SYNERGIES BETWEEN BECCS AND FOREST HEALTH TREATMENTS IN THE WESTERN U.S.

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Dr. Sinéad Crotty is the Associate Director of Science at the Yale Carbon Containment Lab. She has ten years of experience in experimental community ecology, ecosystem restoration, and environmental engineering. At the Carbon Containment Lab, Sinéad leads the design and deployment of field experimentation for the Biological Program, especially focused on utilization of forestry residues from western U.S. wildfire mitigation activities. Her previous work utilized primarily hypothesis-driven field experiments along with regional survey techniques, geospatial analyses, and modeling efforts to investigate the effects of climate change on biodiversity, stability and functionality of coastal ecosystems. Sinéad has conducted research across the many coastal systems of the eastern US, including salt marshes, sand dunes, mangroves, cobble beaches, and live oak savannas. Sinéad holds a Ph.D. from the University of Florida in Environmental Engineering Sciences (2019). Prior to her dissertation work, Sinéad received her Bachelor of Science in Biology (Honors) from Brown University in 2015.

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Dean Takahashi is the founder and executive director of the Yale Carbon Containment Lab (CC Lab). Previously, Dean was Senior Director of the Yale Investments Office for more than 33 years. During his tenure, the Yale Endowment was one of the world's top performing institutional funds, growing from $1.5 billion to more than $30 billion. Annual spending from Endowment increased from $49 million to $1.4 billion. Dean received his BA magna cum laude with distinction in Economics and his MPPM in 1983 from Yale University. A Lecturer in Economics since 1992 and Adjunct Professor at the Yale School of Management since 2006, Dean teaches a senior economics seminar and a course on endowment management. In 2018, he received the Merton J. Peck Prize for distinction and excellence in teaching in the Department of Economics. Dean is, or has been, a member of investment committees for numerous philanthropies such as the Kresge Foundation and Save the Children. Dean formerly served as a board member of a variety of community and educational organizations as well as two NYSE-listed investment companies. Prior to his employment at Yale, Dean worked at Affirmative Investments in Boston and as a VISTA volunteer in Vermont. During the financial crisis, he served briefly in 2009 as a Special Governmental Employee to help at the U.S. Department of the Treasury.

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Executive Summary

This Whitepaper explores the complementarities between restorative forest management practices and the deployment of bioenergy with carbon capture and storage (BECCS) in the western United States (California, Idaho, Nevada, Oregon, and Washington.) This is a region of particular importance given the mechanical thinning planned in response to elevated wildfire risk, which has the potential to generate large volumes of low-value biomass. This Whitepaper contributes to the forthcoming Energy Future Initiative (EFI) planned synthesis report *Taking Root: A Policy Blueprint for Responsible BECCS Development in the United States* . It is organized around three main research questions: what is the supply of low-value woody biomass and what are the opportunities for geological sequestration in the region?; what are the potential net emissions benefits of different options for removing and utilizing this biomass from a life cycle perspective; and what are the policy actions necessary to generate these benefits?

To estimate the total potential volume of woody biomass in the region (measured in bone dry tons [BDT] and in tons of CO_2e) we analyze Forest Inventory and Analysis (FIA) data for overstocked forest biomass in high wildfire-risk counties in the region that could be used in BECCS or other biomass-based technologies. We present four scenarios of biomass availability using relatively conservative assumptions for forest restoration treatments. We find that there is a stock of between 265 million and >1 billion BDT of overstocked biomass at risk of wildfire potentially available, an amount equivalent to 487-1,960 million tons (Mt) of CO_2e. Over 50% of this biomass is located in California.

We then investigate the potential *net* emissions benefits from the removal and utilization of this biomass from a life cycle perspective, comparing BECCS to different utilization or removal opportunities. We find that, depending on the system being deployed, the total net carbon storage for BECCS technologies ranges from 223-408 Mt CO2e in the most conservative biomass availability scenario, and 310-797 Mt CO2e when the benefits of substituting other products are included. Of the utilization options considered, hydrogen with CCS has the greatest net potential carbon benefits. In general, we find that products that displace carbon-intensive alternatives, like hydrogen, have large substitution benefits; and products with CCS have the highest net carbon storage potential.

