has gone through some preliminary environmental reviews. The revenue model for this project has explored selling electricity to MCE at a price based on the BioMAT program, using electricity behind the meter to power a potential fleet of electric garbage trucks, and generating and selling carbon credits from biochar produced

Give Further Consideration To:

- **Development of gasification-based power plant**
- **Sale of renewable electricity to local community choice energy program**

⁶² If the energy content of woody materials is 8,000 Btu per pound, at a minimum power purchase price of \$60/MWh (e.g., from MCE), this opportunity cost could well be in the range of \$1 million annually.

⁶³ This size of facility is estimated to be capable of absorbing 14,800 dry metric tons of woody materials per year. If a modular system were designed and later expanded to 3 Megawatts, it could absorb 21,000 dry metric tons of woody materials per year — a meaningful redirection of materials destined for the Central Valley. While this is theoretically possible and even practicable, a 2-Megawatt system based on MSS's plans was imagined as part of this analysis.

as a secondary product.⁶⁴ Initial exploration of a project like this looks promising, but operational risks, price uncertainties, and market nascencies keep risks high enough that securing capital and investors has slowed forward progress.⁶⁵

Waste Management has also considered development of a gasification and electricity generation facility at Redwood Landfill. That preliminary design is for a 3- to 5-Megawatt facility and potential power sales of electricity to MCE and/or PG&E. A facility this size could consume up to 35,000 dry metric tons of woody materials per year — enough to divert all materials being sent to the Central Valley and then some. Because the landfill already has a power purchase agreement (PPA) in place with MCE for electricity generated from captured landfill gas (permitted for 3.9 Megawatts), they have existing infrastructure that could support development of a gasification project.

In sum, **development of a gasification and electricity generation** system should be considered. This system would vastly reduce, if not eliminate, the costly chipping and shipping of biomass to the Central Valley. It would also create local, renewable power that is a priority for MCE.

Dry Anaerobic Digestion

Dry anaerobic digestion relies on many of the same principles as wet anaerobic digestion to decompose biomass into biogas and digestate. One of the primary advantages over wet anaerobic digestion is the reduced need for water and the greater ability to introduce woody materials to the digestion chambers. Given that woody materials make up a large

⁶⁴ Because 90% of the feedstock supply would be clean, processed woody construction and demolition material, a program like the BioMAT program would consider this facility eligible for the Category 1 electricity tariff. The financing of a gasification system is more attractive when Community Choice Aggregators (CCAs) have a rate structure like California's Bioenergy Market Adjusting Tariff (BioMAT) program. This feed-in-tariff (FIT) program, established in 2012 by Senate Bill (SB) 1122 and implemented in 2015 by the three large investor-owned utilities (IOUs) in the state — Pacific Gas & Electric (PG&E), Southern California Edison (SCE), and San Diego Gas & Electric (SDG&E) — would represent a step change for CCAs, allowing previously uneconomical bioenergy projects to be competitive with other renewables. For example, the current FIT price available for new renewable energy projects from MCE (the regional CCA, formerly Marin Clean Energy) is \$60 per Megawatt-hour (MWh). Bioenergy projects participating in a tariff like the previous BioMAT program could receive at least \$127/MWh for plants fueled by municipal wood waste (BioMAT Category 1), or up to \$199/MWh for facilities utilizing feedstocks sourced from sustainable forest management practices (BioMAT Category 3).

⁶⁵ These concerns could be assuaged by the higher tariff potentially available through the BioMAT program and MCE, as well as the emerging market for the biochar that would be produced as a co-product of the gasification process. This could include both revenues from direct biochar sales (currently valued at \$200-800/ton, depending on the producer) as well as the sale of carbon dioxide removal (CDR) credits in one of the voluntary markets, now valued at approximately \$250 per ton of biochar (based on \$100/ton of carbon dioxide equivalent (CO₂e) and a factor of 2.5 tons of sequestered CO₂e per ton of biochar).

percentage of Marin’s biomass stream, dry anaerobic digestion could be a valuable part of an integrated biomass management system and functioning biomass economy.

At present, Marin has no dry anaerobic digestion capability. The closest facility that uses this technology is in Napa County, and that facility is still relatively new and novel.⁶⁶ Like a wet anaerobic digestion system, the dry digestion chambers will produce a methane-rich biogas that can be used as a fuel. Different from the food scrap pilot at CMSA, the biogas will be cleaned, compressed and dispensed as compressed natural gas, a transportation fuel, and dispensed at an onsite fueling station for the municipal garbage fleet.

In sum, **additional exploration of dry anaerobic digestion** may be worth considering, should enough biomass be available to justify development or expansion. This would be particularly true if Marin needed to process a commingled biomass stream that includes not just food scraps, but also green and woody materials — such as the stream from residential green cart collection.

Consider in the Future:

- **Development of dry anaerobic digestion for hard-to-separate streams containing woody biomass**

Small-scale Milling and Wood Products

Milling in California declined considerably in the last three decades, particularly as public lands across the State shifted their management regimes from timber harvesting to mixed-use and recreation. A considerable amount of milling infrastructure and economy has been mothballed or left to degrade. The creation of a biomass economy that can support wildfire safety is causing a resurgence of interest in milling around the State as a biomass solution.

Marin is fortunate to have recent experience with milling. To manage larger-diameter logs from roadway maintenance and other sources, West Marin Compost installed a small mill that

Give Further Consideration To:

- **Resumption of small-scale milling**
- **Milling as a regional biomass solution**

⁶⁶ See ww2.arb.ca.gov/sites/default/files/classic/fuels/lcfs/fuelpathways/comments/tier2/d0014_summary.pdf

cut whole logs into artisanal slabs for architectural and decorative uses. A facility of this size could, in theory, also produce modest amounts of dimensional lumber or pieces of mass timber elements, if the volume supported it. However, public concerns about land uses required the sawmill to close. So, while it could be restarted, it is currently shuttered.⁶⁷ As a result, logs that were previously milled are now being chipped and shipped to combustion power plants in the Central Valley or converted to landscape mulch. Increased carbon sequestration is another reason to consider reopening the sawmill. Long-lived wood products can sequester carbon for many decades, compared with the very near-term GHG emissions from bioenergy generation.

In sum, **resumption of small-scale milling** should be considered. The mill would eliminate the need to chip whole logs and ship wood chips to the Central Valley for combustion and support longer-term carbon storage in durable biomass products. Further, it would potentially dovetail with efforts around the State, including in Sonoma, to pursue milling as a component of a functioning biomass economy.

Combustion Power

Biomass can serve as a renewable feedstock for combustion-based electricity production, offering the benefit of displacing fossil fuels, utilizing organic waste streams, and contributing to carbon-neutral energy systems when sourced sustainably. However, when biomass must be transported long distances from its origin to the power plant, the environmental and economic benefits can be diminished by the fuel, emissions, and costs associated with transport. In such cases, the net carbon savings may be reduced, and the process can compete unfavorably with more localized or efficient renewable energy options. Thus, while biomass combustion can play a valuable role in a diversified energy mix, its overall sustainability is highly dependent on feedstock sourcing, transportation logistics, and life-cycle impacts.

Give Further Consideration To:

- Reducing export and long-distance shipment (e.g., local renewable electricity generation)

⁶⁷The land where the sawmill sits is owned by the Marin Municipal Water District (Assessor Parcel Number 121-230-24) and is zoned A-2 Agriculture Limited according to county records. A sawmill in this zone requires approval and conditions from Marin County.

For these reasons, **alternatives to far-away combustion biopower** should be considered. Gasification and electricity generation is one alternative. Another is productive local use of timber fibers through milling and, if volumes justify it, timber product manufacturing.

Landfilling

Sanitary landfills are used to improve the public health of urban environments by removing materials that could create nuisance or disease vectors. They serve this purpose by sequestering materials away from human populations. For years biomass categorized as “waste” has been the largest category of material flowing into Bay Area landfills. We now know that biomass can cause significant GHG emissions when landfilled. In addition, landfill also prevents beneficial terrestrial cycling of carbon and other nutrients.

Give Further Consideration To:

- **Ways to Divert More Biomass from Landfill**

In sum, efforts to **decrease biomass landfilling** should be prioritized. Each ton of material diverted from landfill is another ton of resource that can advance a functioning biomass economy, as well as help achieve Marin’s GHG reduction targets.

Additional Consideration: Expansion of Deconstruction and Reuse

Marin has a promising start on reclamation and reuse, with a few companies already providing deconstruction as a primary service. Although Marin does not currently have any retail businesses in the reuse sector, reuse facilities in adjacent counties offer partnerships and market channels for construction materials and other wood products reclaimed in Marin.⁶⁸ An average of 200 wet short tons of salvaged building materials and other wood products currently flow through this pathway each year.⁶⁹

Deconstruction and hauling companies are exploring alternative collection systems, such as salvage boxes and pilot projects that segregate materials directly at construction sites, to

⁶⁸ Marin was home to a reuse facility called “The Away Station,” but it closed down in 2017. Despite the pandemic and this one closure, according to Nicole Tai at GreenLynx, the reclamation and reuse sector has been mostly steady in the last ten years.

⁶⁹ Reclaimed lumber and wood products are dried wood products and have moisture contents lower than freshly cut wood. For the purposes of this study, the moisture content for all dried wood products — including construction and demolition debris — is assumed to be 20%, even though longstanding wood products may have a moisture content as low as 5%.

support near-term growth in reclaimed wood reuse. Expansion of manufacturing capacity and end markets — particularly for cross-laminated timber and furniture built with reclaimed wood — could provide needed price support, as would certification systems and building code changes that allow reclaimed lumber in factory-built and small stick-built structures such as accessory dwelling units. Local initiatives and state-level actions, including public education campaigns, deconstruction ordinances, and incentives to expand reuse facilities, would further expand this pathway. (For example, a national effort to allow salvaged lumber to be used for structural applications within the International Building Code for 2027 will directly benefit the deconstruction industry.)

Give Further Consideration To:

- Advancement and diffusion of reclamation practices and reuse
- Expansion of local operations and facilities

In sum, **expansion of deconstruction and reuse** should receive further consideration. In addition to its potential to divert materials from landfill, deconstruction and reuse has been a vehicle for creating small businesses, green jobs, and high-road opportunities for the local populations, as well as incubating wood product art and innovation. Each ton of salvaged wood product retains its current carbon content and avoids greenhouse gas emissions associated with its landfilling. It also displaces the greenhouse gas emissions associated with bringing virgin products to market.⁷⁰ The possibility of growth in this sector, particularly with modest support,⁷¹ underlies a projection that 10,000 wet short tons of reclaimed wood products could flow through this pathway in the next decade.

Additional Consideration: Improved C&D Sorting and Recycling

The largest component of landfilled biomass in Marin County is construction and demolition (C&D) material. Around 200,000 wet short tons per year of woody biomass are sent to area landfills, about 40% of which is estimated to originate within Marin. On

⁷⁰ Data on carbon sequestration and displacement for deconstruction is available from a few studies. For example, a study at Cornell University concludes that, compared to demolition, deconstruction can prevent 75% of embodied carbon emissions, as well as create thousands of new green jobs and divert substantial tonnages of waste (Heisel et al, 2024). The California Air Resources Board has also developed a GHG emissions reduction methodology for reclaimed lumber, flooring, doors, and cabinets (CARB, 2020).

⁷¹ Current deconstruction efforts are facilitated by the Reuse Alliance (a nonprofit advocacy coalition) and by the Bay Area Deconstruction Working Group hosted by US EPA Region 9.

average, around 31,000 wet short tons of woody construction and demolition materials are sent to the Marin Resource Recovery Center (MRRC) in San Rafael and to Pacific Sanitation in Windsor for sorting and sale to biopower plants in the Central Valley. An almost equal amount is separated and ground for use as an end-of-day cover over garbage at the active, open face of the landfill. The rest is buried in the landfill.

For these reasons, ways to decrease landfilling are needed. The commingling of biomass — both with other types of biomass and with other materials — makes it unsuitable for the other pathways considered. Investment in additional source separation and recovery systems is needed before higher and better use of biomass is possible.

There are alternatives. Waste Management has considered the development of more advanced sorting and separation operations at Redwood Landfill. This type of facility can process up to 125,000 tons/year of cardboard, pallets, concrete, asphalt, and woody materials and make them available as a bioenergy feedstock.

In sum, **expansion of source separation and enhanced recovery systems** should be considered further. These techniques make biomass reuse more available and economically viable, thereby preventing waste and increasing resources.

Give Further Consideration To:

- **Diversion through better source separation of biomass**
- **Enhanced sorting and recovery systems**

Summary of Promising Alternative Pathways

Marin's current biomass economy is dominated by disposal and combustion pathways. As summarized in Chapter 1, over fifty percent of biomass is either landfilled or burned after being transported considerable distance. Marin's composting pathway is also robust. It recycles Marin's green materials and sells the compost it produces. Marin's pilot co-digestion pathway helps to divert food scraps from landfill and generate local, renewable electricity. Overall, this system lays a foundation for a functional biomass economy.

The survey and analysis of a wide variety of pathways provides a basis for choosing a set that can do better. As identified in the previous section, these include the following:

- *Composting*: expansion of the current system to accommodate projected growth in the flow of green materials and to use compost as a soil amendment on rangelands, croplands and urban lands in Marin.
- *Pyrolysis and Biochar Production*: development of new infrastructure that co-pyrolyzes digestate from Marin's wastewater treatment plants and woody biomass from wildfire prevention projects and produces high-quality biochar that can be used as a soil amendment, among other options.
- *Wet Anaerobic Digestion and Electricity Generation*: expansion of the successful food scrap co-digestion pilot to maximize both food scrap recovery and generation of local, renewable electricity.
- *Gasification and Electricity Generation*: development of new infrastructure that makes local, higher-efficiency use of woody construction and demolition materials — thereby avoiding long-distance transport and generating local, renewable electricity.
- *Small-scale Milling*: revive the milling of locally generated logs to create value added wood products such as slabs, and small dimensional timber products.

Along with these pathways, dry anaerobic digestion was also identified as a pathway with promise, particularly for managing commingled and hard-to-separate biomass streams, such as the flows from green-colored receptacles, whether bins at businesses, in parks, or along streets or residential green carts used to collect organics at a curbside. This pathway may be one to consider for investment in the future, when it can be more closely matched to identified biomass streams.

This chapter's assessment also reflects on the role of exporting and landfilling in the next phase of Marin's biomass economy. Landfilling offers a kind of convenience — i.e., a limited investment in preparing or modifying a biomass stream. However, this comes at an opportunity cost associated with wasting the materials, as well as externalized costs like GHG emissions. For this reason, the inference drawn in this chapter is that future systems should decrease biomass flows to landfill.

A similar inference is drawn for direct combustion, but for different reasons. At present directing biomass into a combustion pathway for electricity generation requires long distance transport of materials that is costly and carbon intensive. Thermal biomass power plants in California are also limited in number and capacity. The location of these plants makes them a potential economic outlet for woody materials from wildfire safety programs in the Sierra Nevada and other northern California lands and for Central Valley agricultural residues in offsetting air pollutant emissions from open burning. Rather than incurring costs associated with transport to combustion power plants, this chapter outlines alternatives for local use, such as pyrolysis and gasification pathways under consideration for development. Whether in-county or in association with neighboring locales, a combustion pathway could be a viable option as well. Like other systems, a local combustion pathway would need an extensive and detailed assessment, including consideration of potential air quality and other environmental impacts and economic feasibility. Absent any start to this in Marin, pyrolysis and gasification are carried forward for further consideration in subsequent chapters.

In sum, there are many ways that biomass can flow in an economy. The objective of this chapter is to assess whether an alternative set of biomass pathways might increase associated economic and environmental benefits. The multi-factor analysis in this chapter considers Marin's biomass flows and current infrastructure as well as the environmental and social benefits and economic opportunities associated with a range of pathways. Based on this analysis, the set of alternative pathways in Figure 2-21 and Table 2-2 are explored further in Chapters 3 and 4 as a potential improvement on Marin's current system.

Figure 2-22. Potential, Alternative System for Marin's Expected Biomass Flows
 (flow diagram read from input materials on the left to final products on the right)

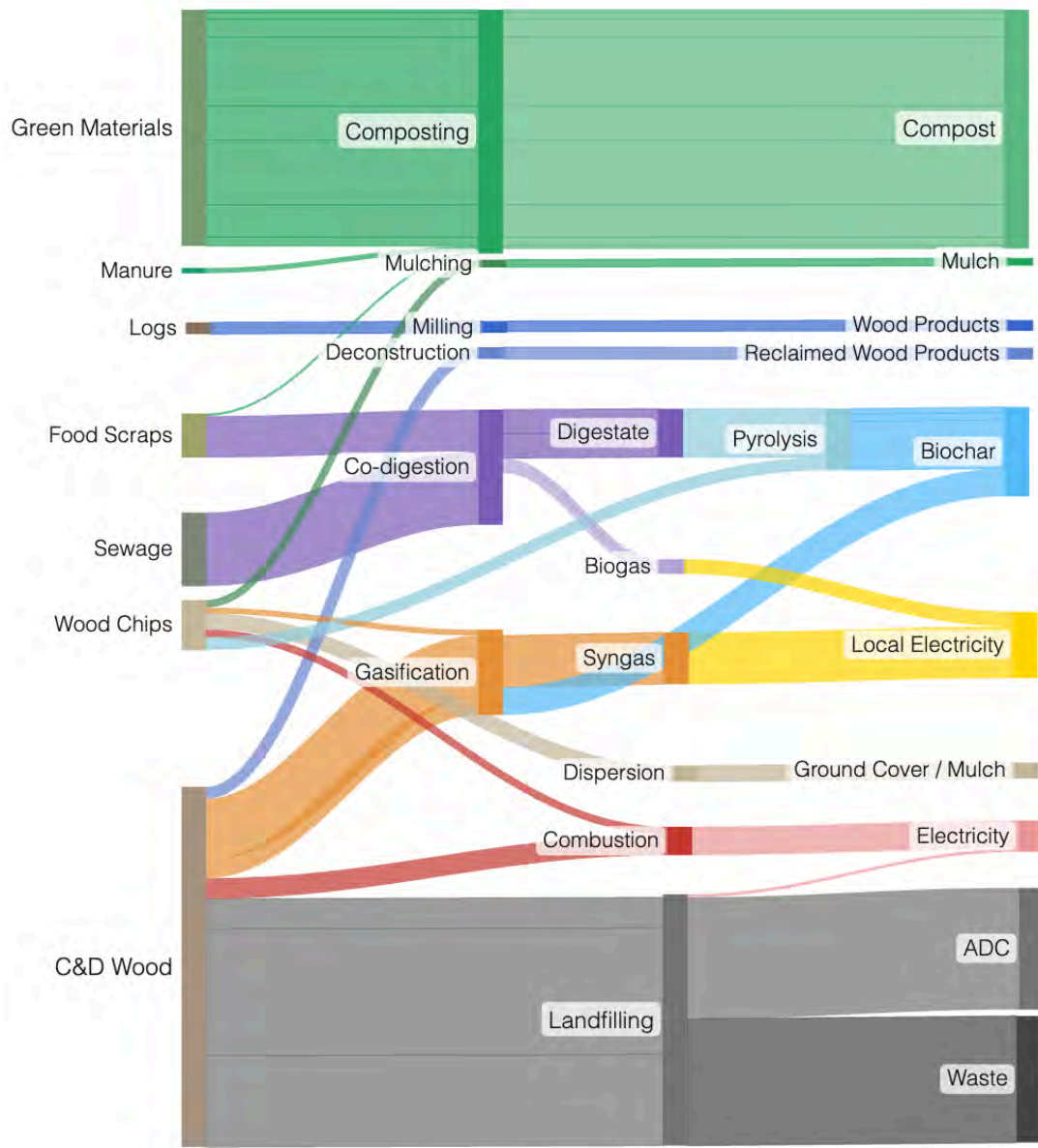


Table 2-2. Expected Biomass Inputs and Product Outputs in the Alternative System
(the categories and colors match the flows in Figure 2-22)

Biomass Type	Utilization Pathway	Annual Input		Product	Annual Output	
		wet short tons	dry metric tons		wet short tons	dry metric tons
Green Materials	Composting	81,000	36,500	Compost	41,800	17,800
Manure	Composting	1,800	360			
Food Scraps	Composting	800	240			
Wood Chips	Mulching	2,600	1,400	Mulch	2,600	1,400
Wood Chips	Dispersion	5,400	2,900	Ground Cover	5,400	2,900
C&D Wood	Reclamation	1,000	725	Wood Products	1,000	725
Logs	Milling	700	400	Wood Products	600	300
Wood Chips	Pyrolysis	2,500	1,400	Biochar	—	1,540 ⁷²
Digestate	Pyrolysis	16,500	3,000			
Mixed Wood ⁷³	Gasification	20,400	14,800	Biochar	—	1,500 ⁷⁴
				Local Electricity	12,500 MWh per yr	
Food Scraps	Co-digestion	14,200	3,900	Local Electricity	3,100 MWh per yr	
Mixed Wood ⁷³	Combustion	18,100	13,100	Electricity ⁷⁵	10,100 MWh per yr	
C&D Wood	Landfill	83,200	60,425	Waste and Daily Cover	83,200	60,425
TOTAL		248,200	139,150			

⁷² Assumes a conversion rate of dry biomass to biochar of 35%.

⁷³ Mixed wood (largely construction and demolition materials) is assumed to have a moisture content of 20%.

⁷⁴ Assumes a conversion rate of dry biomass to biochar of 10%.

⁷⁵ Estimate based on calculation of typical electricity production rate for biopower plants.

Like Figure 1-11 in Chapter 1, the colored bands in Figure 2-22 and Table 2-2 represent individual pathways. Also like that figure, the wider the band, the larger the material flow.

For example, the green band labeled **Compost** at the top of the diagram represents the 61,000 wet short tons per year of green materials generated in Marin and currently being processed in the county or nearby. It also accounts for the additional 20,000 wet short tons per year of green materials that Marin is expected to generate in the next ten years. In contrast to the current system, all of this flows into an expanded composting system.

The bands in the middle of this diagram are alternative pathways that are expanded or (re)developed in the alternative system, as follows:

Co-digestion and Electricity Generation: the lilac band in the middle represents expansion of the current co-digestion for food scraps and sewage and generation of local, renewable electricity.

Gasification and Electricity Generation: the orange band in the middle represents development of a gasification pathway that makes local use of woody construction and demolition materials and generates local, renewable electricity.

Pyrolysis and Biochar Production: the blue band in the middle represents development of a co-pyrolysis pathway for digestate from wastewater treatment and woody materials from fuel treatment that produces a high-quality biochar.

Small-scale Milling: the thinner, light-blue band below imagines a resumption of small-scale milling for logs and the creation of wood slabs instead — a carbon-sequestering localization that skips long-distance transport to the Central Valley and release of carbon dioxide by burning the wood instead.

Deconstruction and Reuse: the medium-blue band estimates the potential expansion of structural material and wood products salvage as policy and market conditions support the practice.

These pathways at the top of the diagram are areas of growth. That is, these bands are bigger in the alternative system than in Marin's current system. By comparison, the long-distance **combustion power**, the **dispersion**, and the **landfill** pathways are reduced in this system. The landfilling pathway shrinks by a total of 39,600 wet short tons per year by diverting digestate into pyrolysis, food scraps to co-digestion, and green materials to

composting. This still leaves 84,000 wet short tons of biomass (mostly woody construction and demolition materials) destined for landfill.⁷⁶

In Marin's current system more than half of its biomass flows into landfill or is chipped and shipped a significant distance to the Central Valley. In the alternative system, the system flips: more than half of the biomass flows into local pathways that may aid transition to a more regenerative economy.

The purpose of the next two chapters is to estimate, respectively, the GHG emission reductions and the economic output that this alternative set of pathways might achieve.

⁷⁶ This flow rate does not represent all potential biomass going to landfill. Biomass mixed with garbage and collected in the "waste" bin (i.e., the bin required to be grey under SB 1383) — is a potentially large flow whose assessment is beyond the scope of this study. Likewise, other materials that meet the definition of "organic" in SB 1383 (e.g., paper, organic textiles, among others) represent additional biomass in the landfill stream, also beyond the scope of this study.

Chapter 3:

Greenhouse Gas Reduction and Sequestration Opportunities

Marin County and its municipalities have established climate action plans. This chapter offers new information that can support these plans, as well as wider discussion and decision-making about carbon management and markets. The first analysis estimates the change in GHGs if the biomass utilization system proposed in Chapter 2 is developed, rather than managing biomass as waste going to landfill or shipping it long distances for combustion at biopower facilities in the Central Valley. The second analysis in this chapter estimates the carbon stored in Marin's landscapes, considering the value of its retention and potential for enhanced sequestration. The third analysis quantifies the GHG and non-GHG emissions avoided by fuel reduction efforts on Marin's forested lands. The objective of these analyses is to provide information that the general public, key stakeholders, and elected officials can consider when investing in biomass utilization pathways and climate actions.

Current and Alternative Biomass Systems

The GHG analyses in this chapter also build on findings from the previous two chapters. In those chapters, the biomass utilization system was explored based on these questions:

- How much biomass will Marin generate from vegetation management activities to reduce wildfire risk on natural and working lands and to protect property on developed lands?
- How much biomass processing capacity does Marin need to meet the landfill diversion goals in Senate Bill 1383 (2016) and to extend its existing landfill's lifetime, considering its expected biomass flows in ten years?
- Which biomass processing technologies and products are the most promising for Marin as pathways for managing its biomass flows?

The feedstock assessment in the first chapter of this Study predicts that each year Marin will generate nearly 250,000 wet short tons (just under 140,000 dry metric tons) of biomass from its wildfire prevention programs, its residences, and its commercial establishments. As illustrated in Figure 3-1, Marin has already developed a robust composting system. However, much of its biomass still flows into landfill or is chipped and shipped long distances to the Central Valley, where it is burned to produce electricity. In all, less than fifty percent of Marin's biomass is currently being managed into recycling pathways, as defined by CalRecycle's regulations under SB 1383.

The pathways assessment in the second chapter builds on these findings. It reviews a range of biomass conversion technologies and their products – what we call “pathways” in this study – and analytically compares potential pathways to the predicted flows of biomass in Marin. It also screens these pathways based on their economic and environmental characteristics and proposes the alternative system of pathways in Figure 3-2. These biomass flows and pathways for Marin's current system and for the proposed system are illustrated in Figures 3-1 and 3-2, and their magnitudes are summarized in Table 3-1.

This chapter uses GHG modeling to evaluate opportunities and to illustrate ways that the alternative system might help Marin manage its biomass in an economically and environmentally sustainable manner — including identifying ways to support progress toward goals for the agricultural sector in the Marin County Climate Action Plan.

Figure 3-1. Marin's Biomass Flows for its Current System

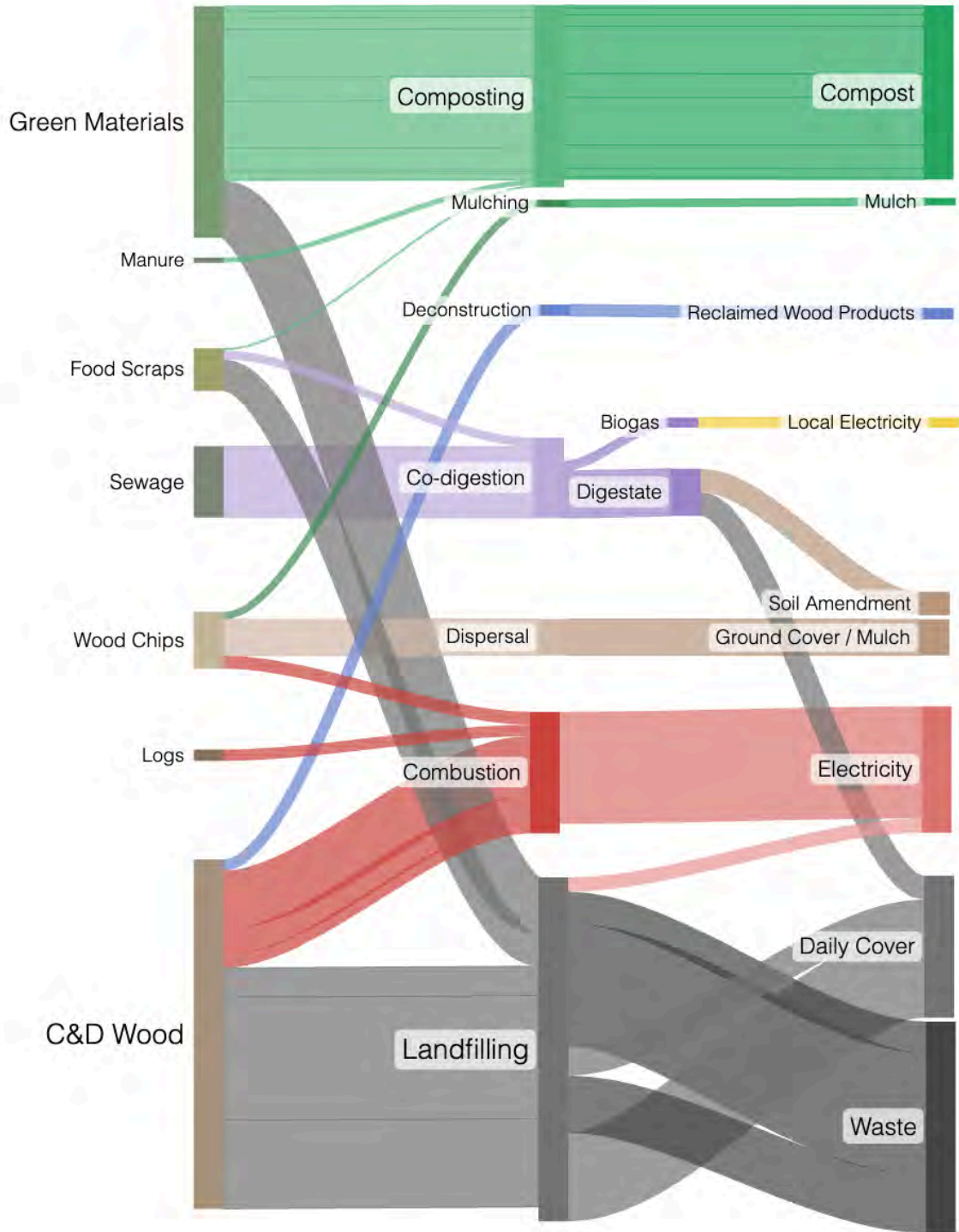


Figure 3-2. Marin's Biomass Flows for the Alternative System

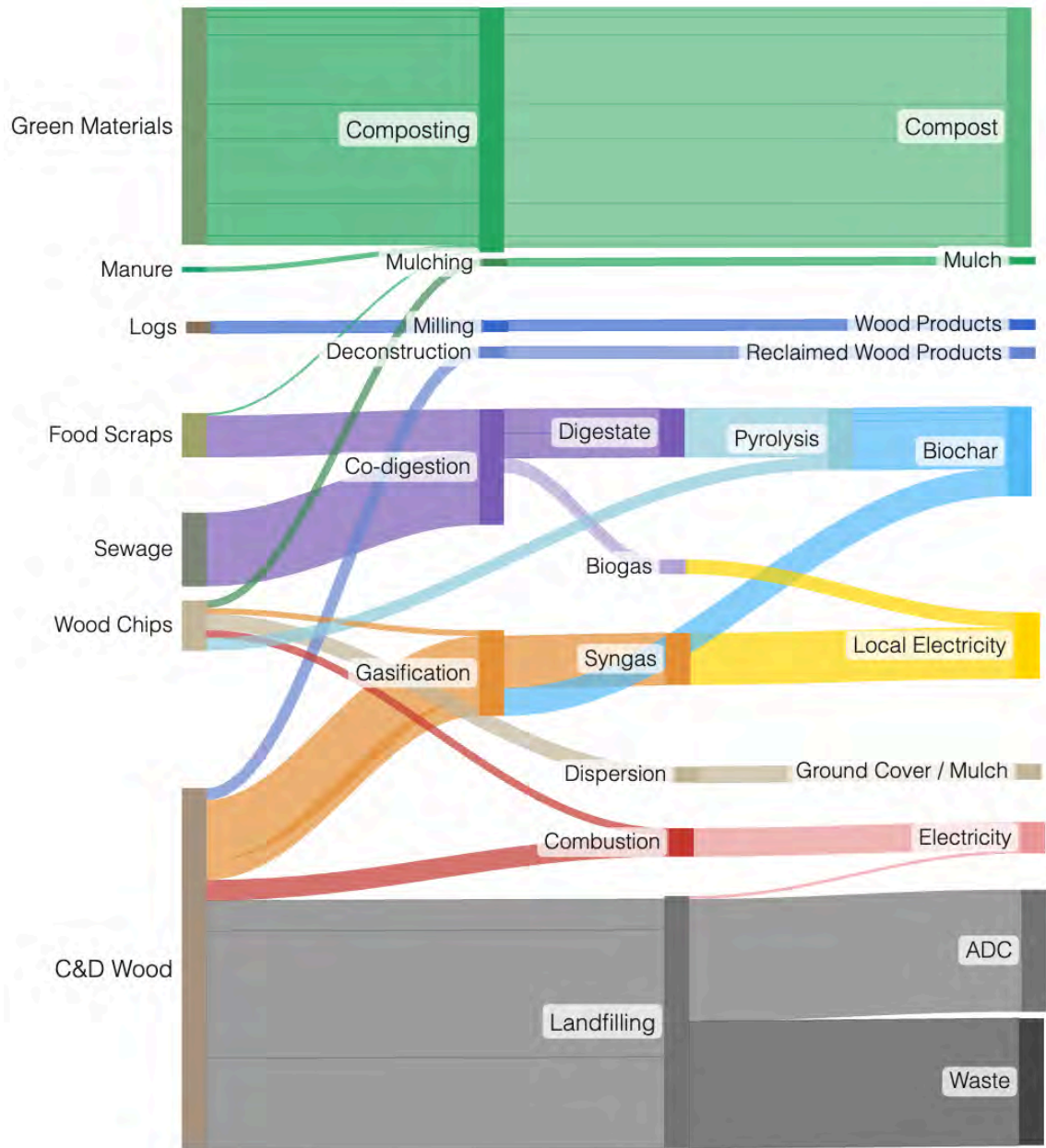


Table 3-1. Biomass Flows for Current System and Alternative System

Current System (Figure 3-1)			Biomass Type ⁷⁷	Alternative System (Figure 3-2)		
Utilization Pathway	wet short tons	dry metric tons		Utilization Pathway	wet short tons	dry metric tons
<i>(see landfilling below)</i>			Green Materials	Composting	20,000	9,000
Composting	61,000	27,500	Green Materials	Composting	61,000	27,500
Composting	1,800	360	Manure	Composting	1,800	360
Composting	800	240	Food Scraps	Composting	800	240
Mulching	2,600	1,400	Wood Chips	Mulching	2,600	1,400
Dispersion	5,400	2,900	Wood Chips	Dispersion	5,400	2,900
Dispersion	2,500	1,400	Wood Chips	Pyrolysis	2,500	1,400
Dispersion	8,000	1,450	Digestate	Pyrolysis	8,000	1,450
<i>(see landfilling below)</i>			Digestate	Pyrolysis	8,500	1,550
<i>(see landfilling below)</i>			Food Scraps	Co-digestion	11,100	3,100
Co-digestion	3,100	800	Food Scraps	Co-digestion	3,100	800
Combustion	700	400	Logs	Milling	700	400
Combustion	34,000	24,600	C&D Wood	Gasification	20,400	14,800
Combustion	4,500	3,300	Mixed Wood	Combustion	18,100	13,100
Landfill	20,000	9,000	Green Materials	<i>(see composting above)</i>		
Landfill	8,500	1,550	Digestate	<i>(see pyrolysis above)</i>		
Landfill	11,100	3,100	Food Scraps	<i>(see co-digestion above)</i>		
Landfill	84,000	61,000	C&D Wood	Landfill	83,200	60,425
Reclamation	200	150	C&D Wood	Reclamation	1,000	725
248,200		139,150	TOTAL	248,200		139,150

⁷⁷ The following moisture contents are assumed for the wet short tons of materials: green materials (50%), food scraps (70%), digestate (80%), manure (80%), recently cut logs and wood chips (40%), and woody construction and demolition materials (20%).

In addition to providing an inventory of Marin’s carbon stocks, this chapter describes the GHG avoided or reduced by improved biomass management:

- An **Emissions Reduction** account. This account identifies and estimates the GHG emission reduction (including sequestration) from investing in the proposed biomass utilization pathways. This account is built using a comparative lifecycle analysis approach that estimates the difference in GHG emissions between Marin’s current biomass utilization system and the proposed set of pathways.
- An **Avoided Emissions** account. This account explains and quantifies the magnitude of GHGs avoided from wildfire prevention work on natural and working lands. This account is built by inventorying the carbon stocks in Marin’s soils and standing biomass and calculating the reduction in wildfire events and the avoidance of GHG emissions that results from improved vegetation management on natural and working lands.

This chapter is divided into three parts. The first part offers the Emissions Reduction account. This account builds on the ten-year, steady-state biomass flow estimate for Marin developed in Chapter 1, and estimates the lifecycle GHG emission reductions for each utilization pathway proposed in Chapter 2. This analysis helps to answer the question, how much GHG emission reduction is possible if Marin diverts biomass from the current system into the alternative set of utilization pathways proposed in Chapter 2?

The second section provides a snapshot of the carbon currently sequestered in Marin’s landscapes — a window into the scale of nature-based carbon storage. The magnitude of carbon stored – and the consequences of its potential release as GHGs from wildfire or mismanagement – forms the basis for a recommendation that strongly encourages Marin’s ongoing maintenance and growth of this landscape carbon stock (see Chapter 5).

The third part of this chapter offers the Avoided Emissions account. This account estimates the GHG emissions “avoided” (i.e., prevented) by fuels treatment on the landscape. It helps to answer the question, how much GHG emission is Marin preventing through its wildfire prevention activities?

The lifecycle analysis provides a basis for the following estimate: management of biomass through the alternative set of pathways can reduce or sequester 31,200 metric tons of carbon dioxide equivalent (CO₂e) per year.⁷⁸ The avoided wildfire emissions analysis provides a basis for the following estimate: fuel treatments can reduce 170,000 metric tons

⁷⁸ CO₂e (CO₂e) emissions are aggregate metric for reporting the combined emissions of carbon dioxide (CO₂), methane (CH₄), nitrous oxide (N₂O), and, in some cases, select other GHGs.

of CO₂e over forty years. (If annualized to satisfy carbon accounting procedures, this would be equivalent to avoiding 4,250 metric tons of CO₂e per year.)

One potential interpretation of this difference is that where Marin puts its biomass is more important for reducing GHGs than undertaking fuel treatments across its landscapes. However, it is important to understand that different carbon pools are being addressed by these two management strategies. They also operate on different spatial and temporal scales and, for this reason, offer different co-benefits. For example, wildfire safety work can produce significant, if unquantified, public benefit by preventing infrastructure damage and loss from otherwise potentially catastrophic wildfire(s). Similarly, sending biomass into low-carbon pathways can help reduce the climate change that is contributing to the increased frequency and intensity of wildfire and other climate impacts. In sum, it is best to view both strategies — i.e., directing biomass into more beneficial pathways and preventing the severity and spread of wildfire — as complementary strategies, each of which can meaningfully help Marin achieve its GHG reduction goals and avoid catastrophic wildfire damage.

Analysis of Reduced Emissions

Within the next ten years, Marin is expected to generate 248,200 wet short tons (139,150 dry metric tons) of biomass per year that needs disposition. This section explores the GHG implications of managing this biomass into the alternative set of pathways identified in Chapter 2. These pathways were chosen, in part, based on their potential to reduce Marin's GHG emissions. This section explores and quantifies this potential.

Lifecycle Analysis Approach

The assessment of GHG reduction potential of the alternative set of pathways uses a lifecycle analysis (LCA) approach. An LCA framework is a way to break down a system into stages and to compare the GHG emissions and sequestration associated with a product, process, or pathways systematically. (See [Appendix G](#) for a longer description of the method.) The LCAs in this chapter explore the GHG emissions for each pathway across the following set of lifecycle stages: biomass collection, biomass transport, biomass processing and conversion, and biomass product usage or disposal.⁷⁹

⁷⁹ The lifecycle stages in an LCA are sometimes described as stretching “from cradle to grave.” The “cradle” refers to the environment from which resources are first acquired. The “grave” refers to the environment into which resources go when they are exhausted. In an extraction-disposal economy, the cradle is often mining or

The Reduced Emissions account in this chapter is built using LCAs for the following five pathways:

- **Composting.** This analysis considers expansion in composting of woody biomass, green materials, and food scraps. It estimates the GHG emissions associated with increasing local composting and with putting compost to local or regional use.⁸⁰
- **Anaerobic Co-Digestion with Electricity Generation.** This assessment explores expansion in the co-digestion of commercial food scraps with sewage and use of the produced biogas to generate electricity. It estimates the GHG emission difference from diverting more food scraps into a co-digestion pilot project at Marin’s largest wastewater treatment plant. It assumes that the biogas produced will be burned onsite to generate electricity, with some of the electricity sold into the power grid.
- **Pyrolysis and Biochar Production.** This analysis considers a novel plan to build a co-pyrolysis plant on land previously used for wastewater treatment and to convert woody biomass and digestate from wastewater treatment into biochar. It estimates the GHG emission difference between co-pyrolysis and disposal of these materials in landfill. It also estimates the GHG benefits of applying biochar to lands in the region.⁸¹
- **Gasification with Electricity Generation:** This analysis considers an existing plan to gasify woody construction and demolition materials at Marin’s largest materials recovery facility (transfer station). It compares the GHG emissions from gasification to combustion at biopower facilities in the Central Valley. It assumes that syngas from gasification will be used to generate electricity for onsite use and for sale into the power grid. It also considers the GHG emission reductions associated with land application of the co-product biochar.
- **Milling:** This analysis considers the resumption of a small-scale mill in Marin for conversion of large-diameter logs into wood products (e.g., slabs, lumber, or pieces for furniture manufacturing). It compares the GHG emissions from local milling to chipping and shipping biomass to combustion power plants in the Central Valley.

landscape harvesting, and the grave is disposal or release into the environment. In a recycling economy, resources are recovered for reuse and go from “cradle to cradle” with a significantly reduced amount of “grave.”

⁸⁰ The findings for the composting LCA are also applicable to mulching as a pathway for biomass.

⁸¹ Another alternative to pyrolysis or landfill for wastewater digestate is transport to a Lystek facility in Fairfield, where thermal hydrolysis is used to convert biosolids into fertilizer. Analysis of this pathway is, however, beyond the scope of this project.

All LCA modeling in this chapter uses custom-built models for the proposed biomass utilization pathways. These models rely on the data available for Marin County and values from peer reviewed literature. Inputs for landfill GHG fluxes were derived from the IPCC's Waste model.⁸² [Appendix G](#) lists values used to calculate GHG emissions for each pathway considered. Results are reported in metric tons of CO₂e (CO₂e).

Composting and Land Application

As described in Chapter 2, composting is a process for managing the biological, aerobic decomposition of organic materials. The product of composting is compost. Suitable biomass for composting includes green materials (e.g., yard trimming, landscaping debris), food scraps, and, in small quantities, woody materials. Marin currently has roughly 61,000 wet short tons (27,500 dry metric tons) of green materials, 1,800 wet short tons (3600 dry metric tons) of dairy manure, and 800 wet shorts tons (240 dry metric tons) of food scraps per year flowing into composting. Based on the analysis and projections in Chapter 1, over the next 10 years Marin will generate 20,000 more wet short tons per year of green materials suitable for composting or mulching.⁸³ (The flow of source-separated commercial food scraps and manure transported off farm for composting is not expected to change.)⁸⁴

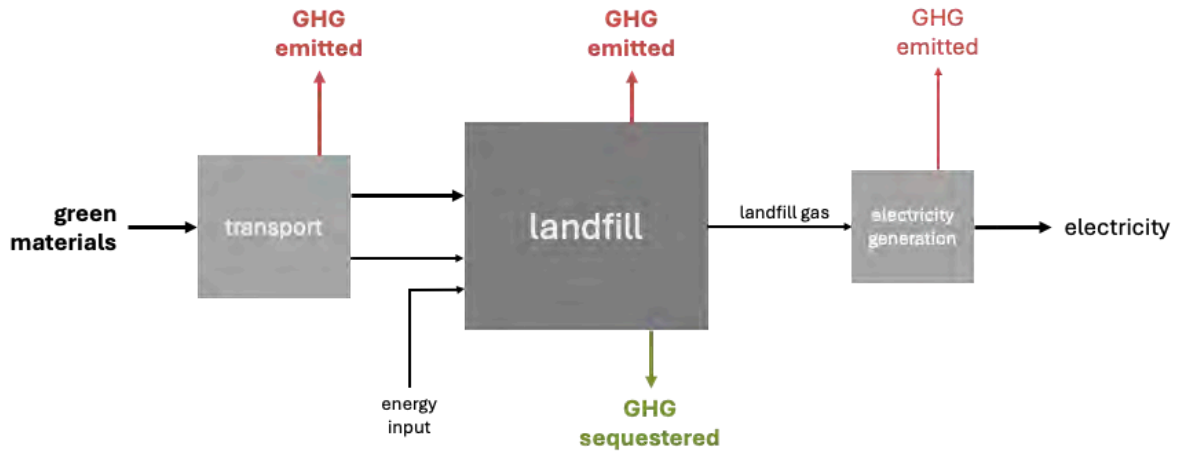
This LCA estimates GHG emissions if the expected increase of 20,000 wet short tons (9,000 dry metric tons) increase in Marin's green material flow are composted. Landfilling is used as the baseline scenario for comparison under the assumption that, unless additional composting capacity is secured for the expected increase in green materials, these materials will be sent to landfill. As illustrated in Figure 3-3, the baseline scenario considers GHG emissions from transportation to landfill, from energy used to operate the landfill, and from methane that will leak after biomass anaerobically decomposes in the landfill.

⁸² Available at: https://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/5_Volume5/IPCC_Waste_Model.xls

⁸³ A small fraction (about 1-2%) of green materials may be diverted to mulching rather than composting. Because mulching and composting have similar applications and environmental impacts, they are combined here in the composting analysis.

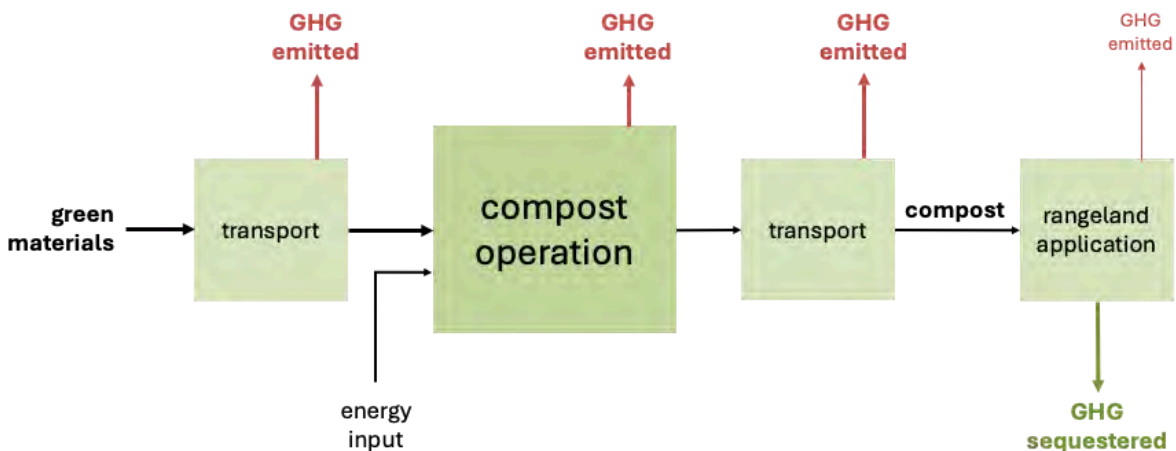
⁸⁴ On-farm manure composting is increasingly common in Marin. Though not quantified for this analysis, it is assumed to absorb growth in manure flows so that off farm composting remains level.

Figure 3-3. Baseline Scenario: Landfilling with Electricity Generation



The proposed alternative scenario estimates the GHG emissions if these same materials are sent into a composting pathway. Like the baseline scenario, the alternative scenario estimates the potential GHG emissions from transport of materials, from the energy used to operate the composting facility, from transport of finished compost and its application to Marin rangelands. (See Figure 3-4). The estimate also includes the expected reduction in methane emissions from not landfilling biomass and the reduced benefit of electricity generated using landfill gas.

Figure 3-4. Alternative Scenario: Expanded Composting with Compost Applied to Land



The analysis compares the GHG emissions of the two scenarios using the common metric of CO₂e (CO₂e). This is noteworthy because these two systems produce different kinds of GHG emissions. Landfills are oxygen-poor environments, and organic materials break down under these conditions through uncontrolled anaerobic decomposition. This process

releases methane, part of which can be captured by landfill gas collection systems and used as an energy resource. The other part of the landfill gas will leak into the atmosphere, where over a 12-year period it will be 85 times more potent than carbon dioxide as a contributor to climate change. Compost piles release relatively little methane. As long as a pile is well-aerated, the oxygen-rich environment will facilitate aerobic decomposition of biomass and release mostly carbon dioxide.⁸⁵

To summarize, the LCA comparison of GHG emissions is between landfill as a baseline scenario and composting as an alternative scenario. The LCA assesses the scenarios within the system illustrated in Figures 3-3 and 3-4, using the input parameters summarized in [Appendix G](#) (Tables G-1 and G-2), and based on the following data and assumptions:

Inputs: Feedstocks

- Baseline Scenario (current): 61,000 wet short tons (27,500 dry metric tons) of green materials, 800 wet short tons (240 dry metric tons) of food scraps, and 1,800 wet short tons (360 dry metric tons) of off-farm manure per year go into commercial composting. Meanwhile, 20,000 wet tons (roughly 9,000 dry metric tons) of green materials end up in landfill.⁸⁶
- Alternative Scenario (considered): 81,000 wet short tons (36,500 dry metric tons) of green materials, 800 wet short tons (240 dry metric tons) of food scraps, and 1,800 wet short tons (360 dry metric tons) of off-farm manure flow into commercial composting.

Outputs: Products

- Baseline Scenario (current): 31,800 wet short tons (14,000 dry metric tons) of compost per year. An estimated 500 MWh per year of electricity generated with landfill gas from green material decomposition in landfill.⁸⁷
- Alternative Scenario (considered): 41,800 wet short tons (17,800 dry metric tons) of compost per year.

⁸⁵ This LCA assumes that compost piles are well aerated and that any methane emissions generated in the composting process is de minimis and can be neglected in the GHG emission comparison.

⁸⁶ Green materials, food scraps, and manure composted on-farm and in residential backyards are not included in this analysis.

⁸⁷ The marginal contribution to electricity generation is an estimate based on known electricity generation and biomass landfilling rates. The marginal contribution of biomass to electricity generation at a landfill considerably lags its introduction and depends significantly on factors, such as when and how it was buried and how well the landfill gas collection system is working. A rounded, fractional contribution is offered as an estimate.

Assumptions about Operational Factors

- Compost is applied to 1,400 acres of rangeland in Marin per year.⁸⁸
- Each compost application to rangeland happens once per 100 years, a minimum frequency suggested by modeling data from the [Marin Carbon Project](#).⁸⁹
- The distance from a waste transfer station to a landfill or to a composting facility is the same. (Therefore, there is no difference in emissions from transportation to a landfill or to a composting facility.)
- Neither landfill nor composting require ongoing process heat to operate.

Assumptions about GHG Emissions

- Composting is assumed to use 0.5 liters of diesel per wet metric ton of food scraps for turning and aeration (Mondello et al. 2017) and is treated as *de minimis*.
- Landfills sequester a portion of the carbon in biomass over long periods and also release carbon as carbon dioxide and methane in the short term.
- A portion of landfill methane (CH₄) is captured and used for onsite electricity production. The remainder of the methane, as well as carbon dioxide produced in the landfill, is assumed to be released to the atmosphere.
- Compost piles are well designed and non-CO₂ GHG emissions (i.e., CH₄ and N₂O) are *de minimis* due to best management procedures (Serafini et al., 2023).
- A portion of the compost applied to land becomes part of the soil carbon fraction and contributes to net primary productivity.
- Mineral nitrogen use on rangeland is not changed upon composting application. This means that both the baseline case (i.e., a rangeland that does not receive mineral fertilizer) and the alternative case (i.e., a rangeland where compost is applied) produce no significant nitrogenous GHG emissions.

⁸⁸ Although compost (and biochar) may be applied to different lands in the county – such as orchards, vineyards, and urban horticulture – this analysis focuses specifically on rangeland application. Rangeland application was prioritized to allow for a clearer and more direct comparison across biomass utilization pathways that include soil amendments. This focus provided a transparent assessment of GHG benefits while aligning with Marin’s significant rangeland acreage and its suitability for compost application. Focusing on rangeland applications also allowed for a direct comparison between biomass utilization pathways. Notably, most compost is currently applied to cropland, urban horticulture, or pasture.

⁸⁹ This application rate and frequency are supported by Ryals et al. (2015) and Ryals and Silver (2013). Ryals and Silver (2013) conclude that a single application of compost increased soil carbon sequestration and promoted plant growth, leading to a sustained increase in soil organic carbon over their study period as the compost continues to drive increases in photosynthetic capture of carbon dioxide from the atmosphere.

Based on these data and assumptions, **composting 20,000 more wet short tons (9,000 more dry metric tons) of green materials will reduce GHG emissions by an additional 11,700 metric tons of CO₂e per year** (Table 3-2).

Table 3-2. Net GHG Emissions for Expansion of Composting (increase in flow only)

Inputs and Outputs	wet short tons per year	dry metric tons per year
Additional Flow of Green Materials (input)	+ 20,000	+ 9,000
Additional Compost (output)	+10,000	+3,800
Reduction in Electricity from Landfill Gas (output)	- 500 MWh per year	
GHG Emissions (100-year timescale)		
Transportation step: change from generation point to landfill	MT CO ₂ e per yr	<i>de minimis</i>
Transportation step: increase from compost site to rangeland	MT CO ₂ e per yr	+ 450
Processing step: increase in composting pile fugitive emissions	MT CO ₂ e per yr	+ 7,760
Processing step: decrease in landfill fugitive emissions	MT CO ₂ e per yr	- 11,640
Usage step: decrease in electricity production at landfill	MT CO ₂ e per yr	+ 30
Usage step: increase in net primary productivity	MT CO ₂ e per yr	- 8,300
Total Emissions for All Lifecycle Steps (<u>increase</u> in flow only)	MT CO₂e per yr	- 11,700

Over half of this emission reduction from composting results from decrease in processing emissions between composting and landfilling (i.e., a net decrease in fugitive emissions of 11,640 metric tons of CO₂e per year). A little less than half is from the sequestration benefits of applying compost to rangeland. (A single application to 1,400 acres has a net absorption of 8,300 metric tons of CO₂e each year and compounds over twenty years). Small net increases in transportation required (from transport of compost to rangelands for application) and in usage (away from electricity production for landfill gas) are also included in these calculations.

Taking account of all expected biomass flows (i.e., the entire 81,000 wet short tons per year of green materials, the 800 wet short tons of food scraps, and the 1,800 wet short tons of manure), **composting will reduce GHG emissions by 48,600 metric tons of CO₂e per year** (Table 3-3).

Table 3-3. Net GHG Emissions for Expanded Composting (total flow)

Total Inputs and Outputs	wet short ton per year	dry metric tons per year
Total Flow of Green Materials (input)	81,000	36,500
Total Flow of Manure (input)	1,800	360
Total Flow of Food Scraps (input)	800	240
Total Flow Compost (output)	41,800	17,800
Reduction in Electricity from Landfill Gas (output)	- 500 MWh per year	
GHG Emissions (100-year timescale)		
Transportation step: change from generation point to landfill	MT CO ₂ e per yr	<i>de minimis</i>
Transportation step: increase from compost site to rangeland	MT CO ₂ e per yr	+ 1,830
Processing step: increase in composting pile fugitive emissions	MT CO ₂ e per yr	+ 31,500
Processing step: decrease in landfill fugitive emissions	MT CO ₂ e per yr	- 48,850
Usage step: decrease in electricity production at landfill	MT CO ₂ e per yr	+ 120
Usage step: increase in net primary productivity	MT CO ₂ e per yr	- 33,200
Total Emissions for All Compost Lifecycle Steps (<u>total flow</u>)	MT CO₂e per yr	- 48,600

Each pathway analyzed using LCA methods in this chapter achieves different per-unit-input reductions in GHGs. To enable comparison, the per-unit GHG savings for the composting pathway are included in Table 3-4.

Table 3-4. Breakdown of Biomass Flows and GHG Emissions for Composting

GHG Emissions	metric tons (MT) of CO ₂ e
Total Emissions for All Lifecycle Steps (increase in flow only)	- 11,700
Total Emissions for All Lifecycle Steps (total flow)	- 46,800
Net GHG Emissions per Unit of Input and Output	MT CO ₂ e per MT
GHG Emissions per Dry Metric Ton of Green Materials (input)	- 1.3
GHG Emissions per Dry Metric Ton of Compost Applied (output)	- 2.6

In sum, expanding composting reduces GHG emissions. Per Table 3-4, for every dry metric ton of green materials composted, Marin reduces GHGs by 1.3 metric tons of CO₂e. Or for every dry metric ton of compost applied, Marin reduces 2.6 metric tons of CO₂e emissions.