Finally, we discuss policy actions with the potential to advance BECCS in the region, and that help generate climate, environmental, and economic benefits. While the opportunity to contribute to climate, energy and wildfire mitigation goals is increasingly recognized, the past 30 years have shown that there is a need for renewed policy and industry support to catalyze action. Given that the majority of the forestland in these five western states is federally owned, clear and consistent federal policy incentives are needed.

To advance this work and to successfully commercialize carbon-negative fuels under federal policy, we propose six recommendations:

1. Update the federal Renewable Fuel Standard's rules to include biomass from forests at high risk of wildfire
2. Allocate existing resources within the Department of Energy to better support BECCS, and expand future appropriations for BECCS programs
3. Enhance USDA's BECCS portfolio in the 2023 Farm Bill
4. Support market development and enhancement within the U.S. Forest Service
5. Enhance federal policy stability
6. Leverage federal and state procurement to catalyze market development for biomass derived products and bioenergy

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1. Introduction

Bioenergy can have climate benefits, especially when coupled with carbon capture and storage systems. However, the extent of the climate benefits depends on several factors, including the biomass source (how and where it is grown, harvested, transported); the processing methodology for energy applications, and the approaches to capture, treatment, storage and/or sequestration.[1] The extent to which forests can and should be used for bioenergy is controversial, especially in western states where there is a history of contested timber and logging practices, as well as ongoing debates over how best to address the increasing number of sever wildfires in the region.[2] It is difficult to generalize about the climate benefits and costs of BECCS compared to other renewable energy systems given that these vary largely on a regional basis and are often highly specific to the natural resources, infrastructure, technical, ecological, and socio-economic systems in question.

This Whitepaper explores the potential for bioenergy from residual and lower-value forestry biomass in the western U.S. states of California, Idaho, Nevada, Oregon and Washington. We chose these states as they have large forest biomass resources, a pressing need to gather and treat low value residual biomass to reduce wildfire risk and to improve forest health, as well as mostly supportive policies and programs designed to address climate change and support the growth of clean energy industries. Importantly, these states also boast significant geologic carbon storage resources which are thus far largely untapped and may help to realize the potential for BECCS from forests.

The research we undertook, as presented in this Whitepaper, was guided by the following key research questions:

1. What is the total amount of overstocked low value biomass in western states?
2. What are the potential life cycle carbon benefits of utilization of overstocked biomass at scale in the region?

3. How can the development of the BECCS industry in western states contribute to state and federal climate and forest management goals; and what recommended policy actions could help to realize the opportunity?

To tackle these questions, we first conducted a literature review on the wildfire history of the region, and the key forest and geologic storage resources potentially available, as well researched relevant federal and state policies. We sought out relevant publicly available forestry data sources, and defined key parameters including definitions of "overstocked" forests and wildfire risk. With this data, we conducted an analysis for four different scenarios, generating initial results. We sought and received feedback on the methods and assumptions from 10 experts – both individually and in a workshop held on 17th of November, 2021 hosted by the Energy Futures Initiative.[a] In each section below, we describe our methods, assumptions, and key limitations.

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[a] Workshop attendees included: Whitepaper Authors (Yale/UC Berkeley), Sam Savitz (EFI), Michael Knotek (EFI), Nicole Pavia (EFI), Ansh Nasta (EFI), Alex Breckel (EFI), Keith Kline (ORNL), Daniel Jacobson (ORNL), Matt Langholtz (ORNL), Virginia Dale (University of Tennessee), Matt Donegan (OR Governor's Wildfire Council/Yale Carbon Containment Lab), Alice Favero (Georgia Tech), Paul Hessburg Sr. (USFS Research & Development), Sam Uden (Conservation Strategy Group), Meron Tesfaye (BPC), Christopher Galik (NC State). Feedback on the draft Whitepaper was also provided by Marc Daudon.

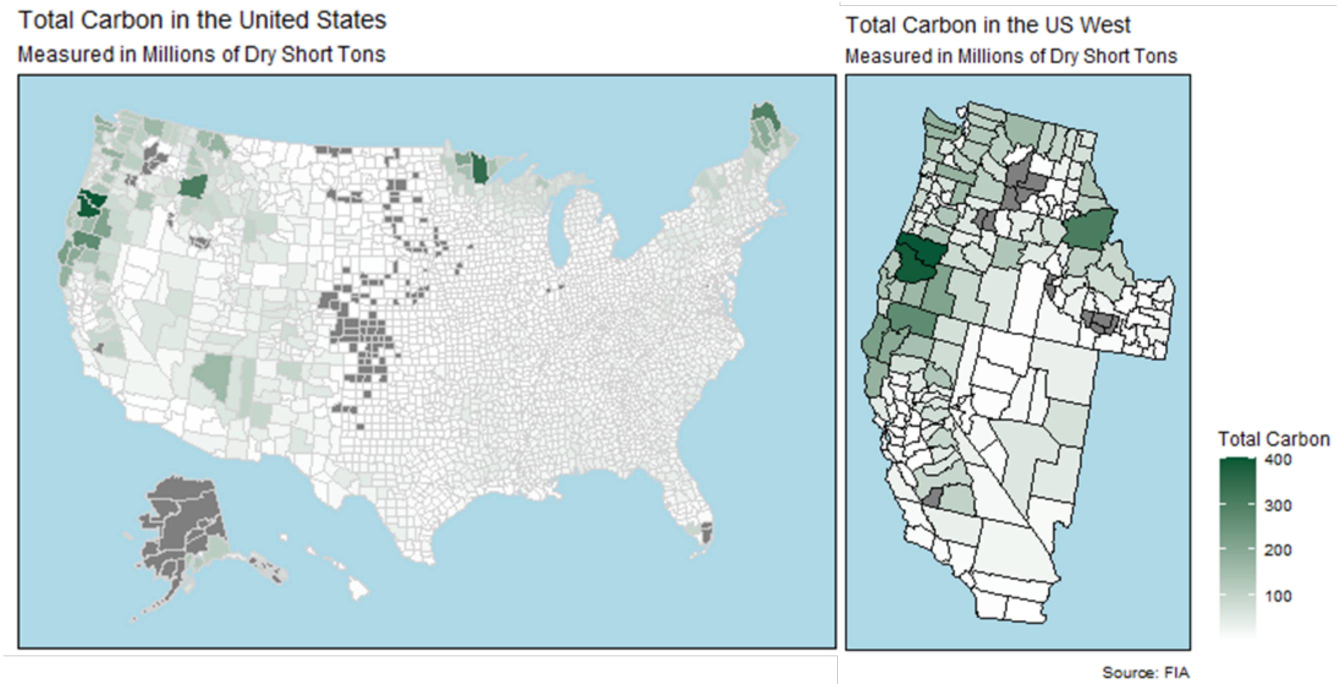
2. Overview of Western Forest and Geological Resources

2.1 Forest Carbon

Across the continental United States, forests represent the greatest land-based source of carbon storage. They hold, by some estimations, roughly 45% of the carbon stored on land.[3] In the United States, the Forest Inventory and Analysis (FIA) program collects and reports information on the status and trends of America's forests, tracking details concerning ownership, health, mortality, and removals. It is managed by the Research and Development organization within the USDA Forest Service through a joint effort with the State and Private Forestry and National Forest Systems and has been continuously publishing reports since its inception in 1930. The FIA uses tens of thousands of monitored plots across the country to record detailed annotations every couple of years regarding a host of features, including basal area, tree size, species, and an estimation of the quantity of carbon stocks. These carbon stocks are broken out across several key carbon pools, including downed woody debris, aboveground biomass, and soil carbon content.

In total, there are 47.2 billion tons of carbon tracked by the FIA across forested counties in the United States. FIA data indicate that Washington and Oregon host 5.7 billion tons of carbon stored in woody biomass, while California has 2.6 billion tons (as shown in Figure 1). Of this 47.2 billion tons of carbon, FIA data estimates that 4.0 billion tons are located in "overstocked" locations, indicating that they may be at higher risk of severe wildfire and/or disease.