Co-Digestion and Electricity Generation

As described in Chapter 2, anaerobic digestion refers to the decomposition of organic material with little or no oxygen present. Outputs from anaerobic digestion are a methane-rich gas generally called “biogas” and a slurry of solids and water called “digestate.” (The digestate from wastewater treatments plants is typically referred to as “biosolids.”) Inputs to anaerobic digestion vary depending on the type and design of anaerobic digester. Marin and its vicinity have only wet anaerobic digesters, and they are located at Marin’s wastewater treatment plants.⁹⁰ Wet anaerobic digesters require relatively wet feedstocks like sewage and are poorly suited to accept woody materials as a feedstock. They can, however, accept and “co-digest” food scraps that are slurried into a consistency compatible for processing with sewage.⁹¹

Marin already has some anaerobic digesters that co-digest sewage with food scraps at the Central Marin Sanitary Agency (CMSA) wastewater treatment plant. CMSA has an agreement with Marin Sanitary Services to receive food scraps from Marin’s commercial food recovery program and co-digest it with sewage. The biogas from this process is burned onsite in internal combustion engines to generate electricity.⁹²

As explained in Chapter 2, CMSA’s anaerobic digesters have processing capacity beyond what is needed to manage expected sewage flows. This extra capacity is the reason that Marin Sanitary Services and CMSA have piloted the co-digestion of food scraps and sewage. In this pilot, CMSA accepts 3,100 wet short tons (800 dry metric tons) of food scraps that are source separated from businesses. CMSA co-digests these food scraps with sewage, collects and burns the product biogas in an engine to generate electricity used onsite to power the wastewater treatment plant.

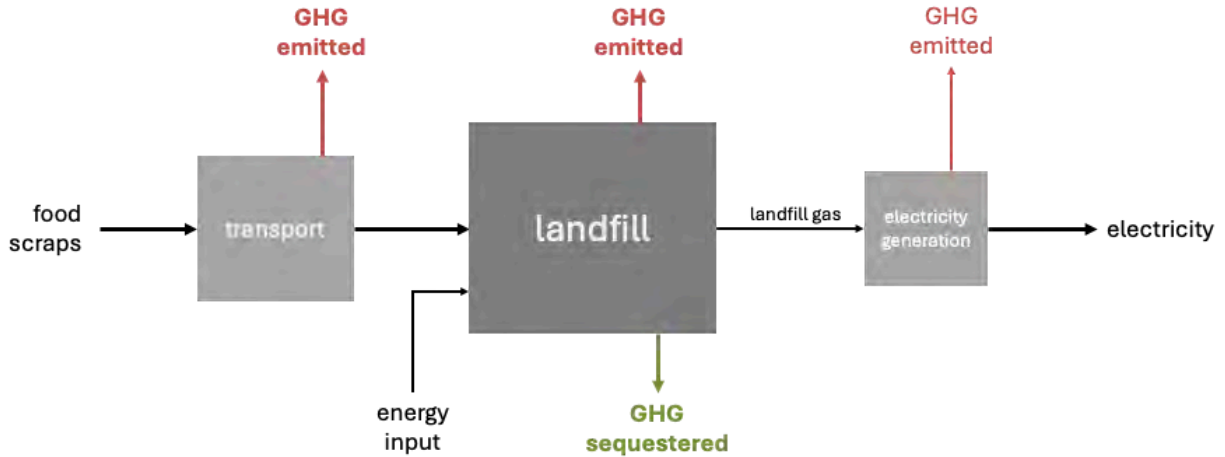
An estimated 11,100 wet short tons (3,100 dry metric tons) per year of commercial food scraps are still being disposed of in landfill. This situation is the baseline case for comparison and is illustrated in Figure 3-5.

⁹⁰ Napa County is the closest location with “dry” anaerobic digesters that accept drier biomass inputs.

⁹¹ The ratio of water to biomaterials in anaerobic digestion depends on process conditions and goals. Similarly, depending on the digesters and operating needs, the tons of food scrap input can be anywhere from 25-80 percent of the sewage sludge input by weight.

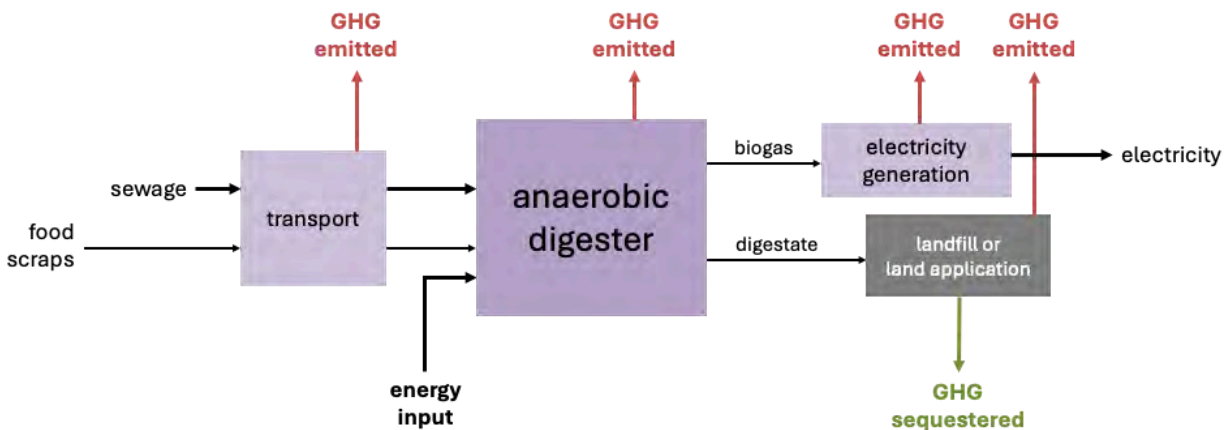
⁹²The co-digestion process also produces a semi-solid digestate. For simplicity’s sake, the LCA for co-digestion omits consideration of digestate to avoid doublecounting, given that a change in this material is considered as part of the LCA for the pyrolysis pathway.

Figure 3-5. Baseline Scenario: Landfilling with Electricity Generation



As illustrated in Figure 3-6, the alternative case is an expanded co-digestion project. Marin generates an additional 14,200 wet short tons (3,900 dry metric tons) of potentially recoverable commercial food scraps per year, all of which could be co-digested at CMSA within its current digester capacity. The recently upsized natural gas combustion engine and generator onsite could utilize all of the biogas that would be produced from this increased flow. However, the amount of electricity produced would exceed current onsite demand and could be sold as renewable electricity to the power grid. The LCA for this alternative case estimates the change in greenhouse gas emissions between the baseline and alternative case. Included in this comparison is the difference in lower carbon intensity of electricity produced from biogas compared to the average carbon intensity of electricity on the local power grid.

Figure 3-6. Alternative Scenario: Expanded Co-digestion with Electricity Generation



The LCA assesses the scenarios within the system illustrated in Figures 3-7 and 3-8, based on the input values summarized in [Appendix G](#) (Table G-3), and based on the following data and assumptions:

Inputs: Feedstocks

- Baseline Scenario (current): 11,100 wet short tons (3,100 dry metric tons) of food scraps landfilled; 3,100 wet short tons (800 dry metric tons) of food scraps co-digested with sewage.
- Alternative Scenario (considered): 14,200 wet short tons (3,900 dry metric tons) dry metric tons of food scraps co-processed in CMSA's anaerobic digesters.

Outputs: Products

- Baseline Scenario (current): co-digestion of 3,100 wet short tons of food scraps is assumed to produce 5.0 million more cubic feet of methane-rich biogas per year than sewage digestion alone. Combustion of this biogas in the engine and generator set produces 380 more Megawatt-hours per year of local, renewable electricity than would be generated from the biogas produced from sewage alone. An estimated 500 MWh per year of electricity generated with landfill gas produced by food scrap decomposition.⁹³
- Alternative Scenario (considered): the proposed increase in food scraps recovery and co-digestion will produce an additional 17.9 million cubic feet per year of methane-rich biogas than sewage digestion alone. Combustion of this biogas will produce 2,600 more Megawatt-hours per year of local, renewable electricity than would be generated from the biogas produced from sewage alone. The total 3,100 MWh of electricity generated from all food scrap co-digestion is assumed to exceed onsite needs and will be sold into the power grid.

Assumptions about Operational Factors

- No significant difference in feedstock transportation and transportation emissions between the baseline system and the proposed system. Any emissions difference is treated as *de minimis*.
- Any difference in haul weight between the baseline and proposed systems is assumed to be not significant and is treated as *de minimis*.

⁹³ The marginal contribution to electricity generation is an estimate based on known electricity generation and biomass landfilling rates. The marginal contribution of biomass to electricity generation at a landfill considerably lags its introduction and depends significantly on factors, such as when and how it was buried and how well the landfill gas collection system is working. A fractional contribution is offered as an estimate.

- No significant difference in process heat is needed for additional food scrap co-digestion. (The assumption is that hot exhaust from biogas combustion is sufficient for process heat, per (Timonen et al. 2019). Any emissions difference is assumed to be insignificant and is treated as *de minimis*.)
- 35% of input biomass leaves as biogas, and 65% leaves as digestate (biosolids).

Assumptions about GHG Emissions

- Whether digestate enters the landfill at the active face or is buried in a closed cell, 60-65% of its carbon is treated as sequestered in a long-term storage pool. (This means that it will not generate GHG emissions in the near term.)
- Landfills sequester a portion of the carbon in biomass over long periods and also release carbon in carbon dioxide and methane emissions in the short term. GHG emissions generated from placement of digestate in landfill (whether as daily cover or as waste) are modeled as being emitted entirely in the first year.
- A portion of landfill methane (CH₄) is captured and used for onsite electricity production. The remainder of the methane, as well as the evolved carbon dioxide, is eventually released to the atmosphere.
- A portion of the digestate applied to land becomes part of the soil carbon fraction and contributes to net primary productivity.
- The average carbon intensity of grid power from US EPA's eGrid database was used to compute the carbon savings from on-site electricity production (versus procurement of grid power).

Based on these data and assumptions, diverting an additional 11,100 wet short tons (3,100 dry metric tons) of food scraps into **co-digestion with electricity generation reduces GHG emissions by an additional 4,700 metric tons of CO₂e per year** (Table 3-5).

Table 3-5. Net GHG Emissions for Co-digestion with Electricity Generation (increase only)

Inputs and Outputs	wet short ton per year	dry metric tons per year
Additional Food Scraps (input)	11,100	3,000
Digestate (output)	3,100	830
Biogas (output) - million cubic feet per year	17.9	
Increase in Electricity from Biogas (output)	2,400 MWh per year	
Decrease in Electricity from Landfill gas (output)	- 500 MWh per year	
GHG Emissions (100-year timescale)		
Transportation step: from origin to processing step	MT CO ₂ e per yr	<i>de minimis</i>
Transportation step: increase from WWTP to land	MT CO ₂ e per yr	+ 60
Processing step: increase in co-digestion emissions	MT CO ₂ e per yr	+ 200
Processing step: decrease in fugitive landfill emissions	MT CO ₂ e per yr	- 4,440
Usage step: decrease in low-GHG electricity from landfill	MT CO ₂ e per yr	+ 10
Usage step: increase in low-GHG electricity from WWTP	MT CO ₂ e per yr	- 230
Usage step: decrease due to digestate application to land ⁹⁴	MT CO ₂ e per yr	- 300
All Lifecycle Steps (additional flow only)	MT CO₂e per yr	- 4,700

By comparison, if the entire, expected biomass flow (i.e., 14,200 wet short tons or 3,900 dry metric tons of food scraps) is considered and the entire food-to-energy system considered, the co-digestion with electricity generation for a scaled-up food scrap recovery program will reduce GHGs by **a total of 5,900 metric tons of CO₂e per year** (Table 3-6).

⁹⁴ The model assumes that, when digestate is applied to land, 60-65% of its carbon is sequestered in a longer-term storage pool, where it can boost net primary productivity (i.e., biotic activity).

Table 3-6. Net GHG Emissions for Co-digestion with Electricity Generation (total flow)

Total Inputs and Outputs	wet short ton per year	dry metric tons per year
Total Food Scraps (input)	14,200	3,900
Total Digestate (output)	3,900	1,060
Total Biogas (output) - million cubic feet per year	27.5	
Total Electricity (output) - Megawatt-hours per year	3,100	
GHG Emissions (100-year timescale)		
Transportation step: from origin to processing step	MT CO ₂ e per yr	<i>de minimis</i>
Transportation step: increase from WWTP to land	MT CO ₂ e per yr	+ 90
Processing step: increase in co-digestion emissions	MT CO ₂ e per yr	+ 340
Processing step: decrease in fugitive landfill emissions	MT CO ₂ e per yr	- 5,440
Usage step: decrease in low-GHG electricity from landfill	MT CO ₂ e per yr	+ 10
Usage step: increase in low-GHG electricity from WWTP	MT CO ₂ e per yr	- 400
Usage step: decrease from digestate application to land	MT CO ₂ e per yr	- 500
All Lifecycle Steps (total only)	MT CO₂e per yr	- 5,900

Table 3-7 provides a more detailed breakdown of the anaerobic digestion pathway's biomass flows and fractional contribution to net GHG emissions.

Table 3-7. Breakdown of Flows and GHG Emissions for Co-Digestion with Electricity Generation

GHG Emissions		
Total Emissions all lifecycle steps (increase in flow only)	MT CO ₂ e per yr	- 4,700
Total Emissions, all lifecycle steps (total flow)	MT CO ₂ e per yr	- 5,900
Net GHG Emissions per Unit of Input and Output (total flow)		
GHG Emissions per Dry Metric Ton of Food Scraps (input)	MT CO ₂ e per MT	- 1.5
GHG Emissions per Cubic Foot of Biogas (output)	MT CO ₂ e per 1,000 cuft	- 0.2
GHG Emissions per Megawatt-hour of Electricity (output)	MT CO ₂ e per MWh	- 2.0

In sum, diverting food scraps from landfill into co-digestion reduces GHG emissions. Per Table 3-7, for every dry metric ton of food scraps co-digested instead of landfilled, Marin reduces GHGs by 1.5 metric tons of CO₂e. For every cubic foot of biogas it produces, Marin reduces GHGs by 0.2 metric tons of CO₂e. For every Megawatt-hour of electricity it produces, Marin reduces GHGs by 2.0 metric tons of CO₂e emissions. In short, the available capacity at CMSA and potentially other wastewater treatment plants offers untapped potential for low-carbon electricity generation in Marin.⁹⁵

Gasification and Electricity Generation

As described in Chapter 2, gasification is a thermochemical process that heats biomass to high temperatures (typically above 700°C) with a controlled amount of oxygen or steam. This process breaks biomass down into a gaseous material called synthesis gas or “syngas.” When air is used as the oxygen supply, syngas is a combination of nitrogen gas (N₂), carbon monoxide (CO), hydrogen (H₂), methane (CH₄), other hydrocarbons, and carbon dioxide (CO₂) among other more minor species.⁹⁶ An advantage of gasification as a pathway is that, after syngas has been cleaned, it can be burned in engines, microturbines, and other smaller-scale power generators and potentially can be more efficient than direct combustion of wood to generate electricity. Gasification also produces some biochar, but the quantities and qualities produced are generally lower than the biochar made through pyrolysis.

Gasification can be a versatile way to utilize two woody biomass streams: chipped materials from fuel treatments on Marin’s landscapes, and segregated woody construction and demolition materials. Currently, most of Marin’s woody biomass from fuel treatments and construction and demolition material recovery is being chipped and shipped over 100 miles to a biomass combustion plant in the Central Valley. In addition to being GHG-intensive and expensive, this pathway is unreliable. That is, the ability for Marin to rely on a combustion power plant to purchase woody biomass depends on the ability of that facility to sell power to the grid. Existing biomass power plants also face an uncertain future as part of California’s energy system.⁹⁷ Advanced combustion and emission controls can reduce these concerns, although typically at higher cost. For these reasons, gasification may be an attractive alternative to combustion, although it is still developing as a pathway.

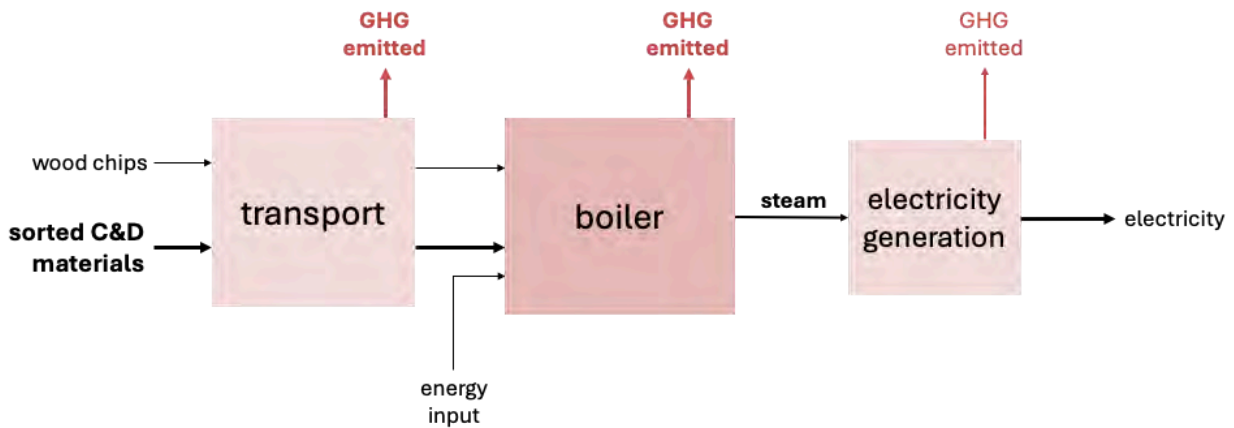
⁹⁵ Based on correspondence with Jason Dow, General Manager for CMSA, co-digestion of food and electricity generation has the potential to be doubled or more.

⁹⁶The output gas can also be called “producer gas” and various other names depending on production technique and composition.

⁹⁷ While we might note that the concerns have economic, regulatory, air quality, and environmental justice dimensions, a detailed discussion of them is beyond the scope of this study.

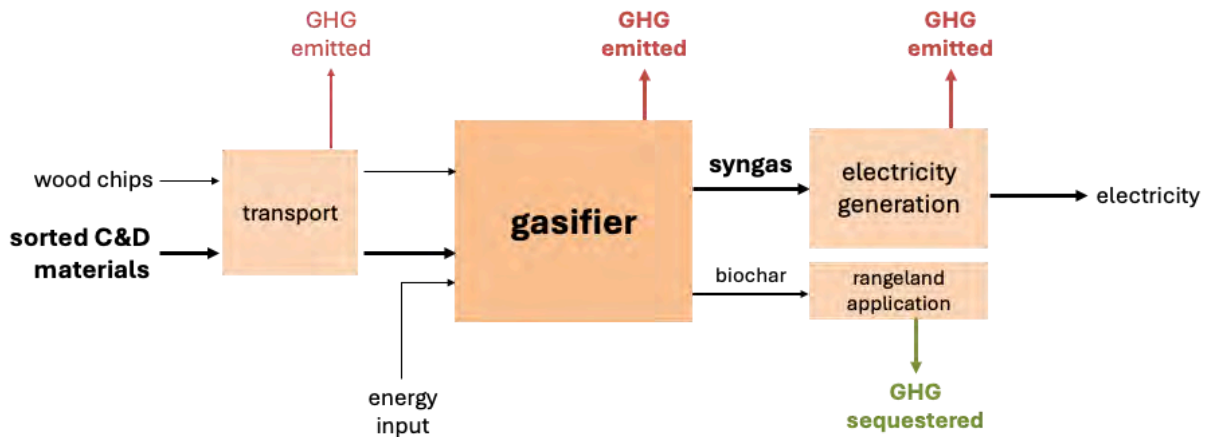
This LCA compares the GHG emissions from managing a mixture of woody biomass in a combustion pathway and in a gasification pathway. The baseline scenario for this analysis is combustion of all woody biomass at a biomass power plant in the Central Valley. As illustrated in Figure 3-7, a large stream of Marin’s recovered woody construction demolition materials is ground into chips and sent to power plants in the Central Valley, where it is burned to generate electricity sold into the Statewide power grid.

Figure 3-7. Baseline Scenario: Combustion with Electricity Generation



The alternative scenario for this analysis is a gasification facility that produces syngas that can be used to generate electricity. As illustrated in Figure 3-8, this facility skips the long-distance transport of woody biomass in favor of local gasification. Syngas produced at this facility is used to power a 2-Megawatt generator, where electricity is generated. Biochar generated is treated as a soil amendment and applied to rangelands in west Marin. In short, this pathway diverts woody construction and demolition materials from both landfill and long-distance transport. The product output is local, renewable electricity, some of which would be used onsite and some of which would be sold to the power grid.

Figure 3-8. Alternative Scenario: Local Gasification with Electricity Generation



The LCA assesses the scenarios within the system illustrated in Figures 3-7 and 3-8, based on the input values summarized in [Appendix G](#) (Table G-4), and based on the following data and assumptions:

Inputs: Feedstocks

- Baseline Scenario (current): 20,400 wet short tons (14,800 dry metric tons) per year of sorted woody construction and demolition materials sent to combustion power plant(s) in the Central Valley.⁹⁸
- Proposed Scenario (considered): 20,400 wet short tons (14,800 dry metric tons) of sorted woody construction and demolition materials sent to gasification with electricity generation.

Outputs: Products

- Baseline Scenario (current): an estimated 11,500 megawatt-hours of electricity sold into the statewide power grid.⁹⁹
- Alternative Scenario (considered): 12,500 megawatt-hours per year of local, renewable electricity, some of which may be used on site and some of which may be sold into the power grid; 1,500 dry metric tons per year of biochar.

⁹⁸ The total woody biomass that Marin sends to combustion power plants in the baseline scenario is 39,200 wet short tons per year. The imagined gasification facility — based on a number of factors — can only process 29,000 wet shorts tons per year. This means that 9,500 wet short tons per year remain un-recaptured and still destined for combustion. (The remaining 700 wet short tons are redirected in the new system to small-scale milling.)

⁹⁹ In the current system a total of 28,300 dry metric tons of mixed woody biomass is shipped from Marin to the Central Valley for combustion power. This smaller amount of 14,800 dry metric tons is the fraction envisioned for diversion into a gasification pathway.

Assumptions about Operational Factors

- The gasifier is assumed to be located at the existing waste transfer station in San Rafael. No additional transport is required or avoided besides transport of biochar to the end user (rangeland).

Assumptions about GHG Emissions

- Segregated woody construction and demolition materials are currently shipped from San Rafael to biomass power plants in the Central Valley — i.e., Woodland (Yolo County), Stockton (San Joaquin County), Anderson (Shasta County), and Jamestown (Tuolumne County). Wood chips from processing of large-diameter logs from roadside maintenance are shipped from Nicasio to the Central Valley.
- Using this biomass in Marin can eliminate trucking to the Central Valley.
- Biochar application on rangeland does not offset mineral nitrogen fertilizer because no fertilizers are used on rangelands.

Based on these data and assumptions, diverting nearly 20,400 wet short tons (14,800 dry metric tons) of woody construction and demolition materials from combustion power plants into **gasification with electricity generation reduces GHG emissions by just over 11,300 metric tons of CO₂e per year** (Table 3-8).

Table 3-8. Net GHG Emissions for Gasification Pathway

Total Inputs and Outputs	wet short ton per year	dry metric tons per year
Woody Materials (input)	20,400	14,800
Biochar (10% of input woody materials) (output)	—	1,500
Electricity (output)	12,500 MWh per year	
GHG Emissions (100-year timescale)		
Transportation step: decrease in transport to Central Valley	MT CO ₂ e per yr	- 7,000
Transportation step: increase from processing to usage	MT CO ₂ e per yr	+ 300
Processing step: increase in emissions from gasification	MT CO ₂ e per yr	+ 27,000
Processing step: decrease in emissions from combustion	MT CO ₂ e per yr	- 27,000
Usage step: increase in low-GHG electricity from gasifier	MT CO ₂ e per yr	- 900
Usage step: increase in net primary productivity	MT CO ₂ e per yr	- 3,700
Net Emissions - All Lifecycle Steps	MT CO₂e per yr	- 11,300

A more detailed breakdown of the biomass flows and their fractional contribution to net GHG emissions for the gasification pathway is shown in Table 3-9.

Table 3-9. Breakdown of Flows and GHG Emissions for Gasification to Electricity Generation

Inputs and Outputs		
Woody Materials (input)	MT (dry) per year	14,800
Electricity (output)	MWh per year	12,500
Biochar (10% of input woody materials) (output)	MT (dry) per year	1,500
Net GHG Emissions per Unit of Input and Output		
GHG Emissions per Dry Metric Ton of Woody Materials (input)	MT CO ₂ e per MT	- 0.8
GHG Emissions per Megawatt-hour of Electricity (output)	MT CO ₂ e per MWh	- 0.9
GHG Emissions per Dry Metric Ton of Biochar Applied (output)	MT CO ₂ e per MT	- 7.5 ¹⁰⁰

In sum, using woody construction and demolition materials and wood chips in a gasification pathway reduces GHG emissions. Per Table 3-9, for every dry metric ton of woody construction and demolition material sent to a gasifier instead of a combustion power plant, Marin reduces 0.8 metric tons of CO₂e. For every megawatt-hour of electricity produced, Marin reduces 0.9 metric tons of CO₂e. Or for every ton of biochar applied to land, Marin reduces 7.5 metric tons of CO₂e emissions.

Pyrolysis and Biochar Production

As described in Chapter 2, pyrolysis refers to thermal decomposition of organic materials at elevated temperatures (typically between 400°F and 1,600°F) with little to no oxygen added. The outputs of pyrolysis are a solid carbon-rich substance called “biochar,” a liquid fraction, and a gaseous material called synthesis gas or “syngas.” Like the syngas from gasification, the syngas from pyrolysis is rich in carbon monoxide and hydrogen. However, the syngas from pyrolysis may require more upgrading for it to be sold as an energy resource. Consequently, syngas may be flared on site or, perhaps, used as a source of

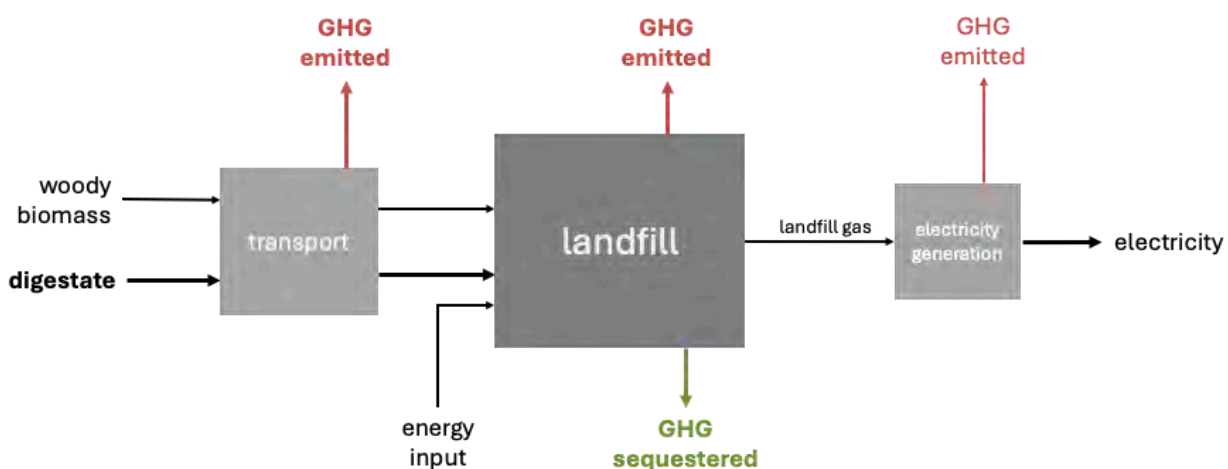
¹⁰⁰ This factor is considerably higher for gasification than pyrolysis for two reasons: avoided transportation emissions, and the higher conversion efficiency associated with producing biochar from woody materials only (Woolf et al., 2021).

process heat for the pyrolysis system.¹⁰¹ Although pyrolysis can convert a wide range of biomass, it is better suited for drier biomass inputs like wood, as opposed to wetter feedstocks like food scraps or sewage unless they are de-watered, either mechanically or by solar drying.

Pyrolysis as a technology is not new, but its commercial use on an industrial scale for biomass utilization is only recently developing in the United States. There are currently only a few biomass pyrolysis facilities in the Bay Area, and there are none in Marin. Developing pyrolysis for biomass means not only building new infrastructure, it also means building a new kind of infrastructure. The novel co-pyrolysis facility imagined in this Study and modeled here is as proposed in Chapter 2: development of a pyrolysis system at the site of a retired wastewater treatment plant, and co-pyrolysis of woody biomass from fuel treatments with wastewater biosolids from around Marin.

The baseline scenario for this analysis is the landfilling of biosolids and of woody biomass. As illustrated in Figure 3-9, there are no product outputs.

Figure 3-9. Baseline Scenario: Landfilling with Electricity Generation

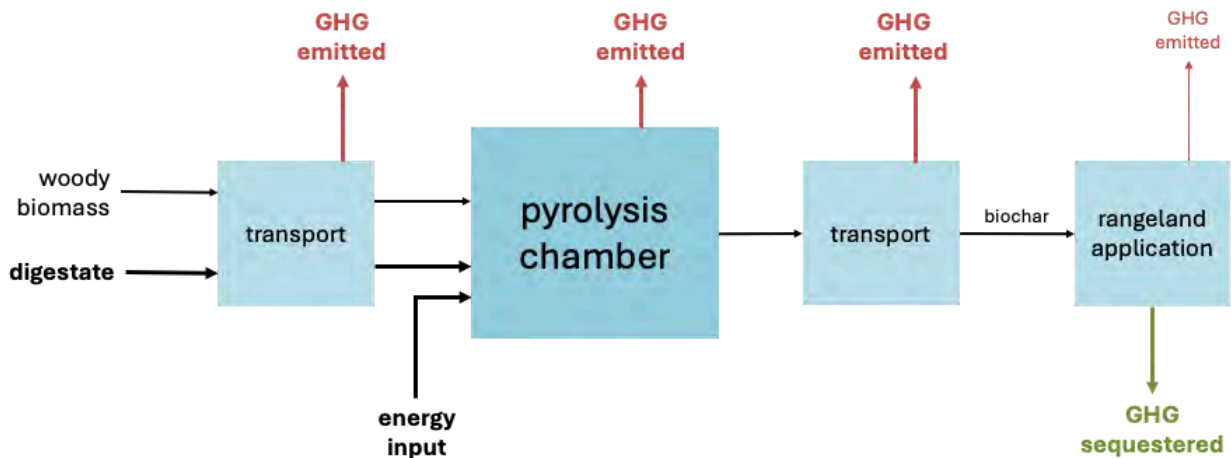


As illustrated in Figure 3-10, the alternative case is the co-pyrolysis of dried biosolids from wastewater treatment facilities and woody biomass from fuel treatment to create a high-quality biochar that is applied as a soil amendment on Marin’s rangelands. The imagined facility that co-pyrolyzes these two feedstocks is optimized for production of biochar and, therefore, produces a lower-quality syngas that is not explored here as a

¹⁰¹ The output gas is also generally higher in tars and condensable oils. Instead of flaring, the output gas could be used to generate process heat if local demand is available. In a large enough volume to achieve a sufficient economy of scale to be refined, these oils are a potential coproduct called “bio-oil.”

salable product. (Instead, a fraction of the syngas is used onsite to generate process heat for the pyrolysis chamber with the remainder being flared on site.) In sum, the proposed pathway combines two streams of materials: (a) all 2,500 wet short tons (1,400 dry metric tons) per year of woody biomass that is practically recoverable from fuel treatment in Marin’s forests and woodlands, and (b) 16,500 wet short tons (3,000 dry metric tons) of biosolids produced in Marin’s wastewater treatment operations.

Figure 3-10. Alternative Scenario: Co-Pyrolysis for Biochar Production



The LCA assesses the scenarios within the system illustrated in Figures 3-9 and 3-10, based on the input values summarized in [Appendix G](#) (Table G-5), and based on the following data and assumptions:

Feedstocks (inputs)

- Baseline Scenario (current): All biosolids and woody biomass are sent to landfill.
- Alternative Scenario (considered): All 2,500 wet short tons (1,400 dry metric tons) per year of practically recoverable woody biomass from fuel treatment work in Marin, and all 16,500 wet short tons (3,000 dry metric tons) of biosolids produced in Marin’s wastewater treatment operations are sent into the co-pyrolysis pathway.

Products (outputs)

- Baseline Scenario (current): all biomass becomes waste in landfill; recovered landfill gas is used to produce electricity.
- Alternative Scenario (considered): 1,540 dry metric tons per year of biochar. (Any syngas produced is assumed to be low quality and too expensive to refine for sale and is assumed to be used to generate process heat on site.)

Assumptions about Operational Factors

- The pyrolysis facility is assumed to be close enough to the waste transfer station that no additional transport is required or avoided.
- Biochar application on rangelands creates new transportation-related GHG impacts.

Assumptions about GHG Emissions

- The pyrolysis process produces biochar with a high carbon content capable of sequestering carbon in soils for long periods.
- Landfills sequester a portion of the carbon in biomass over long periods and also release carbon dioxide and methane in the short term.
- A portion of landfill methane is captured and used for onsite electricity production. The remainder of the methane, as well as the evolved carbon dioxide, is released into the atmosphere.
- No nitrogen is applied as fertilizer in the baseline system or in the proposed system. Biochar application on rangeland also does not replace any fertilizer or otherwise contribute nitrogen.

Based on these data and assumptions, diverting roughly 2,500 wet metric tons (1,400 dry metric tons) per year of woody biomass and 16,500 wet short tons (3,000 dry metric tons) per year of biosolids into **pyrolysis focused on biochar production reduces GHG emissions by 3,000 metric tons of CO₂e per year** (Table 3-10).

Table 3-10. Net GHG Emissions for Co-Pyrolysis for Biochar Production

Total Inputs and Outputs	wet short ton per year	dry metric tons per year
Woody Materials (input)	2,500	1,400
Digestate (input)	16,500	3,000
Biochar (35% of feedstocks) (output)	—	1,540
GHG Emissions (100-year timescale)		
Transportation step: decrease from WWTP to landfill	MT CO ₂ e per year	- 1,460
Transportation step: increase from processing to usage	MT CO ₂ e per year	+ 300
Processing step: increase in co-pyrolysis emissions	MT CO ₂ e per year	+ 5,190
Processing step: decrease in fugitive landfill emissions	MT CO ₂ e per year	- 4,740
Usage step: decrease in low-GHG electricity from landfill	MT CO ₂ e per year	+ 10
Usage step: increase in net primary productivity	MT CO ₂ e per year	- 2,300
Net Emissions - All Lifecycle Steps	MT CO₂e per year	- 3,000

A more detailed breakdown of the biomass flows and their fractional contribution to net GHG emissions for the pyrolysis pathway is shown in Table 3-11.

Table 3-11. Breakdown of Flows and GHG Emissions for Co-Pyrolysis for Biochar Production

Inputs and Outputs		
Woody Materials (input)	MT (dry) per year	1,400
Digestate (input)	MT (dry) per year	3,000
Biochar (35% of inputs) (output)	MT (dry) per year	1,540
Net GHG Emissions per Unit of Input and Output		
GHG Emissions per Dry Metric Ton of Biomass (input)	MT CO ₂ e per MT	- 0.7
GHG Emissions per Dry Metric Ton of Biochar Applied (output)	MT CO ₂ e per MT	- 1.9

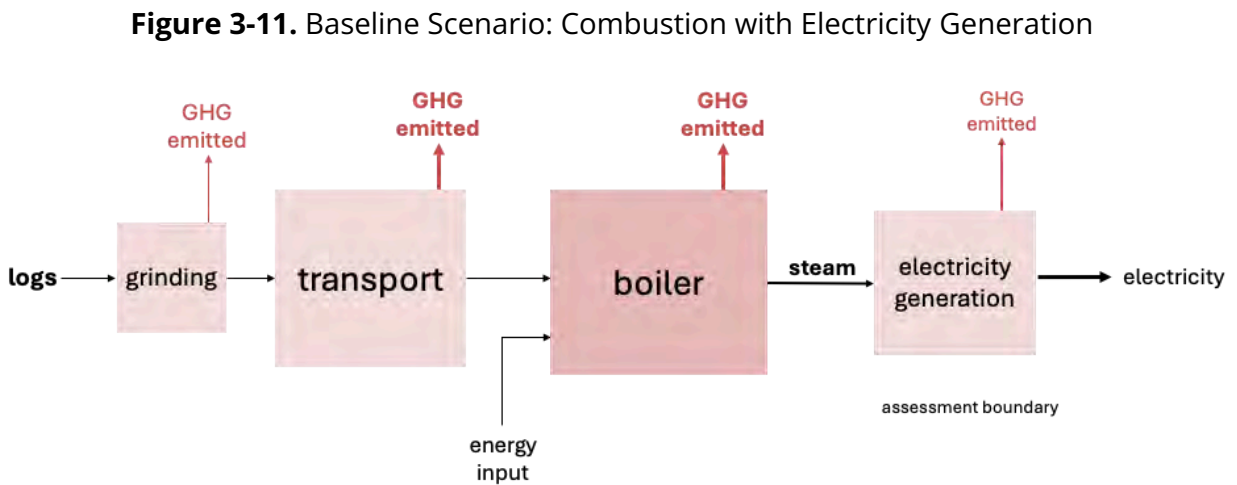
In sum, combining woody materials from fuel treatments and digestate from Marin’s wastewater treatment plants into a pyrolysis pathway reduces GHG emissions. Per Table 3-11, for every metric ton of biomass input (i.e., mixed digestate and woody biomass) sent to pyrolysis instead of landfill, Marin reduces 0.7 metric tons of CO₂e. For every metric ton of biochar applied to land, Marin reduces 1.9 metric tons of CO₂e emissions. In addition to reducing and sequestering GHGs, co-pyrolysis addresses the longer-term management needs for digestate from Marin’s wastewater treatment plants. The application of biochar also increases the water storage capacity of soils where it is applied.¹⁰²

Small-scale Milling and Wood Products

The remaining proposed pathway is milling. Milling refers to the process of cutting timber into usable wood products. In some places in the state with lumbering industries, these wood products could be dimensional lumber produced as a commodity in a large-scale milling operation. However, Marin has neither the type and volume of biomass to support this kind of operation. It produces about 700 wet short tons of logs from roadway maintenance, fallen trees, and fuel treatment annually. While it is possible to grind these logs and use them in the pathways discussed above, their best use can also be wood products, like artisanal slabs useful for furniture production or artistic display. This kind of small-scale mill previously operated at the West Marin Compost drop-off site in Nicasio.

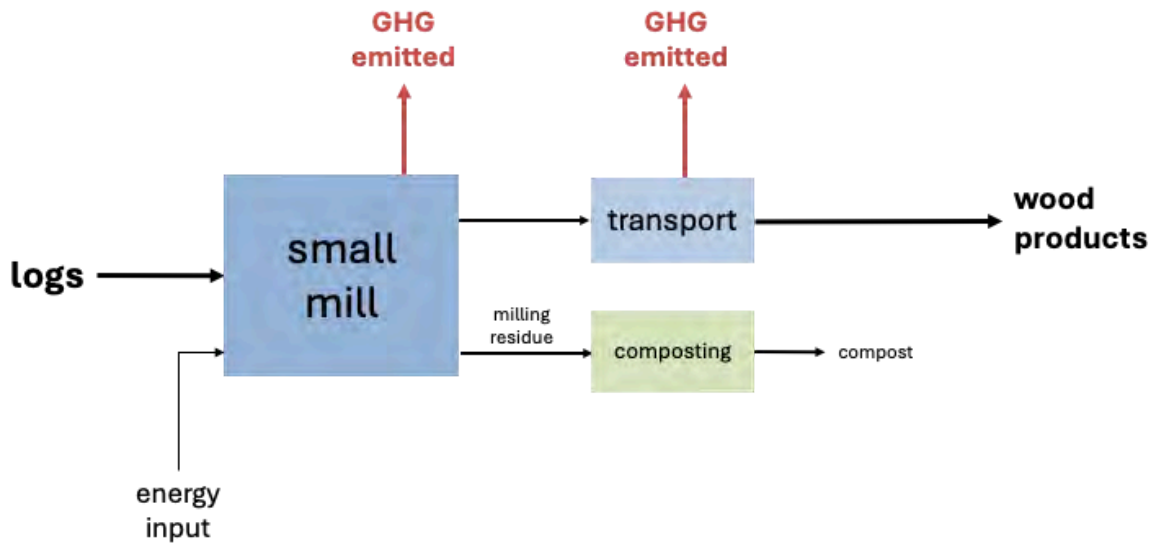
¹⁰² Brown et al. (2023) estimated an optimistic carbon storage value of 4.8 MT CO₂e/MT biochar at a loading rate of 8 MT per acre. The assumptions in this report include a loading rate of 2.5 MT biochar per acre which translates to 1.5 MT CO₂e per MT biochar when using Brown et al. results.

Logs that were previously milled in Marin are now treated as commodity inputs for biomass combustion. That means that they are currently being chipped and shipped to the Central Valley, where they are burned along with construction and demolition materials to generate electricity. This means that, like the gasification pathway, the baseline scenario for the milling pathway is combustion of woody biomass at a power plant that is about a hundred miles away. Like the gasification pathway, the electricity generated at this facility is sold on the spot market into the statewide power grid.



The alternative scenario for this analysis is a resumption of milling. As illustrated in Figure 3-12, this pathway skips the chipping and long-distance shipping of woody biomass in favor of local, small-scale milling that produces wood products for local sale. A local mill also produces byproduct milling residues, which can be used for animal bedding or mulch, or can be added to local composting operations.

Figure 3-12. Alternative Scenario: Small-scale Milling



Analysis of the milling pathway was conducted using the system in Figure 3-11 and 3-12 and these assumptions:

Inputs: Feedstocks

- Baseline Scenario (current): 700 wet short tons (400 dry metric tons) per year of wood chips trucked to combustion power plant(s) in the Central Valley.
- Proposed Scenario (considered): 700 wet short tons (400 dry metric tons) of sorted logs cut at a small-scale, local mill.

Outputs: Products

- Baseline Scenario (current): electricity sold to the statewide power grid
- Alternative Scenario (considered): wood products for local sale

Assumptions about Operational Factors

- The mill is located at the current West Marin Compost receiving and grinding site

Assumptions about GHG Emissions

- Wood chips from grinding of large-diameter logs from roadside maintenance are shipped from Nicasio to the Central Valley.
- Using this biomass in Marin can eliminate trucking to the Central Valley.
- The carbon in logs cut into wood products is retained for at least fifty years.

Based on these data and assumptions, diverting 700 wet short tons (400 dry metric tons) of woody biomass from “chipping and shipping” to combustion power plants into a **milling pathway reduces GHG emissions by 400 metric tons of CO₂e per year** (Table 3-12).

Table 3-12. Net GHG Emissions for Milling Pathway

Total Inputs and Outputs	wet short ton per year	dry metric tons per year
Logs (input)	700	400
Wood Products (output) ¹⁰³	600	320
GHG Emissions (100-year timescale)		
Transportation step: decrease in transport to Central Valley	MT CO ₂ e per yr	- 200
Transportation step: increase in shipment to end user	MT CO ₂ e per yr	+ 20
Processing step: emissions from biopower plant	MT CO ₂ e per yr	- 700
Usage step: emissions from decomposition (> 50 years) ¹⁰⁴	MT CO ₂ e per yr	+ 200
Usage step: decrease in electricity production at power plant	MT CO ₂ e per yr	+ 180
Net Emissions - All Lifecycle Steps	MT CO₂e per yr	- 500

A more detailed breakdown of the biomass flows and their fractional contribution to net GHG emissions for the milling pathway are in Table 3-13.

Table 3-13. Breakdown of Biomass Flows and GHG Emissions for Milling Pathway

Inputs and Outputs		
Logs (input)	MT (dry) per year	400
Wood Products (output) ¹⁰⁵	MT (dry) per year	320
Net GHG Emissions per Unit of Input and Output		
GHG Emissions per Dry Metric Ton of Logs (input)	MT CO ₂ e per MT	- 1.2
GHG Emissions per Thousand Board Feet (output)	MT CO ₂ e per MBF	- 0.7
GHG Emissions per Dry Metric Ton of Products (output)	MT CO ₂ e per MT	- 1.6

¹⁰³ Assumed milling efficiency of eighty percent.

¹⁰⁴ All GHG estimates are on 100-year timeframes. The boards are assumed to last for just fifty years, with decomposition occurring during the second fifty years of the 100-year timeframe.

¹⁰⁵ Assumed milling efficiency of eighty percent.

In sum, retaining logs in Marin and milling them reduces GHG emissions. Per Table 3-13, for every metric ton of logs, Marin reduces 1.2 metric tons of CO₂e. For every board foot of wood product, Marin reduces 0.7 metric tons of CO₂e. Or for every ton of wood products (rather than logs burned), Marin reduces 1.6 metric tons of CO₂e.

GHG Impacts for Alternative Pathways

The lifecycle comparison between Marin’s current biomass management system and the set of alternative pathways from Chapter 2 is to answer the question, will managing biomass in the alternative system reduce GHG emissions and, if so, by how much?

Each pathway is analyzed individually, and, albeit differently, each reduces GHG emissions. When developed, **the combination of pathways will reduce 31,200 metric tons of CO₂e per year** (Table 3-14). To put this reduction in perspective, this is almost three quarters of the GHG emissions generated by Marin’s waste management sector. This represents three percent of Marin's overall greenhouse gas emissions, and its reduction represents a tangible and achievable step toward the countywide goal of net zero emissions.¹⁰⁶

Table 3-14. GHG Emissions for Alternative Pathways (change in flow only)

Biomass	Change in Flow		Pathway	Total GHG (MT CO ₂ e / yr)	Relative GHG* (MT CO ₂ e / dry MT)
	wet short tons	dry metric tons			
Green Materials	20,000	9,000	Composting	- 11,700	- 1.3
Food Scraps	11,100	3,000	Co-digestion	- 4,700	- 1.5
Logs	700	400	Milling	- 500	- 1.3
Digestate	16,500	3,000	Pyrolysis	- 3,000	- 0.7
Wood Chips	2,500	1,400			
Mixed Wood	20,400	14,800	Gasification	- 11,300	- 0.8
TOTAL				- 31,200	

* Computed as a fraction of Total GHG (fifth column) and input dry metric tons (third column).

¹⁰⁶ This percentage reduction is based on 2023 countywide emissions of 43,840 tons from the waste management sector and 1,258,708 tons from all sectors, as reported by the Marin Climate and Energy Partnership (MCEP). The latest information is available in the metrics dashboard on MCEP’s website.

The GHG reduction capacity of a pathway derives from a combination of factors: its transportation needs, process emissions, conversion efficiency, and carbon sequestration potential. It also scales with the magnitude of the biomass flow into it. To create a basis for comparison, the GHG reduction capacity of each pathway is normalized in Table 3-14 by dividing the total estimated GHG reduction by the input flow of biomass in dry metric tons. The result is a basis for a per-unit comparison of the GHG reduction potentials. In rank order, they are co-digestion (-1.5 metric tons CO₂e per dry metric ton), composting (-1.3), milling (-1.3), gasification (-0.8), and pyrolysis (-0.7). When the biomass flows are applied, the order of GHG reductions by pathway are composting (-11,700 metric tons of CO₂e) and gasification (-11,300), followed by co-digestion (-4,700), pyrolysis (-3,000), and milling (-500).

As a reminder, not all biomass is suitable for each pathway. Woody materials, for example, are the largest quantity of biomass and greatest percentage of Marin's biomass flows that would benefit from an alternative pathway. However, woody material is not a good input for pathways like co-digestion or composting, and most of Marin's woody biomass flow consists of woody construction and demolition debris, which do not match a milling pathway either. When clean enough, separated woody materials are, however, suitable for pyrolysis or gasification, each of which has benefits as alternatives to landfill or combustion in the Central Valley. In short, while the total and relative GHG reduction potential can be a powerful way to assess pathways, the per-unit GHG reduction still requires that the material and the pathway match.

Accordingly, a system of complementary pathways is needed to utilize Marin's biomass flows sustainably. The proposed pathways extend the system that Marin has already established. There is already a high rate of green material composting, and expanding the system to accommodate growth can achieve additional GHG reductions. Likewise, the pilot co-digestion system has proven the feasibility of the food scrap recovery program, and expanding it to divert additional commercial food scraps from landfill will contribute more GHG reductions. The largest percentage of biomass needing alternative disposition is woody biomass less suitable to composting and anaerobic digestion. For this reason, the LCAs estimate the potential GHG reductions of directing these woody materials into more suitable pyrolysis or gasification pathways.

Although different pathways are needed to manage different types of biomass, this chapter also compares the GHG reduction potential for each pathway. These per-feedstock metrics are interesting for comparing the pathways' GHG reduction efficiencies, but comprehensive analysis of both the economic and environmental aspects of projects should guide pathway selection and infrastructure investment decisions. All said, the key point is that redirecting

biomass flows into lower-carbon pathways — especially from landfill disposal and export outside Marin to the five alternatives analyzed in this chapter — has the potential not only to reduce the overall GHG impacts of Marin’s biomass system, but to bring Marin closer to its goal of net-zero and ultimately net-negative GHG emissions.

Analysis of Carbon Stocks

A carbon stock is an estimate of the amount of carbon stored in a defined area of the earth. Analysis of a carbon stock can be used to establish a baseline or starting point for monitoring changes in carbon levels over time. This baseline can be especially helpful for evaluating the effect of land management practices on carbon stocks, such as application of compost or biochar on natural and working lands. The carbon analysis undertaken in this Study focuses on establishing this kind of baseline and enhancing carbon sequestration.¹⁰⁷

The term “carbon stock” refers to the total carbon in a given area or “compartment” of the Earth. Analysis of carbon stocks can be a useful way to monitor changes in carbon and management practices over time.

Belowground Carbon

This section provides carbon stock estimates for Marin’s landscapes. Of particular interest in this study is the carbon baseline for rangelands, given that the impact of applying compost and/or biochar to rangeland is a key part of the GHG analysis and pathways comparison in this chapter. This focus on rangelands is based on their spatial extent in Marin County and their carbon sequestration potential, as demonstrated by peer reviewed Marin Carbon Project research. (While not used in this chapter to estimate carbon storage potential, other agricultural lands and public and private urban open spaces are also landcover classes with potential for soil carbon enhancement through the use of compost, mulch, and biochar as soil amendments.)

The analysis uses the USDA’s Natural Resources Conservation Service Gridded Soil Survey Geographic (gSSURGO) database to estimate existing soil carbon in Marin County.¹⁰⁸ Using its raster image with a 10-meter resolution, this dataset was customized to match the

¹⁰⁷ Soil carbon inventories can be based on soil sample collection and laboratory analyses to measure the organic carbon present in a localized soil sample with a high degree of accuracy. This project explores the additional carbon sequestration benefits associated with compost and biochar application to soil.

¹⁰⁸ The dataset used for California is the 2019 data downloaded from the NRCS website.

[Marin County Fine Scale Vegetation Map](#) and to link soil bulk density and soil organic matter values to map units through a lookup table. Using these values and the inverse of the “van Bemmelen factor” (1.724),¹⁰⁹ soil organic carbon per acre was estimated for landcover classes across Marin.¹¹⁰

Estimates of current-day soil carbon levels are summarized in Table 3-15. In total, soils across Marin store an estimated 19 million metric tons of carbon. The largest percentage (37%) is stored in forest soils (7 million metric tons of carbon), followed by soils with herbaceous landcover at 33% (6.2 million metric tons of carbon) and shrubland soils at 17% (3.2 million metric tons of carbon).¹¹¹ The average soil carbon density in Marin is approximately 53 metric tons per acre. The highest densities are in intensively managed hay and silage fields (187 metric tons per acre) and irrigated pastures (100 metric tons per acre). These higher relative densities are likely due to a long history of manure applications on these lands (MCP 2008).

While these numbers are presented with adequate confidence for present purposes, here are a few notes about these numbers to help contextualize them:

- *Assumptions about Soil Data Accuracy.* The gSSURGO database is widely used in natural resource management in California, but it is not frequently updated. This means that its attributes lack data on soil carbon flux (i.e., change over time). So, while it is among the best available data sources with extensive geographic coverage, for some purposes, it may be outdated. In this Study the data in the gSSURGO data is assumed to be current enough to be useful.
- *Assumption about Carbon Stability over Time.* This analysis assumes that, in the absence of compost and biochar added to soils, the soil carbon levels in Marin rangelands are stable over the recent-past and near-future periods.

¹⁰⁹ The van Bemmelen factor is a conversion factor that can be used to estimate the amount of soil organic matter (SOM) from soil organic carbon (SOC), and vice versa.

¹¹⁰ Calculations use this formula: metric tons of soil organic carbon per acre = soil bulk density × SOM % ÷ 1.724.

¹¹¹ This study pays close attention to rangelands because of their spatial extent and potential to receive compost and biochar as soil amendments at the end of the composting and biochar production pathways. Rangelands are included as part of the herbaceous landcover class in the Marin County Fine Scale Vegetation Map. The herbaceous landcover class includes roughly 109,000 acres in Marin. Of this total, we estimate 66,484 acres to be rangelands. Note that this number is relatively close to the 60,000 accessible acres identified in the Marin Climate Action Plan (CMCDA, 2020) as suitable for compost and biochar application.

Table 3-15: Estimated Per-acre Soil Carbon Density and Total Soil Carbon by Landcover Class

Category	Landcover Class	Results		
		Soil Carbon Density (metric tons per acre)	Area of Cover (acres)	Total Soil Carbon (metric tons)
Conifer Forest	Conifer	72	42,600	3,084,000
	Conifer Forest Subtotal	mean = 72	42,600	3,084,000
Hardwood Forest	Deciduous Hardwood	42	5,900	245,000
	Evergreen Hardwood	49	66,900	3,298,000
	Hardwood Forest Subtotal	mean = 49	72,800	3,543,000
Other Forest	Forest Fragment	57	900	51,000
	Non-native Forest	48	4,400	211,000
	Riparian Forest	57	2,300	130,000
	Other Forest Subtotal	mean = 52	7,600	392,000
Forest Subtotal		57	123,000	7,019,000
Agriculture	Annual Cropland	45	200	9,000
	Intensely Managed Hayfield	187	2,600	486,000
	Irrigated Pasture	100	400	40,000
	Nursery or Ornamental Horticulture	—	< 100	1,000
	Orchard or Grove	52	100	6,000
	Perennial Cropland	—	< 100	< 1,000
	Vineyard	55	200	11,000
	Agriculture Subtotal	mean = 150	3,700	554,000
Herbaceous	Eel Grass	59	1,500	89,000
	General Herbaceous (incl. rangeland)	58	105,300	6,137,000
	Non-native Herbaceous	28	1,900	53,000
	Herbaceous Subtotal	mean = 58	108,700	6,279,000
Shrubs	Native Shrub	55	52,600	2,897,000
	Non-native Shrub	52	900	47,000
	Riparian Shrub	51	2,900	147,000
	Shrub Fragment	54	1,200	65,000
	Shrub Subtotal	mean = 55	57,600	3,156,000
Water	Aquatic Vegetation	—	< 100	1,000
	Channel	90	100	9,000
	Freshwater Wetland	81	4,900	399,000
	Mudflat	35	4,000	138,000
	Tidal Wetland	97	5,100	495,000
	Water Other	8	20,400	173,000
	Water Subtotal	mean = 35	34,600	1,1215,000
Urban	Developed	27	25,600	702,000
	Major Road	44	1,600	70,000
	Urban Subtotal	mean = 28	27,200	772,000
Barren	Barren	24	1,600	39,000
	Barren Subtotal	mean = 24	1,600	39,000
Total for All Landcover Classes		mean = 53	356,400	19,034,000

A more nuanced and locally accurate approach to estimating soil organic carbon would involve localized sampling. This could improve scientific confidence in estimates of soil carbon stocks and carbon flux (i.e., the rate and direction at which carbon is exchanged between carbon pools) and in accounts of climate change effects, but at a much finer spatial scale that cannot necessarily be extrapolated to the broader landscape. It could also help establish optimal practices for amending soils with compost and biochar and support data-driven planning and restoration efforts.

Aboveground Carbon

Estimates of belowground carbon provide a basis for understanding durable carbon storage in soil and how it can change over time, particularly with the addition of soil amendments like compost and biochar. Estimates of aboveground carbon provide a basis for evaluating the net primary productivity of lands, as well as provide a basis for estimating the GHG releases from wildfire.

Table 3-16 summarizes the distribution of landscape carbon in Marin’s major landcover classes. Among other things, it shows that most of Marin’s aboveground (vegetated) carbon is stored in its forests and woodlands, and that Marin’s forests and woodlands have a roughly equal amount of carbon stored in its soils.

Table 3-16. Landscape Carbon Estimates for Major Landcover Classes

Landcover Class	Landcover Area (acres)	Aboveground Carbon (metric tons)	Soil Carbon (metric tons)	Total Carbon Density (metric tons/acre)	Total Carbon (metric tons)
All Forests and Woodlands	123,000	7,190,000	7,019,000	114	14,038,000
Agriculture	3,700	de minimis	554,000	150	553,000
Herbaceous	108,700	de minimis	6,279,000	58	6,279,000
Shrubs	57,600	de minimis	3,156,000	55	3,156,000
Water	34,600	--	1,215,000	35	1,215,000
Urban	27,200	de minimis	772,000	28	772,000
Barren	1,600	de minimis	39,000	24	39,000
TOTAL	356,400	7,190,400	19,034,000	--	26,053,000

Above-ground stocks are key to understanding GHG emissions from human activity (e.g., harvest) and from natural and/or climate-driven events (e.g., disease, weather, wildfire, etc) because they are at a much higher risk of loss than belowground stocks. (For this reason,

they are the focus of the Avoided Emissions in the next section.) However, a focus on aboveground carbon should not diminish the importance of belowground carbon management. Given that more than half of Marin's landscape carbon is below ground, Marin should consider pairing its wildfire prevention program with climate actions that boost and stabilize the carbon content of Marin's soils. For example, biomass flows from fuel treatments can be directed into pathways that increase soil carbon.