Figure 1. Total forest carbon in the United States measured in millions of tons of carbon (left). Total forest carbon in western states measured in millions of tons of carbon (right).



Counties with no data are colored dark gray. Source: Yale CC Lab analysis of FIA data, 2021.

2.2 Climate Change and Wildfire Pressure

Anthropogenic climate change is increasing the frequency, extent, and severity of wildfires in forested ecosystems.[4] In the American West, wildfire hazard has increased for decades, driven largely by changes in forest structure and fuel moisture.[5] Meanwhile, land and fire management practices have exacerbated the hazard by promoting a build-up of fuel in overstocked forests.[6] Population and economic growth in key regions have also increased human exposure to fires, and these health impacts are becoming a pressing environmental justice issue as vulnerable populations are more affected by worsening air quality conditions.

The combined result has been a series of catastrophically damaging fires in 2017, 2018, 2020, and 2021. These changes to wildfire regime are costly ($150 billion annually in CA alone[7]) and have the potential to alter forest carbon dynamics and their overall sequestration potential.[8] For example, models project that climate change will drive large increases in area burned (76%–310%) and burn severities (29%–41%) in the American West by 2100.[9]

There is some disagreement in the scientific literature regarding the exact quantification of the carbon effects of wildfire. However, even the most conservative estimates suggest that western U.S. forest fires have emitted 851 ± 228 million metric tons of CO_2 between 2000 and 2016.[10] In 2020 alone, wildfires emitted over an estimated 100 million metric tons of CO_2 in California, equivalent to the emissions of 21.5 million gasoline-powered vehicles driven for one year.[11] Ultimately, with the increasing frequency and intensity of wildfire associated with climate change, scientists agree that there will likely be an upward trajectory of wildfire-related carbon emissions in the coming decades unless forest restoration of high-risk, overstocked lands is substantially increased in its pace and extent.

2.3 Forest Restoration

Forest restoration for wildfire hazard reduction often involves the use of two primary approaches — mechanical thinning and prescribed burning — both used to preemptively reduce fuel loads and therefore reduce wildfire severity. These actions garner a carbon benefit by reducing wildfire severity (thereby reducing the volume of carbon being emitted through combustion) and promoting greater tree survivorship in the event of a fire.[12] Thinning beneath the forest canopy to remove small diameter "ladder fuel" trees and to reduce surface fuel decreases the likelihood that a fire will burn at a high intensity.[13] Over a 50-year period, fuel treatments have been shown reduce wildfire emissions by 46% compared to un-managed forests in the Sierra Nevada, but the effects of these treatments on carbon storage are dependent on the frequency and severity of fires so can be difficult to predict.[14]