Such actions make the biomass utilization pathways analyzed in the previous section that much more relevant to reducing the climate change that is continuing to intensify impacts like wildfire. Not only do these actions have the potential to reduce GHG emissions, they may also transform biomass into products, such as compost and biochar, that can be applied to natural and working lands or to urban landscapes in ways that increase carbon in soils. In addition, they may lead to better economic and environmental outcomes.

The Importance of Carbon Stocks

The soil carbon values in this chapter are best viewed as reasonable estimates. The forest inventory dataset (Riley et al., 2019) and forest growth models (USFS, 2020) used for the Avoided Wildfire Emission methodology account for belowground dead and live carbon pools independent of depth as it relates to trees and shrubs. But other soil carbon pools are only considered to a depth of 20cm (Riley et al. 2019, USFS 2020). In contrast, the Marin soil carbon analysis accounts for soil carbon down to a depth of 100 cm.

According to Ryals & Silver (2013), changes in soil management can impact soil respiration and the emissions of the key greenhouse gases: carbon dioxide (CO₂), methane (CH₄), and nitrous oxide (N₂O). Soil respiration, the process through which soil organisms release CO₂ during organic matter decomposition, is highly sensitive to management practices. For instance, adding organic amendments such as compost or biochar can enhance soil organic carbon, which can increase microbial activity and, consequently, soil respiration. However, these amendments may also create conditions that affect N₂O and CH₄ emissions. For example, compost can boost nitrogen availability, potentially increasing N₂O emissions in poorly drained soils where denitrification occurs. Similarly, biochar amendments may reduce N₂O emissions due to improved soil aeration but could increase or decrease CH₄ flux depending on soil conditions.

Practices like tillage, irrigation, and fertilizer application also play a role. Tillage disrupts soil structure, leading to increased CO₂ emissions by exposing organic carbon to microbial breakdown (Powlson et al. 2011). Over-irrigation can create anaerobic conditions,

promoting CH₄ production. Conversely, no-till practices and optimized irrigation can reduce GHG emissions and enhance carbon sequestration.

Thus, the interplay between soil management practices and environmental factors is critical in determining the balance of GHG fluxes and soil carbon dynamics. In turn, these GHG fluxes are important in considering the potential of various biomass utilization pathways to retain carbon stocks and to enhance carbon sequestration.

Analysis of Avoided Emissions

When wildfire burns a landscape, it releases GHGs. When actions are taken to reduce the probability and severity of wildfire, they can avoid GHG emissions and maintain rates of carbon uptake and sequestration in vegetation and soils.

Public and private land managers undertake vegetation management on natural and working landscapes in Marin County for a variety of reasons. The analysis in this chapter considers activities that reduce the biomass that fuels wildfire. For this reason, these vegetation management activities are called “fuel reduction treatments.” The Avoided Emissions account in this section is built by analyzing the GHG emissions prevented by these fuel treatments.¹¹² While these fuel treatments do not change the probability that a wildfire occurs, they can significantly change the character of a wildfire — i.e., from high-severity fires that burn the crowns of trees over an extended time and kill entire forests, to low-severity fires with short flame length (i.e., three feet or less) and short burn time with smaller wildfire impacts. This analysis builds on the estimates of carbon stored in Marin’s soils and standing vegetation. It then estimates how fuel treatments change carbon storage over time and calculates the GHG emissions expected from wildfire events without and with these treatments.

This analysis begins with an estimation of forest carbon stocks. It then estimates how forest fuel treatments will change fire behavior (e.g., flame length, burn severity, etc.). It concludes by estimating the changed carbon fluxes during and after wildfire, with a focus on the differences between forested lands that have and have not undergone fuel treatments. This analysis includes the likelihood that some stands will not regrow immediately after a high-severity, stand-replacing wildfire (delayed reforestation). The GHG emission estimation technique called Avoided Wildfire Emission analysis uses the predicted

¹¹² The relevant GHGs for emissions estimation are carbon dioxide (CO₂), black carbon (BC), methane (CH₄), and ultra-fine particulate matter (PM_{2.5}).

differences in fire behavior and carbon stocks to estimate the GHG emissions that fuel treatments prevent. This section concludes with an estimate of these avoided GHG emissions.

Overview of Fuel Treatment Options

The term “fuel treatment” refers to removal of materials that enable or fuel wildfire. In Marin, fuel treatment aims to reduce vegetation density to historical norms (i.e., in contrast to the current densities enabled by a century of fire suppression on the landscape). These treatments involve thinning of vegetation, including the removal of smaller diameter trees, lower “fire ladder” branches, and understory vegetation. It can also involve modification or removal of surface-level fuels like forest litter, for example, through prescribed burning.¹¹³ Reducing combustible biomass limits fire severity. Changing the density of vegetation reduces the potential for fire spread. The key objective of fuel treatments is to reduce the potential and destructive consequences of wildfire.

Two aspects of fuel treatment are of interest in this chapter. One is the need for offsite utilization options for biomass generated from fuel treatment – a topic explored further in the second part of this chapter. The other is the avoidance of wildfire-related GHG emissions as a result of fuel treatments. This section explores this topic by evaluating lands in Marin conducive to fuel treatments and assessing the ability of such treatments to reduce the severity of wildfire, prevent GHG emissions, and maintain or increase carbon storage in the landscape.

Modeling of fuel treatment effects involves identification of lands suitable for fuel treatment, which may include areas where fuel treatment has already been implemented. Such suitable lands include the shaded fuel breaks in Novato, Ross Valley, and San Rafael-San Anselmo. Suitability analysis includes factors like ownership, accessibility, and other factors, as outlined in the “Treatment Feasibility Analysis” of the Marin Regional Forest Health Strategy (GGNPC 2023).

The modeling of fuel treatments is based on the following assumptions about Marin’s fire-shed:¹¹⁴

¹¹³ Some fuel treatments involve removal of biomass for offsite processing and utilization. Some involve chipping and spreading on site, and some involve slashing, piling, and burning onsite. Prescribed fire may also be used to reduce vegetation density on the landscape (e.g., Moghaddas et al. 2018).

¹¹⁴ A fire-shed is a term for a bounded geographical area through which a fire is likely to spread.

- *Wildfire Hazard.* Lands are included if characterized as having moderate and above wildfire hazard.¹¹⁵
- *Ownership.* All ownership classes are assumed available for treatment. (The rationale behind this assumption is that all entities have a mandate to reduce wildfire risk/enhance forest health.)
- *Accessibility.* Acreage is included in treatment modeling only if it is accessible by road for (i) mechanical treatment (roughly 10,000 acres) or (ii) hand crews (roughly 15,000 acres). Biological limitations, such as habitat protections, were not used in the accessibility analysis. The consequence is that our modeling may err on the side of being more inclusive (North et al. 2015).
- *Treatment Priority.* Priority is given to areas that have a building density of 0.1 buildings/acre or above and are within a quarter mile of vegetation classified as wildfire hazard.¹¹⁶ However, forested areas provided only a fraction of the acreage accessible by road for mechanical and hand-crew treatment (roughly 3,100 acres out of roughly 25,000 acres, see Table 3-17). To align with a goal used in this analysis of 1,000 acres of treatment per year, the potentially treated area includes areas with a lower building density threshold with fire risk that is moderate or greater. This means that more rural lands were included in the treatment analysis to support the assumed 1,000-acre-per-year treatment goal.
- *Treatment Assignments.* Treatment is randomly allocated across the available acreage. Modeling assumes that treatments will be implemented over the next 10 years and then retreated on 10-year and 20-year intervals, depending on treatment type and the treatment rate of 1,000 acres per year.
- *Shaded Fuel Breaks.* The 4,000 acres of shaded fuel break treatments implemented in Ross Valley, Novato, and San Rafael-San Anselmo since 2020 are included in the first five-year modeling period. The modeling also treats the administrative boundary around lands administered by the National Park Service (NPS) as a shaded fuel break that is 200 feet wide.

¹¹⁵ See ArcGIS REST Services Directory “Layer: Classified Mean Wildfire Hazard Within Stand (ID:1)” https://services5.arcgis.com/tdOLEzq0fgVEIWN3/arcgis/rest/services/Prioritization_Support_Layers_2/FeatureServer/5

¹¹⁶ See ONE TAM Marin Forest Health Web Map for GIS data – ‘Classified Building Density (within 1/4 mile)’ under ‘Prioritization Support Layers’; also available at ArcGIS REST Services Directory ‘Layer: Classified Building Density (within stand) (ID:5)’ https://services5.arcgis.com/tdOLEzq0fgVEIWN3/arcgis/rest/services/Prioritization_Support_Layers_2/FeatureServer/5

- *Prescribed Burns*. Modeling randomly assigned treatment with prescribed burns on 10% of the entire National Park Service acreage and administered over the first five-year period. No other areas were treated within the NPS land area.
- *Omitted Lands*. Land categorized as “limited feasibility” because of poor access or steep slope, as “low feasibility” because near a water body or containing serpentine soil, or as “feasible” but with hand crew needed with only trail access are not modeled as potentially treatable. The reason is that fuel treatment within the given category is unlikely to be implemented due to site constraints and/or the acreage associated with these lands is considered miniscule.

Based on these criteria, Marin’s acreage was analyzed to evaluate which has or could receive fuel treatments. Table 3-17 and Figure 3-13 break lands down by owner. Table 3-18 breaks acreage down by treatment type, and Figure 3-14 maps treatment types onto Marin.

Table 3-17. Potentially Available Acreage for Fuel Treatments

Owner	Limited Feasibility		Low Feasibility			Feasible			Total
	Steep Slope	Poor Access	Near Water Body	Serpentine Soil	Hand Crew (trail)	Mechanical (trail)	Hand Crew (road)	Mechanical (road)	
Private	19,930	5,840	16,090	210	30	10	9,020	6,410	57,540
Nonprofit Trusts and Conservancies	320	140	460	-	-	-	130	120	1,170
Local Government	10,500	2,080	8,030	670	330	160	3,130	1,500	26,400
California Fish and Wildlife	10	-	10	-	-	-	40	30	90
California State Parks	3,560	1,100	2,530	10	210	120	960	540	9,030
Other State Lands	-	-	-	-	-	-	-	10	10
US Fish and Wildlife Service	-	-	-	-	-	-	-	-	-
National Park Service	8,280	6,470	8,660	-	710	740	2,050	1,790	28,700
Total	42,600	15,630	35,780	890	1,280	1,030	15,330	10,400	122,940

Figure 3-13: Potentially Available Acreage for Fuel Treatments¹¹⁷

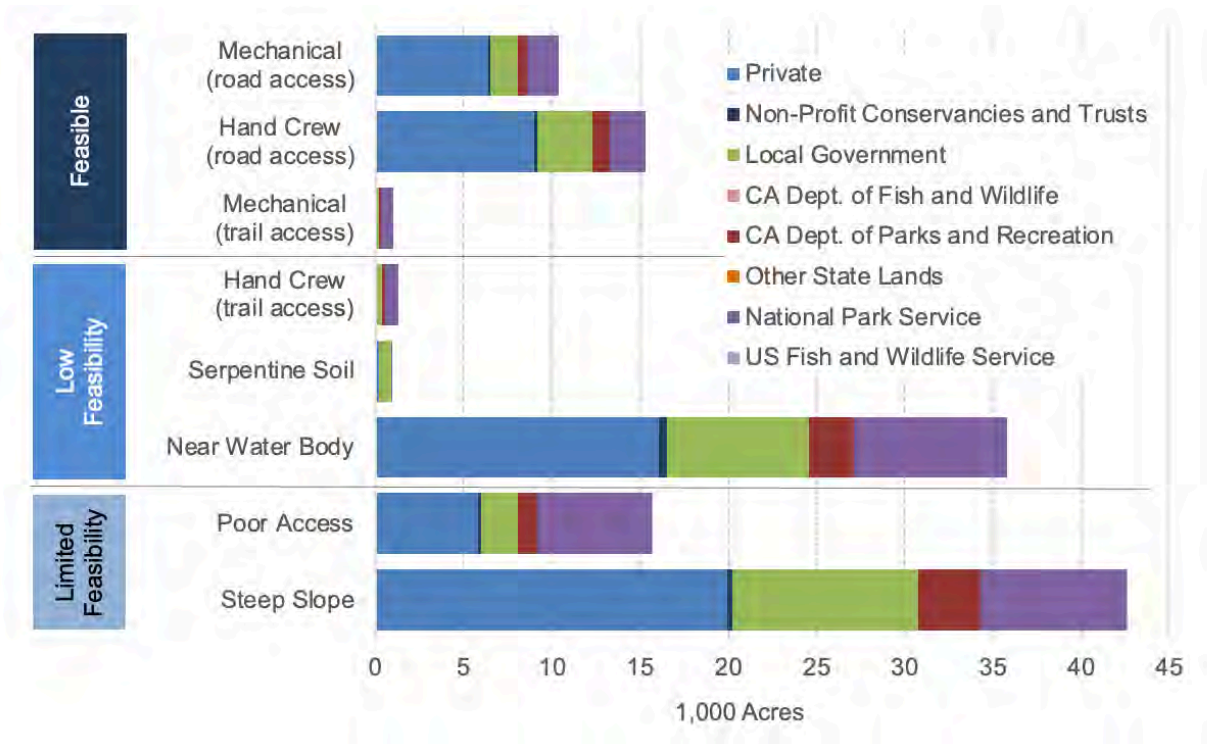
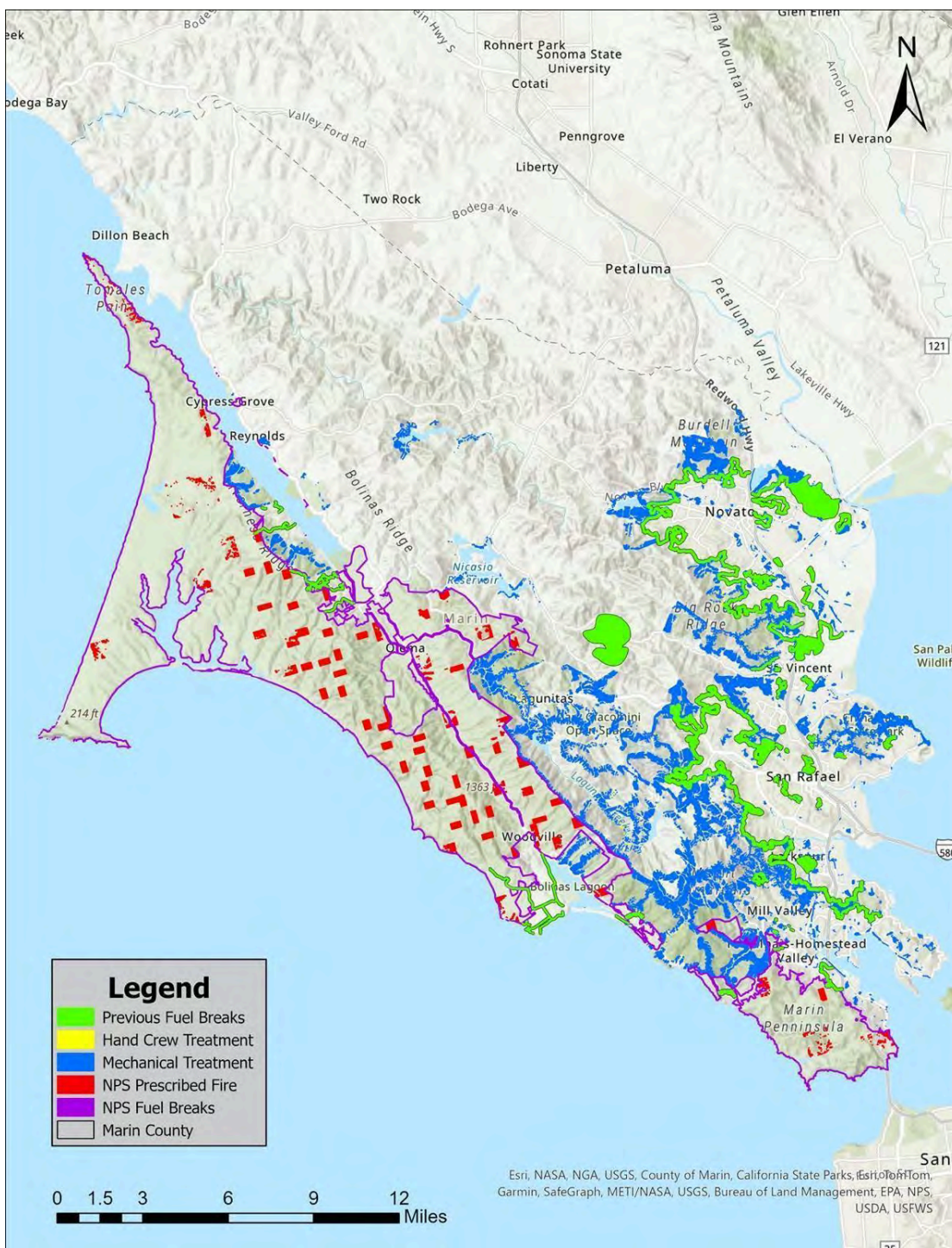


Table 3-18: Treatment Type and Treatable Acreage

Treatment Type	Treatable Acreage
Mechanical Treatments 2023-2027	3,080
Mechanical Treatments 2028-2032	2,030
Hand Crew Treatments 2023-2027	40
Hand Crew Treatments 2028-2032	50
Completed Shaded Fuel Breaks	3,170
Prescribed Fire on Lands Administered by National Park Service, 2023-2027	1,640
Prescribed Fire on Lands Administered by National Park Service, 2028-2032	1,560
Total Area Treated	11,570

¹¹⁷ Data from ONE TAM Marin Forest Health Web Map for GIS – Marin Mechanical Treatment Feasibility (V3) layer <https://parksconservancy.maps.arcgis.com/apps/instant/media/index.html?appid=283456ad496e4a999e74f9501468261c>

Figure 3-14: Fire-shed Area Feasible for Fuel Treatment¹¹⁸



¹¹⁸The category of “Previous Fuel Breaks” identifies locations of the Ross Valley and Novato shaded fuel breaks. Also note that, because of the limited scope of hand crew treatments, there are no visible yellow areas on this map. For acreage by treatment type, see Table 3-18.

The fuel treatments deemed feasible and included in the GHG estimation are as follows:¹¹⁹

- *Shaded Fuel Breaks.* Fuel breaks are modeled as cutting all live and dead trees up to twelve inches in diameter at breast height. Cut biomass is modeled as masticated (chipped) and left onsite. All fuel breaks are modeled as occurring in the first five-year period and being repeated every twenty years. Shaded fuel breaks total roughly 100 miles plus the NPS-administered lands boundary that is 200-foot wide and 500 miles long (Figure 3-14). Note that half of shaded fuel breaks were forested according to TreeMap (Riley et al., 2019) with the remainder identified as shrub and herbaceous landcover.
- *Mechanical Fuel Treatments.* Mechanical treatment refers to vegetation management primarily involving heavy machinery. Three types of mechanical treatments were considered as part of fuel treatment modeling. A first type is the cutting of seventy percent of all dead trees up to twenty inches in diameter at breast height and small diameter hardwoods and douglas fir trees up to twelve inches. A second type involves the cutting of live hardwood trees up to twelve inches in diameter at breast height. This treatment type did not end up needing to be used in modeling because Marin has very little standing hardwoods with these characteristics. A third type involves the cutting of invasive and non-native trees up to twenty-four inches in diameter at breast height with the goal of achieving a residual stand basal area of one hundred square feet. Mechanical treatments are modeled as occurring once every twenty years, and any practically removable biomass is modeled as being removed and sent into a utilization pathway.
- *Hand Crew Fuel Treatments.* Hand crew treatments are modeled as cutting 100% of live trees up to 12 inches in diameter at breast height and 70% of dead trees up to 20 inches in diameter at breast height. All hand crew treatments are modeled as

¹¹⁹ In this analysis, fuel treatment prescriptions are identified by type (e.g., shaded fuel breaks, mechanical treatments, hand crew treatments). However, the 2016 TreeMap-derived tree inventory, as grown forward to 2023, projects a current average stand structure of densely stocked small trees and a relatively low basal area. Thus, more aggressive treatment specifications are recommended, both for mechanical and hand crew treatments, to achieve the thinning in growth and yield simulation using the Forest Vegetation Simulator Fire and Fuels Extension (FVS-FFE, Rebañ et al. 2015). Of note, the original Stand Density Index (SDI) threshold for thinning, while potentially biologically appropriate, results in most stands outside the shaded fuel breaks not being thinned in FVS modeling. Even lowering the basal area to 60 square feet per acre, as suggested by Agee & Skinner (2005) for "a forest type with a historic low-severity fire regime (low elevation ponderosa pine/Douglas-fir/grand fir) and trees up to 40-inch diameter at breast height," did not trigger a thinning in FVS due to SDI thresholds. This results in adjustment to the modeled mechanical and hand crew treatments based on the shaded fuel treatment prescription plus a follow-up burn.

occurring once every 20 years, and, like shaded fuel breaks, all cut biomass is assumed to be chipped and left onsite.

- *Prescribed Burns.* Any prescribed burns, including any prescribed burns following a mechanical or hand treatment, are modeled as occurring every ten years. This means that, every twenty years, a landscape will receive two prescribed burns and one mechanical treatment. Any prescribed grazing in lieu of prescribed burns was modeled as prescribed burning.

Modeling assumes that ten percent of all lands that the National Park Service administers will be treated with shaded fuel breaks and prescribed burns. It also assumes that, over the next ten years, mechanical treatments will occur on nearly seven percent of all forested fire-shed lands in Marin. All fuel treatments in Marin, including the already-planned shaded fuel breaks in Novato, Ross Valley, and San Rafael-San Anselmo, will risk-manage biomass on a total of roughly nine percent (11,000 acres) of the 123,000 acres of forested land in Marin's fire-shed – a number worth noting as lower than recommended to produce meaningful impact on wildfire size and avoided emissions.¹²⁰ It should be noted that these assumptions are projections of fuel treatments based on contemporary best fuel management practices compatible with Marin's forested landscapes and wildland urban interface areas. Actual treatments and project designs vary based on planning, including work undertaken to create the Marin County Wildfire Prevention Plan — which is currently being developed by responsible agencies and due for release in July of 2026.

Overview of Avoided Emission Estimation

This section provides an estimate of the GHG emissions that Marin will avoid by undertaking the planned set of fuel treatments. As explained in more detail in [Appendix G](#), an Avoided Wildfire Emissions estimation method is used to quantify GHG emissions that will not occur as a result of Marin's wildfire prevention efforts.

For a couple of reasons, the estimation of avoided wildfire emissions is narrowed to focus mainly on changes to carbon fluxes in Marin's forests. One reason is that the focus of this Study is on finding sustainable uses for the biomass generated by wildfire management activities. Most wildfire management activities take place on forested lands, and wildfire

¹²⁰ Generally, to have meaningful effects on wildfire size and avoided emissions, a relatively large proportion (e.g., 20%) of a fireshed should exhibit treatment characteristics at any point in time (Moghaddas et al. 2018, Buchholz et al. 2018, Stephens et al. 2012, Schmidt et al. 2008). While the treatments analyzed here covered only 9% of the landscape, the results suggest an effective approach when considering GHG benefits. Fuel treatments have a lifespan of around 15 years after which a treated stand does not show a difference in fire behavior vs. an untreated stand due to regrowth (Collins et al. 2011, Davis et al. 2024).

prevention on non-forested landscapes does not generate significant quantities of woody biomass needing disposition. A second reason is that data suitable for Avoided Wildfire Emission modeling is currently limited by a lack of wildfire behavior models for non-forested lands. Third, non-closed canopy forests contain less carbon and associated treatments that, while being valuable in mitigating wildfire risk, have a lesser impact on carbon fluxes in terms of quantity. So, while a focus on forested lands can provide only a partial picture of overall landscape carbon, it captures the most potent and relevant landscape, both in terms of wildfire prevention activity and biomass flows of interest.¹²¹

This section tells the story of avoided wildfire emissions in three modeling steps. The first estimates the carbon fluxes in forests if Marin experiences no significant wildfire over the next forty years. The second step builds on the carbon flux estimates and considers the difference in GHG emissions between untreated and treated forests when a wildfire occurs. The third step estimates the difference in GHG emissions when changes in fire behavior (e.g., spread, intensity, and severity) are also included. In sum, this section summarizes each step in the process of estimating the GHG emissions avoided by fuel treatments.

Accounting for Stored Carbon and Carbon Fluxes

A forest carbon flux analysis is an approach used to estimate the changing amounts of carbon stored in and fluxing from a forest's trees, soil, deadwood, and litter over time. The following carbon pools are included in this analysis of forest carbon: aboveground live pools, belowground live and dead pools (including soil carbon), standing dead pools, down dead pools, forest floor pools, and shrub and herb pools.

A forest carbon flux analysis also can be used to assess the rate at which the forest captures and stores carbon over time. Like a soil carbon inventory, a forest carbon flux analysis can be used to establish the baseline amount of carbon in the forest and then examine how management activities, such as fuel reduction treatment, changes the amount of stored carbon. This analysis can also estimate the rate of net carbon dioxide (CO₂) drawdown from the atmosphere through photosynthesis. This process of quantifying carbon gains, losses, and long-term storage capacity helps to estimate the ability of a forest to absorb or "sequester" carbon from the atmosphere. This estimate can help establish a baseline for quantifying a forest's potential to mitigate climate change given specific forest management practices such as wildfire risk reduction programs.

¹²¹ It is worth noting that managing fine grassland fuels on lands adjacent to forests can be a critical fire risk reduction strategy.

As summarized in Table 3-19, the carbon stock changes in Marin’s forests are estimated using a five-year accrual method over the time period of 2023 through 2063. The change in carbon stock is predicted based on estimates of forest growth. The difference in carbon stocks, i.e., carbon fluxes, between forests without fuel treatments and forests with fuel treatments is based on the cutting, dispersal, removal, and decay of vegetation in the absence of wildfire.

Table 3-19: Aboveground Forest Carbon Stocks and Fluxes without Wildfire (2023 to 2063)

Five-Year Modeling Interval	Carbon Stock in Forests Without Fuel Treatments (metric ton of carbon per acre)	Carbon Stocks in Forests With Fuel Treatments (metric ton of carbon/acre)	Difference or “Flux” in Forest Carbon Stock (metric ton of carbon/acre)
2023-2028	8,555,000 (69)	8,555,000 (69)	0 (0.0)
2028-2033	9,856,000 (79)	9,826,000 (79)	29,700 (0.2)
2033-2038	11,246,000 (90)	11,160,000 (90)	86,400 (0.7)
2038-2043	12,605,000 (101)	12,472,000 (100)	133,600 (1.1)
2043-2048	13,889,000 (112)	13,711,000 (110)	178,300 (1.4)
2048-2053	15,091,000 (121)	14,878,000 (120)	213,000 (1.7)
2053-2058	16,187,000 (130)	15,952,000 (128)	235,500 (1.9)
2058-2063	17,207,000 (138)	16,957,000 (136)	250,300 (2.0)

In 2023, the forests in Marin’s fire-shed contained an estimated 8.5 million metric tons (MT) of carbon. In the absence of wildfire and with no fuel treatments, the carbon stocks in Marin’s forests will increase from 8.5 million metric tons of carbon in 2023 to 17.2 million metric tons of carbon by 2063. By comparison, if fuel treatments are implemented between 2023 and 2063, Marin forests will still grow. However, they will grow 2.5% less than untreated forests and store just under 17 million metric tons of carbon in 2063.¹²²

Although cutting and removal of landscape biomass and consequent changes in forest growth means that Marin’s forests will accrue roughly 0.2 million metric tons less carbon,

¹²² These results are in line with other studies in forecasting lower carbon stocks over time for the treatment scenarios compared to a no-treatment baseline if no wildfire occurs. Scientific literature (e.g., Hurteau et al. 2016, Krofcheck et al. 2017) suggest that initial removal of live carbon stock will reduce net carbon uptake over the coming decades if no wildfire is present and independent of other effects. (This outcome is the same for any other stochastic event that would disproportionately affect high carbon stocked younger stands that might suffer from severe resource competition due to high tree density).

the difference is not necessarily a complete loss of carbon to the atmosphere. That is, the carbon in biomass removed from forest landscapes may still reside in Marin – provided that it enters utilization pathways that lower GHG emissions and retain or sequester carbon in products and soils. (For more detail, look back at Table 3-14 for the difference in GHG emissions by pathway in the Reduced Emissions.)

Accounting for Wildfire Occurrence

This modeling step estimates GHG emissions from wildfire and builds on the carbon stock estimates in the previous step. Like the previous step, each estimate is based on the average carbon stock in an untreated and in a treated forest during a five-year interval. Each estimate is based on a prediction that a wildfire will occur once (and only once) between now and 2063.¹²³ An occurrence of wildfire is modeled as burning 1,100 forested acres in Marin and as releasing between 10-26%, and an average of 17%, of the carbon stock in a forest.¹²⁴ Table 3-20 reports these estimates for each five-year interval and for treated and untreated forests, as well as for the difference between them.

Table 3-20: Change from a Single Wildfire Event between 2023 and 2063

Five-Year Burn Interval	GHG Emissions For Forest <u>Without</u> Treatments (million metric tons CO ₂ e)	GHG Emissions For Forest <u>With</u> Treatments (million metric tons CO ₂ e)	GHG Emission Difference (million metric tons CO ₂ e)
2023-2028	8.55	8.53	0.02
2028-2033	8.89	8.67	0.22
2033-2038	9.63	9.34	0.29
2038-2043	10.30	9.95	0.35
2043-2048	11.35	10.91	0.44
2048-2053	12.48	11.93	0.55
2053-2058	14.07	13.37	0.70
2058-2063	15.83	15.00	0.83

¹²³ Forecasting forest growth over more than several decades is fraught with uncertainties. For this reason, assessment focuses on the first 40 years post-treatment.

¹²⁴ In the modeling, this loss is treated as instantaneous, independent of project year or treatment type. The estimated carbon loss rate is within the expected range of 10% – 20% in the literature (Moghaddas et al., 2018, North and Hurteau 2011).

The estimates in this table show that the longer forests grow and store carbon before a significant wildfire occurs, the greater the GHG emissions from that eventual wildfire will be. For example, a significant wildfire from an untreated forest would release 8.6 million metric tons of CO₂e in 2023. By comparison, if the same forest stored carbon with no significant fire until 2058, a significant wildfire would release 15.8 million metric tons of CO₂e. This includes the GHG effects not only from released carbon but also from particulate matter. The columns in Table 3-19 illustrate the difference in GHG emissions from forests with and without fuel treatments. If 1,100 untreated forest acres had burned in 2023, it would have released 8.6 million metric tons of CO₂e. Emissions from its treated counterpart would be 0.24% lower or 8.5 million metric tons of CO₂e. This difference grows over time. If Marin's forests store carbon without significant burning until sometime between 2058 and 2063, an 1,100-acre wildfire is predicted to release 15.8 million metric tons of CO₂e from an untreated forest. If those same forests are treated during this period, a wildfire will release 15.0 million metric tons of CO₂e or 5.4% lower.

The difference is the emission of 830,000 additional metric tons of CO₂e. This first difference begins to reveal the benefits of fuel treatment. That is, the larger the difference in carbon stock between an untreated forest and a treated forest, the larger the difference in GHG emissions when a wildfire occurs. However, there is another, important element to the story. That is, the extent of wildfire and carbon release depends on the nature of the standing trees. The more that carbon stocks of the forest are stored in small trees, the larger the GHG emissions will be when there is a wildfire. The more carbon stock is stored in fewer, larger trees — both with fewer ladder fuels and fewer fuels on the forest floor, the more resilient the forest will be during a wildfire, and the less carbon will be released.

While these side-by-side estimates are a useful starting point for comparing the GHG release from untreated and treated forests, they provide a simplified picture of GHG emissions. The Avoided Wildfire Emission analysis offered in the next step offers a more sophisticated estimate based on differences in probability, severity, and after-effects of wildfire. For example, even if treatments cover only a small portion of Marin's fire-shed,

About this Difference:

An untreated forest that burns between 2058 and 2063 would release the equivalent of up to 830,000 metric tons of carbon dioxide more than a treated forest that burns in the same timeframe. This difference is about two and half times larger than the total GHG emissions from Marin's agricultural activities in 2023.

their impact can create a more general impact or “treatment shadow effect” that extends beyond the treated lands. This means that the fuel treatments do more than just reduce fuel load; they also change aspects of fire behavior, such as intensity measures like flame length and fire temperature, as well as fire speed, spread, and overall severity.¹²⁵ In addition, forest treatments can change the recovery path of forests after wildfire. For example, fuel treatments can create conditions that enable forests to regrow more quickly after wildfire and reduce the risk of “delayed regeneration” (i.e., slower regrowth). Modeling that considers these aspects of fire behavior and the impacts of each type of greenhouse gas is believed to improve the GHG estimates.

Accounting for Wildfire Probability and Behavior

The previous two modeling steps estimate GHG emissions based on forest carbon stock estimates (step 1) and changes in carbon release based on wildfire occurrence (step 2). The third step considered here focuses on differences in wildfire probability and behavior. This step involves modeling that accounts for changes in wildfire spread and severity across the landscape, as well as changes in the rate of forest recovery after a wildfire. (For more detailed discussion of these advanced wildfire modeling topics, see Appendix G.)

Estimates of avoided GHG emissions are more sophisticated and, likely, more accurate when they look at wildfire behavior probabilistically. That said, one of the current challenges in predicting wildfire is uncertainty about the probability of burning – as a result of fire suppression and climate change, but also due to the changing scientific understanding of wildfire behavior. Over the last hundred years, fire suppression practiced as part of forest management attempted to reduce the occurrence of wildfire or the “annual burn probability” (ABP). Along with climate change, a century of fire suppression in fire-prone western forests has likely increased the long-term probability and potential severity of wildfire. The challenge lies in estimating by how much.¹²⁶

¹²⁵ Treatments break up the current untreated state of the forests and associated fuels, resulting in openings and gaps. Besides affecting fire behavior (from high to lower severity), fire size, and therefore GHG emissions, the treatments can act as part of safety zones for fire fighters when wildfires occur. Combined, this can result in a forest landscape that is safer, and therefore more conducive to active and aggressive wildfire suppression management. This suppression impact on GHG emissions was beyond the scope for this report.

¹²⁶ For example, fire probability may look different when examined over the last several decades. During this period wildfire was less frequent than over the most recent decade. At present, CAL FIRE proposes a mean Annual Burn Probability of just 1.02% for Marin County and a maximum of 1.89%. These numbers are based on predicted use of fire suppression techniques and are significantly lower than the historic, pre-settlement probabilities. For this reason, scientists are proposing increases in the annual burn probability to account for

One way to meet this challenge is to work with a range of annual burn probabilities. Table 3-20 lists a range of annual burn probabilities, along with GHG emission estimates based on them. The first column of this table lists a range of annual burn probabilities from 1.0% (i.e., the rate that CAL FIRE targets through fire suppression) up to an annual burn probability of 5.0% (i.e., a rate of frequent fire). The second column provides a range of GHG emission estimates for an untreated acre of Marin forest for each of the annual burn probabilities. The third column provides a range of GHG emission estimates, for one of the 11,600 acres of Marin’s forests receiving fuel treatment. The fourth column (in gray) provides estimates of the cumulative GHG emissions differences when wildfire burns on untreated and treated forests. Estimates with negative values in column four indicate, for that annual burn probability, an increase in cumulative GHG emissions and a “climate liability” for Marin. By contrast, estimates with positive values in column four indicate a net decrease in GHG emissions or a “climate benefit” for Marin. In short, as the annual burn probability increases, so does the estimate of avoided GHG emissions from forest treatments.¹²⁷ When the predicted annual burn probability is 2.5% or higher, fuel treatments prevent or “avoid” GHG emissions over a 40-year timespan.

The fifth column in Table 3-21 lists the GHG “Payback Period” associated with different annual burn probabilities. This “Payback Period” is the amount of time over which the avoided GHG emissions exceed all GHG emissions associated with wildfire prevention activities and downstream biomass utilization – unless the utilization options produce net negative GHG emissions. (See the next section for pathways with net negative emissions.) This column indicates that an investment in GHG savings pays off in two decades if the annual burn probability is high, and in a longer period of time if the annual burn probability is low.

For Marin, this Study recommends a GHG estimate based on an annual burn probability of 2.5%.¹²⁸ For this reason, the line with the 2.5% annual burn probability is bolded in Table 3-21. Modeled over a 40-year fire return interval, when all feasible treatments are implemented, Marin’s wildfire prevention activities would avoid emission of 1,000,000 metric tons of CO₂e. (This amount corresponds to 1.4 metric tons of CO₂e per forested

what is believed to be increasing wildfire risks (e.g., Park et al. 2021). See CAL FIRE FRAP Fire Probability for Carbon Accounting: <https://egis.fire.ca.gov/FireProbability/>

¹²⁷ Studies suggest that annual wildfire risk has been rising in the project area (Westerling 2018). Findings from these studies form the basis for modeling with Annual Burn Probabilities above 2%.

¹²⁸ Literature about climate change and wildfire in California (Westerling 2018) supports a constant 2.5% annual wildfire probability (equaling a 40-year fire return interval), while also providing a basis for thinking that this Annual Burn Probability may still underestimate future wildfire risk considerably. For example, an annual increase of wildfire risk by just 2% would result in a 5.5% annual fire probability in the year 2063 ($2.5\% * 102\%^{40}$).

acre or 14.7 metric tons of CO₂e per treated acre.) Some of these projected savings are already being realized. That is, treatments have immediate effects, and treatments that have already been implemented can already be associated with avoided GHG emissions.

Table 3-21: GHG Emission Estimate based on a Range of Annual Burn Probability Estimates.

Annual Burn Probability (ABP)	GHG Difference per forested acre (metric tons CO ₂ e)	GHG Difference per treated acre (metric tons CO ₂ e)	Cumulative GHG Difference from 2023-2063 ¹²⁹ (metric tons CO ₂ e)	Timeframe to Net GHG Savings (years)
1.0%	-10.6	-114.0	- 1,319,000	> 40
1.5%	-7.5	-80.1	- 927,000	> 40
2.0%	-4.3	-46.3	- 535,000	~ 40
2.5%¹³⁰	1.4	14.7	170,000	35-40
3.0%	3.9	41.8	484,000	30-35
5.0%	11.5	123.1	1,424,000	20-25

The immediate GHG impacts from fuel treatments are relevant here. Part of the purpose of this Avoided Wildfire Emission analysis is to quantify the avoided GHGs that Marin can associate with its wildfire prevention programs and to provide Marin with a basis for considering whether to pursue carbon credits for avoided wildfire emissions. For example, a voluntary registry, Climate Action Registry (CAR), through its sub-platform Climate Forward, offers the opportunity to use carbon markets to co-fund forest fuel treatments.¹³¹

Carbon markets could also provide funding for the development of the biomass utilization pathways analyzed in the second half of this chapter.

¹²⁹ This column estimates the predicted difference in GHGs during the forty-year period from 2023-2063. That is, it estimates the difference in GHG emissions between an untreated and a treated forest. When the estimate is negative, it means that the GHG release from wildfire in an untreated forest is less than the combined emissions from a treated forest and the treatment itself. When the number is positive, it means that the GHG release from wildfire in an untreated forest is greater than the combined emissions from a treated forest and the treatment itself. In short, a negative number represents a net benefit from forest treatment.

¹³⁰ For a 2.5% annual wildfire probability (40-year fire return interval), all treatment scenarios predict GHG emissions savings of 170,000 metric tons of CO₂e, 1.4 metric tons of CO₂e per forested acre (or 14.7 metric tons of CO₂e per treated acre) compared to a baseline scenario over the timespan analyzed.

¹³¹ [CF Reduced Emissions from Megafires \(REM\) Forecast Methodology](#)

Estimate of Avoided Emissions

The purpose of an Avoided Emission analysis is to estimate the impact of fuel treatments on GHGs. The estimation process described in this section progressively builds an estimate by taking the following factors into account: stored carbon, carbon fluxes, wildfire occurrence, and wildfire probability in behavior.

Assuming an annual burn probability of 2.5%, **fuel treatments in Marin's forests will avoid 170,000 metric tons of CO₂e** over the next forty years. If this GHG emission rate were amortized and turned into an annual rate, fuel treatments could be considered to prevent 4,250 metric tons of CO₂e per year.

Marin's wildfire prevention initiatives offer many benefits. They reduce loss of life, health impacts, ecological damage, and property loss. The analysis undertaken here adds to this list. It demonstrates that fuel treatments can also avoid significant GHG emissions and retain carbon sequestered in its standing vegetation.

Summary of GHG Findings

This chapter explores ways that Marin's biomass system can affect its GHG emissions and carbon stocks. The first section estimates **a reduction of 31,200 metric tons of CO₂e per year** if Marin's expected biomass flows are managed in the alternative set of pathways identified in Chapter 2, rather than the current system. (That is, the biomass would flow more toward composting, co-digestion, pyrolysis, gasification, milling, and deconstruction pathways and away from landfilling and combustion power plants in the Central Valley).

The second section estimates that Marin has over 26 million metric tons of carbon stored in its soils and standing vegetation. This very large stock underscores the importance for climate protection of maintaining this stored carbon. It also demonstrates the potential to use nature-based solutions — such as the carbon return to land considered here — for reducing Marin's GHG emissions and sequestering more carbon, potentially enabling Marin to achieve its goal of carbon neutrality.

The third section explores the fuel treatments being implemented on these landscapes and how they can reduce wildfire severity and spread. Using an Avoided Wildfire Emission framework, it estimates that fuel treatments are likely to prevent the release of 170,000 metric tons of CO₂e over the next forty years. At an annualized rate, this means that **Marin's fuel treatments avoid the equivalent of 4,250 metric tons of CO₂e each year.**

The reduction of emissions from alternative pathways and the avoidance of emissions through fuel treatments represent different interventions and impacts on Marin's carbon stocks. The combined 31,200 metric tons of CO₂e per year that can be *reduced* through use of alternative pathways represent emissions that, in part, Marin is already emitting. By contrast, the estimated 4,250 metric tons of CO₂e per year that will be *avoided* by Marin's wildfire safety measures about emissions that have not yet occurred. So, while these are different in nature and timeframe, they can produce **the combined effect of reducing Marin's GHG emissions by 35,450 metric tons per year of CO₂e.**

These estimates demonstrate the significance of biomass management as a form of climate action. They also provide a starting point for understanding the potential GHG incentives of better biomass management and provide a basis for certifying reduction and pursuing credits that are available in carbon markets.

These pathways can also produce significant co-benefits. Although they are not quantified here, fuel treatments that reduce fire intensity also help to conserve forest habitat, speed up forest regeneration, improve hydrology, protect infrastructure, reduce the psychological and social trauma of wildfire, and save lives. When a smart set of pathways are in place, they also return carbon to soil (i.e., through application of compost and biochar), boost agricultural productivity, and support a more regenerative agriculture and economy for Marin.

Chapter 4:

Economic Viability and Investment Opportunities

The previous three chapters make several key findings. Chapter 1 finds that Marin is expected to generate 248,200 wet short tons (roughly 139,150 dry metric tons) of biomass each year by the end of the decade. Chapter 2 identifies a set of alternative pathways that offer the best match and use opportunity for Marin's expected biomass flows. (This set of alternative pathways comprises the right half of Table 4-1.) Chapter 3 estimates that the management of Marin's biomass flows into these pathways has the potential to reduce 31,200 metric tons of carbon dioxide equivalent (CO₂e) emissions per year.

This chapter estimates the capital and operating costs needed to build and operate these pathways. It also estimates the potential revenue from sale of their products, including carbon incentives that these operations and products could capture. These data are used to evaluate the financial viability and investment attractiveness of each pathway and create a basis for estimating the public contribution that could accelerate development of this system.

The chapter also touches on ways that these pathways offer economic benefits beyond financial viability and return on investment. This includes the capacity of these pathways to support SB 1383 compliance for cities and the County, and to reduce the long-run costs of biomass recycling. The data in this chapter also provide a basis for estimating job growth associated with these pathways and any boost for economic sectors in Marin (e.g., the agricultural and power sectors).

Table 4-1. Biomass Flows for Marin’s Current and Promising Alternative Pathways

Current System			Biomass Type ¹³²	Alternative System		
Utilization Pathway	wet short tons	dry metric tons		Utilization Pathway	wet short tons	dry metric tons
<i>(see landfilling below)</i>			Green Materials	Composting	20,000	9,000
Composting	61,000	27,500	Green Materials	Composting	61,000	27,500
Composting	1,800	360	Manure	Composting	1,800	360
Composting	800	240	Food Scraps	Composting	800	240
Mulching	2,600	1,400	Wood Chips	Mulching	2,600	1,400
Dispersion	5,400	2,900	Wood Chips	Dispersion	5,400	2,900
Dispersion	2,500	1,400	Wood Chips	Pyrolysis	2,500	1,400
Dispersion	8,000	1,450	Digestate	Pyrolysis	8,000	1,450
<i>(see landfilling below)</i>			Digestate	Pyrolysis	8,500	1,550
<i>(see landfilling below)</i>			Food Scraps	Co-digestion	11,100	3,000
Co-digestion	3,100	800	Food Scraps	Co-digestion	3,100	800
Combustion	700	400	Logs	Milling	700	400
Combustion	20,400	14,800	C&D Wood	Gasification	20,400	14,800
Combustion	13,600	9,800	C&D Wood	Combustion	13,600	9,800
Combustion	4,500	3,300	Wood Chips	Combustion	4,500	3,300
Landfill	20,000	9,000	Green Materials	<i>(see composting above)</i>		
Landfill	8,500	1,550	Digestate	<i>(see pyrolysis above)</i>		
Landfill	11,100	3,000	Food Scraps	<i>(see co-digestion above)</i>		
Landfill	84,000	61,000	C&D Wood	Landfill	83,200	60,425
Reclamation	200	150	C&D Wood	Reclamation	1,000	725
248,200		139,150	TOTAL	248,200		139,150

¹³² The following moisture contents are assumed for the wet short tons of materials: green materials (50%), food scraps (70%), digestate (80%), manure (80%), recently cut logs and wood chips (40%), and woody construction and demolition materials (20%).

Current and Alternative Biomass Pathways

The analysis in this chapter builds on information from the previous three chapters. It takes account of both current infrastructure for pathways in the alternative system, as well as expenditures for permitting and interconnection for infrastructure development already under consideration, when estimating the capital expenditures needed to manage biomass according to the flow distribution in Table 4-1. It uses current prices in its estimation of revenues and operating expenses and in its determination of the net operating income for the pathway.¹³³ It concludes by considering how much supportive investment or potential public funding would aid and accelerate expansion, redevelopment or development of each pathway in Table 4-1.

Economic and Financial Analysis

The assessment of pathways in Chapter 2 surveys conversion technologies, compares them to Marin's expected biomass flows, and identifies a set of pathways that provide an economically promising fit. The result of this assessment is a set of pathways that expands, develops, maintains, and reduces pathways relative to the current system. (See Table 4-2.)

The analysis in this section explores the economics of these proposed changes. It considers the economic opportunities and costs associated with expanding composting and co-digestion. Likewise, it explores the (re)development of small-scale milling and the development of new, local gasification and pyrolysis infrastructure. More briefly, it touches on the economics of maintaining mulching and dispersion pathways, as well as the implications of reducing biomass flows to combustion and landfilling.

The analysis of the economics of each pathway is explored individually. The costs and benefits are estimated at the scale imagined for the alternative system, and the analysis takes account of the existing infrastructure in Marin.

¹³³ New information was obtained through extensive, direct engagement with operators and facility owners at Marin Sanitary Service, Central Marin Sanitation Agency, Novato Sanitary District, Redwood Landfill (Waste Management), and West Marin Compost.

Table 4-2. Changes to Flows and Pathways between the Current and Alternative System

Change in Pathway		Current System		Change	Alternative System	
		wet short tons	dry metric tons	wet short tons	wet short tons	dry metric tons
expand	Composting	63,600	28,100	↑ 20,000	83,600	37,100
scale up	Co-digestion	3,100	800	↑ 11,100	14,200	3,900
expand	Deconstruction	200	150	↑ 800	1,000	725
develop	Gasification	0	0	↗ 20,400	20,400	14,800
develop	Pyrolysis	0	0	↗ 19,000	19,000	4,400
develop	Milling	0	0	↗ 700	700	400
maintain	Mulching	2,600	1,400	↔ 0	2,600	1,400
maintain	Dispersion	15,900	5,750	↔ 0	5,400	2,900
reduce	Combustion	39,200	28,300	↓ (29,700)	18,100	13,100
reduce	Landfill	123,600	74,650	↓ (40,400)	83,200	60,425
		248,200	139,150		248,200	139,150

Composting and Land Application (*expansion*)

As detailed in previous chapters, Marin’s source-separated green materials, food scraps, and manure, as well as its commingled green materials and food scraps already flow to composting operations inside the County. These include the EarthCare operation in Novato, the West Marin Compost facility in Nicasio, and the Bolinas Compost facility in Bolinas. These facilities receive about ninety-five percent of the source-separated and commingled compostable biomass that Marin generates. The remaining five percent flows to Napa Recycling in the City of Napa and to the Republic Services recycling facility in Richmond. (These outflows include some source-separate food scraps collected in the northern part of Marin and some self-hauled green materials.) This system absorbs the 63,600 wet short tons (28,100 dry metric tons) that Marin has historically generated. It produces roughly 31,800 wet short tons (14,000 dry metric tons) of compost per year.¹³⁴

This section explores the economics of composting, first by considering the ability of the current system to absorb the additional 20,000 wet short tons (9,000 dry metric tons) that

¹³⁴ This estimate uses a standard conversion estimate of 0.5 tons of compost per ton of input materials.

Marin is expected to generate over the next decade. It also reflects on the role of compost in Marin's SB 1383 compliance economics, as well as carbon sequestration and soil regeneration on Marin's agricultural lands. It concludes with an estimate of the funding that can close investment gaps and accelerate system expansion.

Production Economics

The expected flow of source-separated and commingled green materials, food scraps, and manure represents a thirty percent increase over the flows into the current system. At present, the infrastructure and operations at West Marin Compost have limited capacity to absorb additional materials, while Bolinas Compost has no capacity to absorb any portion of this increase. However, the EarthCare composting facility is permitted to process 160,000 wet short tons of green materials per year but currently processes only 140,000 wet short tons. This means that the EarthCare operation theoretically could absorb the projected increase in compostable materials.

Market conditions, however, are less conducive to this expansion than the regulatory environment. A majority of the compost produced by EarthCare meets standards as organic¹³⁵ and is sold at a competitive price to vineyards in Marin, Sonoma, Napa, and Mendocino Counties who want high-quality, organic compost. According to Waste Management, EarthCare believes that the market is saturated for its product. That is, they have not found additional customers willing to take their compost at the price that justifies production.

By contrast, an analysis by the Marin Carbon Project in support of the [2030 Marin Climate Action Plan](#) (2020), and a more recent analysis by Placeworks Inc to support SB 1383 compliance, suggest that Marin's compost production is well below potential demand.¹³⁶ This analysis is based in part on the extent of Marin's rangelands and cropland and urban acreage suitable for compost application, the greenhouse gas reduction targets for the agricultural sector in the Climate Action Plan, and the interest in the agricultural community in use of compost as a key carbon farming practice.

Some of the potential market expansion appears to be demand based on SB 1383 compliance and agricultural applications. The demand for both of these applications appears to be price sensitive — enough, at least, at EarthCare's current price point. The use

¹³⁵ See the standards for the Organic Materials Review Institute (OMRI).

¹³⁶ Marin commissioned a study by Placeworks Inc to determine suitable locations for compost placement within Marin. The final report was delivered to Zero Waste Marin.

of compost in the agricultural sector is also quality sensitive, particularly for rangeland.¹³⁷ Largely for this reason, the analysis in this section uses West Marin Compost as an example of the kind of facility(ies) needed to expand Marin’s composting system, match future needs, and achieve the GHG reductions estimated in Chapter 3.

Procurement Economics

Senate Bill 1383 (SB 1383, 2016) establishes an intention to move organic materials out of the waste stream, with the ultimate goal of reducing methane emissions from landfills. It establishes obligations for California jurisdictions to achieve this goal. One is a mandate that jurisdictions support recovery of organic materials. One part of this is setting up systems that encourage separation and collection of organic materials from residents and businesses.¹³⁸ Another part requires that jurisdictions participate in the tracking of source-separated organics and help determine the percentage of organics that are successfully turned into recycled bio-products like compost, mulch, renewable natural gas, or renewable electricity.

The law also contains a provision aimed at growing a market for recycled organics. This provision obliges jurisdictions to procure recycled organic products in proportion to the size of their population.¹³⁹ Beginning in 2023, CalRecycle began requiring jurisdictions to achieve their respective procurement targets. (See Appendix F.) This means that Marin’s municipalities and the unincorporated county need not only have systems for directing biomass into non-landfill pathways; they also need to purchase and use recycled-bioproducts. Zero Waste Marin’s member justifications have authorized them to act on their behalf to fulfill this obligation. Satisfying the requirements means identifying eligible products, vendors from which to buy them, and sites to place them. ZWM has chosen compost procurement as a strategy for Marin’s compliance.¹⁴⁰

¹³⁷ Potential contamination from plastics and other non-biodegradable materials is a concern for some compost uses. Without careful source separation (i.e., beyond what current curbside green cart collection may achieve) and a good system for tracing feedstocks back to their sources, the risk of contamination may be too high for some sensitive applications, such as use on rangelands. This problem seems to befall larger composting facilities (e.g., those at the scale of EarthCare), and it may be difficult for it to adapt its product strategy for some markets. A smaller, more specialized operator may better satisfy this demand.

¹³⁸ Green biomass, food scraps, digestate, and wood are among the materials defined as “organic” in SB 1383.

¹³⁹ CalRecycle has established that the following qualify as recycled organic products under 14 CCR Section 18993.1: mulch, compost, renewable gas used for fuel for transportation, electricity, or heating applications, and electricity from biomass conversion.

¹⁴⁰ Jurisdictions have flexibility in how they meet these procurement targets. They can directly use recycled bio-products in municipal operations or donate them to community organizations. Alternatively, the jurisdictions can contract with direct service providers — such as haulers, composting facilities, and landscaping services — that procure and utilize these products on the jurisdiction’s behalf. For more details, see CCR Title 14, § 18993.1 (Recovered Organic Waste Product Procurement Target).

ZWM has implemented this strategy with some compost purchase in Marin.¹⁴¹ However, because of limits in the compost it could purchase (or afford to purchase) in Marin and a change in Marin’s procurement requirements under SB 1383, most of the compost was procured from a company called Agromin, the state’s largest recycler of organic materials, and placed on farmland in the Central Valley.

Product Economics

Some finished compost is sold with modification. Some is combined with other materials to be sold as a compost blend. An example is compost mixed with biochar to increase its carbon sequestration potential, as well as water retention, nutrient content, and microbial activity in receiving soils.

West Marin Compost sells products like biochar-amended compost and biochar-amended topsoil, and the market has demonstrated a growing demand for these products. In 2022 West Marin Compost sold 35 cubic yards of biochar-amended topsoil. In 2023 they sold 420 cubic yards (i.e., twelve times as much). Sales growth for biochar-amended compost has also been strong. In 2023 West Marin Compost sold 100 cubic yards. In just the first four months of 2024, they sold the same amount. A local source of affordable biochar is expected to help producers meet this kind of market demand and growth.

Price growth is an additional indicator of the market. Between 2022 and 2024, market prices grew alongside demand. (See Table 4-3.) In the last two years West Marin Compost’s product line experienced price growth of 25% or more. The increase for biochar-amended products was the most dramatic: 48% more for biochar-amended topsoil than topsoil alone. Likewise, blending biochar into compost to produce the Marin Hi-Test Compost (which is 15% biochar by volume) resulted in a price premium of 40% over West Marin Compost’s comparable non-amended product.¹⁴²

¹⁴¹ In 2023 roughly 1,500 wet metric tons were purchased from West Marin Compost. That number rose in 2024 before falling in 2025 when Marin’s procurement obligations were reduced under AB 2346.

¹⁴² This presumably is based at least in part on the very high unit price for biochar of \$200 per cubic yard, which in the past has been sourced from a third-party producer outside the county. To the extent that the cost to procure or produce this biochar could be reduced, sales of the potentially lower-priced biochar-amended products could be expected to increase even further.

Table 4-3. Compost Pricing Trends (data from West Marin Compost)

Product	2022 Price per cubic yard	2024 Price per cubic yard	Price Change	Price Premium
Nicasio Blend Compost	\$30	\$40	33%	—
Marin Hi-Test Compost	\$40	\$50	25%	25%
Marin Hi-Test with Biochar	\$54	\$70	30%	40%
Amended Topsoil ¹⁴³	\$54	—	—	—
Biochar-amended Topsoil	—	\$80	48%	14%
Biochar	\$200	\$200	0%	—

A price of \$20 per cubic yard (equal to \$160 per ton based on an average bulk density of 250 pounds per cubic yard) is assumed for biochar based on current market rates for the material from regional biochar producers, aggregators, and brokers.