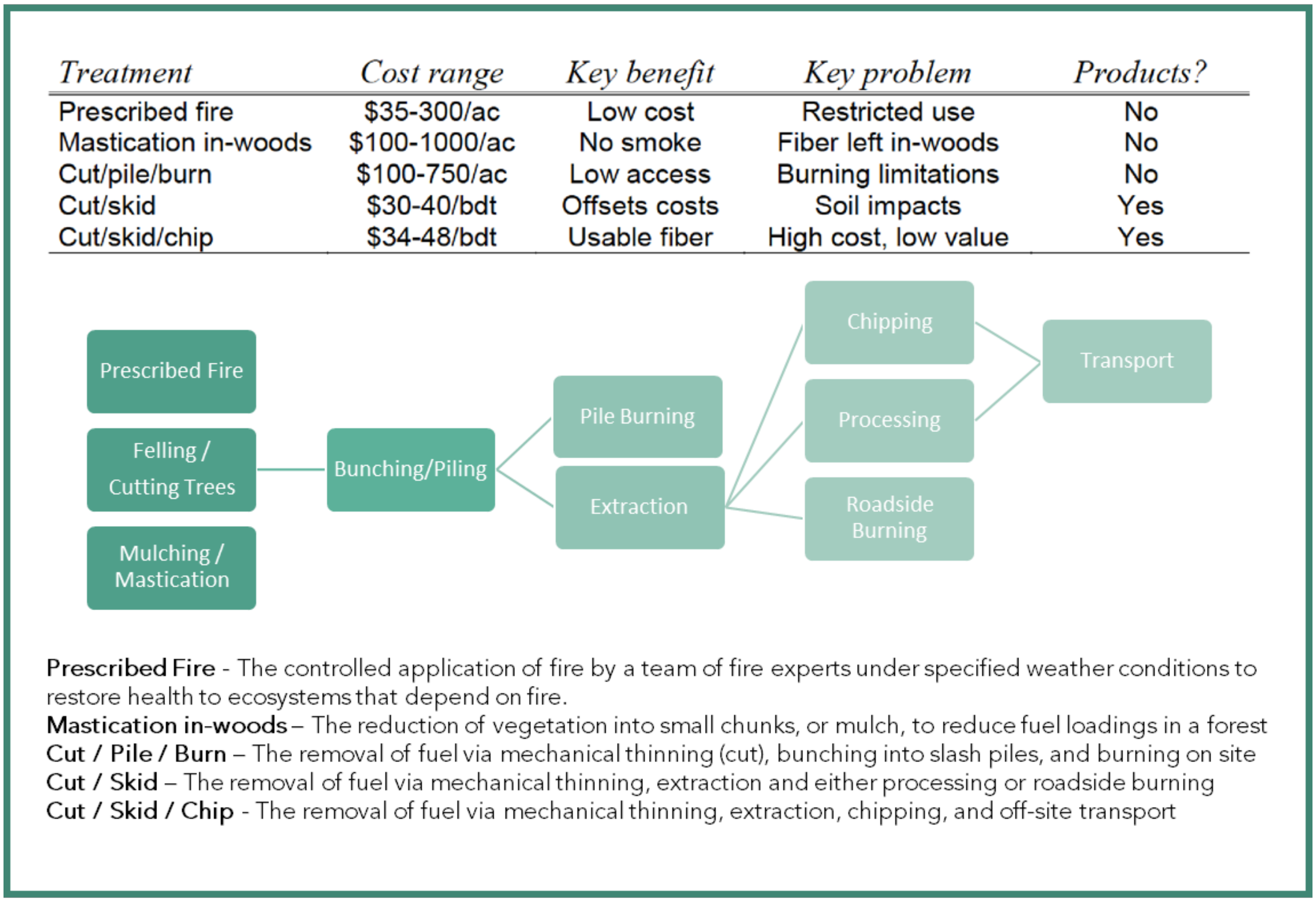
Both models and empirical work suggest that the effects of fire management activities on carbon are context-dependent.[15] However, in areas of high fire risk, the long-term carbon sequestration potential of forests is >125% higher in forests that are treated compared with un-managed forests. Further, owing to high mortality after a fire, un-managed forests have

>250% more carbon in decomposing stocks than managed forests.[16] Simulations in such high-risk areas suggest that un-managed forest plots will emit two to three times more carbon over the next century than managed forests with reduced fuel loads.[17] Therefore, employing a strategy that prioritizes treating a sufficient percentage of the landscape most prone to fire will help to mitigate high severity fire, its associated health and safety effects, and the associated carbon emissions at the landscape level.[18]

To provide perspective on the enormous scale of the treatment needed, on federal land alone, estimates say that more than 60 million acres — an area the size of Oregon — are at risk of unnaturally severe fires.[19] Constrained funding has limited forest restoration to less than 5% of the target regions,[2] leaving both forest carbon and proximate human populations vulnerable to the effects of severe wildfires. Restoring this land would require a massive increase in the pace and scale of annual treatments. It would also potentially generate significant volumes of low value biomass, which could be utilized for bioenergy or building products, which may help to offset the costs of such operations. This type of financing may be needed, as it is both logistically difficult and costly to perform large scale forest restoration particularly on challenging and hard to access terrain.