Funding Needed for Expansion

By some measures, Marin’s composting sector is in good shape. It currently receives and recycles 56,000 wet short tons of biomass — an amount that absorbs nearly ninety-five percent of its source-separated green materials, its commingled green materials and food scraps, and its off-farm manure. To avoid exporting the expected growth in these flows, Marin needs the capacity to process another 20,000 wet short tons (9,000 dry metric tons) per year. As noted above, this capacity is available at the EarthCare composting facility. However, from EarthCare’s perspective, the market for their product is saturated.

Meanwhile, Zero Waste Marin has found it difficult to source affordable, local compost. They have been able to buy some locally, but not yet in sufficient quantities to meet Marin’s SB 1383 obligations without additional purchase and placement of less expensive compost in the Central Valley. In light of considered factors (ie., quality of compost needed to match future needs and achieve the GHG reductions), a facility like West Marin Compost could be a good, local source of compost to meet Marin’s procurement requirements — if production costs are reduced. This is a possibility being considered, with some initial exploration of capital and processing changes to increase throughput and improve economies of scale. Because a public-private partnership like West Marin Compost may not be in a strong position to recapitalize its facility, supportive funding may be needed to bring down costs. An initial estimate of this amount is \$5 million.

¹⁴³ West Marin Compost’s Amended Topsoil product did not include biochar in 2022.

The potential expansion of West Marin Compost could be accomplished by a change in their composting technique.¹⁴⁴ This investment would enable this facility to increase compost outputs between 50-100%. Expansion of West Marin Compost production capacity could further increase the compost amounts and types available for the local community, as well as help attain Marin's climate action goals for agriculture via carbon sequestration.

This brings up a noteworthy aspect of West Marin Compost: its location and connection to the agricultural community in west Marin. West Marin Compost was established as a public-private partnership to enable the co-composting of green materials and manure as a potential manure management solution. West Marin Compost's close ties to agricultural producers is part of the reason that it offers compost blends for different applications. Because it does not receive green can organics, it is able to produce compost free of contaminants.¹⁴⁵

Application of compost on rangelands offers considerable greenhouse gas sequestration opportunities. (See Chapter 3.) The cost of applying compost to rangelands is another area in need of funding. The startup cost, including spreading equipment acquisition by Marin RCD, compost subsidies, and transport costs for a recommended compost application on Marin rangelands is an additional \$2.5 million.

In sum, using West Marin Compost as a basis, the funding needed to expand Marin's compost production and distribution system and support the County's agricultural GHG reduction goals is estimated at \$7.5 million.

Co-digestion with Electricity Generation (*scale-up*)

Senate Bill 1383 obliges cities and counties to establish systems for recovering edible food from the waste stream. It also builds on previous policies, such as AB 1826, which more specifically sought to recover and divert organics generated by businesses. In partnership, Marin Sanitary Service (MSS) and Central Marin Sanitary Agency (CMSA) developed a pilot project to anaerobically co-digest pre-consumer food scraps, such as expired food from grocery stores or food scraps from restaurants and hospitals that MSS collects and

¹⁴⁴ West Marin Compost currently uses a windrow technique to aerate compost. This process requires more time and more land than an alternative technique called covered aerated static piles or "CASP." A change from windrow to CASP would speed up the composting process and make more efficient use of land — thereby increasing throughput and output.

¹⁴⁵ In comparison to rangelands, lands used for row cropping have more intensively managed soils that are more closely observed during tilling, tending, and harvest, meaning any physical contaminants in deployed compost is more readily noticed and removed. Rangelands are more extensive in area and generally do not receive the same level of observation. For this reason, deeper consideration is given to the qualities of compost and the impacts of its (less frequent) application to rangelands.

aggregates at the Marin Resource Recovery Center in San Rafael. At this transfer and processing facility, food scraps are de-packaged (i.e., separated from its non-decomposable plastic and metal packaging), ground, and liquefied into a slurry before being transported by tanker truck to CMSA. At CMSA, this slurry is added alongside sewage into two 130,700 cubic foot mesophilic anaerobic digesters. The addition and co-digestion of food scraps has boosted the output of methane-rich biogas and supported production of an additional 360 Megawatt-hours of electricity per year.¹⁴⁶

The MSS-CMSA pilot project has successfully recycled 3,100 wet short tons (800 dry metric tons) of food scraps per year by anaerobically co-digesting it with sewage at CMSA's large wastewater treatment plant in San Rafael. As discussed in previous chapters, the expected flow of suitable materials for this pathway is much higher: 14,200 wet short tons (3,900 dry metric tons) per year. Co-digestion of this material could be used to generate 3,100 Megawatt-hours per year of local, renewable electricity — the kind of power of greater priority for a local energy procurer like MCE.

The groundwork for expanded co-digestion has been laid by the pilot program. MSS and CMSA already have infrastructure for commercial food depackaging and preparation (Figure 4-1) and for transferring slurried food (Figure 4-2).

Figure 4-1. Commercial Food Waste Depackaging System at MSS



Figure 4-2. Food Waste Slurry Receiving/Processing System at CMSA



¹⁴⁶ CMSA produces electricity using a Jenbacher 1.1 megawatt (MWe) internal combustion engine (ICE) generator set that is derated to 995 kilowatts (kWe). The raw electricity generation potential of this equipment, if a capacity factor of 90% is assumed, is roughly 7,800 Megawatt-hours per year. That said, the analysis in this chapter uses only the new expanded capacity of 395 kWe to estimate the incremental contribution of the food-to-energy program for generating electricity. See Appendix H, Table H-1 for more detail.

Likewise, CMSA already has infrastructure to remove impurities from the biogas (Figure 4-3), as well as an engine-generator set large enough to accommodate the increased biogas that an expanded co-digestion program generates (Figure 4-4). It currently generates an average of 600 kilowatt-hours of electricity per year. The rated capacity of the CMSA Jenbacher system is 995 kilowatts. (The difference of 395-kilowatts is the basis for determining that sufficient capacity exists to support expansion of co-digestion.)

Figure 4-3. Biogas Cleanup System at CMSA



Figure 4-4. Jenbacher Internal Combustion Engine-Generator Set



In short, sufficient capital infrastructure is currently installed to assume that no additional capital expenditure (CAPEX) is needed to expand co-digestion. For this reason, the economic analysis of expanded co-digestion focuses on the market for the local, renewable electricity that it can generate and operating expenses (OPEX).

Electricity Generation Economics

CMSA generates revenue by selling electricity under a power purchase agreement to MCE (formerly Marin Clean Energy). Part of the 600 kilowatts of electricity it currently generates is used to power the wastewater treatment facility. The remainder is sold under a power purchase agreement (PPA) to MCE at a price of \$80.00 per Megawatt-hour. In addition to electricity revenue, CMSA collects a tipping fee from MSS of \$26.75 per ton for the food slurry that it receives. Operating expenses include an annual engine and generator maintenance contract estimated at \$1.5 million per year and a PG&E grid connection

charge that averages \$13,000 per month.¹⁴⁷ As a public facility, CMSA pays no income taxes on realized positive revenues. These modeling parameters are summarized in Table 4-4 and in Appendix H, Table H-1.

Based on the parameters in Table 4-4, net revenues for the expanded co-digestion system are estimated at \$272,000 per year. (This amount is calculated based on the difference between revenues from electricity sales and tipping fees and the costs from engine maintenance and grid connection.) A preliminary pro forma for this expanded co-digestion system is included in Appendix H, Table H-2.

Thus, the increase in food waste used for production of biogas, generation of electricity, and sale of electricity (e.g., to MCE) results in additional revenue to CMSA without any significant further capital investment.

Table 4-4. Modeling Parameters for Scale-up of Co-digestion Pilot

Attribute	Unit of Measurement	Quantity
System Parameters		
Food Scrap (flow increment in analysis)	wet short tons per year	11,100
	dry metric tons per year	3,000
Electricity - current system	kilowatt	600
Electricity - alternative system	kilowatt	995
Electricity - increment in analysis	kilowatt	395
Inflation rate (average CPI)	%	3.0
Revenue		
Electricity available for sale	kilowatt-hour	3,100
Electricity price (from MCE)	\$ per Megawatt-hour	80.00
Tipping fee (from MSS)	\$ per wet short ton	26.75
Capital Expenses		
Infrastructure needed	\$	0.00
Operating Expenses		
Engine maintenance	\$ per year	159,100
Utility charges	\$ per year	156,000
Disposal costs	\$ per year	13,300
Taxes	\$ per year	0

¹⁴⁷ Because wastewater treatment plants operate 24 hours per day and 365 days per year, CMSA maintains a grid connection to draw power during engine generator shutdown for maintenance or shutdown. At \$13,000 per month, the twelve-month cost comes to \$156,000.

Funding Needed for Expansion

The pilot project between MSS and CMSA demonstrates how Marin can convert its source-separated food scraps into an energy resource and how that energy resource can be turned into a useful, local product. Enough capital infrastructure already exists to support expansion, and an expanded co-digestion pathway is estimated to be capable of achieving positive net revenue.

While additional capital for *infrastructure* may not be needed, the expansion of Marin's co-digestion pathway depends on expansion of *operations* (e.g., contracts) to source separate, collect/haul, and prepare the additional 11,100 wet shorts tons of commercial food scraps that are currently going to waste. Between outreach, education, and startup support with additional partners, supportive funding may be needed to motivate and accelerate scale-up of these operations. An initial estimate of this amount is \$1 million.

Gasification and Electricity Generation (*development*)

Marin has no current gasification infrastructure, but Marin Sanitary Service (MSS) has been exploring this as an alternative to chipping and shipping woody C&D materials to combustion power plants in the Central Valley. MSS has undertaken initial planning, conceptual design, and some basic engineering work for a 2-Megawatt gasification facility adjacent to their primary material processing site in San Rafael. They have also completed two significant steps in getting this kind of facility permitted. MSS has received a Conditional Use Permit from the City of San Rafael and has completed a grid interconnection study with Pacific Gas & Electric.

The analysis here explores the economics for this gasification facility based on the electricity and biochar that it could produce and sell.

Energy Generation and Biochar Production Economics

The analysis of the development economics for the gasification pathway is based on a 2-Megawatt plant.¹⁴⁸ The facility is modeled with a relatively conservative electricity generation capacity factor of roughly seventy percent — based on assumptions that the facility would operate twenty-four hours per day, six-days a week year-round, with

¹⁴⁸ This size is based on the design and engineering plans of MSS. Drawing on the assessments in this Study, Marin is generating and exporting enough biomass to support a 3- to 4-Megawatt gasification system. Because gasification technologies can be modular and designed for expansion, one or more additional gasifiers or gasifier-generator systems might be commissioned in complement to the original 2-Megawatt system evaluated here, either during initial design or after, based on available biomass.

shutdowns on holidays and six weeks per year for maintenance. The facility is modeled as a combined heat and power (CHP) plant with a twenty-year design life. In addition to its electricity output for domestic use and sale, it is modeled as supplying 9,500 million BTUs of heat per year for domestic use (e.g., on the host campus).¹⁴⁹ The facility might look similar to the plant in Figure 4-5, although details depend on design selection. (See Appendix H, Table H-3 for a summary of modeling parameters.)

Figure 4-5. Illustrative Biomass Gasification Plant¹⁵⁰



The imagined facility is modeled as processing 20,400 wet short tons (14,800 dry metric tons) of woody C&D materials per year.¹⁵¹ These materials would be redirected from use at combustion power plants in the Central Valley to this local gasification facility, and cost

¹⁴⁹ Based on this design, it is assumed that a CHP facility would be able to take advantage of a 30% Federal Investment Tax Credit (ITC) valued at \$6.3 million.

¹⁵⁰ Image courtesy of SynCraft Engineering GmbH

¹⁵¹ Assumes that the mixed woody biomass has a moisture content of 20%.

savings from avoided hauling costs are included along with the other modeling parameters listed in Table 4-5. They include an average transportation cost of \$20 per wet short ton.

Table 4-5. Modeling Parameters for Financial Analysis of Gasification Pathway

Attribute	Unit of Measurement	Quantity*
<i>Inputs and Outputs</i>		
Woody C&D materials (input)	wet short tons per year	20,400
	dry short tons per year	16,300
	dry metric tons per year	14,800
Electricity generation capacity factor	%	70.6
Electricity (output)	MWh per year	12,500
Feedstock conversion rate (to biochar)	%	10
Biochar flow (output)	dry metric tons per year	1,500
<i>Revenue</i>		
Electricity purchase price	\$ per Megawatt-hour	127
Revenue from electricity	\$ per year	1,600,000
Biochar price	\$ per dry short ton	160.00
Revenue from biochar	\$ per year	260,000
Biochar carbon dioxide removal (CDR) price	\$ per dry short ton	190.00
Biochar CDR production rate	ton CO ₂ e per metric ton	2.5
Revenue from carbon incentives	\$ per year	700,000
<i>Capital Expenses</i>		
Equipment Capital Expense	\$	24,200,000
Estimated Supportive Funding	\$	- 10,800,000
Total Net Capital Expenses	\$	13,400,000
<i>Operating Expenses</i>		
Feedstock Costs (against baseline)	\$ per year	-540,000
Labor Costs	\$ per year	300,000
Insurance and Maintenance Costs	\$ per year	1,390,000
Total Net Operating Expenses	\$ per year	1,150,000

*Some values are rounded to reflect uncertainty of estimate.

The financial modeling for this facility assumes that revenue could be generated from sale of both electricity and biochar. The expected electricity generation rate is 12,500 Megawatt-hours per year, and the revenue was modeled using the electricity price from the Bioenergy Market Adjusting Tariff (BioMAT) program for a Category 1 facility using

metropolitan biomass diverted from landfill.¹⁵² Under this program, the imagined gasification facility could qualify for a twenty-year power purchase agreement (PPA) and an electricity purchase price of \$127 per Megawatt-hour.

The expected biochar production rate is 1,500 dry metric tons per year. As with the analysis for a co-pyrolysis system (see below), the price of biochar is assumed to be \$160 per dry short ton. The biochar is assumed to be eligible for 2.5 carbon dioxide removal credits per metric ton of biochar, and a price in voluntary carbon markets of \$190 per metric ton of CO₂e is used to calculate revenue from carbon dioxide removal (CDR) credits.¹⁵³ At these prices, the sale of biochar would generate roughly \$260,000 per year, and the sale of CDR credits would generate \$700,000 per year — for a total biochar revenue of \$960,000.

As included in Appendix H, Table H-3, the capital expense (CAPEX) to construct a 2-Megawatt gasification plant (including all engineering design, construction management, and ancillary feedstock handling and storage infrastructure) is estimated at \$24.1 million — a number considered consistent with available recent estimates from other comparably-sized bioenergy plants in California. Part of the cost could be defrayed by tax incentives like the Federal ITC (estimated at \$6.3 million) and the California Alternative Energy and Advanced Transportation Financing Authority (CAEATFA) Sales and Use Tax Exclusion Program (estimated at \$1.5 million). It is also estimated that grants (estimated at \$3.0 million) could be secured for this project.¹⁵⁴ These combined tax credits of \$10.8 million are factors into this analysis and results in an estimated net private CAPEX outlay of \$13.3 million.

Operating expenses are broken down into feedstock, labor, and insurance and maintenance costs. In the analyzed scenario, a \$0 cost of importing feedstock is assumed, given that material is already hauled to MSS's operations for sorting. By contrast, a facility at MSS would avoid current transportation and delivery costs estimated at -\$33 per wet short ton or -\$540,000 per year.¹⁵⁵ (See Appendix H, Table H-3.) Its combined labor costs are estimated at \$300,000 per year, and its combined insurance and maintenance costs are estimated at \$1,388,000 per year. In this analysis, the total annual operating expenses (i.e., the combination of feedstock, labor, and insurance and maintenance) equal \$1,150,000.

¹⁵² The State's feed-in tariff program established under Senate Bill 1122 (2012) created a system for selling electricity at small bioenergy facilities into the electrical grid. At the time of this project's analysis, the BioMAT program was operational. Because California Public Utilities Commission ended the BioMAT program in 2025, further consideration of a gasification facility needs to consider the current set of procurement opportunities.

¹⁵³ The carbon dioxide removal (CDR) credit market is growing rapidly both in the United States and internationally, and biochar is a significant product within this market.

¹⁵⁴ This is considered a relatively modest assumption based on recent similar projects in California.

¹⁵⁵ An avoided transportation cost is included here to aid comparison against the baseline condition but is not a direct revenue source for the project unless specifically identified and allocated as such.

Based on a pro forma financial model (see Appendix H, Table H-4), a 2-Megawatt gasification facility is estimated to be capable of a positive return on investment, with an internal rate of return (IRR) of 10.0% and a simple payback period of 9.8 years.¹⁵⁶

Appendix H also includes supplemental IRR calculations with different CDR credit prices. These calculations function as a sensitivity analysis for the amount of supportive funding needed based on revenue from carbon incentives for biochar.¹⁵⁷ This approach takes account of price uncertainty for CDR credits (i.e., one of the most uncertain values in the financial model) and (re)considers the level of supportive funding to assure an IRR, attract private capital, and/or help manage the risk perceived by a commercial lender for a pyrolysis development project like this. As included in Appendix H, Table H-5, the sensitivity analysis varies the CDR credit price (columns) and supportive funding needed (rows) to provide combinations that achieve a minimum attractive rate of return (MARR) of 10%. (The light green shading illustrates combinations that achieve an IRR of at least 10.0%). This table can also be used to estimate the amount of supportive funding needed to achieve a MARR of 20% — a number considered more likely to attract private capital. (The darker green shading illustrates combinations that achieve an IRR of at least 20%.) For example, if the price of CDR credits were \$160 instead of \$190 per metric ton of CO₂e, the supportive funding needed to achieve an IRR of 10% would increase to \$4.5 million from the \$3.0 million used in the analysis. Alternatively, if an IRR of 20% were desired, the estimate of supportive funding increases to \$7.0 million.

Funding Needed for Development

Marin already has some preliminary designs for a gasification plant and some initial experience securing funding for development of a gasification plant. While the operating economics appear favorable, the risks involved with a new kind of project and with the prices for its products are slowing development. Some de-risking investment appears useful, if not necessary, to develop and redirect woody biomass into a gasification pathway.

The pro forma analysis assumes that, with a supportive funding (e.g., a public investment) of \$3.0 million, a gasification plant could be built and profitable with an IRR of 10%. While this defrays some of the estimated capital costs of this project, it does not provide for additional, potentially significant financial uncertainties, including CDR market prices, electricity market prices, inflation in technology prices, and associated price escalation for

¹⁵⁶ Internal Rate of Return is used in financial analysis to estimate the profitability of potential investments. The payback period is the time required to recover an initial investment

¹⁵⁷ Although the biochar market has been growing, it is still nascent, and prices fluctuate. This number is considered to be conservative in the context of recent trends.

labor and workforce development. For these reasons, additional supportive funding may be needed to motivate development of this pathway.¹⁵⁸ Based on projects already under consideration by entities in Marin, initial estimates are in the range of \$15 million.

Pyrolysis and Biochar Production (*development*)

Marin has several wastewater treatment plants that use an anaerobic digestion process to deactivate sewage sludge. The digestate that results from this process is one of the organic materials specifically named and intended for diversion from landfill in Senate Bill 1383 (2016). As a consequence, Marin's wastewater treatment districts, who have relied on landfilling as a lower-cost pathway for managing digestate, need and are seeking in-county alternatives.

Novato Sanitary District (NSD) is actively exploring redevelopment of a decommissioned wastewater treatment facility near the intersection of U.S. Highway 101 and State Highway 37 into a facility that converts digestate into biochar via pyrolysis. The size and scale of the imagined operations would be large enough to recycle digestate from all of Marin's wastewater treatment facilities. This pathway offers several potential benefits: (1) diversion of biosolids from landfilling, (2) more consistent operation than land application, which is only allowed during dry months of the year, (3) reduced environmental and economic costs associated with transporting material outside of Main, and (4) potential destruction of persistent chemicals found in biosolids that are known to cause impacts to human health, such as per- and polyfluoroalkyl substances (PFAS).¹⁵⁹

The imagined pyrolysis system would also create a new pathway opportunity for woody biomass from forests and woodland that wildfire safety initiatives generate. Combining the two in a pyrolysis chamber offers both an opportunity for feedstock balance, as well as a joint opportunity to draw value from two otherwise underutilized biomass streams.

The analysis here explores the economics of this combined pyrolysis or "co-pyrolysis" system and focuses on the economics of biochar production and sale.

¹⁵⁸ This is a tentative estimate. Supportive funding could take different forms (e.g., changes to utility rates; low-interest and long-term public financing — i.e., secondary to private financing; or direct subsidies). Considering the nature of public investment is beyond the scope of this analysis.

¹⁵⁹ PFAS are a large group of synthetic chemicals used in numerous industrial and consumer products since the 1940s. They contain very strong carbon-fluorine bonds, making them highly resistant to degradation. Often called "forever chemicals" due to their extreme persistence in the environment and the human body, they have been linked to serious health issues (e.g., immune system effects, hormonal disruption, increased cholesterol levels, and certain cancers). High temperature pyrolysis has been shown to destroy several classes of PFAS.

Biochar Production Economics

The imagined pyrolysis system is a containerized unit with the rough shape and dimensions of a commercial shipping unit. (See Figure 4-6.) This is a size that can readily fit on NSD's former wastewater treatment site. A pyrolysis system with a capacity to process 20 wet short tons per day of combined feedstocks and that operates on an eight-hour schedule five days a week would have enough capacity to process all the 16,500 wet short tons (dry metric tons) of digestate that Marin produces per year and 2,500 wet short tons (1,400 dry metric tons) of woody biomass — i.e., more than enough capacity to absorb all of the practically removable woody materials from maintenance of Marin's fuel breaks.

Figure 4-6. Illustrative Pyrolysis System



This economic analysis includes a preliminary pro forma financial model of biochar production from a system that co-pyrolyzes sewage digestate and woody materials from forest and woodland management. Based on the modeling parameters in Table 4-6, this pathway could achieve an internal rate of return (IRR) of 15%. (See Appendix H, Table H-7 and Table H-6.)

Table 4-6. Modeling Parameters for Financial Analysis of Co-Pyrolysis Pathway

Attribute	Unit of Measurement	Quantity*
<i>System Parameters</i>		
Digestate flow (input)	wet short tons per year	16,500
	dry metric tons per year	3,000
Woody material flow (input)	wet short tons per year	2,500
	dry metric tons per year	1,400
Feedstock conversion rate (to biochar) ¹⁶⁰	%	35
Biochar flow (output)	dry metric tons per year	1,540
Inflation rate	%	3.0
<i>Revenue</i>		
Tipping fee - biosolids	\$ per wet short ton	55.00
Biochar price	\$ per dry metric ton	160.00
Biochar Carbon Dioxide Removal (CDR) price	\$ per dry metric ton	190.00
Biochar CDR production rate	ton CO2e per ton biochar	2.5
<i>Capital Expenses</i>		
Pyrolysis system (capacity: 20 tons per day)	\$	4,750,000
Supportive Funding (grant)	\$	750,000
Net Capital Expenses	\$	4,000,000
<i>Operating Expenses</i>		
Wood acquisition cost	\$ per dry short ton	40.00
Labor Costs	\$ / yr	600,000
Maintenance and Insurance	\$ / yr	105,000
Electricity	\$ / yr	150,000
Fuel Costs	\$ / yr	14,800
Total Operating Costs	\$ / yr	870,000

*Some values are rounded to reflect uncertainty of estimate.

In addition to the parameters and assumptions in Table 4-6, the analysis assumes steady procurement of input digestate and input woody forest and woodland biomass. Lenders and equity investors typically prefer a project developer for this kind of biomass project to have secured feedstock supply contracts for the duration of the project, and they are unlikely to fund without contracts that are at least ten years or longer. The flow of digestate

¹⁶⁰ Biochar yields, such as the 35% modeled here or yields that are even higher, are possible in so-called “slow” pyrolysis. The design of a slow pyrolysis system is optimized to produce more biochar and less gas.

is expected to be relatively steady over the next twenty years (i.e., over the length of the project), given that digestate comes from public infrastructure and because Marin's population is expected to remain constant or grow. It is also assumed that wastewater treatment districts are willing to write long-term contracts. The procurement contracts for woody biomass from forests and woodlands are more uncertain over this same time period. Although the biomass estimates used are those expected within the next decade and should be part of ongoing fuel break maintenance, they are riskier in the eyes of an investor or lender until the funding stream is more certain (e.g., until Measure C is reauthorized). It is assumed that, at a minimum, an investor or funder would want to see at least five- or seven-year contracts for woody biomass and have some guarantee that alternative sources could be identified. In the absence of this reassurance, a larger public investment may be needed.

Funding Needed for Development

Marin already has some preliminary designs for a co-pyrolysis plant, and Novato Sanitary District (NSD) is demonstrating significant interest in operating this kind of facility. Land needed for a facility is already secured, and suitable biomass flows are already identified.

To spur development of this project, supportive funding of at least \$750,000 is assumed necessary to ensure an IRR that can de-risk the project or secure capital. Considering CDR credit price uncertainty, additional supportive funding may also be needed. An initial estimate is \$5 million. This level of support better accounts for process learning (i.e., higher than expected design costs, startup workforce development) for the first co-pyrolysis facility in Marin. It also better shares costs and risks — considering that NSD's imagined plant could serve as a digestate solution for the entire county and would require coordination with operations beyond NSD's direct purview.

Small-scale Milling (*redevelopment*)

Marin County Department of Public Works and companies like Pacific Gas and Electric cut trees, respectively, during roadway maintenance and vegetation management along the power grid. One option for these logs is to grind them into wood chips and then ship them over one hundred miles to a combustion power plant in the Central Valley. This is a more costly approach than the local milling of these logs and, as the analysis in the previous chapter shows, a more carbon intensive use of this material. There is, however, a higher and better use that is readily available.

An alternative is to cut these materials into different types of wood products. West Marin Compost has used a small logwood processor (see Figure 4-7) to saw these large diameter logs into 3" slabs that could be sold for architectural or artistic use. The analysis in this section looks at economics of small-scale milling in comparison to chipping logs and shipping wood chips considerable distance to be used as a fuel to produce electricity.

Figure 4-7. Wood-Mizer 1000 Logwood Processor



Wood Product Economics

As part of its business relationships (including its relationship with the Department of Public Works), West Marin Compost has been receiving an average of about 700 tons of logs per year. It receives a tipping fee of \$125 per ton for this material, and the biomass power plants that currently purchase wood chips made from them pay a price of \$23.50 per ton. It costs West Marin Compost roughly \$50 per ton to handle and process these logs onsite into wood chips,¹⁶¹ and it costs an average of \$47 per ton to transport the wood chips to the power plants that burn them. The estimated total of taxes, operational, and maintenance costs associated with receiving this material is \$32,200 per year.

As summarized in Table 4-7, the average net revenues from this operation are a little less than \$4,000 per year. (A simplified pro forma is included in Appendix H, Table H-8.)

¹⁶¹ West Marin Compost already has a whole log chipper on site to grind up logs into wood chips. However, this equipment is likely to need replacement soon. The cost for a similar chipper is likely to be in the range of \$1.5 million. This potential amortized capital cost is not included in the analysis below. If it were, the ongoing combustion power pathway would look less favorable.

Table 4-7. Annual Net Revenues for Chipping and Shipping to Combustion Power

	Tons per Year	\$ per Ton	Total (\$)
Chip Sales	700	23.50	16,450
Tipping Fee for Logs	700	125.00	87,500
Total Estimated Annual Revenues			103,950
Chipping Costs	700	50.00	- 35,000
Chip Transport	700	47.00	- 32,900
Other expenses (tax, etc)	—	—	- 32,200
Total Estimated Annual Expenses			- 100,100
Net Revenue			\$3,850

The 700 tons of millable logs that West Marin Compost receives each year translates into roughly three hundred millable logs. From each log their milling operations could, on average, produce two sizes of slabs: four slabs that measure two feet wide, eight feet long, and three inches thick) and two slabs that measure one and half feet wide, eight feet long, and three inches thick. Using units common for wood products, each wide slab contains forty-eight board feet, and each narrow slab contains thirty-six board feet. For the four wide slabs and the two narrow slabs, this means that two hundred sixty-four board feet can be cut from each log. Three hundred milled logs can produce a total of seventy-nine thousand two hundred board feet. (See Table 4-8.)

Table 4-8. Slab Production (scenario 1: more slabs per log)

Slab Size	Width (feet)	Length (feet)	Thickness (inches)	=	Board Feet per Slab	x	Slabs Per Log	x	Logs per Year	=	Total Board Feet
Size 1	2	8	3	=	48	x	4	x	300	=	57,600
Size 2	1.5	8	3	=	36	x	2	x	300	=	21,600
Total					84		6				79,200

The average price for softwood and hardwood slabs is in the range of \$10 per board foot. The tipping fee is still \$125 per ton. West Marin Compost estimates that their annual operational and maintenance costs for milling would be \$229,000 per year. Federal and State income taxes on the sale of slabs are \$236,000.

As summarized in Table 4-9, the estimated net revenues from this operation are a little less than \$415,000 per year. This is one hundred times greater than the net revenue from chipping and shipping wood chips for power combustion in the Central Valley.

Table 4-9. Net Revenues from Slab Production (scenario 1: more slabs per log)

	Unit	\$ per Unit	Total (\$)
Slab Sales (board feet)	79,200	10.00	792,000
Tipping Fee (tons)	700	125.00	87,500
Total Estimated Annual Revenues			879,500
Operating Costs (labor, maintenance, utilities, etc)			229,000
Taxes (Federal 21%, State 8.84%)			236,000
Total Estimated Annual Expenses			465,000
Net Revenue			414,500

To provide a more conservative estimate, consider a second scenario in which milling produces only half as many board feet of the scenario in Table 4-9. The estimated net revenues from this operation are 136,500 per year — more than thirty-five times the yield of chipping and shipping into a power combustion pathway. (See Table 4-10.)

Table 4-10. Net Revenues from Slab Production (scenario 2: fewer slabs per log)

	Unit	\$ per Unit	Total (\$)
Slab Sales (board feet)	39,600	10.00	396,000
Tipping Fee (tons)	700	125.00	87,500
Total Estimated Annual Revenues			483,500
Operational and Maintenance Costs			229,000
Taxes			118,000
Total Estimated Annual Expenses			347,000
Net Revenue			136,500

Appendix H (Tables H-9 and H-10) summarize these amounts in a pro forma format.

Funding Needed for Redevelopment

West Marin Compost has already installed both a Wood-Mizer 1000 and the electricity infrastructure needed to operate it. During the initial operation of this equipment, it also established channels to sell the slabs that it produced. So, the basic physical and market infrastructure is already in place.

West Marin Compost needs to secure land use permissions to resume milling. Beyond that, it could restart operations — making this by far the cheapest pathway to accelerate

forward. Taking into account permitting and other start-ups costs, the funding needed for full redevelopment of the milling pathway is \$500,000.

Mulching (*maintenance*)

The alternative system estimates that input and output flows for mulching will remain the same. Because mulching is a well-developed practice — with existing infrastructure and markets, no need for additional investment is assumed. Therefore, no further economic analysis is included in this chapter.

Dispersion (*maintenance*)

The alternative system reduces the amount of biomass dispersed on the landscape because a portion 2,500 wet short tons (1,400 dry metric tons) is redirected into a co-pyrolysis system. The economics of this change are already covered in the analysis for the pyrolysis pathways above. Therefore, this is considered a well-developed pathway, with existing infrastructure and markets and no need for additional investment. Therefore, no further economic analysis is included in this chapter.

Combustion Power (*reduction*)

Marin currently chips and ships 39,200 wet short tons (28,300 dry metric tons) of woody materials to combustion power plants in the Central Valley each year. According to Marin Sanitary Service and West Marin Compost, shipping this material is a financially costly endeavor with associated high GHG emissions.¹⁶²

The alternative system assumes 20,400 wet short tons (14,800 dry metric tons) of this material get redirected into a gasification pathway.¹⁶³ The redirection of this material is assumed to incur \$0 in direct costs and \$0 in transactions costs and, therefore, warrants no further economic analysis in this chapter. That is, there are no presumed sunk costs that would need to be recovered if Marin stops shipping woody biomass to combustion power plants. Further, there are no long-term supply contracts that need to be paid out. On the contrary, Marin would be freeing up space in these power plants for biomass from nearby counties, who lack conversion infrastructure for biomass removed from the landscape as part of their wildfire safety programs. So, in this sense, Marin could be increasing the public good while incurring no additional transactional costs by redirecting woody materials from

¹⁶² The amount of trucking is estimated to be over 300,000 truck miles annually.

¹⁶³ The residual 18,100 wet short tons (13,100 dry metric tons) still flow into a combustion power pathway.

distant combustion sites into a local gasification pathway. (Overall cost changes depend on investment and operating costs, as outlined here in comparison with existing costs.)

Landfilling (*reduction*)

Marin currently sends 123,600 wet short tons (74,650 dry metric tons) per year of woody construction and demolition materials to landfill. In the alternative system, a portion of this material is redirected into other pathways, such that the flow to landfill is reduced to 83,200 wet short tons (60,425 dry metric tons) per year. The redirection of this material is assumed to incur \$0 in direct costs and \$0 in transactions costs. That is, no costs would be incurred or need to be recovered if Marin stops shipping woody biomass to landfills and no long-term supply contracts that need to be paid out. On the contrary, Marin would be freeing up space in area landfills by recovering and recirculating these materials.

Advanced Construction and Demolition Material Recovery

Marin's current system is able to sort and recover some of the woody biomass from the flow of construction and demolition (C&D) materials that would otherwise go to landfill. A very modest amount of woody biomass is being recovered by small firms specializing in building deconstruction, who have built reuse markets channels for lumber and other materials. The rest of Marin's woody C&D materials flow into waste management supply chains. At Waste Management's Redwood landfill in Novato, at the Marin Resource Recovery Center in San Rafael, and at Pacific Sanitation in Windsor, some of these materials are sorted and segregated into different streams. A portion (34,000 wet short tons) is ground into approximately three-inch pieces and sold as fuel to combustion power plants in the Central Valley. Some are ground to 6-inch size and used as daily cover at the open face of the landfill. The rest is categorized as waste and simply landfilled.

There is more potentially recoverable biomass in C&D materials, but recovery requires stronger incentives, more sophisticated sorting infrastructure, additional source separation, or some combination of all of these. That is, for more biomass to be used in a pathway other than landfilling, it needs to be further separated from the following kinds of C&D materials:

- **Concrete, Bricks, and Asphalt** from building foundations, roads, and sidewalks;
- **Treated Wood**, including wood treated with preservatives, and painted wood;
- **Metals**, including steel, aluminum, and copper in pipes, wiring, beams, and fixtures;

- **Drywall and Plaster** from wall materials;
- **Roofing Materials**, such as as shingles, tiles, and metal panels;
- **Glass** from windows and mirrors;
- **Plastics** from piping, insulation, and other components;
- **Flooring**, including carpets, vinyl, tile, and linoleum;
- **Insulation**, including fiberglass, foam, and mineral wool; and
- **Land Clearing Debris**, like rocks and soil from site preparation.

In addition to these bulk materials, many of which may be attached to wood, C&D debris can potentially contain a range of materials that deserve thoughtful separation:

- **Heavy Metals:** C&D debris can contain lead, arsenic, cadmium, chromium, and mercury from treated wood, paints, and other construction materials. These metals can concentrate in biochar and ash, and raise concerns about use in agriculture or other applications.
- **Chemical Additives:** Treated woods (as mentioned above), adhesives, and coatings in C&D debris often contain chemical preservatives, flame retardants, or formaldehyde that can release toxic substances during conversion.

Conversion systems, whether thermochemical or biochemical, can lead to the formation of various pollutants, particularly in the presence of feedstock contaminants. For example, if biochar is made from materials containing high levels of heavy metals that are not volatilized in conversion and are retained in the product biochar, applying that biochar to land could release toxic substances into soil or water systems, harm ecosystems, and make land unsuitable for agriculture. For these reasons, the design of the conversion system will typically include feedstock testing and monitoring to exclude such contaminants, and post-conversion pollution control to reduce pollutants to below permitted levels. In some cases, a conversion system may also reduce or destroy contaminants that may be present in the feedstock (e.g., per- and polyfluoroalkyl substances (PFAS) commonly found in wastewater sludges or biosolids).

Although it is possible to segregate, sort, unfasten, clean, and prepare these materials, operators of Marin's current infrastructure do not consider it economical or financially prudent to do so. Waste Management recently considered developing additional sorting systems for C&D materials. However, it concluded that no current markets would justify the

extra effort. So, they continue to use these materials as daily cover in landfills. A full cost comparison, however, has not been made here.

Summary of Economic Findings

The analyses in this chapter explore the economics for the alternative system of pathways developed in Chapter 2 and analyzed for their greenhouse gas benefits in Chapter 3. These analyses explore the way that each pathway could relate to public and private sector needs, although most attention is focused on the financial viability of these pathways for private investment. The conclusion in this chapter is that each of these pathways can be considered to have positive economic results. The pro forma evaluations demonstrate that projects that expand, redevelop, or develop these pathways appear to be financially viable, although supportive public funding could make them more attractive for private capital investment and spur their faster development. Table 4-11 contains a summary of the financial picture for the pathways envisioned for Marin’s alternative system.

Table 4-11. Summary from Financial Analyses of Pathways in the Alternative System

	CAPEX (\$000)	OPEX (\$000 per year)	IRR (%)	Payback (years)
Composting	5,000	2,500	—	—
Co-digestion	0	330	—	—
Small-scale Milling	0	230	—	—
Pyrolysis	4,750	970	15.0	8.0
Gasification	24,100	1,150	10.0	9.8
TOTAL				

In addition to the pro forma analyses for each of the pathways, the likelihood of attracting capital and the speed of development was considered for each pathway, with attention to the role that supportive public funding could play.

For **composting**, substantial infrastructure exists to absorb the flow of green materials expected in the next decade. However, given the market strategy of Waste Management and its perception of a saturated market for its compost, the economic analysis of expanded composting focused on a facility of the scale, public orientation, and connection to Marin’s agricultural community like West Marin Compost. Investment in this facility on the scale of \$7.5 million (\$5 million to recapitalize the facility and \$2.5 million in initial operating support to build a rangeland application program) could provide Marin with a reliable source of compost to procure and place per the requirements under SB 1383 and

to develop channels to return carbon to soil and achieve the greenhouse gas sequestration benefits identified in Chapter 3.

For **co-digestion**, a pilot program has already demonstrated that food scraps can be successfully and viably combined with sewage and used to generate local, renewable electricity that can be sold to MCE. As presented in Chapter 1, Marin generates about four times more of the pre-consumer commercial food scraps than used in the pilot. As explained in this chapter, the necessary infrastructure needed to expand the pilot to co-digest these materials is already in place. An expanded program is estimated to generate an estimated \$272,000 per year in positive net revenues without additional capital investment by CMSA. That said, because there may be additional startup operational costs with additional partners, about \$1 million in supportive public funding is recommended to help this pathway grow.

For Marin, **small-scale milling** is an opportunity with some recent on-the-ground experience supporting it. Although Marin does not have the biomass resources or public interest in a timber industry and large-scale milling sector, it has enough large-diameter logs generated from tree removal for wildfire safety, electricity system safety, and landscaping work to support some artisanal milling. Fortunately, West Marin Compost already has the infrastructure in place to support this kind of small-scale, artisanal milling. The initial operation of this mill and the financial analysis in this chapter estimates that this pathway could generate positive net revenues between \$136,000 and \$415,000 per year. What it needs are land use permits, and it could benefit from some small capital investments at its site. Because this is a public-private partnership, restarting this pathway would benefit from about \$500,000 in supportive public funding.

Marin has no current infrastructure that uses **pyrolysis**, but Novato Sanitary District has already invested in some initial planning and design for a facility that could jointly recycle digestate and woody biomass from vegetation management in Marin's forests and woodlands. While this project is capable of becoming self-sustaining, an initial investment that de-risks the project and helps it secure capital would aid and accelerate its development. The estimated supportive public funding that would help build this plant and make its biochar available for local use is \$5 million.

Similar to pyrolysis, Marin has no current infrastructure for **gasification** of biomass and, instead, relies on combustion power infrastructure in the Central Valley to divert woody construction and demolition materials from landfill. There has been some initial exploration of an in-county gasification facility, but uncertainties about biochar and electricity prices have slowed investment. Based on the pro forma analysis in this chapter and ongoing

conversations with MSS about their plans, supportive public funding on the order of \$15 million would help to attract investment, secure financing, and spur development.

In sum, there are two key findings based on the economic analyses in this chapter. One is that, in general, there are significant economic benefits and the potential for positive net revenues for this alternative system of pathways. The other is the benefit of supportive public investment to attract capital investment and to accelerate pathway expansions or development to realize associated economic and environmental benefits. As summarized in Table 4-12, the estimate of supportive investment to spur transition to the alternative system is \$29.0 million — an investment that could return meaningful economic and environmental benefits to Marin.

Table 4-12. Supportive Investment for the Alternative System

	Supportive Funding (\$M)	Economic Benefit Highlights	GHG Benefits ¹⁶⁴ (MTCO ₂ e per year)
Composting	7.5	stable source of compost for SB 1383 procurement and placement	- 11,700
Co-digestion	1.0	more local, renewable energy	-4,700
Small-scale Milling	0.5	higher and better use; structural and artistic wood products	-500
Pyrolysis	5.0	digestate solution for sanitation districts; local source of biochar	-3,000
Gasification	15.0	more local, renewable energy; local source of biochar	-11,300
TOTAL	29.0		-31,200

Additional Considerations and Benefits

The analyses in this chapter have been carefully constructed based on the data most readily available about Marin’s biomass flows, technology costs, and operating expenses for infrastructure partially in existence or not yet developed. Assumptions made to support these analyses are based on information collected through interviews with the lead project developers within the organizations mentioned, as well as the best judgment of the analysts who did the modeling. In all cases the intent was to develop realistic, if not somewhat conservative, estimates for costs and benefits and to estimate the finances for each pathway to create a representative, realistic baseline for decision making about infrastructure development.

¹⁶⁴ Benefit associated only with proposed increases of flow. Benefits for total flows are considerably higher.

Project development, particularly for some of the novel pathways discussed in this chapter, typically undergoes additional value engineering and sensitivity and risk analysis (i.e., beyond those presented here) to update prices, reduce financial and economic uncertainties, and to deepen the quality of predictions. That said, the conclusion drawn here is that the economics of the more integrated, alternative system are favorable, given the underlying financial picture for each of the pathways considered in this chapter, even with limited or no public investment. Supportive funding similar to that estimated in this chapter, would benefit and help stimulate the pathways under consideration to achieve objectives for improved resource management within a shorter time period. Further, beyond those outlined in Table 4-12, these pathways could yield substantial additional economic benefits (e.g., new workforce opportunities, modest job growth, support for transition to a greener economy, potential for lower cost and longer-run stability achieving SB 1383 compliance) and environmental benefits (e.g., significant reduction of greenhouse gas emissions, reduction in transportation-related air pollution, support for regeneration of agricultural lands). Not all of those have been estimated within the scope of this analysis, and we anticipate that they would provide a richer picture of the opportunity.

Chapter 5:

Findings and Recommendations

The previous four chapters of this study explore Marin's expected types of biomass flows. They also evaluate ways to make best economic and environmental use of those flows. Here is a recap of those chapters:

Chapter 1 offers an assessment of Marin's biomass flows and current system for managing them. It answers the questions, how much biomass is Marin expected to generate, and where does Marin's biomass currently go? Answers to these questions provide a basis for thinking about alternatives and are carried forward into Chapter 2.

Chapter 2 provides an assessment of biomass utilization pathways. It asks, do other pathways offer a more promising match for Marin's biomass? An analysis of Marin's expected biomass flows, available technologies, and potential products is used to identify pathway alternatives with potential for greater economic and environmental benefits. This alternative system is then carried forward for deeper analyses in Chapters 3 and 4.

Chapter 3 presents an analysis of greenhouse gas (GHG) emissions for each biomass utilization system. This analysis is broken down into two accounts. One account estimates the GHG emissions avoided when fuel treatments are undertaken in Marin's forests and woodlands. This Avoided Emissions account answers the question, how much does wildfire reduction-related vegetation management reduce GHG emissions from wildfire. The other account estimates the GHG reduced when biomass is used by the alternative set of pathways. This answers the question, does the alternative system reduce GHG emissions compared to the current system? The GHG reduction estimates developed in this chapter

aid analysis of potential revenues from carbon incentives in the economic analysis of Chapter 4.

Chapter 4 estimates the financial requirements, economic performance, and investment attractiveness of different utilization pathways. It answers the questions, which pathways look economically viable as business ventures, and where might supportive investment be needed or help accelerate pathway development? The pro forma economic analyses in this chapter provide a basis for estimating the capital needed to accelerate the flow of Marin's biomass into the proposed biomass utilization system.

This chapter summarizes the findings from these assessments. Based on these findings, it then recommends the system of biomass pathways best suited to Marin's biomass feedstocks. The chapter concludes with strategies that could support and accelerate development of these pathways.

Findings from Feedstock Assessment (*Chapter 1*)

The biomass assessment in Chapter 1 estimates Marin's expected biomass flows in the next ten years. It explores the following four types of biomass: (i) woody biomass generated from wildfire prevention and land management activities in Marin's forests and woodlands; (ii) biomass from management of Marin's metropolitan environments, including from construction and demolition activities, self-haul and curbside collection of green materials, commercial collection of food scraps food and grocery businesses; (iii) digestate from wastewater treatment plants; and (iv) residues and byproducts from agricultural activities. Information about these materials draws from published reports, from correspondence with responsible parties in wildfire prevention and resource recovery, and from interviews with subject matter experts.

Biomass from Forest and Woodland Landscapes

Thirty-three percent (116,781 acres) of Marin's total land area has forest or woodland cover. Over the last one hundred fifty years, wildfire suppression has increased the density of fire-prone biomass in forests. As the available wildfire "fuel" has increased with this densification, so has the risk of wildfire. Land managers, including those working with the support of Marin County's Measure C, are implementing vegetation management plans that reduce the probability and spread of wildfire in Marin forests and woodlands. Under the leadership of the Marin Wildfire Prevention Authority, Marin is developing three significant "shaded fuel breaks" to slow the spread of wildfire on the landscape. Marin is also encouraging property owners to pare back vegetation around structures, thereby

increasing their “defensible space” and decreasing their burn probability. Most of the biomass being generated from these activities consists of small-diameter trees or so-called “ladder fuels” (i.e., shrubs and lower branches of trees that allow fire to travel up the forest canopy), and invasive species, such as French broom. This means that the materials are mostly non-merchantable material and of little or no commercial value.

Chapter 1 also considers the logistical and infrastructure constraints that might hamper biomass removal from the landscape and support the logic of masticating and broadcasting it on the forest or woodland floor. Steep terrain and limited road infrastructure are the biggest accessibility barriers to biomass transport and utilization off site. Land ownership and associated management plans also shape whether and how forest and woodland biomass is managed for offsite utilization or onsite dispersion. Taking this all into account, over the next decade Marin is expected to generate 7,900 wet short tons (4,300 dry metric tons) per year of woody biomass from forest and woodland management. Of this total, 2,500 wet short tons (1,400 dry metric tons) per year could be practical to remove and be turned into a value-added product.

Biomass from Metropolitan Landscapes

In 2016, the California legislature passed Senate Bill 1383, a law to reduce short-lived but potent climate pollutants. The law directs cities and counties to divert carbonaceous or “organic” materials from landfills, where their decomposition in the absence of oxygen produces methane that leaks into the atmosphere.¹⁶⁵ This bill sets a statewide target to divert seventy-five percent of organic materials from landfills by 2025. Although the State has not yet achieved this target, it has succeeded in implementing regulations that require cities and counties to track flows of organic materials and, in proportion to their per capita rate of biomass generation, to procure and use products from biomass pathways, such as compost, mulch, and renewable energy products.

The types of biomass considered in this study all fall under the SB 1383 definition of “organic” materials (i.e., woody discards from landscape management and from construction and demolition activities; food scraps collected from commercial food and grocery businesses; green materials (e.g., yard clippings, tree trimmings, and kitchen

¹⁶⁵ The definition of “organic” under Senate Bill 1383 includes food, green materials, landscape and pruning trimmings, organic textiles and carpets, lumber, wood, paper products, printing and writing paper, manure, biosolids, digestate, and sludges. The “biomass” categories considered in this Study span most of these categories. Paper products, printing and writing paper, organic textiles, and non-wastewater sludges were not examined here.

scraps) collected from residences and businesses at the curbside; digestate from wastewater treatment plants; and agricultural manures).

Woody Construction and Demolition Materials

Marin is expected to generate almost 118,000 wet short tons (85,600 dry metric tons) per year of woody construction and demolition (C&D) materials. The current fate of C&D materials from Marin depends on where they are sorted and processed. Portions of these materials are sent to the Marin Resource Recovery Center, where they are sorted and processed. This segregation allows 34,000 wet short tons (24,600 dry metric tons) to be deemed clean enough to be ground into three-inch chips for use as a fuel in a combustion power plant. Because there are no power plants in or near Marin, these chips are shipped around 100 miles to facilities in the Central Valley.

A portion of the remaining materials is sorted, processed, and ground into 6-inch chips for use as daily cover in a landfill. Waste Management conducts initial processing on site at Redwood Landfill and absorbs some of this material. The remnant is sent to Pacific Sanitation in Windsor, where it is also processed for use as landfill cover. The rest of the material enters the landfill as waste.

While almost all of Marin's woody C&D material is handled this way, there is a noteworthy exception. A few local businesses offer deconstruction services and reclaim an estimated 200 wet short tons per year of building materials and wood products currently with little governmental support. Reuse of these materials retains their embodied energy and carbon, and it prevents the emissions of methane resulting from its anaerobic decomposition in landfills.

Green Materials

As wildfire-related defensible space work increases over the next decade, Marin is expected to generate 81,000 wet short tons (36,500 dry metric tons) of green materials per year. This estimate includes materials from yard work and landscape maintenance. (Roughly 5% of this material is food scraps commingled with green materials in curbside collection systems — i.e., "green bins"). Franchise haulers gather a considerable amount of these materials as part of their municipal waste management contracts. (For example, Marin Sanitary Services collects roughly 25,000 wet short tons per year of green materials). A substantial portion is transported through "self-haul" by homeowners or contractors, rather than through a city's franchise agreement. At present a little more than 80% of Marin's green materials are sent to Waste Management's EarthCare composting operations adjacent Redwood Landfill. The

remaining 20% of materials are composted at West Marin Compost in Nicasio, Republic Services in Richmond, or Resource Recovery in Bolinas.

Food Scraps

In addition to the food scraps commingled with (and counted as) green materials collected in residential green carts, Marin source-separates and recycles roughly 3,900 wet short tons (1,040 dry metric tons) of food scraps per year; 800 wet short tons (240 dry metric tons) are sent for composting in Napa County. The other 3,100 (800 dry metric tons) are collected by Marin Sanitary services from commercial businesses like grocery stores and restaurants. In a noteworthy partnership with Central Marin Sanitation Agency (CMSA), Marin Sanitary Services processes these pre-consumer food scraps into a feedstock that can be co-digested with sewage sludge at CMSA's wastewater treatment plant in San Rafael. This co-digestion of sewage and food increases the methane-rich biogas produced, which CMSA uses to fuel an engine to generate electricity for onsite use. At present another 11,100 wet short tons (3,000 dry metric tons) of food scraps are being generated but going to landfill.

Digestate

Marin County is served by six wastewater treatment districts. The treatment of sewage sludge at these facilities produces reclaimed water as a primary product and two biomass byproducts: a methane-rich biogas and a nutrient-rich digestate (biosolids). Most digestate finds its way into landfills, where it can be used as alternative daily cover. Some agricultural operations accept it as a soil amendment. One fertilizer manufacturer in Fairfield accepts some of it as a feedstock. Wastewater districts are considering alternatives like co-composting or co-pyrolysis as more sustainable pathways for the 16,500 wet short tons (3,000 dry metric tons) of digestate that Marin generates each year.

Agricultural Residues

According to the USDA [National Agricultural Statistics Service](#), Marin County has a little over 44,000 acres dedicated to commercial agriculture, over 99% percent of which is pasture, grassland, silage, and hay that supports pasture-based livestock.¹⁶⁶ Orchards and vineyards

¹⁶⁶ As noted in Chapter 1, numbers vary for the acreage of agricultural land in Marin. The 2024 Marin Crop and Livestock Report from the Marin County Department of Agriculture Weights and Measures estimates 155,000 acres of pasture in Marin. The Marin Climate Action Plan 2030 estimates that Marin has a little over 60,000 acres of grassland suitable for compost and biochar application. This project acknowledges these different numbers, rather than trying to reconcile them.

covering just 268 acres produce relatively small flows of woody biomass from pruning and occasional tree removals. Maintenance of historical agroforestry plantings, such as Eucalyptus and Monterey cypress for windbreaks and shelterbelts, are another source of woody biomass. However, agricultural woody biomass flows are typically managed onsite and repurposed locally as mulch or firewood. (The estimated size of these episodic woody biomass flows is about 1,000 wet tons per year).

Thus, most of the biomass of potential interest in Marin's agricultural sector is from livestock operations, particularly the active dairies in the county. Manure from these operations is estimated to be just over 66,000 wet tons per year. Equestrian facilities in Marin generate an estimated 36,500 wet tons of manure annually. Most dairies handle their manure through onsite composting, anaerobic digestion, and/or use as a soil amendment. Only one dairy and some equestrian operations arrange for 1,800 wet tons per year of manure to be managed offsite, and those are co-composted with green materials at West Marin Compost. In short, with the exception of the dairy and equestrian manure transfer to West Marin Compost, agriculture operations in Marin largely manage their manure onsite, and this seems to align with local environmental priorities around recycling and soil health improvements. For this reason, manure is not treated as an available feedstock and not included in further assessment of utilization pathways.

Marin's Current System

Marin's current system relies heavily on biomass disposal, but it also has a promising start on recycling. In the current system, there are multiple ways that biomass is aggregated: through municipal curbside collection systems, under commercial contracts with business, and through self-hauling from landscape management and landscaping. Regardless of its origin or collection point, most of this material flows through a network of transfer stations and materials sorting and recovery facilities designed to handle materials as wastes. As described below, a majority of materials flow into landfill or are transported to the Central Valley for electricity generation (biopower). However, composting systems absorb almost all of Marin's current flow of green materials, and a pilot project is recycling some of its food scraps. At present, most of the biomass generated by fuels management is dispersed on the land where it is cut.

Landfilling

Marin is on course to landfill over 123,000 wet short tons per year of biomass. Although capable of receiving the widest range of biomass types, landfilling is the pathway with arguably the greatest long-term environmental and economic downsides. When the

legislature passed Senate Bill 1383 in 2016, they did so to reduce short-lived climate pollutants (primarily methane) from landfills. SB 1383 includes a goal to divert seventy-five percent from landfill by 2025, but that goal has not been met. Like other parts of the State, Marin's ability to comply with those requirements depends on the availability of alternative disposition pathways, and more are needed.¹⁶⁷

Composting

Composting is the managed, aerobic (oxygen-rich) decomposition of organic materials into a nutrient-rich and mostly pathogen-free material called compost. Marin has three active composting facilities, as well as some access to the composting facility operated by Republic Serves at the West Contra Costa Landfill. By far the largest operation is the EarthCare composting facility operated by Waste Management. It is permitted to process up to 160,000 wet short tons of biomass annually, and it currently processes 140,000 wet short tons of biomass per year.¹⁶⁸ The second largest is West Marin Compost in Nicasio, which co-composts roughly 5,000 wet short tons per year of green materials and 1,800 wet short tons of manure. Marin sends 4,000 wet short tons of green materials for composting in Richmond, and Resource Recovery in Bolinas processes 2,000 wet short tons per year. Based on these input rates, these four facilities produce between 75,000 and 80,000 wet short tons of compost per year.¹⁶⁹ Compost from Redwood Landfill is certified as organic and sold at a premium, most notably to organic vineyards. West Marin Compost sells both certified organic and non-certified compost, as well as several mulch materials suited for a variety of uses.

Export to Combustion Power

One use option for biomass is combustion to generate electricity. However, Marin does not have any combustion power facilities, such as combined heat and power facilities, on a scale that matches its expected flows. Instead, Marin is exporting (i.e., "chipping and

¹⁶⁷ This diversion has been accomplished in part by Marin jurisdictions enacting mandatory organics recycling ordinances for curbside green carts and other sources, although education and enforcement connected with these ordinances remains uneven. An important goal of this Study is to suggest alternative disposal pathways that can assist further SB 1383 compliance.

¹⁶⁸ A bit less than half (61,000 wet short tons per year) of the 140,000 wet short tons of green materials per year processed at the EarthCare facility come from within Marin. The rest comes from outside Marin, including Sonoma County. EarthCare reports that the inputs to their composting facility are 98% green materials and 2% food scraps.