Incentives and funds to do this difficult work have been lacking. A U.S. Forest Service research report listed costs of each restoration activity as ranging from $35 - $1,000 per acre in 2003.[20] While those costs may seem reasonable at first glance, restoration projects often require multiple activities to be implemented on the same acre (for instance, prescribed burning is often preceded by thinning; see Table 1). Labor shortages, the difficulty of accessing sites, and other planning constraints also add to costs.

Table 1. Comparison of fuel reduction treatment alternatives (source: Rummer et al. 2005).[21]



Treatment	*Cost range*	*Key benefit*	*Key problem*	*Products?*
Prescribed fire	$35-300/ac	Low cost	Restricted use	No
Mastication in-woods	$100-1000/ac	No smoke	Fiber left in-woods	No
Cut/pile/burn	$100-750/ac	Low access	Burning limitations	No
Cut/skid	$30-40/bdt	Offsets costs	Soil impacts	Yes
Cut/skid/chip	$34-48/bdt	Usable fiber	High cost, low value	Yes

Prescribed Fire - The controlled application of fire by a team of fire experts under specified weather conditions to restore health to ecosystems that depend on fire.
Mastication in-woods – The reduction of vegetation into small chunks, or mulch, to reduce fuel loadings in a forest
Cut / Pile / Burn – The removal of fuel via mechanical thinning (cut), bunching into slash piles, and burning on site
Cut / Skid – The removal of fuel via mechanical thinning, extraction and either processing or roadside burning
Cut / Skid / Chip - The removal of fuel via mechanical thinning, extraction, chipping, and off-site transport

Forest restoration tends to cost thousands of dollars per acre.[22] This large range in price is attributable to site differences: slope, stand density, surface fuels, proximity to watersheds, re-entry, time of year, proximity to roads, and other characteristics. As demand has risen for these mitigation methods throughout the first two decades of the 21st century, it has been difficult to scale operations to the extent needed to make western forests resistant to wildfire. Aside from gaining the necessary funding, social barriers have included timing and social acceptance for prescribed burns given smoke impacts and concerns over the risk of uncontrolled fires.

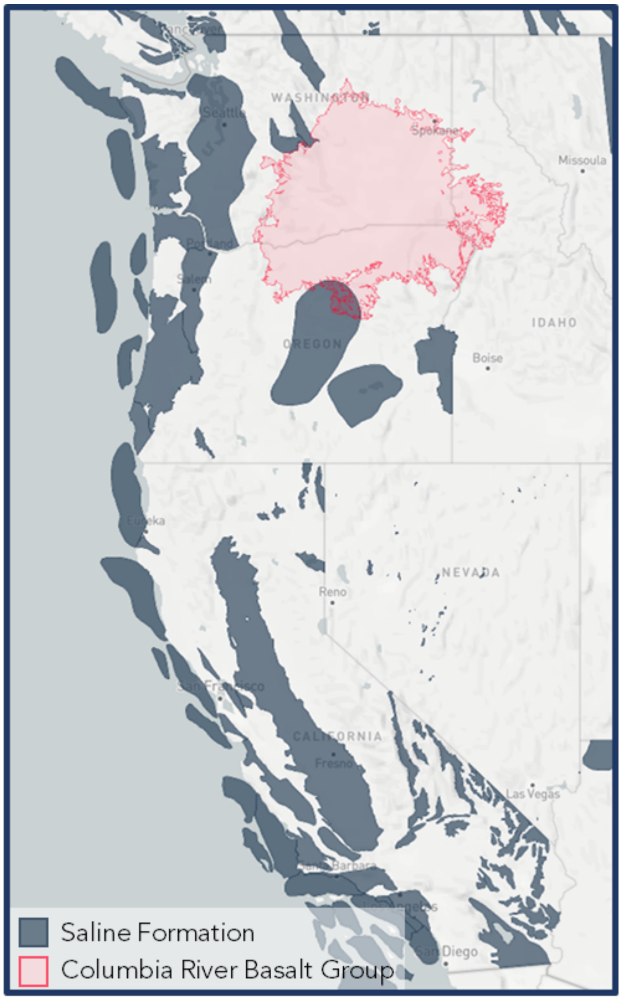
Nonetheless, this biomass can be safely removed to reduce fire risk and utilized to store carbon. In addition, the avoided economic damages from severe wildfire can be substantial. While market demand for this low-value wood is weak and does little to help defray the costs of forest restoration, development of a BECCS industry or other low value biomass utilization markets could have very large positive impacts on forest carbon, on economic resilience, and on human health.