¹⁶⁹ To comply with SB 1383, Marin needs to procure and use roughly 5,900 tons of compost per year. This procurement target is based on population. (See Appendix F.) Even though compost production in Marin greatly exceeds this number, the responsible agencies (now operating through Zero Waste Marin) have yet to be able to procure enough local compost to comply with SB 1383's procurement requirements, due to cost of local product. Instead, compliance has been achieved through attractively cheaper compost procurement and placement in the Central Valley.

shipping”) 39,200 wet short tons (28,300 dry metric tons) of woody biomass per year to combustion power plants in the Central Valley. Although controlled combustion and energy recovery is preferable to open burning or wildfire, it still has some noteworthy economic and environmental costs. One is the economic cost and greenhouse gas emissions from trucks driving roughly one hundred miles one way to haul the materials — for a total of over 300,000 truck miles traveled per year. In addition to these costs, shipping the materials outside of the county deprives Marin of the economic benefits from their use.¹⁷⁰

Dispersion

Reducing vegetation density in forests and woodlands can reduce wildfire fuel and improve wildfire safety. When these “fuel treatments” are undertaken on easily traversable terrain close to a developed roadway, it can be practicable to remove biomass for other uses. Otherwise, on-site biomass dispersion methods may be used. These can include vegetation cutting followed by “lop and scatter,” mastication, broadcast chipping, or use of air curtain burners — all are safer and more environmentally palatable alternatives to piling and burning cut biomass. Alternatively, prescribed grazing and prescribed burning could be used to manage biomass without cutting it first. This study aggregates all of these methods into a single pathway called “dispersion.” Because the biomass managed through on-site dispersion is not typically weighed or documented, the total flow is estimated based on common practices.

Co-digestion

Anaerobic digestion is the managed decomposition of organic materials by microorganisms in the absence of oxygen. This technology produces both a methane-rich biogas and a nutrient-rich and mostly pathogen-free digestate. Anaerobic digestion can be used to decompose a range of wet organic materials like food scraps and sewage. A pilot project has been co-digesting 3,100 wet short tons (800 dry metric tons) per year of food scraps at the wastewater treatment plant run by Central Marin Sanitation Agency (CMSA). The addition of food scraps to the digesters boosts the biogas production at the facility. CMSA uses all the biogas it produces to generate electricity, some of which is used onsite and some of which is sold to MCE.¹⁷¹

¹⁷⁰ The revenue could be in the millions of dollars. For example, the use of Marin’s biomass in combustion power plants generates an estimated 21,900 Megawatt-hours of electricity. At a whole price of \$80 per Megawatt-hour (used in Chapter 4), this translates to \$1.7 million in lost revenue on top of the expense of chipping and shipping this biomass to the Central Valley.

¹⁷¹ CMSA has installed a new 995 kilowatt engine and electricity generator. This unit replaces an older 750 kilowatt engine and electricity generator. The increase means that CMSA could use more biogas if additional prepared food scraps were available.

The digestate from Marin’s wastewater plants flows down two primary pathways.¹⁷² Within careful limits and only during the dry season of the year, partially dried digestate is applied to land. The remainder of the time, digestate is sent to landfill as waste or daily cover.

Summary of Marin’s Current System

The total biomass flows in Marin’s current system are summarized in Table 5-1. This table partitions biomass by type and illustrates the pathways into which they flow.

Table 5-1. Marin’s Current System and Expected Biomass Flows

Biomass Type	Utilization Pathway	Annual Input		Product	Annual Output	
		wet short tons	dry metric tons		wet short tons	dry metric tons
Green Materials	Composting	61,000	27,500	Compost	31,800	14,000
Manure	Composting	1,800	360			
Food Scraps	Composting	800	240			
Wood Chips	Mulching	2,600	1,400	Mulch	2,600	1,400
Wood Chips	Dispersion	5,400	2,900	Litter	5,400	2,900
Wood Chips	Dispersion	2,500	1,400			
Digestate	Dispersion	8,000	1,450	Application	8,000	1,450
C&D Wood	Reclamation	200	150	Wood Products	200	150
Food Scraps	Co-digestion	3,100	800	Local Electricity	400 MWh per year	
Logs	Combustion	700	400	Electricity ¹⁷³	21,900 MWh per year	
Wood Chips	Combustion	4,500	3,300			
C&D Wood	Combustion	34,000	24,600			
Green Materials	Landfill	20,000	9,000	Electricity ¹⁷⁴	1,000 MWh per yr	
Digestate	Landfill	8,500	1,550	Landfill Waste and Daily Cover	123,600	74,650
Food Scraps	Landfill	11,100	3,000			
C&D Wood	Landfill	84,000	61,000			
TOTAL		248,200	139,150			

¹⁷² Without data about the extent of this practice, this study accounts for but does not model the effect of biosolids application to land. That is, although we guess that as much as fifty percent of biosolids may be applied to land (i.e., for half the year), all greenhouse gas modeling assumes that biosolids go to landfill.

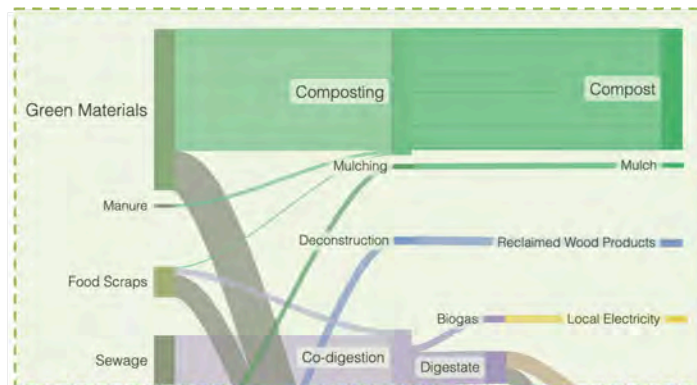
¹⁷³ Estimate based on calculation of typical electricity production rate for biopower plants.

¹⁷⁴ Estimate based on assumptions about methane contribution percentage of studied biomass.

Based on the figures in Table 5-1 and as illustrated in Figure 5-1, two thirds of Marin's biomass is being buried in landfills or exported and then burned in the Central Valley. By this measure, only a third of Marin's current biomass flows in pathways considered building blocks of a regenerative economy — one that that aids wildfire safety, enables compliance with SB 1383, creates value-added products with potential for local use, reduces greenhouse gases, and supports systems that help regenerate Marin's resources.

Figure 5-1. Flows and Fates of Marin's Current System

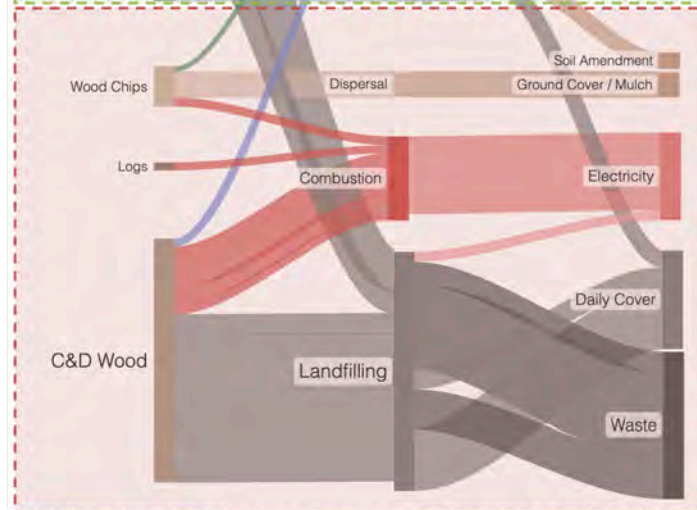
33%
(82,300
wet short
tons per yr)



Compost

Electricity (local, renewable)

67%
(165,900
wet short
tons per yr)



Long-Distance > 100mi
(Electricity)

Waste

Findings from Pathways Assessment (Chapter 2)

This chapter explores the infrastructure that can help Marin make higher and better use of its biomass. Core to this assessment is the concept of a “biomass utilization pathway.” As developed as a framework for this Study, a “pathway” is a term for the combination of a processing technology and its output product that creates an economic engine for transforming biomass into value-added products.¹⁷⁵

This assessment in this chapter surveys pathways and the following management methods:

- **Onsite Dispersion** methods that physically or thermochemically manage biomass where vegetation is cut, rather than transporting it off the landscape and producing salable products. (Surveyed pathways include prescribed burning, piling and burning, combustion in air curtain burners, prescribed grazing, mastication, and broadcast chipping.)
- **Solid Fuel Production** methods that convert bulk biomass into energy resources using primarily physical manipulation methods. (Surveyed pathways include pelletization, briquetting, and firewood production.)
- **Wood Product Pathways** that convert biomass into structural and finished materials — as well as reclaim previously used materials for reuse. (Surveyed pathways include post and pole production, small-scale milling, large-scale milling, particle board manufacturing, and mass timber production. These products include posts and poles, architectural wood products, dimensional lumber, veneers, composite wood products, and engineered wood components — as well as salvaged versions of these products.)
- **Biochemical Conversion** methods that use managed decomposition by microorganisms to convert biomass into material and energy resources. Surveyed pathways include composting and anaerobic digestion that produce compost, biogas, and digestate. Mulch may also be produced from ground wood material, but this process does not involve biochemical conversion. Further processing can turn primary outputs into green hydrogen, fertilizer, and electricity.

¹⁷⁵ For example, anaerobic digestion is a technology that can be used to convert food scraps into a methane-rich biomass that can then be used as an energy resource, along with a nutrient-rich digestate. More specifically, it explores the co-processing or “co-digestion” of source-separated food scraps with sewage at a wastewater treatment plant, to increase its production of biogas that can be sold and, in some cases, carried through natural gas pipelines to customers. In Marin it is currently used to generate electricity for onsite operations or for sale into the electric grid through MCE.

- **Thermochemical Conversion** methods that use higher temperature systems to convert biomass into a mix of solid, liquid, and gaseous materials. Surveyed pathways include gasification, pyrolysis, and combustion. The products include synthesis gas, bio-oil, biochar, and heat. Upgrading steps can turn primary products into green hydrogen, biofuels, electricity, soil amendments, and industrial materials like “carbon black.”
- **Disposal** methods that primarily collect and dispose of materials as waste, although they can generate useful byproducts. Surveyed pathways include landfilling and mixed waste combustion. Examples of byproducts include electricity generated from combustion of landfill gas at Redwood Landfill and from mixed waste combustion facilities elsewhere in the State. This means that, although the primary output of a disposal pathway is “waste,” ancillary products provide economic, social, and environmental benefits that deserve consideration too.

In all, the assessment surveys twenty-nine pathways and follow-on upgrading options and screens them as a match for the types and quantities of Marin’s expected biomass, as well as the economic and environmental characteristics associated with both the process and the product. The assessment identifies a handful of pathways — composting, anaerobic digestion, small-scale milling, pyrolysis, and gasification — as promising matches for Marin’s expected biomass flows. The conclusion is that the expansion and (re)development of these pathways (as suggested below) should undergo further analysis of their potential to produce economic and environmental benefits for Marin:

Expansion of Composting

Within the next decade Marin is expected to generate 81,000 wet short tons per year of source-separated green materials. Currently 61,000 wet short tons flow into composting pathways in Marin and Contra Costa County. Increasing processing capacity is proposed to absorb this increase of 20,000 wet short tons per year, as well as to meet potential demand for compost. Recent assessments have determined that Marin has considerable acreage suitable for compost application and that compost application on these lands will support attainment of the County’s greenhouse gas reduction goals and the procurement requirements in Senate Bill 1383.¹⁷⁶ In addition to increasing processing capacity, expansion of composting may need more sophisticated systems to avoid contaminants. For

¹⁷⁶ Demand for compost has grown in the last decade and is predicted to increase further because of the procurement requirements in Senate Bill 1383 and interest in more regenerative agricultural practices like carbon farming. The Marin Carbon Project predicts that up to 50,000 tons of compost could be applied annually on new rangeland acreage each year and contribute to attainment of the goals in the 2030 Marin Climate Action Plan. This total does not include the roughly 150,000 tons of compost that Placeworks, Inc. has identified could be applied on Marin’s non-agricultural lands each year.

example, so-called compostable packaging materials can be a problem when commingled with food scraps because of potential contamination with plastics and other non-organic materials.

Scaling Up of Co-digestion with Electricity Generation

A pilot project between Marin Sanitary Service and Central Marin Sanitation Agency (CMSA) co-digests 3,100 wet short tons (800 dry metric tons) per year of source-separated commercial food scraps with sewage at a wastewater treatment plant. This successful pilot and the available capacity at CMSA's plant suggest that Marin could co-digest all or nearly all of the 14,200 wet short tons (3,900 dry metric tons) of commercial food scraps that it is expected to generate each year and needs to divert from landfill. Because CMSA recently upgraded its engine and generator, it is also equipped to burn the additional biogas that it will produce, and to sell more electricity to MCE.

Redevelopment of Small-scale Milling

Tree removal by County road crews and companies like Pacific Gas & Electric is producing large-diameter logs in need of local processing. As an alternative to chipping these logs and shipping the chips to combustion power plants in the Central Valley, West Marin Compost has explored milling them into artisanal slabs or utility grade lumber for sale. Milling (instead of "chipping and shipping") reduces transportation costs, reduces greenhouse gas emissions during biomass processing, sequesters carbon in milled products, and expands local economic and employment opportunities. It also supports an emerging local economy for milling of large timbers that includes nascent restart of a similar small-scale mill in central Sonoma County.

Development of Pyrolysis and Biochar Production

Digestate from wastewater treatment plants is included in the definition of organic materials to be diverted from landfill under SB 1383. Co-pyrolysis of digestate and woody biomass offers Marin's wastewater treatment plants this alternative to landfill disposal. Novato Sanitary District is exploring this kind of system to produce local biochar that could be used in fertilizers, as a compost additive, or as a stand-alone soil amendment. At the scale being explored, the imagined co-pyrolysis system could process the 16,500 wet tons (3,000 dry metric tons) per year of digestate produced across Marin's wastewater treatment plants and all 2,500 wet tons (1,400 dry metric tons) per year of the practically removable woody biomass from wildfire prevention operations in Marin.

Development of Gasification with Electricity Generation

Marin currently sends 39,200 wet short tons (28,300 dry metric tons) of woody construction and demolition material to combustion power plants in the Central Valley. To reduce the long-distance transport, Marin Sanitary Service is exploring the feasibility of a community-scale gasification plant that converts woody biomass into a burnable synthesis gas (syngas) with some secondary biochar. This plant would be a source of local, renewable electricity of potential interest to MCE.

Expansion of Woody Construction and Demolition Material Recovery

Arguably the most underutilized biomass flow in Marin is woody construction and demolition (C&D) materials. Although a sizable amount of woody C&D materials is being turned into an energy resource, an even greater amount remains in the landfill stream.¹⁷⁷ Initial screening suggests that increased C&D recovery could produce energy resources (such as fuel for gasification). However, stronger incentives appear necessary to motivate investment in additional infrastructure and additional source separation and preparation of these materials, particularly materials reclaimed for reuse by deconstruction practices.

Summary: An Alternative System of Biomass Utilization for Marin

The assessment in Chapter 2 explores alternative pathways, with the goal of identifying those that not only match Marin's expected biomass flows — but also make better economic and environmental use of them.

As laid out in Table 5-2, these pathways are more local and show potential to boost Marin's economic use of biomass, both by putting it to higher and better use and by reducing greenhouse gases associated with it.

¹⁷⁷ Of the roughly 200,000 short tons of C&D materials received at Redwood Landfill, roughly half are woody biomass. Current practice is to avoid immediate landfilling for all of this material, but only about 60,000 short tons per year are evaluated and processed for use as a combustion feedstock (3" grind) or as alternative daily cover (6" grind). Of this amount, roughly 40,000 is either sorted onsite by Waste Management for use as daily cover at Redwood Landfill or is returned by Marin Sanitary Service to Waste Management and then added to the daily cover stockpile. This means two things. One is that a substantial portion does not get evaluated for utilization. The other is that only a portion of woody C&D materials enters a utilization pathway other than landfill. That pathway is the "chipping and shipping" pathway through combustion in the Central Valley.

Table 5-2. Alternative System and Marin’s Expected Biomass Flows

Biomass Type	Utilization Pathway	Annual Input		Product	Annual Output	
		wet short tons	dry metric tons		wet short tons	dry metric tons
Green Materials	Composting	81,000	36,500	Compost	41,800	17,800
Manure	Composting	1,800	360			
Food Scraps	Composting	800	240			
Wood Chips	Mulching	2,600	1,400	Mulch	2,600	1,400
Wood Chips	Dispersion	5,400	2,900	Litter	5,400	2,900
C&D Wood	Reclamation	1,000	725	Wood Products	1,000	725
Logs	Milling	700	400	Wood Slabs	600	300
Wood Chips	Pyrolysis	2,500	1,400	Biochar	—	1,540
Digestate	Pyrolysis	16,500	3,000			
Mixed Wood	Gasification	20,400	14,800	Biochar	—	1,500
				Local Electricity	15,300 MWh per yr	
Food Scraps	Co-digestion	14,200	3,900	Local Electricity	3,100 MWh per yr	
Mixed Wood ¹⁷⁸	Combustion	18,000	13,100	Electricity	10,100 MWh per yr	
C&D Wood	Landfill	83,200	60,425	Waste and Daily Cover	83,200	60,425
TOTAL		248,200	139,150			

The proposed system differs from the current system in the following ways:

- It expands the capacity of the composting system to absorb the expected growth in green materials, to enhance the quality of compost, and to achieve GHG reductions

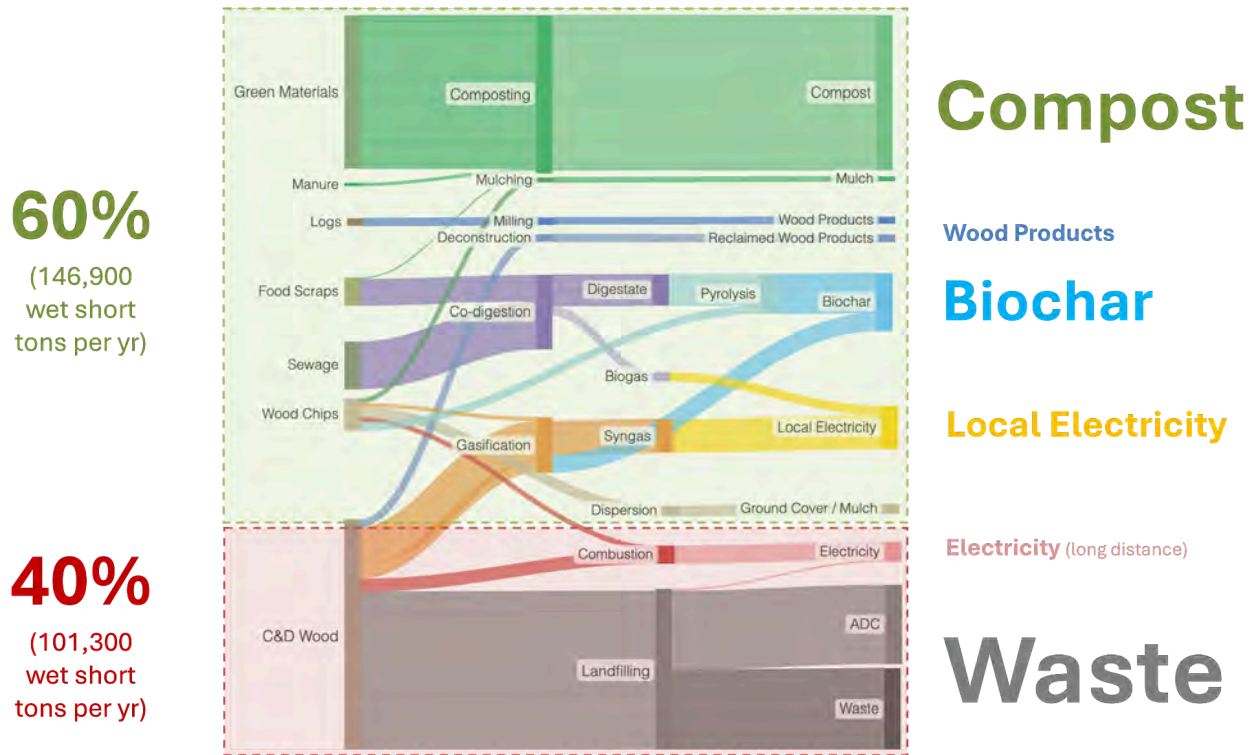
¹⁷⁸ This stream is a mixture of woody construction and demolition materials and more recently cut woody biomass from vegetation management activities.

through application of compost on rangelands (the single most extensive land type in Marin County).

- It replaces all long-distance “chipping and shipping” of woody biomass with development of a local gasification system that produces local, renewable electricity and biochar.
- It diverts woody materials from wildfire prevention activities away from landfill and combustion and toward new pyrolysis operations. This system also meets Marin’s need for alternative management of digestate from its wastewater treatment plants.
- It replaces chipping of large logs with local milling operations that create materials that can be used for local furniture production or, potentially, structural materials.
- It supports additional food scrap recovery by scaling up co-digestion with sewage sludge. The biogas from this expanded co-digestion can be used to generate additional local, renewable electricity of interest to MCE.
- It recognizes the potential of deconstruction and reclamation practices to pull more materials out of the construction and demolition stream for reuse. (Although more detailed analyses of these flows were not undertaken in this Study, such practices are included in the recommendations as a potentially important part of future biomass utilization systems.)
- It helps Marin achieve compliance with SB 1383 and aids the State’s goal of seventy-five percent diversion of biomass from landfill, as well as contributing significantly to meeting Marin’s local and countywide climate action goals.

As illustrated in Figure 5-2, this alternative system relies on a more diverse set of pathways and can turn sixty percent of Marin’s surplus biomass into local products like renewable electricity, compost, wood products, and biochar. Compared to Marin’s current system, it more than doubles the amount put to local, productive use.

Figure 5-2. Flows and Fates in an Alternative System for Marin’s Biomass



Findings from Greenhouse Gas Analysis (Chapter 3)

The objective of the third chapter is to determine whether the alternative system reduces greenhouse gas (GHG) emissions and can contribute to the climate action plans for Marin County and its municipalities. It also aims to determine whether and how much Marin’s wildfire prevention program prevents carbon loss from its landscapes. To do so, this chapter builds two kinds of carbon accounts: (i) a “Reduced Emissions” account that quantifies the difference in GHG emissions between the current and alternative system of biomass pathways, and (ii) an “Avoided Emissions” account that quantifies the carbon conserved by using fuel treatments to reduce GHGs released by wildfire.

Estimate of Reduced Emissions

A Reduced Emissions analysis is used to predict the GHG reductions that can be achieved by moving biomass through the suggested alternative set of utilization pathways. This estimate is built using a comparative lifecycle analysis (LCA) approach that estimates the difference in Marin’s GHG emissions associated with biomass cutting, transport,

processing, and product use, between the current biomass utilization system and an alternative set of pathways. The results are as follows:

Composting

Composting of an additional 20,000 wet short tons of green materials per year combined with rangeland application of the produced compost reduces 11,700 metric tons of CO₂e per year.¹⁷⁹

Co-digestion

Co-digestion with sewage of an additional 11,100 wet short tons (3,900 dry metric tons) of pre-consumer, commercial food scraps followed by use of the produced biogas to generate 1,700 Megawatt-hours of electricity reduces 4,700 metric tons of CO₂e per year.¹⁸⁰

Small-scale Milling

Resumption of small-scale milling for the 700 wet short tons (400 dry metric tons) of logs, instead of chipping and shipping this material to combustion power plants in the Central Valley, reduces 500 metric tons of CO₂ per year.¹⁸¹

Co-pyrolysis

Rangeland application of biochar¹⁸² produced through the co-pyrolysis system of 2,500 wet short tons (1,400 dry metric tons) of woody biomass from fuel treatments and 16,500 wet short tons (3,000 dry metric tons) of digestate from wastewater treatment reduces 3,000 metric tons of CO₂e per year.

Gasification

Development of a local gasifier that converts 20,400 wet short tons (14,800 dry metric tons) of woody construction and demolition materials into syngas used to generate 12,500 Megawatt hours of electricity and into byproduct biochar applied to rangelands reduces 11,300 metric tons of CO₂e per year.

¹⁷⁹ The application of compost produced through composting of all of Marin's 81,000 wet short tons (36,500 dry metric tons) of green materials, 1,800 wet short tons (300 dry metric tons) of manure, and 800 wet short tons (200 dry metric tons) of food scraps reduces 48,600 metric tons of CO₂e. This estimate is highly conservative, as it is based solely on enhanced photosynthetic capture of carbon dioxide from improved rangeland net primary productivity, and it does not consider other GHG benefits associated with compost production and use.

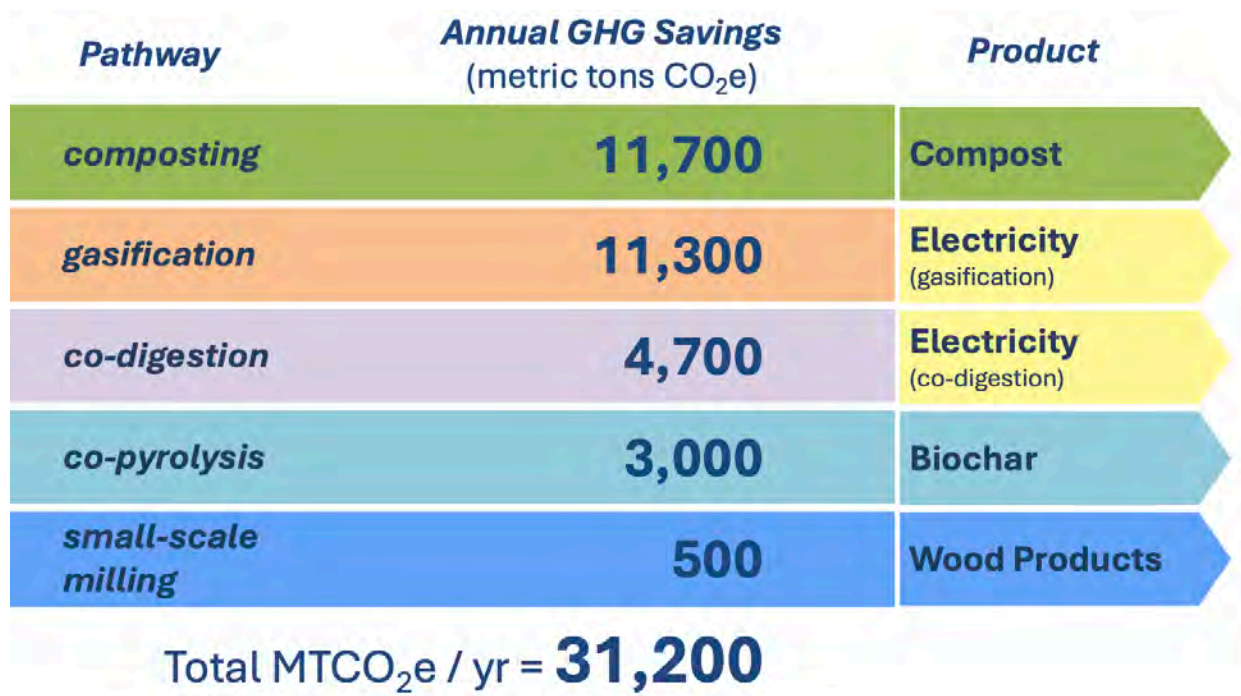
¹⁸⁰ The composting of all of Marin's 14,200 wet short tons (3,900 dry metric tons) of pre-consumer, commercial food scraps reduces a total of 5,900 metric tons of CO₂e.

¹⁸¹ The assumption is that milling of biomass into wood products sequesters carbon for fifty years.

¹⁸² The analysis was confined to rangelands as the single largest land type in Marin; both biochar and compost can be applied to all land types, including urban lands, depending on soil characteristics.

Figure 5-3 summarizes the GHG reduction estimates for pathways in the alternative system — naming both the conversion technology and the products that underlie them. The combined reduction from redirection of flows into the alternative system is 31,200 metric tons of CO₂e per year. This reduction would cut Marin’s countywide GHG emissions from the waste sector by almost three-quarters. This amount is equal to about three percent of Marin’s overall greenhouse gas emissions, and its reduction represents a tangible and achievable step toward the countywide goal of net zero emissions.

Figure 5-3. GHG Emissions for Alternative Pathways (flow increase only)



Estimate of Avoided Emissions

Vegetation management — specifically fuel treatments in forests and woodlands — can reduce the burn intensity, spread, and overall severity of wildfire.¹⁸³ In doing so, it can also avoid GHG emissions. The avoidance of potential GHG emission from wildfire is estimated using a carbon flux analysis based on several factors: the carbon stocks in Marin’s soils and

¹⁸³ The analysis considers forests at higher risk of severe wildfires due to climate change and historical land management practices. It assumes that fuel treatments reduce the density of smaller trees, understory vegetation, and surface fuels, thereby decreasing fire size and severity. These measures can reduce wildfire-associated GHG emissions and maintain or increase carbon storage by improving growing conditions for remaining vegetation (i.e., lower vegetation density results in less competition for resources such as water, nutrients, and sunlight).

standing biomass; the effect of fuel treatments on the landscape; the change in wildfire burn probability resulting from the treatments, and the avoided GHG emissions from fuels reduction work on natural and working lands.

The estimate of avoided GHG emissions uses an Avoided Wildfire Emissions (AWE) model. An AWE framework estimates how fuel treatments reduce forest burning and, consequently, prevent GHG emissions. The model is based on the amount of carbon stored on the landscape, the rate of carbon accrual, the extensiveness of the fuel treatments, a time horizon, and an assumed annual burn probability. As detailed in Chapter 3, modeling of Marin's avoided GHG emissions assumes that 8% of Marin's forested lands receive fuel treatments, a time horizon of forty years, and an annual burn probability of 2.5%. Based on these factors, fuel treatments will reduce 170,000 metric tons of CO₂e over the next forty years. If annualized, this equates to 4,250 metric tons of CO₂e per year.¹⁸⁴ This rate of carbon loss translates to 1.4 metric tons of CO₂e per treated forest acre.¹⁸⁵

Reducing the risk of wildfire does more than avoid GHG emissions. It also reduces the loss of long-term carbon sequestration — an impact that occurs when forest regeneration is delayed after a wildfire. (Many of Marin's forest species, such as Tanoak, Black Oak, and Douglas Fir, are susceptible to delayed regeneration after high-severity wildfire.) More widespread fuel treatments (i.e., more than 8%) would further prevent GHG emissions and reductions in carbon sequestration.

Findings from Economic Analysis (Chapter 4)

This chapter explores the economics of pathways in the alternative system. This analysis explores the ways that each pathway earns revenues, and it uses pro forma analyses to evaluate the financial viability, investment attractiveness, and economic development potential of these pathways. The goal is to determine ways to grow a more robust biomass economy in Marin based around higher and better use of its underutilized biomass, including how supportive investment (such as public funding) might help attract capital. It also considers how these uses support Marin's attainment of the diversion and procurement requirements in SB 1383 and its achievement of the GHG reduction targets in the climate action plans of Marin County and its municipalities.

¹⁸⁴ Approximately 40% of wildfire emissions savings were attributed to avoidance of non-carbon dioxide GHG emissions like methane (CH₄), nitrous oxide (N₂O), or other GHGs.

¹⁸⁵ Avoided wildfire emissions modeling looks only at GHG emissions avoided by reduced wildfire frequency, severity, and spread. It does not include any GHG reductions associated with shifting the woody biomass resulting from wildfire prevention treatments into the proposed pathways. Those GHG reductions could be attributed to wildfire prevention if data for the per-metric ton GHG reduction for a proposed pathway were applied to biomass recovered after fuel treatment.

These analyses suggest that almost all pathways in the alternative system can be economically viable with little or no supportive funding. The following are core findings:

Composting

Marin's existing composting system appears to have the physical, permitted capacity to process another 20,000 wet short tons of green materials each year — i.e., the increase that Marin is expected to generate in the next ten years. The challenge is the lack of economic pull of these materials through the composting system. EarthCare has saturated the local, private market for compost at the price that supports its operations. Other operators, who may be better able to support more specialized uses and demand for niche products (e.g., biochar-amended compost), need new capital to build systems that can handle Marin's growth in green materials. Marin's public sector has the potential to create additional economic pull by purchasing local compost in compliance with SB 1383's procurement requirements for local jurisdictions. Local procurement and application on local landscapes would also contribute to Marin's achievement of GHG reduction targets in its climate action plans. There is also opportunity for specialty products, such as biochar-amended compost, to synergize with development of the gasification and pyrolysis pathways. Although it may be possible to expand composting without public sector funding, supportive investment of \$7.5 million is recommended to expand processing capacity, to secure the compost needed to meet SB 1383 obligations, to reduce GHG emissions from the agricultural sector, and to increase the productivity and climate resilience of Marin's working land soils.

Co-digestion

A joint program of the Central Marin Sanitation Agency (CMSA) and Marin Sanitary Service demonstrates the financial viability of co-digesting pre-consumer commercial food scraps with sewage at Marin's largest wastewater treatment plant. A key question is whether this program can be expanded from the current 3,100 wet short tons per year of pre-consumer commercial food scraps to the 14,200 wet short tons per year that Marin is expected to produce. The financial analysis suggests that the answer is yes. CMSA has sufficient capacity in its anaerobic digesters to absorb this increase in food scraps, and its recently upgraded engine and generator set has the capacity to convert the additional biogas into local, renewable electricity. Further, expansion of this pathway has the potential to generate an additional \$270,000 in net revenues per year through sale of electricity to MCE. That said, between outreach, education, and startup support with partners to divert the additional 11,100 wet shorts tons per year of food scraps, about \$1 million in supportive public funding is recommended to expand this pathway.

Small-scale Milling

Marin does not have a lumbering economy, but it still generates enough large-diameter logs from tree removal for wildfire safety, electricity system safety, and landscaping work to support some small-scale milling. Based on the initial operation of a mill at West Marin Compost in Nicasio and the pro forma financial analysis, small-scale milling of 700 wet short tons of logs per year could generate positive net revenues between \$136,000 and \$415,000 per year. Although infrastructure already exists for this pathway, the public-private partnership needs to secure land use permits and make some small capital investments to restart this operation. For this reason, about \$500,000 in supportive public funding is needed to reinvigorate this pathway.

Co-pyrolysis

Marin has no current pyrolysis systems, but Novato Sanitary District has completed initial planning and design for a facility that jointly recycles digestate and woody biomass from wildfire prevention. Based on the pro forma financial analysis, this pathway can be self-sustaining and achieve an internal rate of return (IRR) of twenty percent. That said, supportive public funding around \$5 million can de-risk the project, help it secure capital, and speed up its development.

Gasification

Like pyrolysis, Marin has no current biomass gasification infrastructure. However, Marin Sanitary Service (MSS) has been exploring development of a system that would make local use of woody construction and demolition materials rather than sending them to combustion power plants in the Central Valley. The pro forma analysis on this facility suggested that it could achieve an IRR of ten percent and a payback period of under ten years. However, uncertainties in the price of bio-electricity, biochar, and carbon credits, on top of the challenge of developing new operational competencies underlie the estimate of \$15 million in supportive public funding that would reduce risk, facilitate investment, secure financing, and spur development of this pathway.

Summary

Two key findings are drawn from the economic analyses in this chapter. One is that, as summarized in Table 5-3, there are positive investment indicators and meaningful economic benefits for this alternative system of pathways. The other is that supportive public investment can play a meaningful role in accelerating development of these pathways. Estimates are provided in Table 5-4 for the amount that will attract capital and

derisk investments enough to secure financing. Because each pathway can be supported individually, the total supportive funding could range from \$1 million to \$29 million.

Table 5-3. Economic Benefits from Pathway Expansion and Development

	IRR (%)	Payback (years)	Economic Benefit Highlights	GHG Benefits (MTCO ₂ e per year)
Composting	—	—	stable source of compost for SB 1383 procurement and placement	- 11,700
Co-digestion	—	—	more local, renewable energy	-4,700
Small-scale Milling	—	—	higher and better use; structural and artistic wood products	-500
Pyrolysis	15.0	8.0	digestate solution for sanitation districts; local source of biochar	-3,000
Gasification	10.0	9.8	more local, renewable energy; local source of biochar	-11,300

Table 5-4. Financial Indicators and Supportive Funding Estimates

	CAPEX (\$000)	OPEX (\$000 per year)	Annual Revenue Estimate (\$)	Supportive Funding (\$M)
Composting	5,000	2,500	—	7.5
Co-digestion	0	350	270,000	1.0
Small-scale Milling	0	250	275,250*	0.5
Pyrolysis	4,750	1,000	—	5.0
Gasification	24,000	1,200	—	15.0
TOTAL				29.0

* Average between \$136,000 and \$414,500, the outcome of the two modeled scenarios.

Overall, the analytical objective in Chapter 4 is to assess the economic opportunities and study the business cases that accelerate the conversion of the current system into a more economically and climatically beneficial one. The prospects for all pathways are positive. That said, the economic prospects improve when carbon removal and sequestration credits are both leveraged and predictable. The analysis relies on the existence of multiple carbon removal accreditation systems and voluntary markets, and it has used recent market prices as predictors. (For example, it assumes a biochar carbon dioxide removal

credit price of \$190 per metric ton of CO₂e — a number based on recent price history.) Overall, the economic analyses are most sensitive to the price of carbon credits. For this reason, a sensitivity analysis on the price of carbon credits was conducted as a supplement to the economic analysis. This analysis evaluates the capital needed if the price of carbon credits drops enough that the project cannot reach an IRR of at least twenty percent. This capital gap assessment informs the estimate of supportive funding needed to attract investment and facilitate pathway investment.

Recommendations for a Better Biomass System

The analyses and findings in the first four chapters lay the groundwork for the set of recommendations laid out in this section. The first chapter describes and quantifies Marin's biomass flows, and it shows that, in its current set of pathways, a majority of biomass is landfilled or transported significant distances before being burned to generate electricity. The inference drawn is that Marin's biomass is not going to its highest and best uses, not setting it up to meet its SB 1383 obligations, and not setting Marin up to achieve the goals in its climate action plans. The second chapter surveys technologies and product combinations before proposing a set of pathways that best match Marin's biomass flows and offer the prospect of more promising environmental and economic outcomes. The third chapter carries forward this alternative set of pathways. Using a comparative lifecycle analysis, it estimates the difference in GHG emissions if biomass flows into the set of alternative pathways instead of the current set. Based on this analysis, the alternative system would reduce GHGs by a little more than 31,000 metric tons of CO₂e per year. The fourth chapter offers an economic analysis of the alternative set of pathways. It demonstrates that this alternative set of pathways can produce positive net revenues and investment-worthy rates of return between ten and twenty percent. It also suggests ways that supportive investments, such as public funding, could spur and accelerate near-term development.¹⁸⁶

¹⁸⁶ Public support could range from \$1 to 29 million and could be provided, among other options, as help securing loans, one-time grants, or incremented utility rates.

This section builds on these findings to recommend investment in the alternative system of pathways in Table 5-5. This recommendation is offered with the following objectives in mind:

- Ensuring economically sustainable pathways for biomass generated within Marin,
- Ensuring that Marin has access to pathways that support its SB 1383 compliance and climate action plan goals,
- Maximizing recovery of biomass feedstocks and local use biomass products, and
- Accelerating growth of a more regenerative biomass economy.

These objectives are part of a larger goal of developing a better biomass system for Marin. This means that, while each of these pathways could be individually developed, growing them together is likely to lead to synergies and system efficiencies that they will not achieve on their own. (One example is the development of local biochar that can be sold locally to produce biochar-amended compost that is then applied to rangeland to maximize climate benefits). Each of these elements can be undertaken alone, but their concomitant development is likely to facilitate growth of each of them.

In this vein, a set of supporting activities is also recommended to aid the growth of these pathways, lead to higher and better use of materials, and maximize the benefits for Marin's biomass economy. These include further investigation of upstream source separation and recovery infrastructure for biomass still going to landfill or far-away combustion power plants in the system, summarized in Table 5-5.

The remainder of this chapter lays out recommendations for growing pathways and an improved biomass economy. This discussion begins with a primary set of recommendations focused on growth of Marin's composting, co-digestion, milling, pyrolysis, and gasification pathways. It continues with a second set of contributing recommendations that aid growth of these pathways and a third set of institutional recommendations that more broadly advance cooperation and governance of this system. The recommendations conclude with an ultimate set of recommendations focused on keeping carbon on the landscape and growing a well-functioning, more circular and regenerative economy in Marin and beyond.

Table 5-5. System of Pathways Leading to Better Biomass Management in Marin

Biomass Type	Utilization Pathway	Annual Input		Product	Annual Output	
		wet short tons	dry metric tons		wet short tons	dry metric tons
Green Materials	Composting	81,000	36,500	Compost	41,800	17,800
Manure	Composting	1,800	360			
Food Scraps	Composting	800	240			
Wood Chips	Mulching	2,600	1,400	Mulch	2,600	1,400
Wood Chips	Dispersion	5,400	2,900	Litter	5,400	2,900
C&D Wood	Reclamation	1,000	725	Wood Products	1,000	725
Logs	Milling	700	400	Wood Slabs	600	300
Wood Chips	Pyrolysis	2,500	1,400	Biochar	—	1,540
Digestate	Pyrolysis	16,500	3,000			
Mixed Wood	Gasification	20,400	14,800	Biochar	—	1,500
				Local Electricity	12,500 MWh per yr	
Food Scraps	Co-digestion	14,200	3,900	Local Electricity	3,100 MWh per yr	
Mixed Wood	Combustion	18,000	13,100	Electricity ¹⁸⁷	10,100 MWh per yr	
C&D Wood	Landfill	83,200	60,425	Waste and Daily Cover	83,200	60,425
TOTAL		248,200	139,150			

¹⁸⁷ Estimate based on calculation of typical electricity production rate for biopower plants.

Primary Recommendations

A core objective of the Marin Biomass Project is to recommend pathways that add value to bio-materials otherwise managed as wastes and that grow a more regenerative bioeconomy in Marin. The primary recommendations offered here focus on expansion and development of five pathways poised to make the most meaningful contribution to an improved biomass system in Marin. These are the pathways identified as economically viable and environmentally attractive, whether developed individually or jointly to achieve synergies and greater systemwide outcomes.

Recommendation 1

Expand and improve composting of green materials

Marin already has a robust system for the collection, aggregation, and composting of green materials. This system currently processes 61,000 wet short tons per year, but within the next decade Marin is expected to generate 81,000 wet short tons per year as vegetation management increases to create and maintain defensible space around buildings. Marin needs access to infrastructure and an economic driver for the composting of this additional 20,000 wet short tons per year. This study identifies two economic drivers. One is local compost procurement that supports and sustains SB 1383 compliance for the County and its cities and towns. The other is local land application that advances carbon farming, supports regenerative agriculture, builds climate resilience and helps attain Marin's climate action goals.

For these reasons, Marin is encouraged to grow its local composting system.¹⁸⁸ One option is to increase the processing capacity at West Marin Compost, to align it more explicitly to local

Recommendation 1

Expand and improve composting of green materials.

- **Capacity needed for additional 20,000 tons per year**
- **Max GHG benefits from land application**

¹⁸⁸ There is, at least theoretically, enough permitted capacity at EarthCare to process another 20,000 wet short tons of green materials per year. However, the available space is not a given. Green material flows are increasing throughout the Bay Area region as jurisdictions implement their SB 1383 programs and as more wildfire prevention work is undertaken. More capacity will be needed, and different product strategies for composting are also likely needed.

compost procurement under SB 1383, and to create readier channels to apply compost to lands in Marin. This pilot project was developed as a public-private partnership to grow the connection between biomass recovery and agricultural operations. West Marin Compost has proven this concept through both co-composting of dairy and equestrian manures with green materials and success selling a variety of compost mixes to agricultural producers and the local community. Scaling up a facility like this creates geographically rational composting infrastructure and makes attainment of climate action goals possible. It does so by operating at a scale that can better trace materials and respond to local markets.

The growth of West Marin Compost might best occur by expanding the nexus of its public partnerships. Marin Resource Conservation District is already a project sponsor, and West Marin Compost already has a strong relationship with the local community and agricultural producers through its dropoff, delivery and pickup options. Further engagement with Marin Wildfire Prevention Authority (through its Chipper Day Program) and with Marin County Public Works (through its roadway maintenance program) is recommended to build feedstock channels and agreements (e.g., paying market rate, less 10%). Engagement with Zero Waste Marin opens up a channel for compost procurement and placement under SB 1383 that also aligns with climate action goals. Establishing long-term agreements with these entities creates conditions for securing the capital needed to scale this facility.

Recommendation 2

Scale up co-digestion of food scraps

A pilot project between Central Marin Sanitation Agency (CMSA) and Marin Sanitary Service (MSS) already collects, prepares, transfers, and co-digests 3,100 wet short (800 dry metric) tons of source-separated food scraps with sewage at Marin's largest wastewater treatment plant. Although the recovery of these materials from commercial operations like restaurants, grocery stores and hospitals is already required under AB 1826 (2014), it is the visionary, public-private partnership between Marin Sanitary Service and Central Marin Sanitation Agency that has made this creative reuse possible.

Senate Bill 1383 is expected to drive diversion from landfill of more food scraps over the next decade. As collection of this material expands, Marin is expected to generate another 11,100 wet short tons (3,000 dry metric tons) of potentially digestible food scraps per year. Based on the analyses in this study, expansion of co-digestion can produce economic benefits; 3,100 Megawatt-hours of local renewable electricity, reduce another 4,700 metric tons of CO₂e per year, and produce positive net revenues of \$270,000 per year. For this

reason, expansion of the program to accommodate the total 14,200 wet short tons (3,900 dry metric tons) of recoverable food materials is recommended.

Several entities could make valuable contributions to this effort. The cities, towns, and the County could launch an outreach campaign that educates and encourages businesses to improve food source separation and recovery — perhaps launching a recognition program to spur participation. MCE could help promote the effort by explaining the benefits of renewable electricity generated from co-digestion. It would be even greater if MCE developed long-term contracts for electricity produced through co-digestion at or above the price of \$0.08 per kilowatt hour and with an escalation factor that ensures the long-term financial sustainability of the enterprise. Though outside their current scope, an entity like Zero Waste Marin could seek approval from their board to take on a role as a countywide leader by helping bring more haulers into the co-digestion pilot and more generally expanding the circular economy in Marin. In short, there are multiple avenues for the public sector to get behind and help accelerate an expanded co-digestion system.

Recommendation 2

Scale up co-digestion of food scraps.

- Builds on successful pilot project
- Increases local, renewable electricity generation

Recommendation 3

Develop gasification for mixed woody materials

Of the roughly 100,000 wet short tons of woody construction and demolition debris that Marin generates each year, roughly a third is sorted and processed into “clean lumber” that can be used as a feedstock to a combustion power plant. Along with other types of woody biomass, these materials are currently being chipped and shipped an average of one hundred miles and then burned to produce grid electricity. The export costs make this a relatively expensive outlet for this biomass, as well as a drag on Marin’s climate goals. It also stops short of providing Marin with any meaningful economic benefit.

A gasification system is recommended to make higher and better use of this biomass resource. Fortunately, steps have already been taken toward this kind of pathway by

several entities in Marin. For example, Marin Sanitary Service has explored development of a gasification system capable of processing Marin’s woody construction and demolition materials. It would generate local, renewable electricity and a meaningful amount of biochar. Based on the pro forma analysis, this project could achieve an internal rate of return of ten percent with a payback period of less than ten years — two results that make this an economically viable solution.¹⁸⁹ It would reduce 11,300 metric tons of CO₂e per year.

Multiple organizations could help Marin get this kind of infrastructure across the finish line. Marin Sanitary Service and other entities could be encouraged to continue pursuing their plans and working to secure capital. MCE could enter into a long-term power purchase agreement (PPA) for the renewable electricity from the project and help secure financing. (MCE's existing power procurement process includes a Feed-In Tariff Plus Program that incentivizes development of small-scale renewable energy projects within their service area.) Organizations with relevant experience could partner with MSS and others to help obtain and monetize carbon credits that boost project viability. Jurisdictions with franchise agreements could work with their vendors to explore ways to provide supportive funding (e.g., rate adjustments, grants, or public bonds) to meet the project’s capital requirements. Public agencies, whether Zero Waste Marin as a convener or others interested in facilitating a circular economy, could help bring together relevant stakeholders or stakeholder collaborations to discuss project benefits and financing. All entities could participate in a public outreach campaign to highlight economic and environmental benefits of the program (e.g., more local, renewable, dispatchable, and reliable power), as well as to allay concerns and build community support for the project.

Recommendation 3

Develop gasification for woody materials

- Increase local, renewable electricity and reduce GHGs
- Produce local biochar

¹⁸⁹ This analysis was completed based on rates for the BioMAT program, which has now ended. Before these projects move forward, some of their calculations will need updating based on available tariffs.

Recommendation 4

Develop co-pyrolysis of woody biomass and wastewater digestate

Fuel treatments in Marin are expected to generate a steady flow of 7,900 wet short tons (4,300 dry metric tons) of woody materials per year. Currently, most of this biomass is being handled with onsite management methods. Of this material, roughly a third of this material (i.e., 2,500 wet short tons or 1,400) dry metric tons per year) is practically removable from the landscape and could be directed into a value-adding utilization pathway that furthers wildfire safety and greenhouse gas reduction. A parallel story can be told about the 16,500 wet short tons (3,000 dry metric tons) per year of digestate generated from Marin’s wastewater treatment plants.

A co-pyrolysis system is recommended to make higher and better use of these two biomass flows. It creates a combined solution that adds value to both streams by creating a high-quality biochar and makes it available to local markets. It also sequesters more carbon and creates a more consistent and reliable SB 1383 compliance option for Marin’s wastewater sector. Co-pyrolysis is also attractive because its modularity makes it easier to expand if the flow of woody materials or digestate increases. As analyzed in Chapter 4, a co-pyrolysis system like the one being considered by Novato Sanitary District can achieve an internal rate of return of 15%.

Bringing this pathway to life will benefit from contributions from multiple entities. Marin Wildfire Prevention Authority could lead development of systems for removing and aggregating woody materials from fuel treatments into a co-pyrolysis pathway, with the goal of creating a predictable, stable flow. Similarly, Novato Sanitary District could convene the wastewater treatment districts and build a program for delivery of their digestate to a co-pyrolysis facility. If California designates biochar as an acceptable “recycled organic waste product” (CCR Title 14 18998.3 and CA PRC 42652.5), Zero Waste Marin could consider biochar made through co-pyrolysis as a

Recommendation 4

Develop co-pyrolysis for digestate and woody materials

- Produces high-quality, local biochar
- Creates long-term solution for wastewater treatment plants
- Boosts funding for wildfire safety

compliance option under SB 1383. Statements of support from municipal governments and memoranda of understanding among public agencies could also facilitate long-term capital investments, including supportive funding. Financial support could include rate adjustments, low-interest loans, and one-time grants. It might also include leasing of land at low cost, support for acquiring and selling carbon dioxide removal credits for biochar, and support for other kinds of supplemental revenue.¹⁹⁰

Recommendation 5

(Re)develop small-scale milling for large-diameter logs

From both an economic and GHG standpoint, the highest and best use of the logs being received at West Marin Compost appears to be their use as structural wood products, like artisanal slabs and utility-grade lumber. Grinding them into chips to be shipped to the Central Valley for combustion at power plants not only incurs greater economic and environmental costs, but deprives the community of the local value of the wood products compared to importing slabs and commercial forest products from outside Marin. Restarting the small-scale sawmill that is already owned by West Marin Compost requires little or no additional capital expense and could increase the net revenues of the project by \$269,000 per year.

Bringing small-scale milling online requires some legwork to find a good fit under current zoning and planning rules. Marin County's Department of Public Works, who drops off logs at this site, and Marin County's Planning Department, who governs land uses, have a crucial role to play in facilitating this fit. They can consider small-scale milling to be a sensible biomass and climate solution and support its (re)development through zoning interpretations, permitting, and environmental and regulatory reviews. (This could include a special-use permit or variance if required.) In addition to these departments, others like

Recommendation 5

Revive small-scale milling instead of chipping up large logs

- **Higher and better use of biomass re: GHGs**
- **Creates local artisanal products**

¹⁹⁰ For example, the Los Angeles Department of Water and Power's Feed-in Tariff program allows commercial property owners to sell solar energy generated on their properties back to the utility company, which has attracted large real estate operators while also supporting environmental justice goals in disadvantaged communities.

Marin Resource Conservation District and Marin County Community Development Agency, could also promote this project as a local economic and environmental opportunity and build awareness and support for this pathway in the local community. Milling logs otherwise destined for combustion produces a higher-value product that is better able to support local employment and follow-on trades like woodworking — in addition to delivering sustainability commitments like supporting healthy local ecosystems, reducing GHG emissions, and sequestering carbon in longer-lasting wood products.

Recommendation 6

Prioritize Deconstruction and Reuse

Many pathways recycle biomass by breaking it down physically, biologically, or chemically into more basic materials that can be used as fuels, fertilizers, soil amendments, or manufacturing feedstocks. While recycling is valuable, other options like source reduction and reuse are considered thermodynamically and environmentally better. When available, those should be prioritized. A key example in a more circular biomass economy is building deconstruction, lumber reclamation, and reuse. As an alternative to demolition (which largely commingles materials for disposal), deconstruction is an intentional disaggregation of building materials that enables their reuse, or, for materials where reuse is not possible, more recycling options because of better source separation.

The Bay Area is home to a longstanding, although still emerging, building deconstruction and reuse economy. Last year North Bay building deconstruction innovator GreenLynx achieved a 69% reuse rate for its deconstruction projects. (That recovery percentage is above and beyond the materials that they sent to recycling. When metals and woody biomass sent to combustion are included, their recovery practices reached a total diversion rate of 94%.) By their estimate, if Marin put itself on a path to encourage or require deconstruction and reuse as a practice, it could cut its construction and demolition

Recommendation 6

Prioritize Deconstruction and Reuse

- **Lowers GHGs by retaining carbon in wood products**
- **Spurs local workforce and retail opportunities**

waste stream by at least 50%.¹⁹¹

Zero Waste Marin and Marin’s waste management Local Taskforce (LTF) are interested in promoting deconstruction, and Zero Waste Marin has developed an educational brochure¹⁹² posted on its website that, ideally, will be provided to all building projects seeking a permit in Marin. Various jurisdictions in California have deconstruction ordinances either incentivizing salvage (Belvedere, Portola Valley, Hillsborough), requiring a Deconstruction Survey (County of San Mateo), or a mandate for deconstruction (Palo Alto). Jurisdictions considering mandates or voluntary deconstruction ordinances include San Francisco, Oakland, Sonoma County, and Santa Monica. San Francisco will change its regulations in 2027, begin requiring a “deconstruction survey” similar to the one in place in San Mateo County, and offer education and incentives to promote voluntary deconstruction.

Marin should support growth of this small but mighty pathway — whether with ordinances, procurement practices, or public policy advocacy that grows the pathway. This can and should build on support for deconstruction and reuse already underway at Zero Waste Marin.¹⁹³ Their work includes campaigns to increase public awareness about deconstruction opportunities and to build infrastructure that aids reuse. Marin can build on this foundation by considering adoption of a model deconstruction ordinance or procurement requirements that include used building materials. Jurisdictions and the public are encouraged to voice support for this effort.

Recommendation 7

Incentivize Additional C&D Sorting and Recycling

Based on best estimates, Marin generates 118,00 wet short tons (85,600 dry metric tons) of woody construction and demolition materials. A sequence of sorting processes currently separates 34,000 wet short tons (24,600 dry metric tons) deemed clean enough to be ground and sold as a fuel to combustion power plants in the Central Valley. This means 84,000 wet short tons (61,000 dry metric tons) of woody construction and demolition

¹⁹¹ This estimate is loosely based on results in Portland, Oregon after their deconstruction ordinance was passed in 2016. The ultimate rate depends on the skill of the deconstruction crew and their level of commitment to recovery and recycling.

¹⁹² See <https://zerowastemarin.org/construction-demolition/>

¹⁹³ As recommended by the Local Task Force, in 2025 the Board of Directors for Zero Waste Marin directed staff to encourage deconstruction.

(<https://zerowastemarin.org/wp-content/uploads/2025/09/ZWM-JPA-Agenda-Packet-9-15-2025.pdf>)

materials remain unsorted, unseparated, and unrecovered from the landfill stream — whether it enters the landfill as daily cover or as waste.¹⁹⁴ This stream deserves deeper examination. It contains recoverable materials like reusable pallets or pallet pieces, painted reusable redwood, unpainted redwood, other reusable lumber, and other hardwood remnants (e.g., oak stair treads, cabinets, doors, etc.). At present, decisions about whether this material is diverted for recovery are made by individual haulers at the entrance scales for a transfer station.

Municipalities, County departments, and sanitation districts with flow control over these materials should intervene with stronger incentives to choose biomass recovery. Under SB 1383, municipalities, the County (for unincorporated areas), and sanitation districts are considered “generators” of biomass. They hold franchise contracts with materials haulers that give them “flow control” over where loads go and how they are handled, and they are, therefore, obligated to trace and divert flows from landfill. Under the present structure, landfill operators like Waste Management have limited reason to direct materials into recovery or to invest in advanced systems that can recover a larger percentage of this material.¹⁹⁵ Thus, the public entities have both the influence and the incentives to reduce biomass flow to landfill.

More emphasis should be placed on recovery and utilization of woody construction and demolition material. Through the recommended gasification pathway, it can produce biochar and local renewable electricity. To make this possible, Marin needs to change the incentive structure and encourage recovery and use of these materials. In addition to renegotiating its franchise agreements, Marin can invest in greater public education. For example, it could more widely publicize certified construction and demolition recycling facilities to aid compliance with CalGreen’s diversion standards and to reduce tipping costs.

Recommendation 7

Incentivize Additional C&D Sorting and Recycling

- Increases biomass usable for renewable electricity
- Increases biomass available for reuse and recycling

¹⁹⁴ Although most woody construction and demolition materials are being sent to landfill, a portion is separated for use as daily cover at the open face of an active landfill. Although this usage is part of the sanitary operation of a landfill, it still results in decomposition of woody biomass in landfill and the generation of methane emissions in the long run.

¹⁹⁵ Under SB 1383 landfill operators have no obligation to encourage biomass diversion responsibilities. That responsibility falls to municipalities.

Haulers, transfer stations, processors, and facilities with reporting obligations under SB 1383 are now required to share their flow data with Zero Waste Marin (ZWM). As this reporting system matures, ZWM may be able to scrutinize biomass flows going to landfill. This gives ZWM potential leadership in helping its member agencies develop improved recovery and utilization plans, including diverting more potentially recoverable materials at the scales when entering a landfill. This also could include opportunities to co-incentivize infrastructure that enables higher and better uses, like wood product reuse or gasification to produce local renewable electricity from materials that cannot be reused.

Complementary Recommendations

The primary recommendations above focus on expansion and development of pathways at the core of an improved biomass system in Marin. The following complementary recommendations support growth of this system and offer additional synergies.

Recommendation 8

Keep and Increase Carbon Stocks on the Landscape, Particularly in Forests and Soils

Avoiding the loss of carbon from the landscape is critical if we are to benefit from land as a carbon sink, and thus a key element in mitigating and building resilience to climate change. Conserving soil carbon includes maintaining soil cover, limiting physical disturbance such as tillage, and avoiding exposure of soil to the extreme temperatures associated with catastrophic wildfire. Moderate temperatures associated with prescribed fire and cultural burns do not typically significantly impact soil carbon. Above ground forest carbon is typically severely reduced by catastrophic fire, which moves that carbon to the atmosphere as carbon dioxide, other greenhouse gases, and particulates, including black carbon.

Managing forest vegetation to minimize the potential for catastrophic wildfire is key to avoiding carbon losses from these systems. While stand thinning, ladder fuel reduction and similar practices may appear to constitute carbon losses, this does not need to be the case if biomass so removed is directed into one or more of the pathways identified in this report, including disposition on site as chipped material or biochar. Thinning stands may appear to be a step backward from a carbon sequestration perspective, but if wildfire is thereby avoided, and remaining trees respond to thinning, as is typical, through enhanced

rates of growth, any near-term carbon losses can be quickly recovered, and exceeded, as enhanced growth in remaining forest vegetation.

While loss of soil carbon due to human disturbance has been ongoing for thousands of years, the early Anglo-American settlement period saw significantly accelerated losses of soil, and its associated carbon, from Marin's landscape due largely to intensive tillage associated with early agricultural practices. Tillage is relatively rare in Marin today, with the bulk of the county's agriculture based on permanent pasture and rangeland vegetation. While agricultural tillage does occur in Marin, methods for restoring and enhancing soil carbon stocks on tilled croplands have been well understood since at least the 1930s, including compost applications and a broad suite of conservation practices comprising "carbon farming" or "regenerative agriculture" frameworks. As noted in this report, Marin's highest carbon soils are those that have been farmed for well over a century and a half, yet have also received ongoing applications of manure and been managed for maximum forage cover, which has led to significant increases in soil carbon on those sites over time. Groundbreaking work by the Marin Carbon Project has demonstrated the potential to significantly increase soil carbon in the county's rangeland soils as well, through a single surface application of compost leading to increased soil water holding capacity, enhanced forage growth and sustained annual increases in photosynthetic capture of carbon dioxide from the atmosphere. Using the expanded and enhanced compost produced by the composting pathway recommended in this Study to support such sequestration practices on Marin's agricultural lands could amplify the GHG benefits of composting, while also increasing soil fertility. Using the biochar produced by the co-pyrolysis and gasification pathways in such agricultural applications, and perhaps in forest applications as well, could further enhance soil moisture retention where desired.

Today, due to catastrophic wildfire across the state, California's forests are a net source, rather than a sink, for atmospheric carbon dioxide, according to the California Air Resources Board. Marin can avoid contributing to this dilemma by sustaining and enhancing its forest stewardship efforts to avoid wildfire and by managing its forest, rangeland and agricultural and urban soils for enhanced storage of carbon and the associated increase in soil water holding capacity. By increasing soil water holding capacity, increasing soil carbon also can help increase fuel moisture, reducing wildfire probability and intensity. Sustainably managed afforestation or reforestation, and other fire-resistant vegetation strategies, can additionally increase carbon transfer from the atmosphere to the soil to sequester carbon emissions and provide continuing, long-term ecosystem and economic benefits. Land stewardship in the county must be rooted in the understanding that Marin's soils represent the county's largest sink for carbon, while its forests are its

largest aboveground carbon reservoir.

Recommendation 9

Promote biochar production, products and markets

Depending on its quality and purity, biochar has a variety of uses as a concentrated form of carbon. For example, it can be used in water filtration, odor control, or industrial manufacturing. It can also be used as soil amendment, either on its own or blended with compost or topsoil. Incorporating biochar into soil amendments offers a variety of benefits, including enhanced nutrient and moisture retention, reduced emissions of volatile organic compounds, and carbon sequestration. There is also evidence that addition of biochar-amended compost to soil boosts soil microbial activity and agricultural productivity — even above application of compost and biochar independently.

The use of biochar considered most in this study is rangeland application. This usage maximizes the potential GHG benefits because of the spatial extent of rangelands in Marin. Biochar and compost both have additional use potential on other agricultural lands and urban landscapes. West Marin Compost is producing biochar-amended compost and exploring ways to grow the market for this product. They are currently procuring biochar from sources outside of Marin, but their sources could be localized if Marin supports development of the recommended gasification and pyrolysis pathways.

There are multiple entities that could help build the biochar production capacity and market in Marin. Marin Resource Conservation District (MRCD) could be a catalyst for building interest and opportunities for biochar application on agricultural land. Through their connections to agricultural producers and through initiatives like their carbon farm planning program, they can educate and advocate for the use of biochar as a soil management practice and pursue funding to acquire equipment and develop a workforce knowledgeable about different kinds of soil amendments, soil nutrient levels, and optimal application rates. As part of its broader carbon farming initiative, MRCD could also lead on-farm trials, help biochar users identify opportunities to obtain and sell carbon dioxide removal credits, and disseminate information about the economic costs and benefits of biochar use. Collaborations between entities, such as MRCD and MWPA, could support development of biochar markets by helping entities source biomass feedstocks and by helping entities gain access to mobile pyrolysis units or air curtain burners. They could also identify and encourage use of digital marketplace tools (i.e., online platforms) that help match biomass generators with biochar producers, and biochar producers and consumers.

Recommendation 10

Encourage Ongoing Collaboration with Public and Private Entities around Shared Objectives and Actions

Effective collaboration among a wide range of public and private entities is needed to achieve higher and better use of Marin’s recoverable but currently underutilized biomass. A wide range of entities — including, among others, Marin Wildfire Prevention Authority, Marin Resource Conservation District, Zero Waste Marin, MCE, County departments, sanitation districts, haulers, processing facility owners and operators, and entrepreneurs — should continue to engage in collaborative exploration of ways to improve biomass utilization.

The Marin Biomass Collaborative (Collaborative) is a forum created to foster this collaboration and facilitate development of shared objectives, alignment of business practices (e.g., contracting), help identify areas benefitting from memoranda of understanding, and even encourage joint investment. The Collaborative has served as a forum for stakeholders to review and provide feedback on draft chapters of this study, as well as to share ideas, get to know counterparts, find common ground on topics related to biomass availability and disposition, and even develop new partnerships. The Collaborative can continue to be an important facilitator of an improved biomass economy by providing a forum for stakeholders to share ideas and progress updates, discuss challenges and opportunities, brainstorm solutions, and lay a foundation for core agreements, partnerships, and contracts. The Collaborative might also be a useful place to host a centralized information hub for stakeholder data, reports, and resources.

This suggestion also carries a recommendation for entities to stay abreast of relevant regional activities. Such information sharing will help Marin more cohesively support development of a biomass utilization economy and maximize its positive impacts. Sharing information regularly also will help align goals and avoid wasteful duplication of efforts. As an example, Marin Wildfire Prevention Authority (MWPA) could regularly share its objectives and progress on moving biomass into recommended utilization pathways, and Zero Waste Marin (ZWM) could track and share progress related to SB 1383 reporting and goals.

To further support these efforts, members of the Marin Biomass Collaborative could work to develop joint initiatives or pilot projects that involve multiple entities. For instance, a project combining MWPA’s wildfire prevention efforts with Novato Sanitation District’s co-pyrolysis project could yield a locally produced biochar. This project could be paired with

ZWM's procurement initiatives and with Marin Resource Conservation District's carbon farming initiatives to enable and encourage local biochar and compost use, thereby creating a more full-cycle and sustainable biomass utilization economy.

In short, by fostering a collaborative economic development environment as a strategy, Marin can create a more cohesive, efficient, and flexible approach to biomass utilization that increases its viability, resilience, and overall success. This unified effort not only would support the implementation of new and enhanced biomass utilization pathways, it also would align with Marin's broader sustainability goals and address climate and environmental concerns, working toward achieving a target of increasing economically and environmentally sustainable utilization of available biomass feedstocks.

Recommendation 11

Increase Public Outreach and Community Engagement

Public outreach is an important component of growing a more sustainable biomass economy in Marin — both to improve access to information and to build community support for the project. Messaging is recommended that connects growth of an improved biomass economy to an increase in wildfire safety, decrease in greenhouse gases, expansion of local products, soil health, more renewable electricity, increased climate resilience and new employment opportunities.

Public feedback processes (e.g., community forums, surveys, public advisory committees) are valuable ways to solicit and incorporate public feedback, during both project planning and implementation. All of the public entities named in this report have important roles to play in hearing community concerns, communicating opportunities, building community support, and growing awareness and markets through their own purchasing power. They could build on a variety of existing platforms, such as a "Zero Waste Challenge" or videos tracing the journey of materials from consumption through collection and processing to their final fates. They could involve discussions about metropolitan material flows from countywide waste characterization studies and public-facing dashboards showing how much biomass recovery and a more regenerative bioeconomy is growing. They could also involve new programs, such as a "Local Carbon" initiative that includes a campaign to build public awareness about efforts to return carbon to soil through compost and biochar application on agricultural lands. This effort could grow from workshops into eco-labels and joint projects with the Agricultural Institute of Marin to help residents support local food purchases, participate in community gardens, and find composting dropoff and pickup

opportunities. Similarly, efforts between CMSA and MCE could promote the amount of renewable electricity generated and consumed in Marin from food scrap co-digestion.

In sum, public organizations in Marin are encouraged to incorporate the benefits of an improved biomass economy into their work with the public. Ongoing collaboration across outreach platforms is similarly encouraged to reinforce a common message and avoid “outreach overload.” A forum like the Marin Biomass Collaborative is one way to stay abreast of engagement efforts, develop a common language, and maximize synergies.

Recommendation 12

Leverage Funding and Rulemakings to Spur and Speed Growth of an Improved Biomass System in Marin

Biomass pathways recommended in this report may need or be considerably accelerated by supportive public funding. Some of them also may benefit from rulemaking actions by governance organizations that range from the Public Utilities Commission to the local Board of Supervisors. They also could be eligible for funding for biomass project planning and development grants from resource management agencies like the Department of Conservation and State Coastal Conservancy or from fire reduction agencies like CAL FIRE and the US Forest Service.¹⁹⁶

Similarly, resolutions and ordinances by public entities in Marin could speed the review and approval process for key pathways — a factor that can significantly reduce planning costs, improve access to capital, and help localize the biomass economy. Such measures could expedite approval by establishing a dedicated review board or streamlining environmental reviews for biomass projects to reduce the administrative costs and capital needed or to jumpstart projects as climate solutions.

¹⁹⁶ For example, the Wood Innovations Grant Program funds projects expanding wood use in construction and manufacturing. The Community Wood Grant Program finances woody biomass energy systems and innovative wood product facilities. These programs provide funding that can be used for architectural design, equipment purchases, heating systems, and/or healthy forest initiatives. Their goal is to boost innovation and create new markets in the forestry sector.

Unifying Vision

These recommendations lay out ways to develop a better biomass economy in Marin — one that can support wildfire safety, expand local products and employment opportunities, reduce greenhouse gas emissions, facilitate SB 1383 compliance, and improve Marin's affordability and resilience in the long run. The concluding recommendation offers a vision that unifies these ideas.

Recommendation 13

Grow a Regenerative Biomass Economy

The Marin Biomass Project is motivated by the urgency of the climate crisis and its intersection with the increasing biomass flows being generated from Marin's wildfire prevention initiatives and landfill diversion obligations. It also connects to deeper undercurrents that come through in the analysis and recommendations. The Study can be seen as an effort to build both improved material recovery practices and a better biomass economy in Marin and beyond.

Encouragement to improve utilization of biomass is an important step toward this end, but it is not the end itself. The combined goals of landfill diversion and carbon retention are part of a larger effort to build systems that are conscious of the Earth's biogeochemical cycles and how our movement of resources contributes to harmful depletion or useful regeneration. Looking through this lens, climate change is a symptom caused by human movement of too much carbon from underground storage reservoirs (i.e., fossil fuel deposits) into the atmosphere. Reducing greenhouse gas emissions, along with increasing carbon sequestration, is needed to help slow or reverse this transfer of fossil carbon from terrestrial pools to the atmosphere. To that end, there is great value in looking to new solutions to reverse the accumulation of GHGs in the atmosphere. For this reason, California's state agencies are paying more attention to and putting more funding behind nature-based solutions to help protect, manage, and restore the state's ecosystems and resources.

The pathways advocated in this report are important ways that Marin can help grow a more regenerative regional biomass economy while advancing material and economic wellbeing. The local retention of carbon in the landscape and the return of atmospheric carbon to the soil are two nature-based solutions examined in this report that Marin must accelerate if it is to achieve its climate goals. Land application of locally produced compost

and biochar is a way to enhance productive capacity while also sequestering carbon. Avoiding emissions from wildfires and reducing emissions associated with transport and processing of biomass outside of Marin are important. In the end, this Study and the wider Marin Biomass Project is about moving carbon from places of higher risk – e.g., from forests where excessive wildfire fuel has accumulated or from landfills emitting potent greenhouse gases – to areas of higher reward, such as biomass-based products that can support local employment or agricultural soils that can support long-term cycles of stewardship and production.

This Study was developed with these ideas in mind, and the implementation of its recommendations are, ultimately, a step toward a more functional and regenerative biomass economy. The project explores and presents a platform for biomass recovery and utilization, which could support better coordination among public agencies in their biomass and climate policies and administration, while creating conditions that favor investment in biomass recovery and a more robust biomass economy for all.

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Appendices

Appendix A – Glossary

air curtain burners

Portable combustion devices used to dispose of woody materials.

anaerobic digestion

The decomposition of organic material in the absence of oxygen, which produces a methane-rich gas called biogas and a semi-solid called digestate. The digestate from wastewater treatment plants is typically referred to as “biosolids.”

biochar

A charcoal-like byproduct of pyrolysis that is valued as a soil amendment and that simultaneously provides carbon sequestration.

bioenergy

Renewable energy derived from plants and animal waste.

biogas

A gaseous material rich in methane that results from the anaerobic digestion process and can be used as a fuel.

biomass

Material derived from living organisms (i.e., plants, animals, and microorganisms).

bioresource

Biological material developed as a renewable energy or material resource source, typically through agriculture or forestry and refined using industrial technology.

biosolids

Solid organic matter recovered from a sewage treatment process, also referred to as digestate or sludge.

capital expenditure (CAPEX)

Funding needed to buy, maintain, or improve the required fixed assets. CAPEX for the pyrolysis system includes the cost of the conversion system, pre-conversion handling and processing equipment, feedstock and biochar storage equipment, site improvements, and construction of the plant.

carbon stock

An estimate of the amount of carbon stored in a defined area of the earth.

circular economy

An economic system that prioritizes reuse and regeneration of materials used in daily life.

co-digestion

The digestion of more than one type of material together. For example, wet anaerobic digesters require relatively wet feedstocks like sewage but can also accept and co-digest food scraps that are slurried into a consistency compatible for processing with sewage.

combustion

A thermochemical conversion process that relies on the direct incineration of biomass in the presence of oxygen.

compost

Product of managed, aerobic thermophilic biochemical decomposition process, suitable for beneficial application to soils. Its production and use can reduce greenhouse gas emissions and support soil carbon sequestration.

construction and demolition materials

Material byproducts from construction, renovation, demolition, or dismantling of buildings.

compressed natural gas (CNG)

A fuel gas mainly composed of methane, compressed to less than 1% of the volume it occupies at standard atmospheric pressure.

defensible space

Defensible space refers to the vegetation-managed buffer zone that makes a building or property more resistant to wildfire and increases the chances of it surviving a wildfire event. Creating defensible spaces can include clearing dead or flammable material, spacing and trimming vegetation, and creating noncombustible zones near the built environment that slow or stop wildfire spread, as well as create safe space for firefighters.

digestate

The semi-solid byproduct from anaerobic digestion. Digestate from anaerobic digestion of sewage at wastewater treatment operations is often called "biosolids."

dry ton

Material weight, exclusive of all moisture content.

essential element

Chemical elements vital for life (carbon, hydrogen, nitrogen, oxygen, phosphorus, sulfur) whose fluxes are studied in biogeochemistry.

feedstock

Biomass feedstocks are naturally renewable and low-value organic materials, such as agricultural and forestry discards, that serve as sources of organic carbon for the production of valuable compounds.

feedstock cost

Procurement costs and/or tipping fees for the biomass conversion facility by type of feedstock.

feedstock conversion rate

Percentage of product output yielded by a conversion process. This number is applied to the biomass input or “feedstock” flow rate to determine the product output flow rate.

fire breaks

A gap in vegetation that acts as a barrier to slow or stop the progress of wildfire.

fire-shed

A term for a geographical area that bounds an area through which a fire is likely to spread.

flux

The direction and rate of transfer — also known as the “flow” — of essential elements (like carbon) among compartments of the Earth, such as the oceans, atmosphere, land, and living organisms.

fuel break

A strip of land where vegetation has been removed for firefighting purposes.

fuel break installation

Fuel break installation involves strategically clearing or modifying vegetation in a strip of land to create a fire-resistant barrier.

fuel break maintenance

The regular inspection and management of areas where vegetation has been modified, conducted at three-to-five year intervals.

fuel reduction

Removal of materials that enable or fuel wildfire. Fuel reduction efforts can also break up

the path of fire spread on the landscape and decrease the intensity and severity of wildfire burning. Fuel reduction initiatives produce woody biomass, sometimes in the form of logs and mostly likely as wood chips if moved.

fuel treatment

Vegetation management on natural and working landscapes that reduces the amount of combustible biomass that can fuel wildfire. The purpose of fuel treatments is to decrease the availability of fuel and, in so doing, reduce the risk and intensity of wildfires. Fuel treatments also increasingly aim to manage the landscape so that its burn frequency is similar to historical average and supportive of California’s native ecology.

gasification

A thermochemical process that heats biomass to high temperatures (typically above 700°C) with a controlled amount of oxygen or steam.

GHG

Greenhouse gas (e.g., carbon dioxide, methane, nitrous oxide, and fluorinated gases) that trap heat in the atmosphere and create a warming effect essential for life but dangerous in excess.

graminoids

True grasses, sedges and rushes that have narrow upright leaves and reduced flowers and that often grows in tufts or clumps.

green materials

Materials generated from landscape management, parkland maintenance, and commercial and residential materials collection. Examples include leaves, grasses, branches, and other landscape trimmings that are designated organic materials in SB 1383. It may also include food residues when referring to materials from the green carts used in municipal material collection programs, including for residences, businesses, other buildings, open spaces, and sidewalks.

hand crew fuel treatments

Treatments that involve manual cutting , and lop and scatter and/or chipping of live trees and brush.

home hardening

Vegetation management and building features used to resist the intrusion of flames or embers projected by a wildland fire. It can be applied to new construction or for retrofitting an older home. Home hardening considers the relationship between a home and its

exposure to nearby combustible features such as vegetation, vehicles, accessory buildings, or even miscellaneous structures like a fence.

JPA

Joint Powers Authority.

ladder fuels

Live or dead vegetation that allows fire to climb from the ground level into the tree canopy.

land manager

Public land managers are stewards of an area that has been set aside for public purposes. Land management agencies take on the full stewardship responsibility of the land and any use or impact on the natural resources of that area.

life cycle analysis or life cycle assessment

A methodology for assessing impacts associated with all the stages of the life cycle of a product, process or service. Also known as “LCA” for short.

lop and scatter

Cutting and distribution on site of forest biomass generated during thinning and fuel reduction activities.

mastication

The process of using specialized machinery to grind and shred trees, branches, and other forest debris into smaller pieces at its place of origin. Mastication is often used in forest management and wildfire prevention efforts.

mechanical fuel treatment

Mechanical treatment refers to vegetation management involving heavy machinery.

metric ton

1,000 kilograms or 2,200 pounds.

milling

The process of cutting timber into usable wood products.

mixed wood

A combination of woody construction and demolition materials and wood chips from more recently cut vegetation. Overall assumed moisture content of 20%.

municipal solid waste

Materials that are not recycled or reused that are treated as wastes and sent to disposal.

nature-based solutions

Nature-based solutions use natural materials and ecosystem processes to mitigate the effects of climate change.

operational expenditure (OPEX)

Expenses required to operate the facility, such as labor, utilities, parts, maintenance, etc.

overstocked

Forestland or woodland with an excessive number of stems per acre (typically due to successful fire suppression). Overstocked conditions are considered a fire hazard.

potentially available

Biomass material available assuming no restrictions (environmental or physical constraints) to its movement or use.

practically available

Biomass material available after accounting for physical, economic, and regulatory constraints (e.g., road systems, topography, available equipment, CEQA).

pre-consumer food waste

Any food discarded before it reaches the end consumer, generated at various points in the food supply chain such as during farming, processing, distribution, and within commercial kitchens.

prescribed burning

A land management technique that involves intentionally setting fires under specific conditions to achieve specific ecological objectives.

prescribed grazing

Management of domestic livestock to achieve specific vegetation management objectives.

pyrolysis

Thermal decomposition of large molecules into smaller ones at elevated temperatures (typically between 400°F and 1,600°F) with little to no oxygen. The outputs of pyrolysis are a carbon-rich substance called “biochar” and a gaseous mixture, including a condensable fraction that upon cooling produces a pyrolysis oil .

regeneration

Actively restoring, renewing, and revitalizing natural and social systems to create positive and thriving conditions for people and the planet; balancing out human activities with natural cycling of essential elements to create long-term health and resilience.

renewable

Able to be reproduced by an ecological system on a human timescale.

resilience

the capacity to absorb system disturbances (like fires, floods, or pollution), maintain an essential structure, function, and identity and sustain vital services; bouncing back or adapting to change without collapsing into a completely different system state.

shaded fuel breaks

Landscape-level fuel treatment that not only reduces fuel, but can also change the potential spread of wildfire. Shaded fuel breaks involve thinning understory vegetation while maintaining a shading tree canopy sufficient to suppress understory regrowth.

shelterbelts

Woody agroforestry plantings that provide shade and shelter.

short ton

An imperial ton = 2,000 pounds.

supportive funding

Financial contribution with little or no expectation of a return.

syngas

Synthesis gas (syngas) results from gasification or pyrolysis, both of which are thermochemical processes that heat biomass to high temperatures (typically above 700°C) with a controlled amount of oxygen or steam. Syngas is a combination of primarily nitrogen gas (N₂) from air for gasification, carbon monoxide (CO), hydrogen gas (H₂), methane (CH₄), other higher hydrocarbons, and carbon dioxide (CO₂). Syngas can be used as a gaseous energy resource (fuel) or for other chemical synthesis (e.g., liquid hydrocarbons).

tipping fee

A charge levied per unit of material (see waste) received at a processing facility. It can be thought of as the cost per unit to “tip” the delivery truck and dump out the material.

vegetation management

Targeted control or removal of vegetation (overgrown or invasive plants, hazardous trees, weeds and other fireprone vegetation) to reduce the speed and intensity of fire and that improves safety for residents and first responders.

waste

A material, substance or byproduct discarded because it is seen as having little or no economic value.

wet ton

Material weight, inclusive of its moisture content.

wildland urban interface

Areas located between wilderness and developed land.

windbreaks

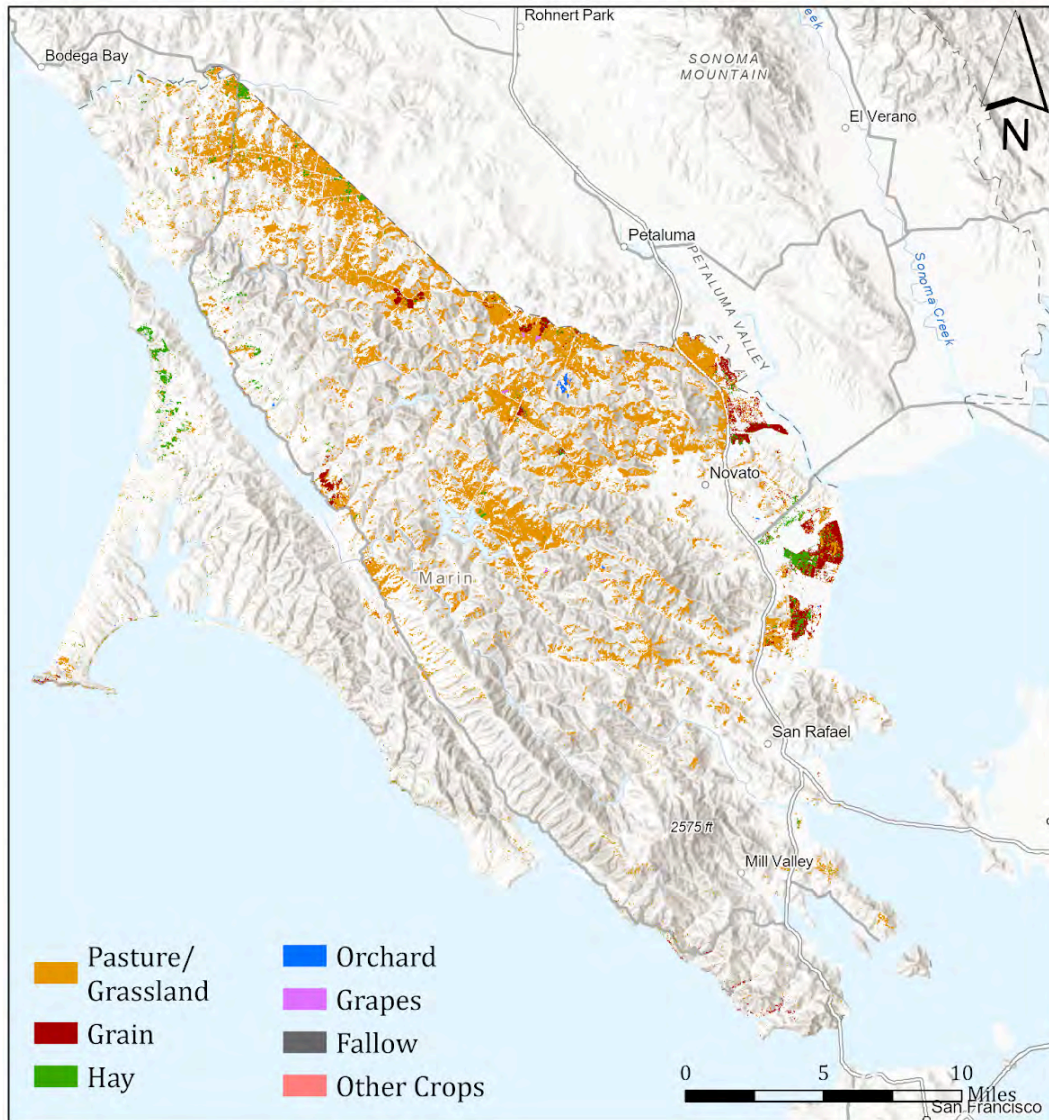
Woody agroforestry plantings that provide wind protection to downwind land area, as well as shade and shelter.

woody materials

High-lignin plant matter, such as logs, wood chips, and woody construction and demolition materials; biomass generated by wildfire prevention activities, roadway and power line maintenance, and countywide commerce and consumption.

Appendix B - Atlas of Marin County

Map 1: Commercial Crops



Marin County Biomass Utilization Study Commercial Crops


Spatial Informatics Group
Coordinate System: NAD83 California (Teale) Albers (Meters)

Map Date: 11-08-22
Source Data: 2021 USDA NASS Program

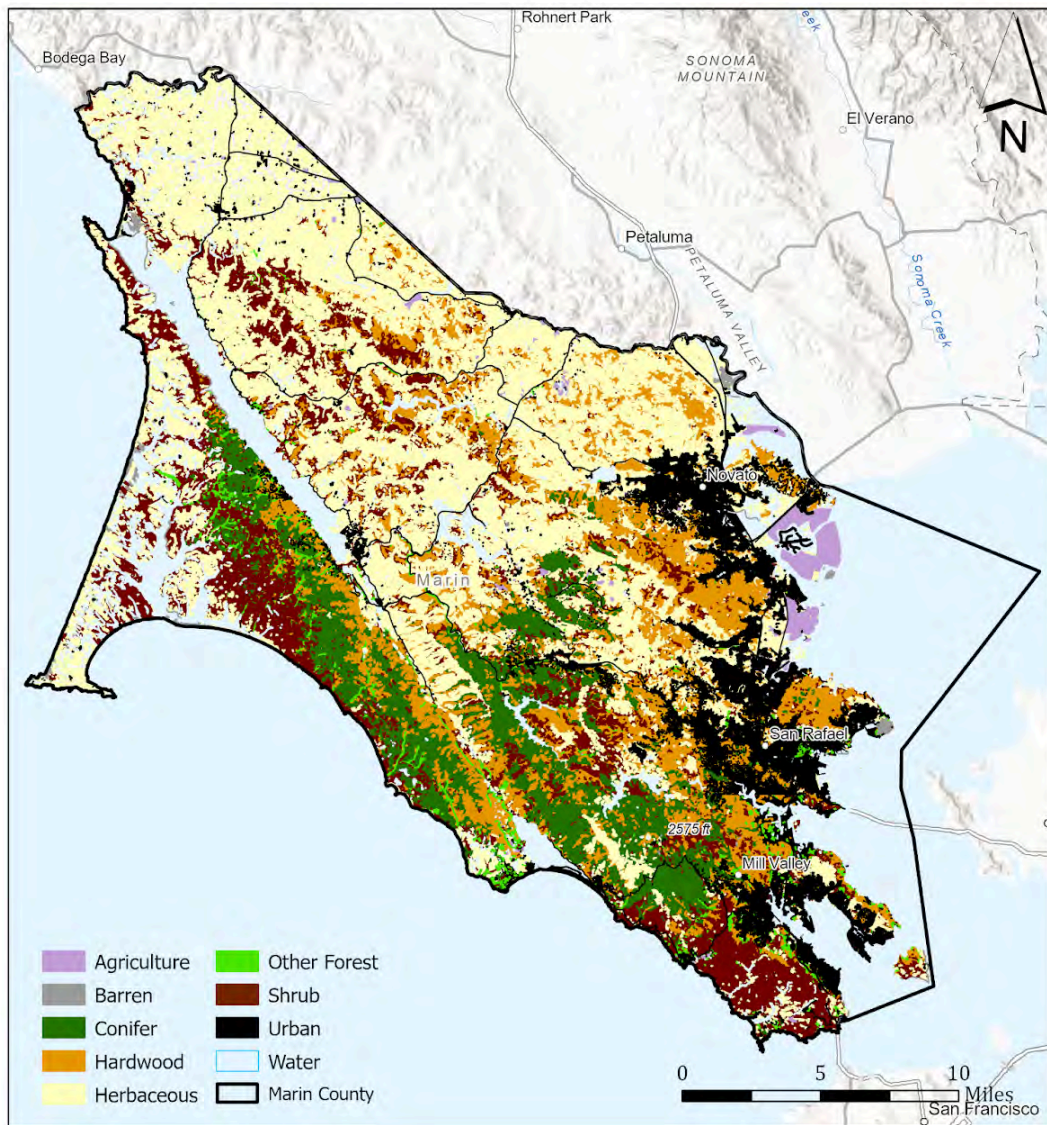
Map 2: County Overview



Marin County Biomass Utilization Study
County Overview


Spatial Informatics Group
Coordinate System: NAD83 California (Teale) Albers (Meters)

Map 3: Vegetation & Land Cover I

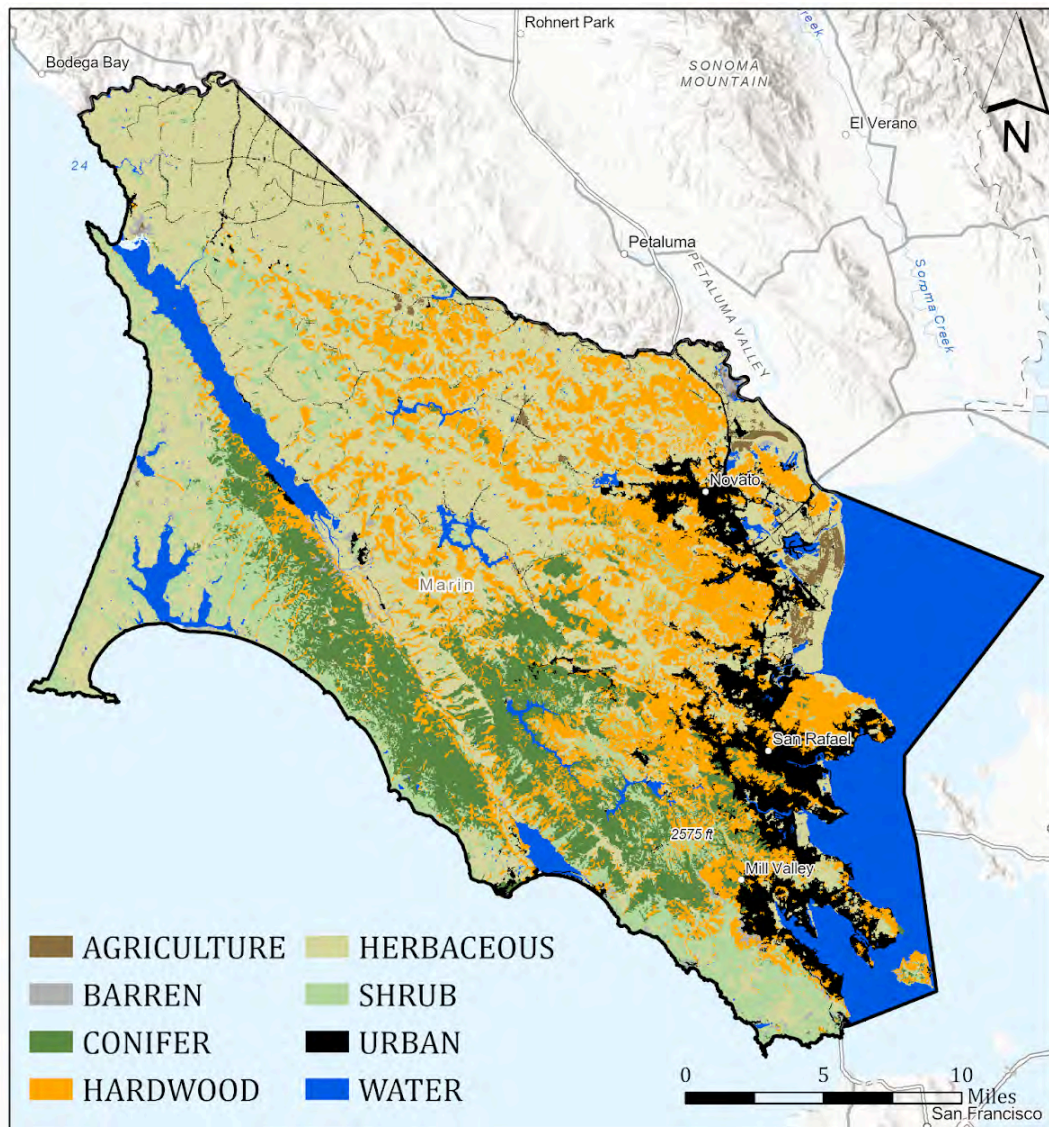


Marin County Biomass Utilization Study Vegetation & Land Cover

Spatial Informatics Group
 Coordinate System: NAD83 California (Teale) Albers (Meters)

Map Date: 11-08-22
 Source Data: Marin County Fine Scale Vegetation Map

Map 4: Vegetation & Land Cover II

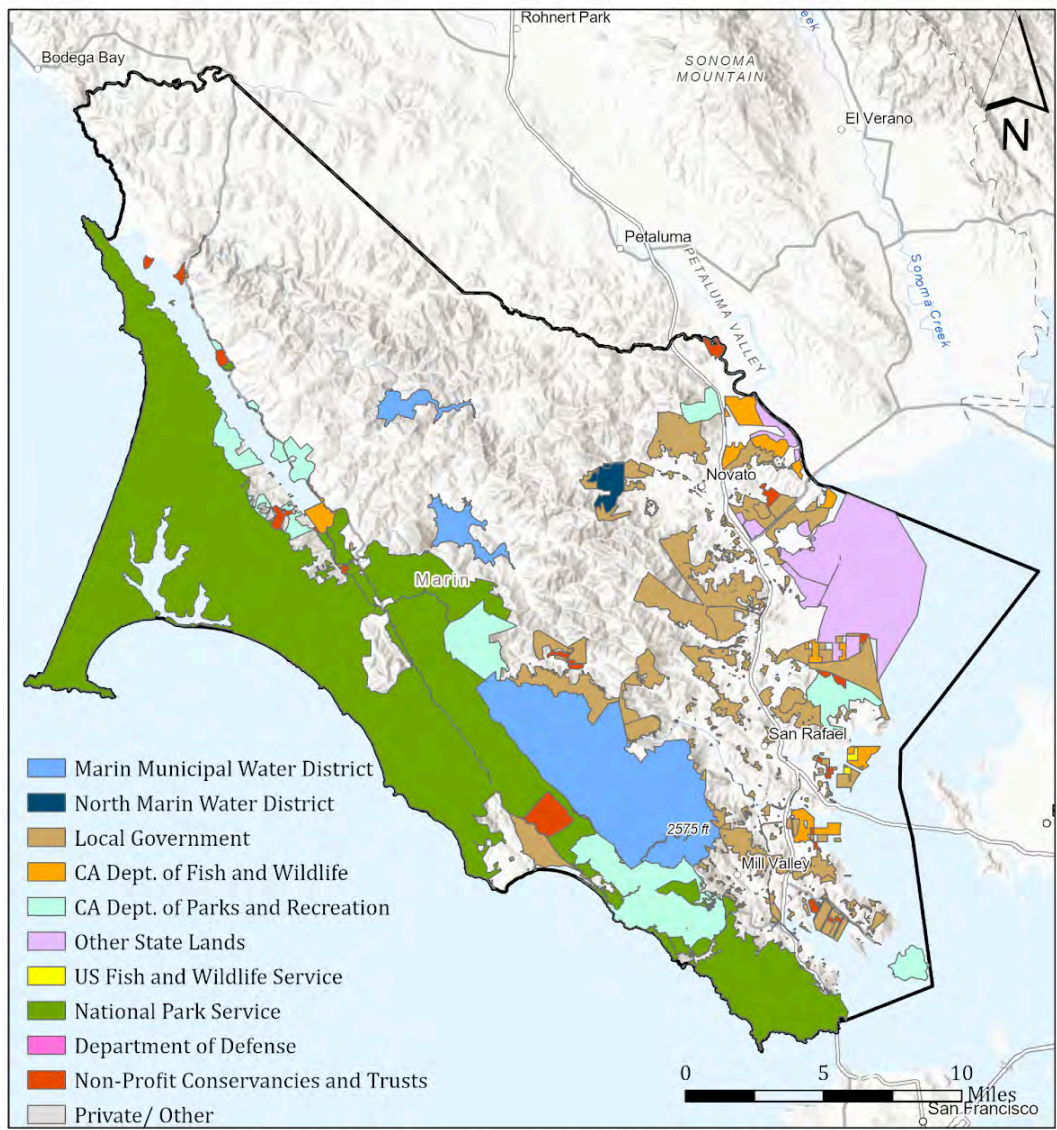


Marin County Biomass Utilization Study Vegetation & Land Cover


Spatial Informatics Group
Coordinate System: NAD83 California (Teale) Albers (Meters)

Map Date: 10-5-22
Source Data: FRAP Vegetation (FVEG15_1)

Map 5: Land Ownership

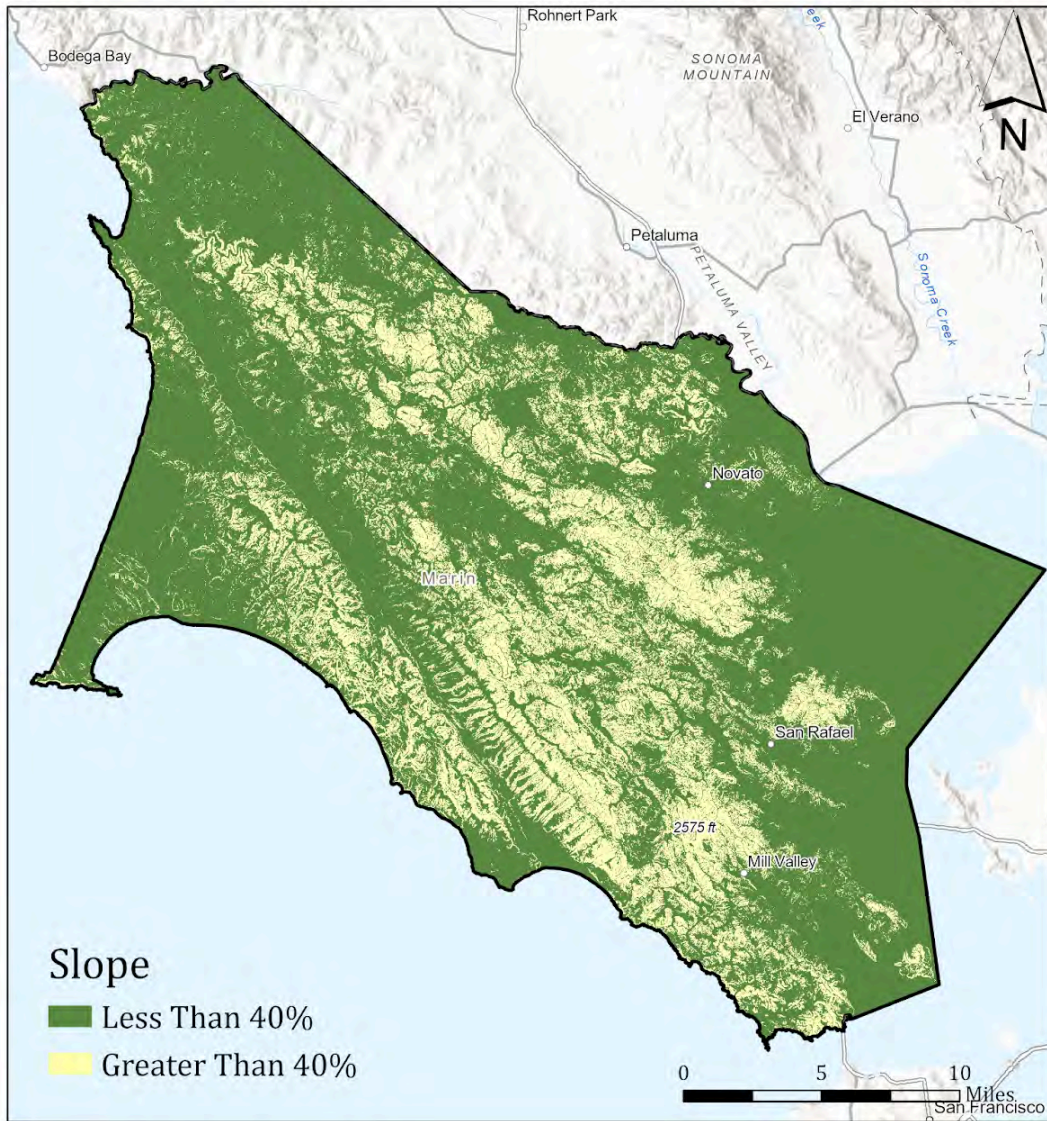


Marin County Biomass Utilization Study Land Ownership

Spatial Informatics Group
 Coordinate System: NAD83 California (Teale) Albers (Meters)

Map Date: 11-08-22
 Source Data: CA Multi-Source Land Ownership

Map 6: Topography



Marin County Biomass Utilization Study Topography

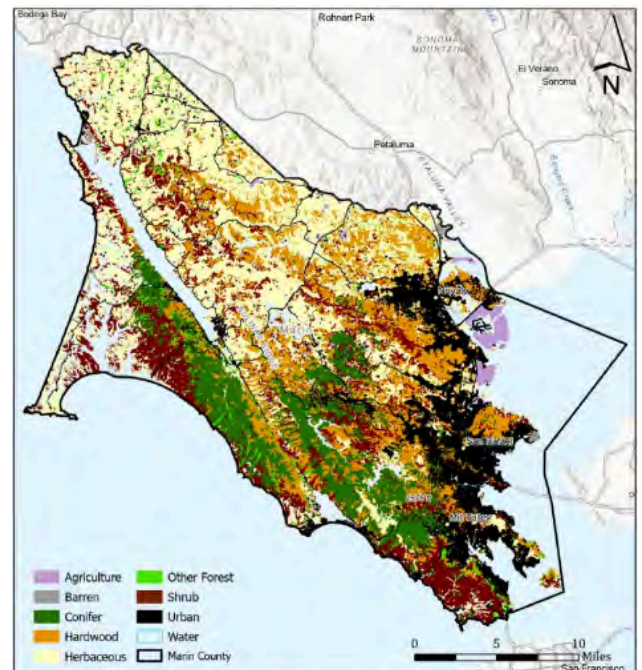
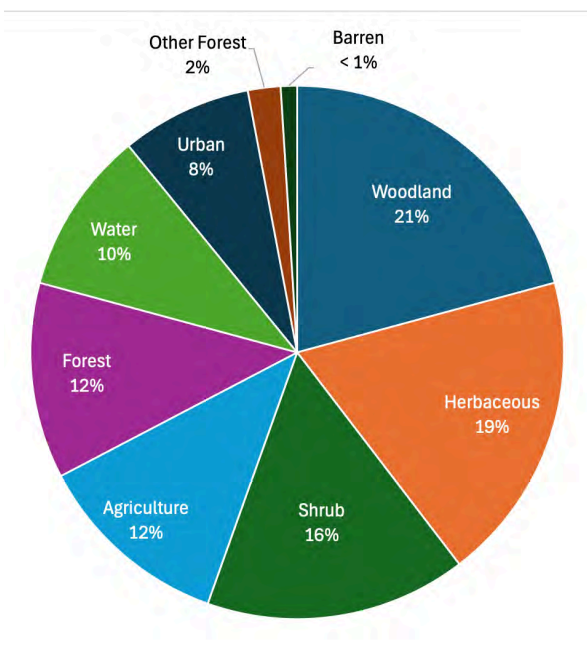

Spatial Informatics Group
Coordinate System: NAD83 California (Teale) Albers (Meters)

Map Date: 11-08-22
Source Data: 2020 USGS National Elevation Dataset (1/3 Arc Sec)

Appendix C. Land, Fuel Treatment, and Biomass Flow Data

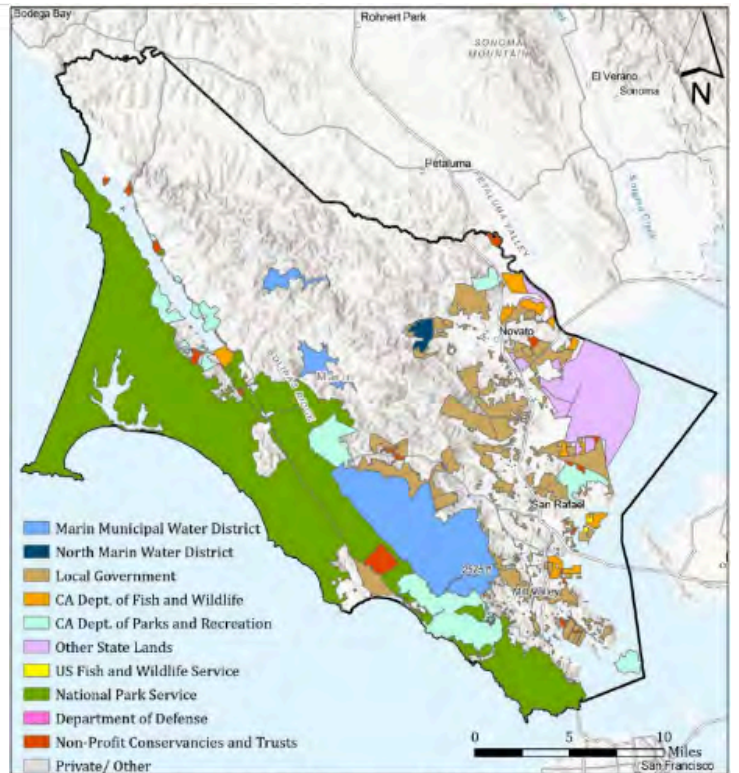
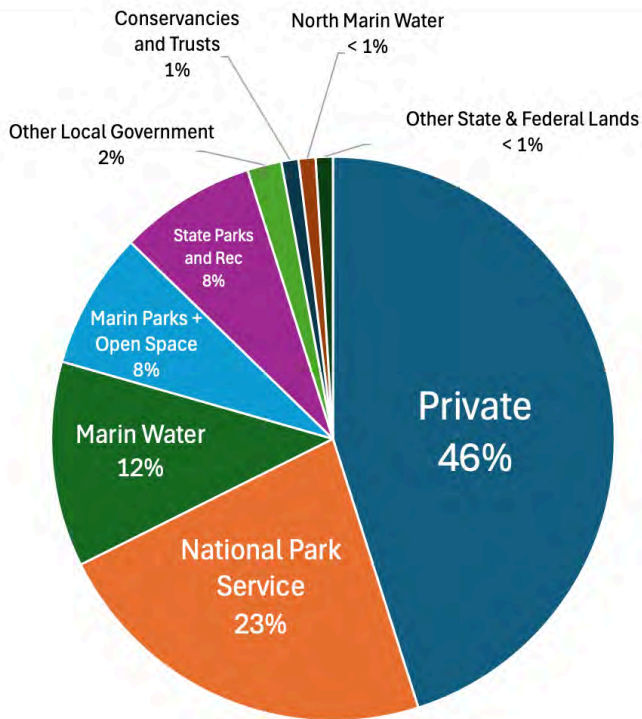
Land Cover in Marin

Land Cover	Acres	% of Total	Description
Woodland	72,775	21%	Land with an even distribution of overstory hardwood trees. In Marin these are primarily California bay, tanoak, live oak, and sycamore.
Herbaceous	66,484	19%	Land with vegetation that is non-woody, including grasses, graminoids, and broad-leaved herbaceous species.
Shrub	57,517	16%	Land dominated by small- to medium-sized perennial woody plants.
Agriculture	44,293	12%	Land used for cultivated crops, including pasturelands, orchards, and vineyards, that produce milk vegetables, fruits, nuts, grains, or hay.
Forest	44,006	12%	Land with an even distribution of overstory conifer trees. In Marin these are primarily redwood, douglas fir, and bishop pine.
Water	34,777	10%	
Metropolitan	27,254	8%	Land developed for human residence and commerce.
Other Forest	6,243	2%	Land with an even distribution of overstory trees classifiable as riparian forest, forest fragment, or non-native forest in Marin Fine Scale Vegetation Data Set. (Eucalyptus tree canopies are included in this category.)
Barren	1,355	< 1%	Land with little or no dominant vegetation.
Total	354,704	100%	



Forest and Woodland Ownership

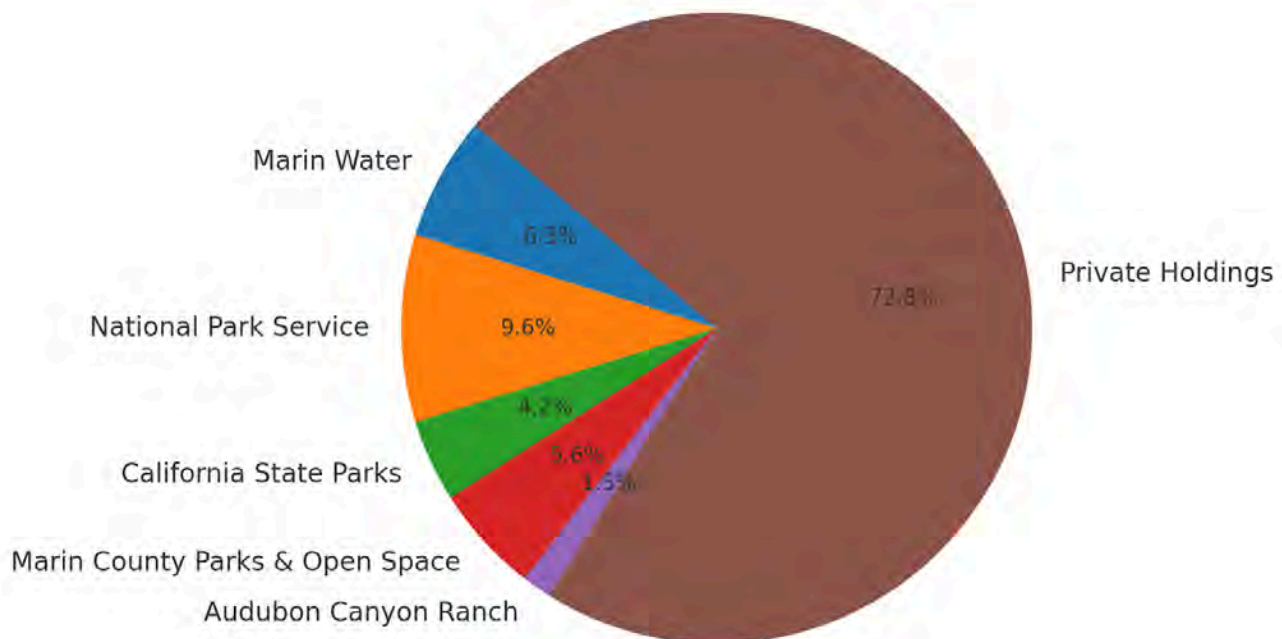
Ownership	Forest		Woodland		Total	
	Acres	%	Acres	%	Acres	%
Private	9,706	22%	44,070	61%	53,776	46%
National Park Service	18,059	41%	8,752	12%	26,811	23%
Marin Water	8,482	19%	5,869	8%	14,351	12%
Marin Parks + Open Space	1,863	4%	7,026	10%	8,889	8%
State Parks and Rec	4,984	11%	3,850	5%	8,834	8%
Other Local Government	146	<1%	2,411	3%	2,557	2%
Conservancies and Trusts	727	2%	413	1%	1,140	1%
North Marin Water	33	<1%	297	<1%	330	< 1%
Other State & Federal Lands	6	<1%	87	<1%	93	< 1%
Total	44,006	100%	72,775	100%	116,781	100%



Land Ownership in Marin

Ownership		
	Acres	%
Private	242,300	72.8
National Park Service	32,000	9.6
Marin Water	21,000	6.3
Marin Parks + Open Space	18,500	5.6
State Parks and Rec	14,000	4.2
Conservancies and Trusts	5,000	1.5
Total	332,800	100

Land Ownership in Marin County (Total: 332,800 acres)



Historic Fuel Reduction Activities

Land managers have confirmed that fuel reduction has been practiced to mitigate wildfires for many years, using chip and scatter or pile and burn, popular methods for disposing of woody biomass. Very little biomass is currently chipped and transported off site for disposal at a collection yard, transfer station, resource recovery yard, or landfill. The table below summarizes historical fuel reduction activity accomplishments (acres treated per year) by jurisdiction from 2018 through 2022.

Historical Fuel Reduction Activity

Land Manager	Acres Treated per Year					Annual Average
	2018	2019	2020	2021	2022	
Marin County Parks	33	33	0	30	30	25
Marin Water	0	56	109	161	213	108
MWPA (Greater Novato Shaded Fuel Break)	0	0	0	0	0	0
MWPA (Greater Ross Valley Shaded Fuel Break)	0	0	0	0	200	40
MWPA (other treatments, including roadside)	0	0	0	788	650	288
MWPA (maintenance of fuel treatments)	0	0	0	0	0	0
National Parks	25	25	25	25	25	25
State Parks	15	15	15	15	20	16
Other Public Land Owners or Managers	20	20	20	20	20	20
Other Private Land Owners	20	20	20	20	20	20
Totals	113	169	189	1,059	1,203	542

Planned Fuel Reduction Activity (Five-year Time Horizon)

Land Manager	Acres Treated per Year					Annual Average
	2023	2024	2025	2026	2027	
Marin County Parks	28	28	28	28	28	28
Marin Water	220	316	316	316	316	297
MWPA (Greater Novato Shaded Fuel Break)	425	425	425	425	425	425
MWPA (Greater Ross Valley Shaded Fuel Break)	200	200	100	0	0	120
MWPA (other treatments, including roadside)	600	400	300	200	100	320
MWPA (maintenance of fuel treatments)	100	300	500	600	700	440
National Parks	35	50	75	100	100	72
State Parks	30	30	40	40	40	36
Other Public Land Owners or Managers	20	30	50	50	50	40
Other Private Land Owners	20	20	20	20	20	20
Totals	1,678	1,799	1,854	1,779	1,779	1,778

Biomass Estimates for Forest and Woodland Landscapes

Estimated Biomass Removed and Flowing off Forest and Woodland Landscapes (wet short tons per year)

Land Owner or Landscape Manager	2023	2024	2025	2026	2027	Average
Marin County Parks	70	70	70	70	70	70
Marin Water	1,320	1,896	1,896	1,896	1,896	1,781
MWPA (Greater Novato Shaded Fuel Break)	797	797	797	797	797	797
MWPA (Greater Ross Valley Shaded Fuel Break)	336	336	168	0	0	168
MWPA (other treatments, including roadside)	1,008	672	504	336	168	538
MWPA (maintenance of fuel treatments)	60	180	300	360	420	264
National Parks	88	125	188	250	250	180
State Parks	75	75	100	100	100	90
Other Public Land Owners or Managers	50	75	125	125	125	100
Other Private Land Owners	50	50	50	50	50	50
Totals	3,854	4,276	4,198	3,984	3,876	4,038

Total Biomass Cut on Forest and Woodland Landscapes (wet short tons per year)

Land Owner or Landscape Manager	2023	2024	2025	2026	2027	Average
Marin County Parks	140	140	140	140	140	140
Marin Water	6,600	9,480	9,480	9,480	9,480	8,904
MWPA (Greater Novato Shaded Fuel Break)	1,190	1,190	1,190	1,190	1,190	1,190
MWPA (Greater Ross Valley Shaded Fuel Break)	560	560	280	0	0	280
MWPA (other treatments, including roadside)	1,680	1,120	840	560	280	896
MWPA (maintenance of fuel treatments)	100	300	500	600	700	440
National Parks	175	250	375	500	500	360
State Parks	150	150	200	200	200	180
Other Public Land Owners or Managers	100	150	250	250	250	200
Other Private Land Owners	100	100	100	100	100	100
Totals	10,795	13,440	13,355	13,020	12,840	12,690

Estimated Biomass Left Behind in Forests and Woodlands after Fuel Treatment (wet short tons per year)

Land Owner or Landscape Manager	2023	2024	2025	2026	2027	Average
Marin County Parks	70	70	70	70	70	70
Marin Water						
MWPA (Greater Novato Shaded Fuel Break)						
MWPA (Greater Ross Valley Shaded Fuel Break)						
MWPA (other treatments, including roadside)						
MWPA (maintenance of fuel treatments)						
National Parks						
State Parks						
Other Public Land Owners or Managers						
Other Private Land Owners						8,652
Totals	3,854	4,276	4,198	3,984	3,876	4,038

Biomass Characterization

The following biomass characterization is based on feedstock sample testing and is generally applicable and representative of biomass in Marin. In addition, recent publications provide indicative descriptions of organic feedstock physical properties. Physical property data were also sourced from the 2015 Assessment of Biomass Resources in California report as generated by the California Biomass Collaborative.

Physical Properties of Biomass

Feedstock Type	Moisture Content (Wet Basis)	Ash Content (Percent)	High Heat Value (Btu/Dry Pound)
Biosolids (sewage waste)	80	45	6,620
Chaparral	40	3	8,000
Construction/Demolition Wood	15	3	8,304
Dairy Cow Manure	88	40	7,308
Food	70	5	6,019
Forest Thinning and Slash	50	3	9,027
Leaves and Grass	60	4	6,449
Paper/Cardboard	10	5.3	7,653
Pruning and Tree Trimming	40	3.6	8,169

For more localized and current data, feedstock sampling and testing is needed. This includes contamination. All biomass in this table may have some form of contamination. For example, in the process of collection and processing some plastics and paper are a component of green materials, metal in the form of nails and screws are included with construction and demolition materials and dirt is invariably included with forest thinning and slash. Strategies to mitigate this contamination include hand sorting at the collection facility, transfer station or landfill, using large magnets to remove metal and diligent handling of forest residuals (small stems and limbs) to minimize dirt. In addition, public outreach and education will help minimize contamination of self hauled or green bin organics.

Seasonal Availability of Feedstocks

Feedstock Type	Availability	Comments
Forest and Woodland Biomass	August through January	Forest fuels reduction activities are conducted between August and January to accommodate northern spotted owls and other nesting birds. In addition, wet weather or windy conditions will cause operations to pause.
Food Waste, Green Waste and Tree Trimmings	Year Round	Communities produce food waste and tree trimmings on a year-round basis. Some slowdown over the Thanksgiving and Christmas/New Year holiday periods.
Construction and Demolition Wood	Year Round	Construction is typically conducted year-round. Some slowdown over the Thanksgiving and Christmas/New Year holiday periods.
PG&E Powerline Vegetation Management	Year Round	Tree service contractors working for PG&E conducting hazard tree removal and tree trimming operations typically work year-round. Some slowdown over the Thanksgiving and Christmas/New Year holiday periods.
Biosolids	Year Round	Stable all year round. Some increase during summer months due to uptick in visitors to Marin.
Commercial Food Waste	Year Round	Stable all year round. Some increase during summer months due to uptick in visitors to Marin.

Appendix D. Example Operators and Operations in Marin

Fuel Treatment Contractors

Clements Tree Service
Community Tree Service
Conservation Corp North Bay
Fahey Tree Service
Fire Foundry
Forster & Kroeger Landscape Maintenance
Great Tree Tenders
Mount Tam Crew
Small World Tree Company
The Tree Man
Wilhelm Tree Service
Wrights Tree Service

Biomass Receiving Yards

Bolinas Compost
Green Waste Recycling
Marin Resource Recovery Center
Redwood Landfill
West Marin Compost

Contract Material Haulers

Bay Cities Refuse Service
Green Hauling
Marin Sanitary Service
Mill Valley Refuse Service
Recology Sonoma Marin
Tamalpais Community Service District

Compost Operations

Bolinas Compost
West Marin Compost
WM EarthCare

Deconstruction Service Providers

Hurricane Hauling
GreenLynx
V's Demolition
The Reuse People

Reuse Facilities

Heritage Salvage Petaluma
Recycletown (Petaluma)
GreenLynx (Santa Rosa)
ReStore (Santa Rosa)
Urban Ore (Berkeley)
The Reuse People (Oakland)
Building Resources (San Francisco)

Appendix E. Evaluation of Utilization Pathways

Screening Criteria

Each of the pathways explored in Chapter 2 are evaluated here using eighteen qualitative attributes. These attributes are defined below and then used to screen and score each of the twenty-eight primary and secondary pathways.

Category 1: Inputs and Outputs

1. **Biomass Match.** The primary biomass categories – i.e., woody materials, green materials, food scraps, and digestate – are considered as potential inputs for the pathway. Pathways that could utilize multiple biomass types are given a positive score (2). Those with only a single input type receive a negative score (0).
2. **Primary Product(s).** Each conversion pathway can produce specific outputs, and the primary products are listed here. A readily salable product (i.e., a product that can be sold) receives a 2 rating. Pathways that do not generate a product receive a 1 rating. Pathways that generate a significant waste to be managed receive a 0 rating.

Category 2: Technological Factors

3. **Complexity.** Pathways can vary in the complexity of their technical design, construction, and operation. Conversion technologies that require more complex machines and more specialized operators are considered more difficult to achieve (at least initially) and receive a score of 0. Those considered less intensive receive a score of 2.
4. **Scalability.** Pathways may vary in how readily a pathway can change capacity change (+/-) to match Marin's expected biomass flows. Conversion pathways that offer easier scalability were given more positive values.

Category 3: GHG Emission Reduction and/or Sequestration Potential

5. **Transport from Origin.** Biomass moved by vehicle or rolling stock equipment (tractors, front end loaders, etc.) from its origin point is likely to emit GHGs. Conversion pathways with this transportation need are given a 0 rating.
6. **Processing.** This factor estimates the release of GHGs during the conversion process

of biomass inputs into products.

7. **Transportation to End Use.** Some products may be moved from the point of processing to end use by vehicles that emit GHGs. Some products, such as electricity, may be conveyed by transmission and distribution lines that do not directly emit GHGs. Products moved to markets without GHGs are given a 0 rating.
8. **Product Usage.** The usage of products may emit or sequester GHGs. Products with a lower or net negative carbon intensity are given a 2 rating. Products with a higher carbon intensity receive a 0 rating.

Category 4: Financial Viability

9. **CAPEX.** This factor considers the capital expense (CAPEX) of the conversion technology. A higher CAPEX receives 0 rating. A lower CAPEX receives a 2 rating.
10. **OPEX.** This factor considers the operating expense (OPEX) of the conversion technology. A higher OPEX receives a 0 rating. A lower OPEX receives a 2 rating.
11. **Potential Revenue.** The revenue from a conversion pathway is the basis for servicing debt or meeting investors' expected internal rate of return. A more robust estimated revenue receives a 2 rating. A less robust or less stable revenue stream receives a 0.
12. **Technological Readiness.** If a conversion pathway is well understood and more likely to be eligible for traditional financial instruments (i.e., more likely to be funded), it receives a 2 rating. Less mature technologies receive a 0 rating.

Category 5: Economic and Social Factors

13. **Job Creation.** A positive value indicates that the conversion pathways can lead to job creation with substantive wages and employee benefits.
14. **Societal Benefits.** Societal benefits encompass a variety of environmental, economic, and social benefits that the biomass utilization pathway can provide. For example, forest and woodland thinning in Marin County can assist with reducing catastrophic wildfire, which affects the health and safety of County residents. Food waste conversion to biomethane can help to address landfill diversion needs under state statutes and regulations. Conversion pathways that promote more significant societal benefits received a positive value.

Category 6: Environmental Factors

15. **Air Pollution.** Conversion technologies expected to emit more criteria air pollutants receive a negative value.
16. **Regulatory Status.** California statutes and regulations for waste conversion are complicated, particularly in cases where biomass waste is converted to heat, fuel, and/or electricity. Biomass that meets California Public Resources Code Section 40106 definitions for biomass conversion, such as the woody biomass and green waste (when separated from other solid wastes) can allow for these biomass wastes to be exempt from the more stringent MSW conversion statutes and regulations. Thus, pathways that meet the Section 40106 criteria generally received positive values. This attribute is related to, but distinct from, the air pollutant emissions attribute, although the pathways that produce higher emissions also may affect acceptance by the regulatory agencies.
17. **Public Perception.** Public perception evaluations were based on past experience with the deployment of the various utilization pathways, and take into account the air pollutant emissions and regulatory acceptance evaluations as well.

Category 7: Infrastructure Readiness

18. **Status of Installation(s).** This final criterion considers the extent of installation and operations already in or accessible to Marin. More installed capacity receives a 2 rating. No installed capacity receives a 0 rating.

Evaluation of Pathways

In this section each pathway is scored qualitatively as positive (score = 2), neutral (score = 1), or negative (score = 0) for each of the eighteen criteria above. The individual scores are summed to create an Overall Score for each pathway.

Each page in the remainder of this appendix screens and scores one of the pathways.

Pathway: **Prescribed Burning**
 Inputs: **woody materials, green materials**
 Outputs: **none**
 Capacity: **modest** (some occurring in Marin)

Category	Criteria	Score
Inputs and Outputs	Biomass Match (input)	0
	Primary Product (output)	0
Technological	Complexity	2
	Scalability	2
GHGs	Transport from origin	2
	Processing	2
	Transport to end use	1
	Product usage	1
Financial	Potential CAPEX	1
	Potential OPEX	0
	Potential revenue	0
	Technological readiness	2
Economic and Social	Job creation	1
	Societal benefits	1
Environmental	Air pollution	0
	Regulatory status	0
	Public perception	1
Infrastructure	Status of Installation(s)	0
OVERALL SCORE		16

Additional Notes

- Prescribed burning is a lower-cost approach to managing fuels on the landscape but produces no product output.
- Prescribed burning is a significant source of air pollution.

Pathway: **Piling and Burning**
 Inputs: **woody materials, green materials**
 Outputs: **none**
 Capacity: **significant** (regularly used by land managers in Marin)

Category	Criteria	Score
Inputs and Outputs	Biomass Match (input)	0
	Primary Product (output)	0
Technological	Complexity	2
	Scalability	2
GHGs	Transport from origin	2
	Processing	2
	Transport to end use	1
	Product usage	1
Financial	Potential CAPEX	1
	Potential OPEX	0
	Potential revenue	0
	Technological readiness	2
Economic and Social	Job creation	1
	Societal benefits	1
Environmental	Air pollution	0
	Regulatory status	0
	Public perception	1
Infrastructure	Status of Installation(s)	0
OVERALL SCORE		16

Additional Notes

- Piling and burning is a lower-cost approach to managing fuels on the landscape but produces no product output.
- Prescribed burning is a significant source of air pollution.

Pathway: **Air Curtain Burners**
 Inputs: **woody materials, green materials**
 Outputs: **biochar, potentially**
 Capacity: **somewhat significant** (some available in the region)

Category	Criteria	Score
Inputs and Outputs	Biomass Match (input)	0
	Primary Product (output)	0
Technological	Complexity	1
	Scalability	2
GHGs	Transport from origin	2
	Processing	2
	Transport to end use	2
	Product usage	1
Financial	Potential CAPEX	1
	Potential OPEX	0
	Potential revenue	2
	Technological readiness	1
Economic and Social	Job creation	1
	Societal benefits	1
Environmental	Air pollution	0
	Regulatory status	0
	Public perception	1
Infrastructure	Status of Installation(s)	0
OVERALL SCORE		17

Additional Notes

- Air curtain burners are available in the region, but none are known to be deployed in Marin.
- Air curtain burners that do not produce biochar are essentially a disposal option for wildfire reduction thinnings.

Pathway: **Mastication**
 Inputs: **woody materials**
 Outputs: **mulch** (non-merchantable)
 Capacity: **not significant** (little evidence currently occurring in Marin)

Category	Criteria	Score
Inputs and Outputs	Biomass Match (input)	0
	Primary Product (output)	0
Technological	Complexity	2
	Scalability	2
GHGs	Transport from origin	2
	Processing	0
	Transport to end use	1
	Product usage	1
Financial	Potential CAPEX	1
	Potential OPEX	0
	Potential revenue	0
	Technological readiness	2
Economic and Social	Job creation	1
	Societal benefits	1
Environmental	Air pollution	2
	Regulatory status	2
	Public perception	1
Infrastructure	Status of Installation(s)	0
OVERALL SCORE		18

Pathway: **Broadcast Chipping**
 Inputs: **woody materials**
 Outputs: **mulch** (non-merchantable)
 Capacity: **somewhat significant** (currently occurring in Marin)

Category	Criteria	Score
Inputs and Outputs	Biomass Match (input)	0
	Primary Product (output)	0
Technological	Complexity	2
	Scalability	2
GHGs	Transport from origin	2
	Processing	0
	Transport to end use	1
	Product usage	1
Financial	Potential CAPEX	1
	Potential OPEX	0
	Potential revenue	0
	Technological readiness	2
Economic and Social	Job creation	1
	Societal benefits	1
Environmental	Air pollution	2
	Regulatory status	2
	Public perception	1
Infrastructure	Status of Installation(s)	1
OVERALL SCORE		19

Pathway: **Prescribed Grazing**
 Inputs: **woody materials, green materials**
 Outputs: **none** (unless you consider the goats)
 Capacity: **not significant**

Category	Criteria	Score
Inputs and Outputs	Biomass Match (input)	0
	Primary Product (output)	0
Technological	Complexity	2
	Scalability	2
GHGs	Transport from origin	2
	Processing	2
	Transport to end use	1
	Product usage	1
Financial	Potential CAPEX	1
	Potential OPEX	0
	Potential revenue	0
	Technological readiness	1
Economic and Social	Job creation	1
	Societal benefits	1
Environmental	Air pollution	2
	Regulatory status	2
	Public perception	2
Infrastructure	Status of Installation(s)	0
OVERALL SCORE		20

Pathway: **Baling**
 Inputs: **woody biomass**
 Outputs: **semi-compacted woody materials**
 Capacity: **not significant** (not currently happening in Marin)

Category	Criteria	Score
Inputs and Outputs	Biomass Match (input)	0
	Primary Product (output)	0
Technological	Complexity	1
	Scalability	2
GHGs	Transport from origin	0
	Processing	0
	Transport to end use	0
	Product usage	2
Financial	Potential CAPEX	2
	Potential OPEX	2
	Potential revenue	0
	Technological readiness	2
Economic and Social	Job creation	1
	Societal benefits	1
Environmental	Air pollution	2
	Regulatory status	2
	Public perception	2
Infrastructure	Status of Installation(s)	0
OVERALL SCORE		19

Pathway: **Briquetting**
 Inputs: **woody materials**
 Outputs: **solid fuel** for cooking and space heating
 Capacity: **not significant** (no infrastructure in or near Marin)

Category	Criteria	Score
Inputs and Outputs	Biomass Match (input)	0
	Primary Product (output)	0
Technological	Complexity	1
	Scalability	2
GHGs	Transport from origin	0
	Processing	0
	Transport to end use	0
	Product usage	2
Financial	Potential CAPEX	2
	Potential OPEX	2
	Potential revenue	0
	Technological readiness	2
Economic and Social	Job creation	1
	Societal benefits	1
Environmental	Air pollution	2
	Regulatory status	0
	Public perception	1
Infrastructure	Status of Installation(s)	0
OVERALL SCORE		16

Additional Notes

- Additional rules limiting or prohibiting combustion of woody materials are likely in the Bay Area Air Quality Management District (BAAQMD) and other air districts in California.

Pathway: **Pelletization**
 Inputs: **woody materials**
 Outputs: **solid fuel** for cooking and space heating
 Capacity: **not significant** (no infrastructure in or near Marin)

Category	Criteria	Score
Inputs and Outputs	Biomass Match (input)	0
	Primary Product (output)	0
Technological	Complexity	1
	Scalability	2
GHGs	Transport from origin	0
	Processing	0
	Transport to end use	0
	Product usage	2
Financial	Potential CAPEX	2
	Potential OPEX	2
	Potential revenue	0
	Technological readiness	2
Economic and Social	Job creation	1
	Societal benefits	1
Environmental	Air pollution	2
	Regulatory status	0
	Public perception	1
Infrastructure	Status of Installation(s)	0
OVERALL SCORE		16

Additional Notes

- Additional rules limiting or prohibiting combustion of woody materials are likely in the Bay Area Air Quality Management District (BAAQMD) and other air districts in California.
- There is a growing market for wood pellets to grill or smoke meat and other foods.

Pathway: **Firewood Production**
 Inputs: **woody biomass**
 Outputs: **heat**
 Capacity: **somewhat significant**

Category	Criteria	Score
Inputs and Outputs	Biomass Match (input)	0
	Primary Product (output)	1
Technological	Complexity	2
	Scalability	2
GHGs	Transport from origin	0
	Processing	0
	Transport to end use	0
	Product usage	1
Financial	Potential CAPEX	2
	Potential OPEX	2
	Potential revenue	1
	Technological readiness	2
Economic and Social	Job creation	0
	Societal benefits	1
Environmental	Air pollution	0
	Regulatory status	0
	Public perception	0
Infrastructure	Status of Installation(s)	2
OVERALL SCORE		16

Additional Notes

- Marin Firewood sells oak, almond, and walnut firewood sourced from the Central Valley. Firewood is also produced at the Marin Resource Recovery Center and various landscape contractors in Marin County. The total amount of firewood produced is not recorded or known.
- Similar to briquettes and pellets, rules are likely to limit or prohibit combustion of woody biomass for heating residential and commercial units.

Pathway: **Post and Pole Production**
 Inputs: **logs**
 Outputs: **fencing materials, tree stakes**
 Capacity: **not significant** (not occurring in or around Marin)

Category	Criteria	Score
Inputs and Outputs	Biomass Match (input)	0
	Primary Product (output)	1
Technological	Complexity	2
	Scalability	2
GHGs	Transport from origin	0
	Processing	0
	Transport to end use	0
	Product usage	1
Financial	Potential CAPEX	1
	Potential OPEX	1
	Potential revenue	1
	Technological readiness	2
Economic and Social	Job creation	1
	Societal benefits	1
Environmental	Air pollution	2
	Regulatory status	2
	Public perception	2
Infrastructure	Status of Installation(s)	0
OVERALL SCORE		19

Additional Notes

- Biomass materials in Marin are generally not conducive to making posts and poles.

Pathway: **Small-scale Milling**
 Inputs: **woody materials, generally logs**
 Outputs: **artisanal slabs, dimensional lumber**
 Capacity: **somewhat significant** (suspended small-scale mill in west Marin)

Category	Criteria	Score
Inputs and Outputs	Biomass Match (input)	0
	Primary Product (output)	1
Technological	Complexity	2
	Scalability	2
GHGs	Transport from origin	0
	Processing	2
	Transport to end use	0
	Product usage	1
Financial	Potential CAPEX	2
	Potential OPEX	2
	Potential revenue	1
	Technological readiness	2
Economic and Social	Job creation	0
	Societal benefits	1
Environmental	Air pollution	1
	Regulatory status	1
	Public perception	1
Infrastructure	Status of Installation(s)	2
OVERALL SCORE		21

Additional Notes

- Saw logs of commercial value are limited in Marin.
- Other than the small mills in west Marin, there are no other lumber operations in Marin.

Pathway: **Large-scale Milling**
 Inputs: **logs**
 Outputs: **dimensional lumber, other millwork**
 Capacity: **not significant** (no infrastructure in or near Marin)

Category	Criteria	Score
Inputs and Outputs	Biomass Match (input)	0
	Primary Product (output)	1
Technological	Complexity	2
	Scalability	2
GHGs	Transport from origin	0
	Processing	1
	Transport to end use	0
	Product usage	1
Financial	Potential CAPEX	1
	Potential OPEX	1
	Potential revenue	1
	Technological readiness	2
Economic and Social	Job creation	1
	Societal benefits	1
Environmental	Air pollution	1
	Regulatory status	1
	Public perception	1
Infrastructure	Status of Installation(s)	0
OVERALL SCORE		17

Additional Notes

- Very little merchantable timber is available in Marin — far too little for the economy of scale needed to support a larger mill.

Pathway: **Particle Board Manufacturing**
 Inputs: **woody materials**
 Outputs: **particle board or similar composite wood product**
 Capacity: **not significant** (no infrastructure in or around Marin)

Category	Criteria	Score
Inputs and Outputs	Biomass Match (input)	0
	Primary Product (output)	1
Technological	Complexity	1
	Scalability	2
GHGs	Transport from origin	0
	Processing	0
	Transport to end use	0
	Product usage	2
Financial	Potential CAPEX	0
	Potential OPEX	0
	Potential revenue	1
	Technological readiness	1
Economic and Social	Job creation	1
	Societal benefits	1
Environmental	Air pollution	2
	Regulatory status	2
	Public perception	2
Infrastructure	Status of Installation(s)	0
OVERALL SCORE		16

Pathway: **Mass Timber Production**
 Inputs: **woody biomass**
 Outputs: **structural panels**
 Capacity: **not significant** (no infrastructure in or around Marin)

Category	Criteria	Score
Inputs and Outputs	Biomass Match (input)	0
	Primary Product (output)	1
Technological	Complexity	1
	Scalability	2
GHGs	Transport from origin	0
	Processing	0
	Transport to end use	0
	Product usage	2
Financial	Potential CAPEX	0
	Potential OPEX	0
	Potential revenue	1
	Technological readiness	1
Economic and Social	Job creation	1
	Societal benefits	1
Environmental	Air pollution	2
	Regulatory status	2
	Public perception	2
Infrastructure	Status of Installation(s)	0
OVERALL SCORE		16

Additional Notes

- Entry costs into mass timber manufacturing are high.
- Biomass materials in Marin are generally not conducive to this type of wood product.

Pathway: **Reclamation and Reuse**
 Inputs: **woody biomass**
 Outputs: **recovered lumber, wood products, and wood fiber**
 Capacity: **moderate** (some infrastructure in or around Marin)

Category	Criteria	Score
Inputs and Outputs	Biomass Match (input)	1
	Primary Product (output)	1
Technological	Complexity	1
	Scalability	1
GHGs	Transport from origin	1
	Processing	1
	Transport to end use	1
	Product usage	2
Financial	Potential CAPEX	1
	Potential OPEX	0
	Potential revenue	1
	Technological readiness	1
Economic and Social	Job creation	1
	Societal benefits	2
Environmental	Air pollution	2
	Regulatory status	2
	Public perception	1
Infrastructure	Status of Installation(s)	1
OVERALL SCORE		21

Additional Notes

- Marin’s reclamation sector is modest but better developed than elsewhere.

Pathway: **Composting**
 Inputs: **green materials, food scraps, some woody materials**
 Outputs: **compost**
 Capacity: **significant** (both in and near Marin)

Category	Criteria	Score
Inputs and Outputs	Biomass Match (input)	2
	Primary Product (output)	2
Technological	Complexity	0
	Scalability	0
GHGs	Transport from origin	0
	Processing	2
	Transport to end use	2
	Product usage	2
Financial	Potential CAPEX	2
	Potential OPEX	2
	Potential revenue	2
	Technological readiness	2
Economic and Social	Job creation	2
	Societal benefits	2
Environmental	Air pollution	1
	Regulatory status	2
	Public perception	2
Infrastructure	Status of Installation(s)	2
OVERALL SCORE		29

Additional Notes

- Composting is used to process most green materials in Marin.
- There are currently three composting facilities in Marin and additional facilities near Marin.

Pathway: **Wet Anaerobic Digestion**
 Inputs: **sewage, food scraps, manure**
 Outputs: **biogas, digestate**
 Capacity: **significant** (additional capacity at Marin’s wastewater treatment plants)

Category	Criteria	Score
Inputs and Outputs	Biomass Match (input)	1
	Primary Product (output)	1
Technological	Complexity	0
	Scalability	1
GHGs	Transport from origin	0
	Processing	2
	Transport to end use	1
	Product usage	1
Financial	Potential CAPEX	1
	Potential OPEX	1
	Potential revenue	2
	Technological readiness	2
Economic and Social	Job creation	1
	Societal benefits	2
Environmental	Air pollution	1
	Regulatory status	2
	Public perception	2
Infrastructure	Status of Installation(s)	2
OVERALL SCORE		23

Additional Notes

- Wet anaerobic digestion of food scraps with sewage at a wastewater treatment plant is often called “co-digestion.”
- Currently, only Central Marin Sanitary Agency (CMSA) co-digests food scraps with sewage.

Pathway: **Dry Anaerobic Digestion**
 Inputs: **woody materials, green materials, food scraps**
 Outputs: **biogas, digestate**
 Capacity: **not significant** (closest facility is in Napa County)

Category	Criteria	Score
Inputs and Outputs	Biomass Match (input)	1
	Primary Product (output)	2
Technological	Complexity	0
	Scalability	2
GHGs	Transport from origin	0
	Processing	2
	Transport to end use	1
	Product usage	1
Financial	Potential CAPEX	0
	Potential OPEX	0
	Potential revenue	2
	Technological readiness	2
Economic and Social	Job creation	1
	Societal benefits	2
Environmental	Air pollution	1
	Regulatory status	2
	Public perception	2
Infrastructure	Status of Installation(s)	0
OVERALL SCORE		21

Additional Notes

- One benefit of dry anaerobic digestion is its readier ability to process woody materials.

Pathway: **Gasification**
 Inputs: **woody materials, some green materials**
 Outputs: **syngas, some biochar**
 Capacity: **somewhat significant** (no infrastructure in or around Marin)

Category	Criteria	Score
Inputs and Outputs	Biomass Match (input)	2
	Primary Product (output)	1
Technological	Complexity	1
	Scalability	1
GHGs	Transport from origin	0
	Processing	1
	Transport to end use	2
	Product usage	2
Financial	Potential CAPEX	1
	Potential OPEX	1
	Potential revenue	2
	Technological readiness	2
Economic and Social	Job creation	1
	Societal benefits	1
Environmental	Air pollution	1
	Regulatory status	1
	Public perception	1
Infrastructure	Status of Installation(s)	0
OVERALL SCORE		21

Additional Notes

- Marin Sanitary Service has conducted a feasibility study and initial design for a 2.0-Megawatt facility that could gasify construction and demolition materials and generate electricity from it. However, the capital costs, operational risks, and market uncertainties have slowed forward momentum for this project.

Pathway: **Pyrolysis**
 Inputs: **woody materials, green materials, digestate**
 Outputs: **biochar**, some bio-oil and syngas
 Capacity: **not significant** (although facility being developed in Napa County)

Category	Criteria	Score
Inputs and Outputs	Biomass Match (input)	2
	Primary Product (output)	2
Technological	Complexity	1
	Scalability	0
GHGs	Transport from origin	1
	Processing	1
	Transport to end use	2
	Product usage	2
Financial	Potential CAPEX	1
	Potential OPEX	1
	Potential revenue	1
	Technological readiness	2
Economic and Social	Job creation	1
	Societal benefits	2
Environmental	Air pollution	1
	Regulatory status	1
	Public perception	1
Infrastructure	Status of Installation(s)	1
OVERALL SCORE		23

Additional Notes

- Sonoma Ecology Center is working with Napa Recycling in Napa, CA to develop a pyrolysis system. This system is operational but still undergoing permitting.

Pathway: **Hydrogen Production**
 Inputs: **woody materials, green materials, food scraps**
 Outputs: **green hydrogen**
 Capacity: **not significant** (no infrastructure in or near Marin)

Category	Criteria	Score
Inputs and Outputs	Biomass Match (input)	2
	Primary Product (output)	1
Technological	Complexity	0
	Scalability	0
GHGs	Transport from origin	0
	Processing	2
	Transport to end use	1
	Product usage	2
Financial	Potential CAPEX	0
	Potential OPEX	0
	Potential revenue	2
	Technological readiness	0
Economic and Social	Job creation	1
	Societal benefits	2
Environmental	Air pollution	2
	Regulatory status	1
	Public perception	1
Infrastructure	Status of Installation(s)	0
OVERALL SCORE		17

Additional Notes

- While there is no biomass-based hydrogen production in or near Marin yet, a facility being developed by Raven SR is being developed in Richmond, CA.
- Hydrogen is attractive as a carrier of potentially renewable energy, and considerable State and Federal funding has been devoted to its development.

Pathway: **Renewable Natural Gas Production**
 Inputs: **woody materials, green materials**
 Outputs: **biomethane**
 Capacity: **not significant** (no infrastructure in or around Marin)

Category	Criteria	Score
Inputs and Outputs	Biomass Match (input)	2
	Primary Product (output)	1
Technological	Complexity	0
	Scalability	0
GHGs	Transport from origin	0
	Processing	2
	Transport to end use	0
	Product usage	2
Financial	Potential CAPEX	0
	Potential OPEX	0
	Potential revenue	2
	Technological readiness	0
Economic and Social	Job creation	2
	Societal benefits	2
Environmental	Air pollution	2
	Regulatory status	1
	Public perception	1
Infrastructure	Status of Installation(s)	0
OVERALL SCORE		17

Additional Notes

- Renewable natural gas is sometimes called “biomethane.”
- Renewable natural gas production likely needs a larger facility due to economies of scale. There are technology providers, however, who are actively working to develop cost-competitive production systems at smaller scales.

Pathway: **Biofuel Production**
 Inputs: **woody materials, green materials**
 Outputs: **renewable transportation fuels**
 Capacity: **not significant** (no infrastructure in or near Marin)

Category	Criteria	Score
Inputs and Outputs	Biomass Match (input)	2
	Primary Product (output)	1
Technological	Complexity	0
	Scalability	0
GHGs	Transport from origin	0
	Processing	2
	Transport to end use	1
	Product usage	2
Financial	Potential CAPEX	0
	Potential OPEX	0
	Potential revenue	2
	Technological readiness	1
Economic and Social	Job creation	2
	Societal benefits	2
Environmental	Air pollution	2
	Regulatory status	1
	Public perception	1
Infrastructure	Status of Installation(s)	0
OVERALL SCORE		19

Additional Notes

- Liquid biofuels production generally requires larger facilities for successful economics.

Pathway: **Electricity Generation**
 Inputs: **syngas or biogas**
 Outputs: **electricity**
 Capacity: **somewhat significant**

Category	Criteria	Score
Inputs and Outputs	Biomass Match (input)	2
	Primary Product (output)	1
Technological	Complexity	1
	Scalability	2
GHGs	Transport from origin	1
	Processing	1
	Transport to end use	1
	Product usage	1
Financial	Potential CAPEX	1
	Potential OPEX	1
	Potential revenue	1
	Technological readiness	2
Economic and Social	Job creation	1
	Societal benefits	1
Environmental	Air pollution	1
	Regulatory status	1
	Public perception	1
Infrastructure	Status of Installation(s)	2
OVERALL SCORE		22

Additional Notes

- Central Marin Sanitary Service currently burns the biogas from its wet anaerobic digestion system in an engine that is used to produce electricity.
- Combustion of syngas is similarly possible in Marin and is part of the design for gasification facilities being considered.

Pathway: **Biochar Production**
 Inputs: **woody materials, green materials**
 Outputs: **biochar**
 Capacity: **not significant** (no infrastructure in or near Marin)

Category	Criteria	Score
Inputs and Outputs	Biomass Match (input)	2
	Primary Product (output)	1
Technological	Complexity	1
	Scalability	2
GHGs	Transport from origin	0
	Processing	2
	Transport to end use	1
	Product usage	2
Financial	Potential CAPEX	1
	Potential OPEX	2
	Potential revenue	2
	Technological readiness	2
Economic and Social	Job creation	2
	Societal benefits	2
Environmental	Air pollution	2
	Regulatory status	1
	Public perception	1
Infrastructure	Status of Installation(s)	0
OVERALL SCORE		26

Additional Notes

- Biochar is currently imported into Marin. For example, West Marin Compost imports biochar for some of its compost blends.

Pathway: **District Heating**
 Inputs: **woody materials, green materials**
 Outputs: **heat**
 Capacity: **not significant** (i.e., no significant infrastructure or operations identified)

Category	Criteria	Score
Inputs and Outputs	Biomass Match (input)	2
	Primary Product (output)	2
Technological	Complexity	2
	Scalability	1
GHGs	Transport from origin	0
	Processing	2
	Transport to end use	1
	Product usage	2
Financial	Potential CAPEX	2
	Potential OPEX	2
	Potential revenue	0
	Technological readiness	1
Economic and Social	Job creation	0
	Societal benefits	2
Environmental	Air pollution	0
	Regulatory status	1
	Public perception	0
Infrastructure	Status of Installation(s)	0
OVERALL SCORE		20

Additional Notes

- Because of its temperate climate and relatively low building density, Marin is not particularly conducive to district heating.

Pathway: **Combined Heat and Power**
 Inputs: **woody materials, green materials**
 Outputs: **electricity, heat**
 Capacity: **not significant** (no infrastructure in or near Marin for this pathway)

Category	Criteria	Score
Inputs and Outputs	Biomass Match (input)	2
	Primary Product (output)	1
Technological	Complexity	1
	Scalability	1
GHGs	Transport from origin	0
	Processing	1
	Transport to end use	2
	Product usage	2
Financial	Potential CAPEX	1
	Potential OPEX	1
	Potential revenue	2
	Technological readiness	2
Economic and Social	Job creation	1
	Societal benefits	1
Environmental	Air pollution	1
	Regulatory status	1
	Public perception	0
Infrastructure	Status of Installation(s)	0
OVERALL SCORE		20

Pathway: **Mixed Waste Combustion** (including energy recovery)
 Inputs: **woody materials, green materials, food scraps**
 Outputs: **electricity**
 Capacity: **not significant** (no infrastructure in or near Marin)

Category	Criteria	Score
Inputs and Outputs	Biomass Match (input)	2
	Primary Product (output)	1
Technological	Complexity	1
	Scalability	0
GHGs	Transport from origin	0
	Processing	1
	Transport to end use	2
	Product usage	1
Financial	Potential CAPEX	1
	Potential OPEX	1
	Potential revenue	0
	Technological readiness	0
Economic and Social	Job creation	0
	Societal benefits	0
Environmental	Air pollution	0
	Regulatory status	0
	Public perception	0
Infrastructure	Status of Installation(s)	0
OVERALL SCORE		10

Pathway: **Landfill**
 Inputs: **all biomass types**, except as diminished by law
 Outputs: **waste, alternative daily cover, landfill gas**
 Capacity: **significant**

Category	Criteria	Score
Inputs and Outputs	Biomass Match (input)	2
	Primary Product (output)	0
Technological	Complexity	2
	Scalability	2
GHGs	Transport from origin	0
	Processing	0
	Transport to end use	0
	Product usage	1
Financial	Potential CAPEX	1
	Potential OPEX	2
	Potential revenue	0
	Technological readiness	2
Economic and Social	Job creation	0
	Societal benefits	0
Environmental	Air pollution	0
	Regulatory status	1
	Public perception	0
Infrastructure	Status of Installation(s)	2
OVERALL SCORE		15

Appendix F. SB 1383 Procurement Targets

The provisions in Senate Bill 1383 (2016) and its ensuing regulations require cities and counties to procure compost or other products from biomass recycling in proportion to their populations.¹ The per-capita procurement target set in CCR Tit. 14, § 18993.1 is 0.08 tons of recycled organic product per person. Per AB 2346 (2024), CalRecycle updated the procurement targets in August 2025 to reflect Zero Waste Marin’s new calculation based on its Countywide Waste Characterization Study. The per-capita procurement target allocated to ZWM’s member agents has been updated to 0.042 of recycled organic waste product per person. Additionally, per AB 2902 (2024), some jurisdictions in Marin have received a rural exemption waiver from the ROWP mandates, as reflected in the table below. When applied to compost, a factor of 0.58 is multiplied times this number to calculate the amount of compost needed to satisfy the procurement target.

The table below lists the procurement targets for each of Marin’s jurisdictions.

Jurisdiction	Population (2021)	Procurement Target (tons per year)	Valid Until
Belvedere	2,066	0	2030
Corte Madera	10,029	421	2030
Fairfax	7,498	315	2030
Larkspur	12,194	512	2030
Mill Valley	14,550	611	2030
Novato	53,486	2,246	2030
Ross	2,547	107	2030
San Anselmo	12,689	533	2030
San Rafael	59,016	2,479	2030
Sausalito	7,355	309	2030
Tiburon	9,456	397	2030
Unincorporated County	66,888	2,174	2030
Total	257,774	9,554	

¹ Senate Bill 1383 uses the term “organic waste” instead of biomass.

Appendix G. GHG Analysis

Summary of Lifecycle Analysis Approach

A lifecycle analysis (LCA) approach is used in this Study to assess greenhouse gas (GHG) emissions. The framework is based on the International Organization of Standardization (ISO) 14040 and 14044 standards (ISO 2006a, ISO 2006b). In particular, the analysis uses a 'consequential' LCA approach, where the interest is in understanding the potential climate impact from changing the level of outputs of a product (e.g., energy, biochar, compost) from different biomass utilization pathways. A LCA for GHG impacts and biomass utilization pathways evaluates the environmental consequences of changes within the system. For example, a scenario where green waste and food waste in Marin County are diverted from landfill to produce compost. In the baseline (business-as-usual) scenario (landfill), this organic waste would decompose, releasing methane (CH₄), a potent GHG, with some emissions captured for energy generation at the landfill and others escaping into the atmosphere. In the consequential LCA, implementing composting as a biomass utilization pathway reduces landfill methane emissions by diverting the waste. Composting itself generates some GHG emissions from processing (nitrous oxide and methane) and transportation but provides net long-term carbon sequestration benefits when compost is applied to soils. Compost enhances soil organic carbon (SOC) directly, and improves plant productivity, increasing photosynthetic capture of atmospheric CO₂. Additionally, the compost pathway reduces the need for synthetic fertilizers, further reducing emissions from fertilizer production and application. By comparing the GHG impacts of the landfill baseline with composting, the consequential LCA highlights the overall net reduction in emissions and the long-term climate benefits from this alternate pathway.

According to ISO standards, LCA is an iterative process that combines scientific data (knowledge production) with policy considerations (norm creation). The process consists of four phases (Figure G-1), which were used to guide the analysis of different biomass utilization pathways, including:

- *Goal and Scope Definition*: Defines the study's purpose, system boundaries, and level of detail, which may vary depending on the LCA's objectives.
- *Inventory Analysis (LCI)*: Collects input and output data related to the system being studied to meet the study's goals.
- *Impact Assessment (LCIA)*: Interprets the inventory results to evaluate their environmental significance. LCIA results are relative measures and do not predict specific risks, thresholds,

or impacts.

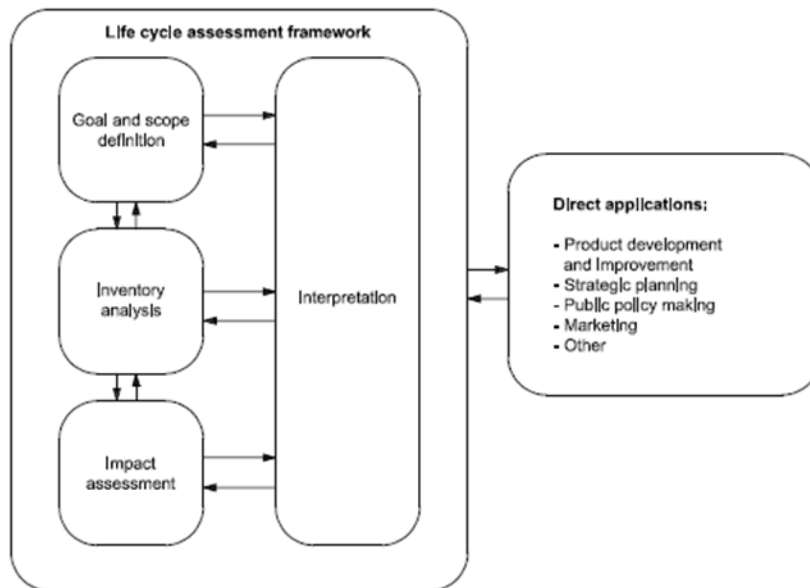
- *Interpretation*: Summarizes results from the LCI and LCIA phases to draw conclusions and provide recommendations aligned with the study's goals.

The ISO framework allows significant flexibility in conducting LCA studies to meet specific needs and applications. However, ISO 14040 (2006a) emphasizes that LCA results address potential environmental impacts rather than precise or absolute predictions. This is due to:

- Results being expressed relative to a reference unit.
- Environmental data being integrated over time and space.
- Inherent uncertainties in modeling environmental impacts.
- Some impacts occurring in the future, which introduces additional variability.

This flexible, yet structured approach ensures that LCA studies provide valuable insights for decision-making while acknowledging the complexities and uncertainties of environmental assessments.

Figure G-1: LCA phases (ISO 2006a).



Boundaries and Functional Units Used in this Study

The following assessment boundaries were applied to all biomass utilization pathways that were evaluated, unless specified otherwise:

- **Scope of GHG Emissions:** The analysis focuses only on GHG emissions directly related to the production process, operational activities, and the end fate of the product. Emissions resulting from construction, material maintenance, or decommissioning of infrastructure were not included in this assessment.
- **Temporal and Spatial Boundaries:** The temporal and spatial limits of the analysis differ depending on the specific biomass utilization pathway. These boundaries are determined by the availability of information, such as the longevity of carbon storage in soils for compost or biochar applications. Details for each pathway are provided in their respective sections.
- **GHG Impact Category:** The analysis primarily focuses on GHG impacts (i.e., GHG emissions or sequestration) and includes emissions of carbon dioxide (CO₂), methane (CH₄), and nitrous oxide (N₂O) wherever possible. For pathways involving wildfire emission avoidance, the impact of fine particulate matter (PM_{2.5}) was also considered due to its relevance to air quality and climate impacts.
- **Functional Unit:** The functional unit is the key measurement used to report and compare GHG impacts across pathways. For this analysis, the functional unit is expressed in metric tons of carbon dioxide equivalents (MTCO_{2e}). A 100-year time horizon is applied to capture the long-term effects of GHG emissions and sequestration. This approach allows non-CO₂ gases, like methane and nitrous oxide, to be included by converting them into CO_{2e} values. These conversions use the global warming potential (GWP) factor, which accounts for both the radiative forcing (warming effect) and the atmospheric lifespan of each gas relative to CO₂.
- **De Minimis Rule:** Certain GHG impact categories, while quantifiable, are excluded if their overall contribution to GHG impacts is insignificant. This is referred to as the *de minimis* rule, where minor impacts do not justify the additional effort for analysis. Specific instances of applying the de minimis rule are outlined in the sections describing each biomass utilization pathway.

Table G-1: Key input variables for the landfill GHG flux calculations

General inputs	Unit	Value	Source
Methane 100 year Global Warming Potential (CH ₄ GWP)	CO ₂ e	28	Mythe et al. (2013)
Methane Lower Heating Value (CH ₄ LHV)	GJ/MT	50	US EPA Landfill Gas Emission Model (LandGEM)
Methane (CH ₄) Captured	%	75%	US EPA (2016)
Methane (CH ₄) Electricity Conversion Efficiency	%	50%	Wood et al. (2023)
Electricity Grid Mix	MTCO ₂ e/ MWh	0.2420673	EPA (2023) for CAMX Region)

Table G-2: Key inputs for **compost** production and associated baseline assumptions.

Variable	Unit	Value	Source	Comment
General Inputs				
Green Materials	dry metric tons (MT) per year	27,500	Chapter 1	
Food Scraps	dry metric tons (MT) per year	240	Chapter 1	Novato Sanitary District per capita estimates of up to 5,100 MT(dry)
Compost Conversion Rate	dry ton of compost (output) per dry ton of biomass (input)	0.5	Chapter 2	
Compost Moisture Content	% of total weight	50%	Chapter 2	
Carbon Content Feedstock	% of dry weight	50%		
Carbon Content Compost	% of dry weight	20%	Ryals & Silver (2013)	1.42 kg C/m ² or 7.0 kg of dry matter /m ² @ 1.3 cm application rate
Processing Emissions				
Electricity	MWh/MT feedstock (wet)	0.145	Mondello et al. (2017)	
Machinery (fossil fuel)		N/A		de minimis
Electricity Grid Mix	MTCO ₂ e /MWh	0.242	EPA (2023)	Emissions for CAMX region
Transportation	miles (return trip)	60		Transport to end use
Truck Emissions	MTCO ₂ e /short ton/mile	0.002	EPA (2023)	Total Global Warming Potential
Compost Application on Rangeland				
Marin Rangeland Available	Acres	62,054	Chapter 1	Contains ~3.5k acres non-rangeland - See Marin_Carbon_by_Landuse; 930 acres currently receive compost as of CMCDA 2020
Application Rate	MT (dry)/acre	15.4	CMCDA (2020), based on Ryals & Silver (2013)	One time application, 35 cubic yards (17 tons)/acre (1/4").
Sequestration Factor	MT CO ₂ e /acre/year	1.49	CMCDA (2020), based on Ryals & Silver (2013)	Compare to Tukman (2018) Activity sheets (soil amendments: grassland/ irrigated pasture): 4.45 MTCO ₂ e/ac/year (10 yrs).
Sequestration Lifespan	Years	20	CMCDA (2020), based on Ryals & Silver (2013)	Compare to Tukman (2018) Activity sheets (soil amendments: grassland/ irrigated pasture): 4.45 MTCO ₂ e/ac/year (10 years).

Table G-3: Key inputs for co-digestion with electricity generation

Variable	Unit	Value	Source	Comment
General Inputs				
Food Waste - current	dry metric tons	800	Chapter 1	
Food Waste - alternative	dry metric tons	3,900	Chapter 2	
Carbon in Biosolid Converted to CH ₄	% of dry weight	5%	EPA (2014)	
Current Biogas Production	ft ³ /y	8,618,715	Carollo (2023)	
Energy Content Biogas	MWh/m ³ LHV	0.006	IEA (2023)	Equivalent to ~700 BTU/ft ³
Generating Capacity	MW	0.995	Carollo (2023, Fig B-1)	
Conversion Efficiency	%	40%	GE (2023)	
Capacity Realized	%	60%	Carollo (2023, Fig B-1)	
Load Factor	proportion time in operation	0.77	CMSA (2023)	Monthly summary report - 18.5 h/day
Baseline Assumptions				
Biosolid Residue as Digestate	%	65%	CMSA (2023, p3)	Average volatile solids reduction of 35%
Electricity Grid Mix	MT CO ₂ e /MWh	0.242	EPA (2023)	Emissions for CAMX region
Processing Emissions				
Internal Electricity Need	% of generating capacity	10%		
Machinery		N/A		Fossil fuel input (machinery) de minimis
Transport to End Use	miles	60		
Transportation Emissions	MT CO ₂ e /short ton/mile	0.002	EPA (2023)	Total GWP; truck emissions

Table G-4. Key inputs for **gasification with electricity generation**

Variable	Unit	Value	Source	Comment
General Inputs				
Mixed Wood	dry metric ton	14,800	Chapter 2	90% from C&D biomass, 10% from green waste
Feedstock Energy Content	MWh/ dry MT; HHV	5.6	Freund et al. (2012)	
Biochar Yield (from feedstock)	% of Dry Weight	10%	Chapter 2	Focus on biochar production. Regular pyrolysis (focus on elec. gen): 5-25%
Electric Conversion Efficiency	%	36%		Applies to only the biomass fraction not used for biochar production.
Load Factor	Proportion	0.8		
Baseline Assumptions				
Electricity Grid Mix	MT CO ₂ e/MWh	0.242	EPA (2023)	Emissions for CAMX region
Mixed Wood Shipped to Out-of-County Power stations	dry metric ton	14,800	Chapter 2	
Avoided Transportation	Miles (roundtrip)	160	Chapter 2	
Truck Emissions	MT CO ₂ e / short ton / mi	0.002	EPA (2023)	Total GWP; truck emissions
Processing Emissions				
Internal Electricity Need	% of generating capacity	10%		
Transport to End Use - Biochar	Miles (return trip)	120		
Marin Rangeland Available for Application	Acres	62,054	Chapter 1	Contains ~3.5k acres non rangeland - See Marin_Carbon_by_Landuse; 930 acres currently receive compost as of CMCD (2020)
Biochar GHG Impact Factor	MT CO ₂ e per acre	5	Woolf et al. (2021)	
Biochar GHG Impact Factor	MT CO ₂ e per MT Biochar	2	Woolf et al. (2021)	
Biochar Application Rate	MT (dry)/Acre	2.25		Consider 15% blended biochar-compost application equaling ~2.25 tons biochar/acre when applying 15 tons of compost ; 15MT/ha equals ~6MT/acre for cropland example in Woolf et al. (2021)
C Fraction of Biochar	C fraction biochar	0.81	Woolf et al. (2021), Table 2	100-year permanence

Table G-5: Key inputs for co-pyrolysis and biochar production

Variable	Unit		Source	Comment
General Inputs				
Biosolids	dry metric ton	3,000	Chapter 2	
Forest Biomass	dry metric ton	1,400	Chapter 2	
Biochar Yield	% of dry weight	35%	Assumption	Focus on biochar production. Regular pyrolysis (focus on elec. gen): 5-25%
C Biosolid Converted to CH4		5%	EPA (2014)	
Current Biogas Production	ft3/y	88,618,715	Carollo (2023)	
Energy Content Biogas	MWh/m3 LHV	0.006	IEA (2023)	Equivalent to ~700BTU/ft3
Generating Capacity	MW	0.995	Carollo (2023), Figure B-1	
Conversion Efficiency	%	40%	GE (2023)	
Capacity Realized	%	100%	N/A	
Load Factor	% time in operation	0.77	CMSA (2023)	Monthly summary report - 18.5 h/day
Baseline Assumptions				
Biosolid Residue/Digestate		65%	CMSA (2023), p3	Average volatile solids reduction is 35%
Electricity Grid Mix	MTCO2e/ MWh	0.242	EPA (2023)	Emissions for CAMX region
Processing Emissions				
Internal Electricity Need	% of generating capacity	10%		
Roundtrip Transport - Biochar to End Use	Miles	120		
Roundtrip Transport - Digestate to End Use	Miles	60		
Truck Emissions	MT CO2e / short ton/mile	0.002	EPA (2023)	Total GWP; truck emissions
Biochar Application on Rangeland				
Marin Rangeland Available (note: Marin Crop Report)	acre	62,054	Chapter 1	Includes ~3.5k non-rangeland acres; 930 acres currently receive compost as of CMCDCA (2020)
Biochar Sequestration Lifespan	Years	100	Woolf et al. (2021)	
Biochar GHG Impact Factor	MT CO2e per acre	5		Output calculations based on data from Woolf et al. (2021)
Biochar GHG Impact Factor	MT CO2e per MT biochar	2		Output calculations; entirely based on data from Woolf et al. (2021)

Summary of Avoided Wildfire Emissions Estimation Approach

The avoided wildfire emissions (AWE) methodology in this project is built on latest science and has over the years led to an increased consensus amongst the scientific and wider stakeholder community on how to standardize the accounting steps. SIG has led (e.g., Gunn et al. 2016, Moody et al. 2014 and 2015, Saah et al. 2010 and 2012) and contributed to a multitude of AWE accounting publications and projects (e.g., Collins et al. 2011 and 2016, Moghaddas et al. 2010, Moghaddas and Craggs 2007, Moody et al. 2016). These efforts culminated in a 2015-2018 project: *“Quantifying ecosystem service benefits of reduced occurrence of significant wildfires”* (QUEBROW; Buchholz et al. 2019).

The goal of the QUEBROW project was to create broad scientific and stakeholder support for an AWE accounting framework, test this framework on a challenging case study, and submit it for endorsement to a carbon offset registry. In June 2018, the QUEBROW project completed the case study on 216,000 forested acres in the Eldorado National Forest and adjacent private and other public forests (Buchholz et al. 2018). In December 2019, SIG started the submission process for the AWE accounting framework to the Climate Forward¹ program under the Climate Action Reserve (CAR)² for endorsement as a carbon offset protocol, a process that resulted in the endorsement of the Reduced Emissions from Megafires (REM) methodology (Ebert et al. 2023)³ in March 2023 and is now ready to accept projects.

The following provides a general description of the parameterization for the AWE/REM accounting framework. This involves the following steps, for both the baseline and project scenarios.

Project Area. Define the geographic boundary of the project. Quantify the forest condition - including tree stands, tree list, species, height, and diameter, and surface fuels - in the project area existing at the start of the project through site characterization measurements.

Management Scenario Development. Define the details of the fuel treatment - including fuel reduction harvesting levels, procedures, location, timing, and fate of residuals.

Forest Carbon. Project the growth of the forested land at five-year intervals over the project term (40 years).

Forest Removals Life Cycle Assessment. Determine sequestration in wood products and avoided/displaced/reduced/sequestered fossil fuels emissions from wood products, bioenergy, and other biomass pathways.

¹ <https://climateforward.org/>

² <https://www.climateactionreserve.org/>

³ <https://climateforward.org/program/methodologies/reduced-emissions-from-megafires/>

Fire Ignition Probability. Determine the project area's expected fire return interval. Use the fire return interval to determine statistical fire probability over the project term.

Weather Data. Define weather conditions under which to simulate fire over the project term. Weather parameters are set to represent 97th percentile conditions based on historical weather conditions data (covering at least the previous 10 years). Factoring for projected climate change is not considered in these methods.

Wildfire Emissions. Determine emissions from wildfire that burn the entire project area, at five-year timesteps over the project term. Amortize emissions by statistical fire probability.

Delayed Reforestation. Quantify the area, emissions, and sequestration over the project term associated with project land temporarily or permanently converted from forestland to grassland or shrubland following high severity fire.

Aggregated Emissions Accounting. Determine the difference between the baseline and project scenario GHG emissions, for each five-year interval period over the project term.

Figure G-2. Conceptual framework of AWE accounting (Buchholz, Schmidt, et al., 2019).

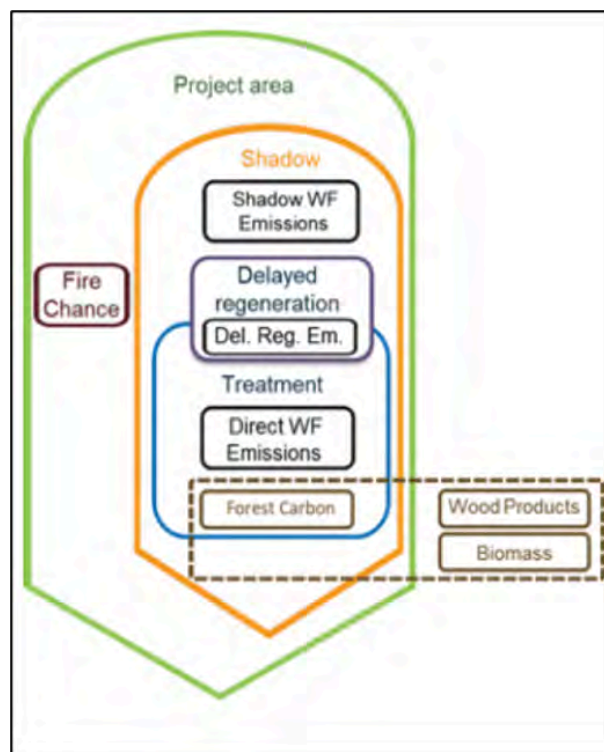
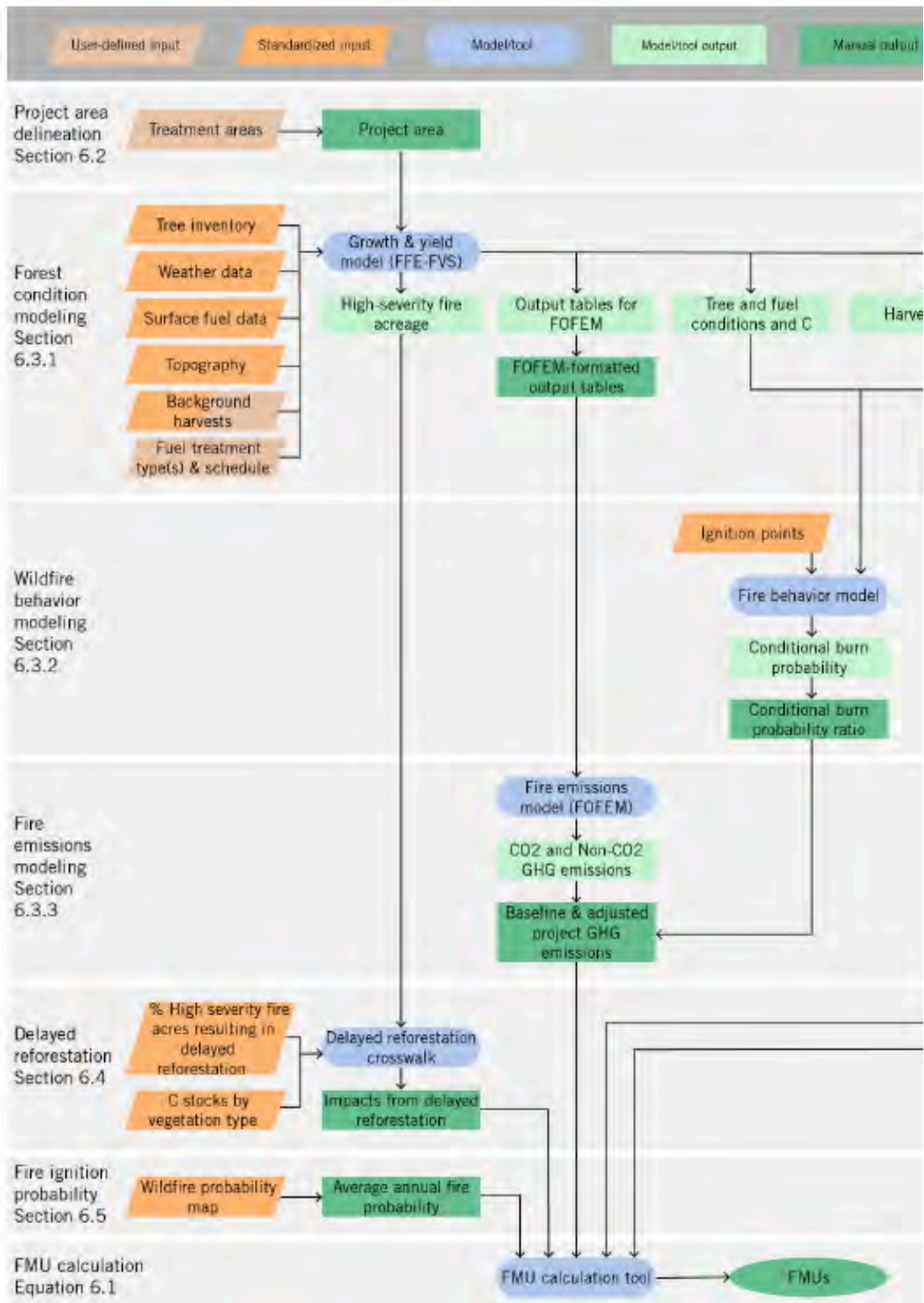


Figure G-3. AWE accounting - data inputs, models, and aggregation elements (right). Global warming impact is measured in MT CO₂e; labeled Forecasted Mitigation Units (FMUs) in the above graph (Ebert et al., 2023).



The AWE accounting framework is executed using the following five steps:

- **Step 1.** For project-specific landscape-level and AWE accounting, we augmented local datasets with the 2016 TreeMap tree list from the Missoula Fire Lab (TreeMap; Riley et al. 2019). The TreeMap dataset has also been approved by the California Air Resources Board for carbon modeling in support of applications for funding from the State's Greenhouse Gas Reduction Fund. The TreeMap dataset is a 30-m interpolated raster map that covers the entire contiguous United States and can be used to explore tree-level data as of 2016. We simulated disturbances such as wildfires that occurred between 2017 and 2022 with FVS to update the tree inventory to current conditions (as of 2022).
- **Step 2.** In collaboration with stakeholders, we identified fuel treatment locations, types and schedules to be modeled. This effort also considered insights gained in Task A on forest-based biomass supply projections.
- **Step 3.** We projected the carbon stocks and flows of the forested land over the project term (40 years) at five-year intervals. Live above ground, live and dead below ground (soil C in roots), and dead and down wood were estimated for the baseline (no treatments) and fuel treatment scenarios using models of forest management across the full project term. Modeling of forest growth was completed using the regional variant of the Forest Vegetation Simulator – Fire and Fuels Extension (FVS-FFE).⁴ FVS-FFE calculates and tracks carbon in the following pools: total aboveground live which includes merchantable and unmerchantable live stems, branches, and foliage, standing dead, understory (shrub and herbaceous layers), forest floor (litter and duff), forest down dead wood, belowground live roots and belowground dead roots. FVS-FFE outputs include projected volume in live aboveground tree biomass and (wildfire) emission by appropriate strata in the baseline scenario. FVS-FFE outputs were used to also account for non-CO₂ GHG relevant emissions (e.g., N₂O, CO, CH₄, PM_{2.5}) in the First Order Effects Model (FOFEM) model⁵ which translates FVS-FFE outputs into emission estimates. The baseline FVS simulations assuming no project implementation included all stands but no treatments were simulated.
- **Step 4.** We ran a fire behavior model in GridFire⁶ to determine a change in fire behavior due to fuel treatments and to capture GHG benefits from a change in wildfire behavior at treated and in non-treated forested stands ('wildfire shadow effect').

⁴ <https://www.fs.usda.gov/fvs/>

⁵ <https://www.firelab.org/project/fofem-fire-effects-model>

⁶ <https://github.com/pyregence/gridfire/>

- **Step 5.** In a last AWE-related step, we considered GHG flux consequences if high-severity wildfire occurrence decreases due to fuel treatments and a reduced acreage of stands that would experience prolonged periods of delayed regeneration (temporary or permanent vegetation type change from forests to grass or shrub dominated landscape). Such acreage would therefore exhibit a carbon sequestration potential. This step included a full AWE accounting and resulted in an estimation of avoided wildfire emissions measured in metric tons of CO₂e, aggregated over 40 years and then annualized. Estimates considered all treatments implemented as described in ‘Identification of Acreage’ and ‘Fuel Treatment Prescriptions’ sections.

Wildfire Modeling

Chapter 3 discusses the effect of annual probability of wildfire. GHG emissions also vary based on wildfire risk and severity, other greenhouse gases, and the rate of forest (re)growth. These other modeling factors were considered in our modeling and briefly discussed here.

- **Reduction in Fire Severity.** When a small proportion of a firehed is treated, predictions of effect can be influenced by sources of variation that disappear at larger scales, for example, individual stand anomalies. Since we did not have specific fuel treatment locations for mechanical and hand crew thinning or prescribed burns, this is of relevance when modeling AWE on randomly allocated fuel treatments based on defined geospatial constraints (rather than, e.g., assigning specific 50-acre contiguous treatment blocks). For instance, fuel treatments can create higher ground wind speeds by opening the understory so that mid-flame wind speed will increase with a resulting increase in fire severity and GHG emissions (van Wagtendonk 1996 *in*: Agee & Skinner 2005). Therefore, it is important to also consider other (non-climate) benefits of fuel treatments to fully understand their wider ecosystem service benefits.
- **Reduced Risk of Delayed Regeneration.** All treatment scenarios show clear benefits due to a reduced risk of delayed regeneration (Table G-6). Up to 50% of forests experiencing high-severity wildfire also experience delayed regeneration depending on forest type (e.g., Buchholz et al. 2019), resulting in delayed forest carbon accumulation. Based on average shrub carbon stocks in the western U.S. (11 MTCO₂e/acre; Zhu and Reed 2012), the AWE methodology suggests a maximum carbon stock of 21.3 MTCO₂e/acre if some sparse tree cover is present over a 40-year time period on post high-severity wildfire patches, including potential re-established tree cover. This is weighted against a typical forest stock volume 20 years post wildfire (e.g., 31.6 MT CO₂e/acre for regional Ponderosa Pine forests) if a forest could have reestablished itself shortly after a low-severity wildfire occurrence.

The uncertainty in delayed regeneration assumptions is not only driven from fire behavior metrics (e.g., flame length) but is likely also driven by landscape data. For instance, it is very likely that elevation (e.g., precipitation) impacts results, as would slope (erosion), or aspect. The current approach does not take these variabilities into consideration.

Wildfire severity is predicted to decrease considerably in treated areas but only slightly in adjacent, untreated areas since the treatments add more open-canopy structure and lower associated fuels to Marin’s current forest conditions, resulting in openings and gaps. We quantified acreage that experienced a significant drop in wildfire severity (i.e., average flame length of < 4 feet; Table G-6). Most acres ‘saved’ from high-severity wildfires are accounted for in the first project period when treatments are showing full efficacy. Total acreage saved from high severity wildfire was within treated acreage. In other words, most acres saved from delayed regeneration were treated acres.

Of those acreages, a fraction will also avoid a delayed regeneration risk, i.e., an absence of tree-dominated vegetation cover after 20 or more years following high-severity wildfire. The most relevant forest types in this context for the study area are Tan Oak, Black Oak and Douglas-fir with the latter associated with a delayed regeneration risk of 50% (Buchholz et al. 2019). The impact of sudden oak death on future forest conditions was out of scope for the current analysis but should be analyzed in future more detailed analyses due to its potential significant impact on wildfire behavior.

Table G-6: Acres at risk of high-severity wildfire (flame length > 4 ft) for each scenario and wildfire year. These acres are at high risk for delayed regeneration and forgone carbon sequestration in the near to mid-term future. The analysis focused on Tan Oak, Black Oak and Douglas fir, since these forest types were modeled with the highest level of high-severity fire activity and had the most notable reduction in fire severity.

Year	No Fuel Treatments (acres)	Fuel Treatments (acres)	Reduction in Acreage with Flame Length > 4ft
2023	73,400	68,900	4,500
2028	91,600	84,500	7,100
2033	105,900	101,000	4,900
2038	111,400	106,500	4,900
2043	112,900	105,400	7,400
2048	113,600	105,900	7,700
2053	113,300	108,000	5,300
2058	110,800	105,400	5,400

Table H-1. Modeling Parameters for Financial Analysis of Co-digestion Pathway

Feedstock	Value	Units	Notes
Biomass Type			
Food Scraps (increment only)	11,100	wet short tons/yr	Assume 80% moisture content
Food Scraps (increment only)	4,300	dry short tons/yr	
Food Scraps (increment only)	3,900	dry metric tons/yr	
Food Scraps (increment only)	40	wet short tons per day	
Operations			
Engine Details			
Rated Capacity (baseline)	600	kW	Capacity needed for current system (baseline)
Rated Capacity (alternative)	995	kW	Capacity needed for alternative system
Capacity Increment (used in analysis)	395	kW	Capacity used to calculate GHG and finances
Capacity Factor	90%	%	% of equipment capacity used
Revenue			
Electricity			
Electricity Power Increment	395	kW	Assumed to operate 90% of year
Electricity Generation Increment	3,100	MWh	
Electricity Price	80.00	\$/MWh	
Revenue from Electricity	249	\$000/yr	
Price Escalation	0.0	%	
Biomass Recovery			
Tipping Fee	26.75	\$/wet short ton	
Revenue from Biomass Recovery	351	\$000/yr	
Price Escalation	3.1	%	
Capital Expenses			
Infrastructure Expenses			
Equipment Cost	0.0	\$	
Upfront Soft Costs	0.0	\$	
Supportive Funding			
Grants	0.0	\$000	No grant funding assumed
Other Incentives	0.0	\$000	35% Federal investment tax credit (ITC) for CHP
Total Capital Expenses	0.0	\$000	
Operating Expenses			
Feedstock Expenses			
Acquisition Costs	0.0	\$/yr	Assumption of no incremental costs
Price Escalation	3.0	%/yr	
Labor Expenses			
All Labor Cost Increments	0.0	\$/yr	Assumption of no incremental costs
Price Escalation	1.5	%/yr	Based on BLS employe cost index summary (June 2023)
Insurance and Maintenance			
Maintenance (incremental cost)	159,135	\$/yr	
Insurance (incremental cost)	0.0	\$/year	
Utility Charges	156,000	\$/yr	
Disposal Costs	13,261	\$/year	
Price Escalation	3.0	%/yr	
Total Operating Expenses	328,396	\$/yr	
Financing			
Debt			
Debt %	0.0	%	
Debt Amount	0.0	\$000	
Finance Rate	6.0	%	
Finance Term	10.0	year	
Equity			
Equity Amount	0.0	\$000	
Tax Rates			
Federal	35.0%	%	
State	8.8%	%	
Depreciation			
Depreciation	SL		
Asset Term	20	years	

Table H-2. Pro Forma Financial Analysis for Co-Digestion Pathway

	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Revenue (\$000)																					
Electricity	\$ -	\$ 249	\$ 249	\$ 249	\$ 249	\$ 249	\$ 249	\$ 249	\$ 249	\$ 249	\$ 249	\$ 249	\$ 249	\$ 249	\$ 249	\$ 249	\$ 249	\$ 249	\$ 249	\$ 249	\$ 249
Biomass Recovery (tipping fee)	\$ -	\$ 351	\$ 362	\$ 374	\$ 385	\$ 397	\$ 409	\$ 422	\$ 435	\$ 449	\$ 463	\$ 477	\$ 492	\$ 507	\$ 523	\$ 539	\$ 556	\$ 573	\$ 591	\$ 609	\$ 628
Total Revenue	\$ -	\$ 601	\$ 612	\$ 623	\$ 634	\$ 646	\$ 659	\$ 671	\$ 684	\$ 698	\$ 712	\$ 726	\$ 741	\$ 756	\$ 772	\$ 788	\$ 805	\$ 822	\$ 840	\$ 858	\$ 877
Operating Expenses (\$000)																					
Feedstock	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -
Labor	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -
Maintenance	\$ -	\$ 159	\$ 164	\$ 169	\$ 174	\$ 179	\$ 184	\$ 190	\$ 196	\$ 202	\$ 208	\$ 214	\$ 220	\$ 227	\$ 234	\$ 241	\$ 248	\$ 255	\$ 263	\$ 271	\$ 279
Insurance	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -
Disposal (digestate)	\$ -	\$ 13	\$ 14	\$ 14	\$ 14	\$ 15	\$ 15	\$ 16	\$ 16	\$ 17	\$ 17	\$ 18	\$ 18	\$ 19	\$ 19	\$ 20	\$ 21	\$ 21	\$ 22	\$ 23	\$ 23
Utility charges	\$ -	\$ 156	\$ 161	\$ 166	\$ 170	\$ 176	\$ 181	\$ 186	\$ 192	\$ 198	\$ 204	\$ 210	\$ 216	\$ 222	\$ 229	\$ 236	\$ 243	\$ 250	\$ 258	\$ 266	\$ 274
Total Operating Expenses	\$ -	\$ 328	\$ 338	\$ 348	\$ 359	\$ 370	\$ 381	\$ 392	\$ 404	\$ 416	\$ 428	\$ 441	\$ 455	\$ 468	\$ 482	\$ 497	\$ 512	\$ 527	\$ 543	\$ 559	\$ 576
EBITDA Cash Flow	\$ -	\$ 272	\$ 273	\$ 274	\$ 275	\$ 277	\$ 278	\$ 279	\$ 280	\$ 282	\$ 283	\$ 285	\$ 286	\$ 288	\$ 290	\$ 291	\$ 293	\$ 295	\$ 297	\$ 299	\$ 301
Capital Expenses (\$000)																					
Equity	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -
Debt Balance	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -
Interest	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -
Principal	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -
Debt Service (incl. Interest)	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -
Debt Service Coverage Ratio	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Depreciation (\$000)	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -
Taxes (\$000)																					
Taxable Income	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -
Federal Taxes	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -
State Taxes	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -
Results (\$000)																					
Net Income	\$ -	\$ 272	\$ 273	\$ 274	\$ 275	\$ 277	\$ 278	\$ 279	\$ 280	\$ 282	\$ 283	\$ 285	\$ 286	\$ 288	\$ 290	\$ 291	\$ 293	\$ 295	\$ 297	\$ 299	\$ 301
Net Cash Flow	\$ -	\$ 272	\$ 273	\$ 274	\$ 275	\$ 277	\$ 278	\$ 279	\$ 280	\$ 282	\$ 283	\$ 285	\$ 286	\$ 288	\$ 290	\$ 291	\$ 293	\$ 295	\$ 297	\$ 299	\$ 301
Internal Rate of Return (IRR)	n/a	n/a																			
Simple Payback Period (SPP)	n/a	Year																			

Table H-3. Modeling Parameters for Financial Analysis of Gasification Pathway

Feedstock	Value	Units	Notes
Biomass Type			
Mixed Wood	20,400	wet short tons/yr	Assume 20% moisture content
Mixed Wood	16,300	dry short tons/yr	
Mixed Wood	14,800	dry metric tons/yr	

Operations	Value	Units	Notes
Size			
Rated Capacity	2.00	MW	
Operating Time			
Average Days per Week	7	days	
Average Shifts per Day	3	shifts	
Shift Length	8	hrs	
Maintenance Downtime per Year	6	weeks	Holidays are counted as additional downtime
Capacity Factor	80.0%		Applied as a % of nameplate capacity
Combined Capacity and Availability Factor	70.6%		Combined capacity and availability

Revenues	Value	Units	Notes
Electricity			
Electricity Generated	12,500	MWh/yr	
Electricity Price	127	\$/MWh	Assumed PPA price, using BioMAT tariff as reference
Revenue from Electricity	1,590	\$000/yr	
Price Escalation	0.0	%/yr	Assume fixed price, such as through BioMAT
Biochar			
Production Rate	10%	%	Conversion of biomass feedstock to biochar
Biochar Generated	1,500	dry metric ton/yr	Rounded up from 1,480 dry metric tons per year
Biochar Price	160	per dry short ton	Assume \$20/cy and 250lb/cy dry bulk density
Biochar Revenue	260	\$000/yr	
MTCO _{2e} per Ton of Biochar	2.5	MTCO _{2e} /metric ton	Per carbon dioxide removal (CDR) credit system
CDR Credit Price	190	\$/MTCO _{2e}	Based on spot price at the time of this analysis
CDR Credit Revenue	700	\$000/yr	
Price Escalation	0.0	%/yr	Assume no escalation due to market uncertainties
Heat			
Heat Available	10.0	MMBtu/hr	
Heat Demand	3.1	MMBtu/hr	
% of Time Heat Used	50	%	
Total Heat Used	9,500	MMBtu/yr	
Price	15	\$/MMBtu	
Revenue from Heat	140	\$000/yr	
Price Escalation	0.0	%/yr	Assume no escalation due to gas price volatility
TOTAL REVENUE	2,690	\$000/yr	

Capital Expenses	Value	Units	Notes
Infrastructure Expenses			
Bioenergy Equipment CAPEX	18,000	\$000	Based on current estimate of \$8-9M per Megawatt
Feedstock Handling Eqmt CAPEX	1,800	\$000	Assume 10% of bioenergy equipment cost
Building and Storage Eqmt CAPEX	1,200	\$000	
Interconnection CAPEX	0	\$000	Assume use of MSS's prior PG&E interconnect study
Engineering and Construction CAPEX	3,150	\$000	Assume 15% of equipment CAPEX (see above)
Subtotal of Capital Expenses	24,200	\$000	
Supportive Funding			
Grants	3,000	\$000	Minimum needed to ensure 10% IRR
CAEATFA	yes		California state sales and use tax exemption
Estimate CAEATFA Value	1,500	\$000	Based on 7.25% state sales tax rate
Other Incentives (ITC)	6,300	\$000	30% Federal investment tax credit (ITC) for CHP
Subtotal of Supportive Funding	10,800	\$000	
Total Capital Expenses	13,400	\$000/yr	

Table H-3 (continued)

Operating Expenses	Value	Units	Notes
Feedstock Expenses			
Cost of Feedstock Acquisition	0.0	\$000/yr	Feedstock already held by MSS
Per-unit Cost of Feedstock Acquisition	-33.0	\$/dry short ton	Includes avoided trucking costs of \$20/short dry ton
Cost of Feedstock Acquisition	-540	\$000/yr	
Price Escalation	2.5%	%/yr	
Labor Expenses			
Operations Manager	0.25	# of FTE per shift	
Wage Labor	0.25	# of FTE per shift	
Administration	4.0	# of hrs per day	Assume 9-5, M-F
Subtotal of Labor Cost	300	\$000/yr	Cost without burden
Price Escalation	1.5%	%/yr	Based on BLS employe cost index summary (June 2023)
Insurance and Maintenance Expenses			
Mainteannce as % of CAPEX	5.0	% of total CAPEX	
Maintenance Cost	1,210	\$000/yr	
Insurance as % of CAPEX	1.0	% of total CAPEX	Insured equipment = bioenergy equipment
Insurance Cost	180	\$000/yr	
Price Escalation	2.5%	%/yr	Applied to maintenance and insurance costs
Total Operating Expenses	1,150	\$000/yr	Total of feedstock, labor, and insurance and maintenance

Financing Parameters	Value	Units	Notes
Debt			
Debt %	60.0	%	
Debt Amount	8,100	\$000	
Finance Rate	6.0	%	
Finance Term	20.0	year	
Equity			
Equity Amount	5,300	\$000	
Tax Rates			
Federal	21.0%	%	
State	8.8%	%	
Other			
Depreciation	MACRS 20		

Table H-4. Pro Forma Financial Analysis for Gasification Pathway

	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	
Revenue (\$000)																						
Electricity	\$ -	\$ 1,590	\$ 1,590	\$ 1,590	\$ 1,590	\$ 1,590	\$ 1,590	\$ 1,590	\$ 1,590	\$ 1,590	\$ 1,590	\$ 1,590	\$ 1,590	\$ 1,590	\$ 1,590	\$ 1,590	\$ 1,590	\$ 1,590	\$ 1,590	\$ 1,590	\$ 1,590	\$ 1,590
Heat	\$ -	\$ 140	\$ 140	\$ 140	\$ 140	\$ 140	\$ 140	\$ 140	\$ 140	\$ 140	\$ 140	\$ 140	\$ 140	\$ 140	\$ 140	\$ 140	\$ 140	\$ 140	\$ 140	\$ 140	\$ 140	\$ 140
Biochar	\$ -	\$ 960	\$ 960	\$ 960	\$ 960	\$ 960	\$ 960	\$ 960	\$ 960	\$ 960	\$ 960	\$ 960	\$ 960	\$ 960	\$ 960	\$ 960	\$ 960	\$ 960	\$ 960	\$ 960	\$ 960	\$ 960
Total Revenue	\$ -	\$ 2,690	\$ 2,690	\$ 2,690	\$ 2,690	\$ 2,690	\$ 2,690	\$ 2,690	\$ 2,690	\$ 2,690	\$ 2,690	\$ 2,690	\$ 2,690	\$ 2,690	\$ 2,690	\$ 2,690	\$ 2,690	\$ 2,690	\$ 2,690	\$ 2,690	\$ 2,690	\$ 2,690
Operating Expenses (\$000)																						
Feedstock	\$ -	\$ (540)	\$ (554)	\$ (567)	\$ (582)	\$ (596)	\$ (611)	\$ (626)	\$ (642)	\$ (658)	\$ (674)	\$ (691)	\$ (709)	\$ (726)	\$ (744)	\$ (763)	\$ (782)	\$ (802)	\$ (822)	\$ (842)	\$ (863)	
Labor	\$ -	\$ 300	\$ 305	\$ 309	\$ 314	\$ 318	\$ 323	\$ 328	\$ 333	\$ 338	\$ 343	\$ 348	\$ 353	\$ 359	\$ 364	\$ 370	\$ 375	\$ 381	\$ 386	\$ 392	\$ 398	
Maintenance	\$ -	\$ 1,210	\$ 1,240	\$ 1,271	\$ 1,303	\$ 1,336	\$ 1,369	\$ 1,403	\$ 1,438	\$ 1,474	\$ 1,511	\$ 1,549	\$ 1,588	\$ 1,627	\$ 1,668	\$ 1,710	\$ 1,752	\$ 1,796	\$ 1,841	\$ 1,887	\$ 1,934	
Insurance	\$ -	\$ 180	\$ 185	\$ 189	\$ 194	\$ 199	\$ 204	\$ 209	\$ 214	\$ 219	\$ 225	\$ 230	\$ 236	\$ 242	\$ 248	\$ 254	\$ 261	\$ 267	\$ 274	\$ 281	\$ 288	
Total Operating Expenses	\$ -	\$ 1,150	\$ 1,176	\$ 1,202	\$ 1,229	\$ 1,257	\$ 1,285	\$ 1,314	\$ 1,343	\$ 1,374	\$ 1,405	\$ 1,436	\$ 1,469	\$ 1,502	\$ 1,536	\$ 1,571	\$ 1,606	\$ 1,643	\$ 1,680	\$ 1,718	\$ 1,757	
EBITDA Cash Flow		\$ 1,540	\$ 1,514	\$ 1,488	\$ 1,461	\$ 1,433	\$ 1,405	\$ 1,376	\$ 1,347	\$ 1,316	\$ 1,285	\$ 1,254	\$ 1,221	\$ 1,188	\$ 1,154	\$ 1,119	\$ 1,084	\$ 1,047	\$ 1,010	\$ 972	\$ 933	
Capital Expenses (\$000)																						
Equity	\$ 5,300	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	
Debt Balance	\$ 8,100	\$ 7,884	\$ 7,654	\$ 7,410	\$ 7,152	\$ 6,877	\$ 6,585	\$ 6,275	\$ 5,947	\$ 5,598	\$ 5,227	\$ 4,834	\$ 4,416	\$ 3,972	\$ 3,502	\$ 3,002	\$ 2,471	\$ 1,908	\$ 1,309	\$ 674	\$ -	
Interest	\$ -	\$ 480	\$ 467	\$ 453	\$ 438	\$ 422	\$ 405	\$ 387	\$ 368	\$ 347	\$ 326	\$ 303	\$ 279	\$ 253	\$ 226	\$ 196	\$ 166	\$ 133	\$ 98	\$ 61	\$ 22	
Principal	\$ -	\$ 216	\$ 230	\$ 244	\$ 259	\$ 275	\$ 292	\$ 310	\$ 329	\$ 349	\$ 371	\$ 393	\$ 418	\$ 443	\$ 471	\$ 500	\$ 531	\$ 563	\$ 598	\$ 635	\$ 674	
Debt Service (Incl. Interest)	\$ -	\$ 696	\$ 696	\$ 696	\$ 696	\$ 696	\$ 696	\$ 696	\$ 696	\$ 696	\$ 696	\$ 696	\$ 696	\$ 696	\$ 696	\$ 696	\$ 696	\$ 696	\$ 696	\$ 696	\$ 696	
Debt Service Coverage Ratio		2.2	2.2	2.1	2.1	2.1	2.0	2.0	1.9	1.9	1.8	1.8	1.8	1.7	1.7	1.6	1.6	1.5	1.5	1.4	1.3	
Depreciation (\$000)	\$ -	\$ 227	\$ 1,794	\$ 1,660	\$ 1,535	\$ 1,420	\$ 1,314	\$ 1,215	\$ 1,124	\$ 1,077	\$ 1,077	\$ 1,077	\$ 1,077	\$ 1,077	\$ 1,077	\$ 1,077	\$ 1,077	\$ 1,077	\$ 1,077	\$ 1,077	\$ 1,077	
Taxes (\$000)																						
Taxable Income	\$ -	\$ 756	\$ 463	\$ 494	\$ 523	\$ 549	\$ 572	\$ 594	\$ 613	\$ 608	\$ 598	\$ 589	\$ 581	\$ 574	\$ 567	\$ 562	\$ 557	\$ 553	\$ 551	\$ 549	\$ 550	
Federal Taxes	\$ -	\$ 159	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	
State Taxes	\$ -	\$ 67	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	
Results (\$000)																						
Net Income	\$ -	\$ 618	\$ 818	\$ 792	\$ 765	\$ 737	\$ 709	\$ 680	\$ 650	\$ 620	\$ 589	\$ 557	\$ 525	\$ 492	\$ 458	\$ 423	\$ 388	\$ 351	\$ 314	\$ 276	\$ 237	
Net Cash Flow	\$ (5,300)	\$ 618	\$ 818	\$ 792	\$ 765	\$ 737	\$ 709	\$ 680	\$ 650	\$ 620	\$ 589	\$ 557	\$ 525	\$ 492	\$ 458	\$ 423	\$ 388	\$ 351	\$ 314	\$ 276	\$ 237	
Internal Rate of Return (IRR)		10.0																				
Simple Payback Period (SPP)		9.8																				
		Year																				

Table H-5. Sensitivity Analysis for Gasification based on Biochar Price Variation

		Biochar CDR Credit Price (\$/MTCO2e)														
		\$110	\$120	\$130	\$140	\$150	\$160	\$170	\$180	\$190	\$200	\$210	\$220	\$230	\$240	\$250
CAPEX Grant Funding (\$000)	\$3,000	-3.2%	-0.7%	1.3%	4.3%	5.6%	6.8%	7.9%	9.0%	10.0%	10.9%	11.9%	12.8%	13.6%	14.4%	15.1%
	\$3,500	-0.8%	1.3%	3.0%	5.8%	7.1%	8.2%	9.3%	10.4%	11.3%	12.3%	13.2%	14.1%	15.0%	15.7%	16.5%
	\$4,000	1.3%	3.1%	4.7%	7.4%	8.6%	9.7%	10.8%	11.8%	12.8%	13.7%	14.7%	15.5%	16.4%	17.2%	17.9%
	\$4,500	3.3%	4.9%	6.4%	8.9%	10.1%	11.2%	12.3%	13.3%	14.3%	15.2%	16.1%	17.0%	17.9%	18.7%	19.4%
	\$5,000	5.2%	6.7%	8.1%	10.5%	11.7%	12.8%	13.8%	14.8%	15.8%	16.8%	17.7%	18.6%	19.5%	20.3%	21.1%
	\$5,500	7.0%	8.4%	9.8%	12.2%	13.3%	14.4%	15.5%	16.5%	17.5%	18.5%	19.4%	20.3%	21.2%	22.0%	22.8%
	\$6,000	8.9%	10.8%	10.8%	14.0%	15.1%	16.2%	17.2%	18.3%	19.3%	20.3%	21.2%	22.1%	23.0%	23.9%	24.7%
	\$6,500	10.8%	10.8%	13.4%	15.8%	16.9%	18.0%	19.1%	20.2%	21.2%	22.2%	23.2%	24.1%	25.0%	25.9%	26.7%
	\$7,000	12.8%	14.1%	15.4%	17.8%	18.9%	20.1%	21.1%	22.2%	23.3%	24.3%	25.3%	26.2%	27.1%	28.1%	29.0%
	\$7,500	14.9%	16.2%	17.5%	19.9%	21.1%	22.2%	23.3%	24.4%	25.5%	26.6%	27.6%	28.6%	29.5%	30.5%	31.4%
	\$8,000	17.2%	18.5%	19.8%	22.2%	23.4%	24.6%	25.8%	26.9%	28.0%	29.1%	30.1%	31.1%	32.2%	33.1%	34.1%
	\$8,500	19.6%	21.0%	22.3%	24.8%	26.0%	27.2%	28.4%	29.6%	30.7%	31.9%	32.9%	34.0%	35.1%	36.1%	37.2%
	\$9,000	22.3%	23.7%	25.0%	27.6%	28.9%	30.2%	31.4%	32.6%	33.8%	35.0%	36.1%	37.2%	38.4%	39.5%	40.6%
	\$9,500	25.3%	26.7%	28.1%	30.8%	32.1%	33.5%	34.8%	36.0%	37.3%	38.5%	39.7%	40.9%	41.2%	43.3%	44.4%
\$10,000	28.6%	30.1%	31.6%	34.4%	35.8%	37.2%	38.6%	39.9%	41.2%	42.5%	43.8%	45.1%	46.3%	47.6%	48.8%	

light green cells = IRR > 10%
 dark green cells = IRR > 20%
 red cell = negative IRR

Table H-6. Modeling Parameters for Financial Analysis of Co-pyrolysis Pathway

Feedstock	Value	Units	Notes
Biomass Type			
Digestate	16,500	wet short tons/yr	Assume 80% moisture content
	3,308	dry short tons/yr	
	3,000	dry metric tons/yr	
Wood chips	2,500	wet short tons/yr	Assume 40% moisture content
	1,544	dry short tons/yr	
	1,400	dry metric tons/yr	

Revenue	Value	Units	Notes
Biochar			
Production Rate	35%	%	Conversion of biomass feedstock to biochar
Biochar Generated	1,697	dry short ton/yr	
	1,540	dry metric ton/yr	
Biochar Price	160	per dry short ton	Assume \$20/cy and 250lb/cy dry bulk density
Biochar Revenue	272	\$000/yr	
MTCO2e per Ton of Biochar	2.5	MTCO2e/metric ton	Per carbon dioxide removal (CDR) credit system
CDR Credit Price	190	\$/MTCO2e	Based on spot price at the time of this analysis
CDR Credit Revenue	731	\$000/yr	
Price Escalation	0.0	%/yr	Assume no escalation due to market uncertainties
Biomass Recovery			
Tipping Fee for Digestate	55.00	\$/wet short ton	
Revenue from Biomass Recovery	908	\$000/yr	
Price Escalation	3.0	%	
Total Revenue	1,910	\$000/yr	

Capital Expenses	Value	Units	Notes
Infrastructure Expenses			
Pyrolysis Equipment Cost	3,500	\$000	Assume 1-5 train unit
Transportation and Installation	500	\$000	
Site Preparation and Building	250	\$000	
Other Handling, Processing, and Packagin	500	\$000	
Subtotal of Infrastructure Expenses	4,750	\$000	
Supportive Funding			
Grants	750	\$000	
Other Incentives	0.0	\$000	
Total Capital Expenses	4,000	\$000	

Operating Expenses	Value	Units	Notes
Feedstock Expenses			
Acquisition Price	40.0	\$/wet short ton	Cost of acquiring woody biomass
Acquisition Costs	100	\$/yr	
Price Escalation	3.0	%/yr	
Labor Expenses			
Labor Demand	10,000	hrs/yr	
Labor Price	60.0	\$/hr	
Labor Expenses	600	\$000/yr	
Price Escalation	3.0	%/yr	Based on BLS employe cost index summary (June 2023)
Insurance and Maintenance			
Maintenance and Insurance	105	\$000/yr	Assume 3% of pyrolysis equipment cost
Electricity	150	\$000/yr	
Fuel Costs	15	\$000/yr	7,400 gallons at \$2.00 per gallon
Price Escalation	3.0	%/yr	
Total Operating Expenses	970	\$/yr	

Financing	Value	Units	Notes
Equity			
Equity %	10%	%	
Equity Amount	400	\$000	
Debt			
Debt %	90%	%	
Debt Amount	3,600	\$000	
Finance Rate	7.0	%	
Finance Term	15.0	year	
Tax Rates			
Federal	0.0%	%	Assume 0.0% tax rate because public entity
State	0.0%	%	Assume 0.0% tax rate because public entity
Depreciation			
Depreciation	SL		
Asset Term	15.0	years	

Table H-7. Pro Forma Financial Analysis for Co-Pyrolysis Pathway

	Year															
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Revenue (\$000)																
Biochar sales	\$ -	\$ 272	\$ 272	\$ 272	\$ 272	\$ 272	\$ 272	\$ 272	\$ 272	\$ 272	\$ 272	\$ 272	\$ 272	\$ 272	\$ 272	\$ 272
CDR credit sales	\$ -	\$ 732	\$ 732	\$ 732	\$ 732	\$ 732	\$ 732	\$ 732	\$ 732	\$ 732	\$ 732	\$ 732	\$ 732	\$ 732	\$ 732	\$ 732
Biomass Recovery (tipping fee)	\$ -	\$ 908	\$ 935	\$ 963	\$ 992	\$ 1,021	\$ 1,052	\$ 1,084	\$ 1,116	\$ 1,150	\$ 1,184	\$ 1,220	\$ 1,256	\$ 1,294	\$ 1,333	\$ 1,373
Total Revenue	\$ -	\$ 1,911	\$ 1,938	\$ 1,966	\$ 1,995	\$ 2,025	\$ 2,055	\$ 2,087	\$ 2,119	\$ 2,153	\$ 2,187	\$ 2,223	\$ 2,259	\$ 2,297	\$ 2,336	\$ 2,376
Operating Expenses (\$000)																
Feedstock Acquisition	\$ -	\$ (100)	\$ (103)	\$ (106)	\$ (109)	\$ (113)	\$ (116)	\$ (119)	\$ (123)	\$ (127)	\$ (130)	\$ (134)	\$ (138)	\$ (143)	\$ (147)	\$ (151)
Labor Cost	\$ -	\$ (600)	\$ (618)	\$ (637)	\$ (656)	\$ (675)	\$ (696)	\$ (716)	\$ (738)	\$ (760)	\$ (783)	\$ (806)	\$ (831)	\$ (855)	\$ (881)	\$ (908)
Maintenance and Insurance	\$ -	\$ (105)	\$ (108)	\$ (111)	\$ (115)	\$ (118)	\$ (122)	\$ (125)	\$ (129)	\$ (133)	\$ (137)	\$ (141)	\$ (145)	\$ (150)	\$ (154)	\$ (159)
Electricity	\$ -	\$ (150)	\$ (155)	\$ (159)	\$ (164)	\$ (169)	\$ (174)	\$ (179)	\$ (184)	\$ (190)	\$ (196)	\$ (202)	\$ (208)	\$ (214)	\$ (220)	\$ (227)
Fuel Costs (propane)	\$ -	\$ (15)	\$ (15)	\$ (16)	\$ (16)	\$ (17)	\$ (17)	\$ (18)	\$ (18)	\$ (19)	\$ (19)	\$ (20)	\$ (20)	\$ (21)	\$ (22)	\$ (22)
Total Operating Expenses	\$ -	\$ (970)	\$ (999)	\$ (1,029)	\$ (1,060)	\$ (1,092)	\$ (1,124)	\$ (1,158)	\$ (1,193)	\$ (1,229)	\$ (1,265)	\$ (1,303)	\$ (1,342)	\$ (1,383)	\$ (1,424)	\$ (1,467)
EBITDA Cash Flow		\$ 941	\$ 939	\$ 937	\$ 935	\$ 933	\$ 931	\$ 929	\$ 927	\$ 924	\$ 922	\$ 919	\$ 917	\$ 914	\$ 912	\$ 909
Capital Expenses (\$000)																
Equity	\$ 400	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -
Debt Balance	\$ 3,600	\$ 3,459	\$ 3,308	\$ 3,146	\$ 2,973	\$ 2,787	\$ 2,587	\$ 2,373	\$ 2,144	\$ 1,898	\$ 1,634	\$ 1,351	\$ 1,048	\$ 723	\$ 374	\$ -
Interest	\$ -	\$ 248	\$ 237	\$ 226	\$ 215	\$ 202	\$ 189	\$ 174	\$ 159	\$ 142	\$ 124	\$ 105	\$ 85	\$ 63	\$ 40	\$ 14
Principal	\$ -	\$ 141	\$ 151	\$ 162	\$ 174	\$ 186	\$ 200	\$ 214	\$ 229	\$ 246	\$ 264	\$ 283	\$ 303	\$ 325	\$ 349	\$ 374
Debt Service (incl. Interest)	\$ -	\$ 388	\$ 388	\$ 388	\$ 388	\$ 388	\$ 388	\$ 388	\$ 388	\$ 388	\$ 388	\$ 388	\$ 388	\$ 388	\$ 388	\$ 388
Debt Service Coverage Ratio		2.42	2.42	2.41	2.41	2.40	2.40	2.39	2.39	2.38	2.37	2.37	2.36	2.35	2.35	2.34
Depreciation (\$000)		\$ 267	\$ 267	\$ 267	\$ 267	\$ 267	\$ 267	\$ 267	\$ 267	\$ 267	\$ 267	\$ 267	\$ 267	\$ 267	\$ 267	\$ 267
Taxes (\$000)																
Taxable Income	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -
Federal Taxes	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -
State Taxes	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -
Results (\$000)																
Net Income		\$ 427	\$ 465	\$ 505	\$ 547	\$ 590	\$ 635	\$ 682	\$ 732	\$ 783	\$ 836	\$ 892	\$ 951	\$ 1,012	\$ 1,075	\$ 1,142
Net Cash Flow	\$ (3,600)	\$ 553	\$ 581	\$ 610	\$ 640	\$ 671	\$ 702	\$ 735	\$ 769	\$ 804	\$ 839	\$ 876	\$ 914	\$ 953	\$ 993	\$ 1,035
Internal Rate of Return (IRR)		15%														
Simple Payback Period (SPP)		8.0	year													

Table H-8. Pro Forma Financial Analysis for Wood Chips to Combustion Power Pathway

	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	
Revenue (\$000)																						
Wood Chip Sales	\$ -	\$ 16	\$ 17	\$ 17	\$ 18	\$ 19	\$ 19	\$ 20	\$ 20	\$ 21	\$ 21	\$ 22	\$ 23	\$ 23	\$ 24	\$ 25	\$ 26	\$ 26	\$ 27	\$ 28	\$ 29	
Biomass Recovery (tipping fee)	\$ -	\$ 88	\$ 90	\$ 93	\$ 96	\$ 98	\$ 101	\$ 104	\$ 108	\$ 111	\$ 114	\$ 118	\$ 121	\$ 125	\$ 128	\$ 132	\$ 136	\$ 140	\$ 145	\$ 149	\$ 153	
Price Escalation Rate = 3.0%	3.0																					
Total Revenue	\$ -	\$ 104	\$ 107	\$ 110	\$ 114	\$ 117	\$ 121	\$ 124	\$ 128	\$ 132	\$ 136	\$ 140	\$ 144	\$ 148	\$ 153	\$ 157	\$ 162	\$ 167	\$ 172	\$ 177	\$ 182	
Operating Expenses (\$000)																						
Chipping Cost	\$ -	\$ 35	\$ 36	\$ 37	\$ 38	\$ 39	\$ 41	\$ 42	\$ 43	\$ 44	\$ 46	\$ 47	\$ 48	\$ 50	\$ 51	\$ 53	\$ 55	\$ 56	\$ 58	\$ 60	\$ 61	
Transport Costs	\$ -	\$ 33	\$ 34	\$ 35	\$ 36	\$ 37	\$ 38	\$ 39	\$ 40	\$ 42	\$ 43	\$ 44	\$ 46	\$ 47	\$ 48	\$ 50	\$ 51	\$ 53	\$ 54	\$ 56	\$ 58	
Chipper Maintenance	\$ -	\$ 7	\$ 7	\$ 7	\$ 8	\$ 8	\$ 8	\$ 8	\$ 9	\$ 9	\$ 9	\$ 9	\$ 10	\$ 10	\$ 10	\$ 11	\$ 11	\$ 11	\$ 12	\$ 12	\$ 12	
Labor	\$ -	\$ 10	\$ 10	\$ 11	\$ 11	\$ 11	\$ 12	\$ 12	\$ 12	\$ 13	\$ 13	\$ 13	\$ 14	\$ 14	\$ 15	\$ 15	\$ 16	\$ 16	\$ 17	\$ 17	\$ 18	
Insurance	\$ -	\$ 5	\$ 5	\$ 5	\$ 5	\$ 6	\$ 6	\$ 6	\$ 6	\$ 6	\$ 7	\$ 7	\$ 7	\$ 7	\$ 7	\$ 8	\$ 8	\$ 8	\$ 8	\$ 9	\$ 9	
Utilities	\$ -	\$ 4	\$ 4	\$ 4	\$ 4	\$ 5	\$ 5	\$ 5	\$ 5	\$ 5	\$ 5	\$ 5	\$ 6	\$ 6	\$ 6	\$ 6	\$ 6	\$ 6	\$ 7	\$ 7	\$ 7	
Administration	\$ -	\$ 6	\$ 6	\$ 6	\$ 7	\$ 7	\$ 7	\$ 7	\$ 7	\$ 8	\$ 8	\$ 8	\$ 8	\$ 9	\$ 9	\$ 9	\$ 9	\$ 10	\$ 10	\$ 10	\$ 11	
Price Escalation Rate = 3.0%	3.0																					
Total Operating Expenses	\$ -	\$ 100	\$ 103	\$ 106	\$ 109	\$ 112	\$ 116	\$ 119	\$ 123	\$ 127	\$ 130	\$ 134	\$ 138	\$ 142	\$ 147	\$ 151	\$ 156	\$ 160	\$ 165	\$ 170	\$ 175	
EBITDA Cash Flow	\$ -	\$ 4.1	\$ 4.2	\$ 4.3	\$ 4.4	\$ 4.6	\$ 4.7	\$ 4.8	\$ 5.0	\$ 5.1	\$ 5.3	\$ 5.4	\$ 5.6	\$ 5.8	\$ 5.9	\$ 6.1	\$ 6.3	\$ 6.5	\$ 6.7	\$ 6.9	\$ 7.1	
Capital Expenses (\$000)																						
Equity	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	
Debt Balance	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	
Interest	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	
Principal	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	
Debt Service (incl. Interest)	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	
Debt Service Coverage Ratio	\$ -	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	
Depreciation (\$000)	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	
Taxes (\$000)																						
Taxable Income	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	
Federal Taxes	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	
State Taxes	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	
Results (\$000)																						
Net Income	\$ -	\$ 4.1	\$ 4.2	\$ 4.3	\$ 4.4	\$ 4.6	\$ 4.7	\$ 4.8	\$ 5.0	\$ 5.1	\$ 5.3	\$ 5.4	\$ 5.6	\$ 5.8	\$ 5.9	\$ 6.1	\$ 6.3	\$ 6.5	\$ 6.7	\$ 6.9	\$ 7.1	
Net Cash Flow	\$ -	\$ 4.1	\$ 4.2	\$ 4.3	\$ 4.4	\$ 4.6	\$ 4.7	\$ 4.8	\$ 5.0	\$ 5.1	\$ 5.3	\$ 5.4	\$ 5.6	\$ 5.8	\$ 5.9	\$ 6.1	\$ 6.3	\$ 6.5	\$ 6.7	\$ 6.9	\$ 7.1	

Table H-9. Pro Forma Financial Analysis for Small-Scale Milling
(Scenario 1: more slabs produced per log)

	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	
Revenue (\$000)																						
Slab Sales	\$ -	\$ 792	\$ 816	\$ 840	\$ 865	\$ 891	\$ 918	\$ 946	\$ 974	\$ 1,003	\$ 1,033	\$ 1,064	\$ 1,096	\$ 1,129	\$ 1,163	\$ 1,198	\$ 1,234	\$ 1,271	\$ 1,309	\$ 1,348	\$ 1,389	
Biomass Recovery (tipping fee)	\$ -	\$ 88	\$ 90	\$ 93	\$ 96	\$ 98	\$ 101	\$ 104	\$ 108	\$ 111	\$ 114	\$ 118	\$ 121	\$ 125	\$ 128	\$ 132	\$ 136	\$ 140	\$ 145	\$ 149	\$ 153	
Price Escalation Rate = 3.0%	3.0																					
Total Revenue	\$ -	\$ 880	\$ 906	\$ 933	\$ 961	\$ 990	\$ 1,020	\$ 1,050	\$ 1,082	\$ 1,114	\$ 1,148	\$ 1,182	\$ 1,217	\$ 1,254	\$ 1,292	\$ 1,330	\$ 1,370	\$ 1,411	\$ 1,454	\$ 1,497	\$ 1,542	
Operating Expenses (\$000)																						
Labor Cost	\$ -	\$ 200	\$ 206	\$ 212	\$ 219	\$ 225	\$ 232	\$ 239	\$ 246	\$ 253	\$ 261	\$ 269	\$ 277	\$ 285	\$ 294	\$ 303	\$ 312	\$ 321	\$ 331	\$ 340	\$ 351	
Saw Maintenance	\$ -	\$ 7	\$ 7	\$ 7	\$ 8	\$ 8	\$ 8	\$ 8	\$ 9	\$ 9	\$ 9	\$ 9	\$ 10	\$ 10	\$ 10	\$ 11	\$ 11	\$ 11	\$ 12	\$ 12	\$ 12	
Insurance	\$ -	\$ 5	\$ 5	\$ 5	\$ 5	\$ 6	\$ 6	\$ 6	\$ 6	\$ 6	\$ 7	\$ 7	\$ 7	\$ 7	\$ 7	\$ 8	\$ 8	\$ 8	\$ 8	\$ 9	\$ 9	
Utilities	\$ -	\$ 4	\$ 4	\$ 4	\$ 4	\$ 5	\$ 5	\$ 5	\$ 5	\$ 5	\$ 5	\$ 5	\$ 6	\$ 6	\$ 6	\$ 6	\$ 6	\$ 6	\$ 6	\$ 7	\$ 7	
Administration	\$ -	\$ 4	\$ 4	\$ 4	\$ 4	\$ 5	\$ 5	\$ 5	\$ 5	\$ 5	\$ 5	\$ 5	\$ 6	\$ 6	\$ 6	\$ 6	\$ 6	\$ 6	\$ 6	\$ 7	\$ 7	
Legal	\$ -	\$ 2	\$ 2	\$ 2	\$ 2	\$ 2	\$ 2	\$ 2	\$ 2	\$ 3	\$ 3	\$ 3	\$ 3	\$ 3	\$ 3	\$ 3	\$ 3	\$ 3	\$ 3	\$ 3	\$ 4	
Other	\$ -	\$ 7	\$ 7	\$ 7	\$ 8	\$ 8	\$ 8	\$ 8	\$ 9	\$ 9	\$ 9	\$ 9	\$ 10	\$ 10	\$ 10	\$ 11	\$ 11	\$ 11	\$ 12	\$ 12	\$ 12	
Price Escalation Rate = 3.0%	3.0																					
Total Operating Expenses	\$ -	\$ 229	\$ 236	\$ 243	\$ 250	\$ 258	\$ 265	\$ 273	\$ 282	\$ 290	\$ 299	\$ 308	\$ 317	\$ 326	\$ 336	\$ 346	\$ 357	\$ 367	\$ 379	\$ 390	\$ 402	
EBITDA Cash Flow	\$ -	\$ 651	\$ 670	\$ 690	\$ 711	\$ 732	\$ 754	\$ 777	\$ 800	\$ 824	\$ 849	\$ 874	\$ 900	\$ 927	\$ 955	\$ 984	\$ 1,013	\$ 1,044	\$ 1,075	\$ 1,107	\$ 1,141	
Capital Expenses (\$000)																						
Equity	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	
Debt Balance	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	
Interest	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	
Principal	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	
Debt Service (incl. Interest)	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	
Debt Service Coverage Ratio		n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	
Depreciation (\$000)																						
Taxes (\$000)																						
Taxable Income	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	
Federal Taxes (21%)	\$ -	\$ 166	\$ 171	\$ 176	\$ 182	\$ 187	\$ 193	\$ 199	\$ 205	\$ 211	\$ 217	\$ 224	\$ 230	\$ 237	\$ 244	\$ 252	\$ 259	\$ 267	\$ 275	\$ 283	\$ 292	
State Taxes (8.84%)	\$ -	\$ 70	\$ 72	\$ 74	\$ 77	\$ 79	\$ 81	\$ 84	\$ 86	\$ 89	\$ 91	\$ 94	\$ 97	\$ 100	\$ 103	\$ 106	\$ 109	\$ 112	\$ 116	\$ 119	\$ 123	
Results (\$000)																						
Net Income	\$ -	\$ 414	\$ 499	\$ 514	\$ 529	\$ 545	\$ 561	\$ 578	\$ 595	\$ 613	\$ 632	\$ 651	\$ 670	\$ 690	\$ 711	\$ 732	\$ 754	\$ 777	\$ 800	\$ 824	\$ 849	
Net Cash Flow	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	

Table H-10. Pro Forma Financial Analysis for Small-Scale Milling
(Scenario 2: fewer slabs produced per log)

	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	
Revenue (\$000)																						
Slab Sales	\$ -	\$ 396.0	\$ 407.9	\$ 420.1	\$ 432.7	\$ 445.7	\$ 459.1	\$ 472.8	\$ 487.0	\$ 501.6	\$ 516.7	\$ 532.2	\$ 548.2	\$ 564.6	\$ 581.5	\$ 599.0	\$ 617.0	\$ 635.5	\$ 654.5	\$ 674.2	\$ 694.4	
Biomass Recovery (tipping fee)	\$ -	\$ 87.5	\$ 90.1	\$ 92.8	\$ 95.6	\$ 98.5	\$ 101.4	\$ 104.5	\$ 107.6	\$ 110.8	\$ 114.2	\$ 117.6	\$ 121.1	\$ 124.8	\$ 128.5	\$ 132.4	\$ 136.3	\$ 140.4	\$ 144.6	\$ 149.0	\$ 153.4	
Price Escalation Rate = 3.0%	3.0																					
Total Revenue	\$ -	\$ 483.5	\$ 498.0	\$ 512.9	\$ 528.3	\$ 544.2	\$ 560.5	\$ 577.3	\$ 594.6	\$ 612.5	\$ 630.9	\$ 649.8	\$ 669.3	\$ 689.4	\$ 710.0	\$ 731.3	\$ 753.3	\$ 775.9	\$ 799.2	\$ 823.1	\$ 847.8	
Operating Expenses (\$000)																						
Labor Cost	\$ -	\$ 200	\$ 206	\$ 212	\$ 219	\$ 225	\$ 232	\$ 239	\$ 246	\$ 253	\$ 261	\$ 269	\$ 277	\$ 285	\$ 294	\$ 303	\$ 312	\$ 321	\$ 331	\$ 340	\$ 351	
Saw Maintenance	\$ -	\$ 7	\$ 7	\$ 7	\$ 8	\$ 8	\$ 8	\$ 8	\$ 9	\$ 9	\$ 9	\$ 9	\$ 10	\$ 10	\$ 10	\$ 11	\$ 11	\$ 11	\$ 12	\$ 12	\$ 12	
Insurance	\$ -	\$ 5	\$ 5	\$ 5	\$ 5	\$ 6	\$ 6	\$ 6	\$ 6	\$ 6	\$ 7	\$ 7	\$ 7	\$ 8	\$ 8	\$ 8	\$ 8	\$ 8	\$ 8	\$ 9	\$ 9	
Utilities	\$ -	\$ 4	\$ 4	\$ 4	\$ 4	\$ 5	\$ 5	\$ 5	\$ 5	\$ 5	\$ 5	\$ 5	\$ 6	\$ 6	\$ 6	\$ 6	\$ 6	\$ 6	\$ 7	\$ 7	\$ 7	
Administration	\$ -	\$ 4	\$ 4	\$ 4	\$ 4	\$ 5	\$ 5	\$ 5	\$ 5	\$ 5	\$ 5	\$ 6	\$ 6	\$ 6	\$ 6	\$ 6	\$ 6	\$ 6	\$ 7	\$ 7	\$ 7	
Legal	\$ -	\$ 2	\$ 2	\$ 2	\$ 2	\$ 2	\$ 2	\$ 2	\$ 2	\$ 3	\$ 3	\$ 3	\$ 3	\$ 3	\$ 3	\$ 3	\$ 3	\$ 3	\$ 3	\$ 3	\$ 4	
Other	\$ -	\$ 7	\$ 7	\$ 7	\$ 8	\$ 8	\$ 8	\$ 8	\$ 9	\$ 9	\$ 9	\$ 9	\$ 10	\$ 10	\$ 10	\$ 11	\$ 11	\$ 11	\$ 12	\$ 12	\$ 12	
Price Escalation Rate = 3.0%	3.0																					
Total Operating Expenses	\$ -	\$ 229	\$ 236	\$ 243	\$ 250	\$ 258	\$ 265	\$ 273	\$ 282	\$ 290	\$ 299	\$ 308	\$ 317	\$ 326	\$ 336	\$ 346	\$ 357	\$ 367	\$ 379	\$ 390	\$ 402	
EBITDA Cash Flow	\$ -	\$ 255	\$ 262	\$ 270	\$ 278	\$ 286	\$ 295	\$ 304	\$ 313	\$ 322	\$ 332	\$ 342	\$ 352	\$ 363	\$ 374	\$ 385	\$ 397	\$ 408	\$ 421	\$ 433	\$ 446	
Capital Expenses (\$000)																						
Equity	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	
Debt Balance	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	
Interest	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	
Principal	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	
Debt Service (incl. Interest)	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	
Debt Service Coverage Ratio	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	
Depreciation (\$000)																						
Taxes (\$000)																						
Taxable Income	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	
Federal Taxes (21%)	\$ -	\$ 83.2	\$ 85.7	\$ 88.2	\$ 90.9	\$ 93.6	\$ 96.4	\$ 99.3	\$ 102.3	\$ 105.3	\$ 108.5	\$ 111.8	\$ 115.1	\$ 118.6	\$ 122.1	\$ 125.8	\$ 129.6	\$ 133.4	\$ 137.5	\$ 141.6	\$ 145.8	
State Taxes (8.84%)	\$ -	\$ 35.0	\$ 36.1	\$ 37.1	\$ 38.3	\$ 39.4	\$ 40.6	\$ 41.8	\$ 43.1	\$ 44.3	\$ 45.7	\$ 47.0	\$ 48.5	\$ 49.9	\$ 51.4	\$ 53.0	\$ 54.5	\$ 56.2	\$ 57.9	\$ 59.6	\$ 61.4	
Results (\$000)		\$ 347.2																				
Net Income	\$ -	\$ 136.3	\$ 176	\$ 182	\$ 187	\$ 193	\$ 199	\$ 205	\$ 211	\$ 217	\$ 224	\$ 230	\$ 237	\$ 244	\$ 252	\$ 259	\$ 267	\$ 275	\$ 283	\$ 292	\$ 300	
Net Cash Flow	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	



(c) The Marin Biomass Project, 2026.