2.4 Key Carbon Storage Opportunities

The western U.S. has several major geologic formations that could potentially be utilized for carbon storage for CO2 sourced from biomass, direct air capture, or other industrial point sources, as shown in Figure 2. The U.S. Department of Energy and many others are investigating the capacity, feasibility, and safety of each of these geologic formations to store carbon long-term, or even permanently.[23] Aside from understanding the geologic formations, studies are being undertaken to map the needed infrastructure to cost effectively move CO_2 from sources to sequestration sites, especially in contrast to other US regions such as the Gulf Coast where energy infrastructure already exists.

The most mature geologic storage technique is CO_2 sequestration worldwide is in *deep saline aquifers*. Saline formations are widespread brine-saturated sedimentary permeable and porous rocks formed in layers at depths of relevance for geologic storage.[24] An extensive caprock is required to seal or trap CO_2 in the porous rock layer. Trapping mechanisms can include: solubility trapping, mineral trapping, structural trapping, and residual trapping.[25] In the U.S., most pilot projects were initially established under the Department of Energy's (DOE) Regional Carbon Sequestration Partnership program.[26]

Figure 2. Key carbon storage opportunities in the western U.S., including saline formations (blue polygons) and the Columbia River Basalt Group (CRBG; red polygon).



The only U.S. facility injecting the CO_2 solely for geologic sequestration currently is the Archer Daniels Midland (ADM) facility in Decatur, IL; although there are many more currently in development across the country. At this facility, CO_2 is captured from the production of ethanol and is subsequently injected into a saline reservoir. As of 2019, 1.5 million metric tons of CO_2 had been injected at the site.[27] Further, estimates from the WESTCARB Regional CCS partnership, an organization led by the California Energy Commission (CEC) and the U.S. DOE, suggest that the CO_2 storage capacity of saline formations in the ten largest basins in California alone ranges from 150 to 500 gigatons. Across the whole of the US, estimates of storage capacity in saline formations range from 2,618 Gt to 21,978 Gt.[28]

Another storage option of relevance to western states is in-situ carbon mineralization of mafic and ultramafic basalt rocks.[29] The presence of both a reservoir with sufficient injectivity and a seal to prevent migration are necessary conditions for a CO_2 storage site.[30] When CO_2-bearing fluids or supercritical CO_2 are injected at depth into geologic formations, the sequestration of CO_2 in the subsurface porosity relies on the impermeability of the caprock of the reservoir.[31] Basalt formations are prominent in the Pacific Northwest, where solidified lava flows form a massive series of formations known as the Columbia River Basalt Group (CRBG). Because basalts contain high concentrations of calcium and magnesium ions that chemically react with CO_2 to make calcite, dolomite, and magnesite, the CO_2 can be permanently mineralized and therefore stored as a solid carbonate. A pilot test of this approach was undertaken by the Pacific Northwest National Lab (PNNL) and partners in 2013, and further characterization is currently being conducted by Yale University's Carbon Containment Lab to understand its potential for BECCS. PNNL studies estimated that the CRBG may have a storage capacity of 100Bn tons of CO_2, though not all of this will be permittable or easy to access.[32]

In addition to options of injecting in geologic formations, researchers are investigating the possible storage of CO_2 in depleted oil and gas wells, especially in California where many such wells exist. For example, the "Getting to Neutral" study led by Lawrence Livermore National Lab (LLNL) found two main oil and gas regions in California that could potentially securely hold "at least 17 billion tons" of CO2… with the upper limit being 200 billion tons".[33]

3. RESEARCH QUESTION 1: What is the Total Amount of Overstocked, Low Value Biomass in Western U.S. States?

To assess the potential for a BECCS industry to support the restoration of overstocked U.S. forests and mitigate severe wildfire risk, a key first step is to quantify the total stock of low value biomass in need of removal and utilization. To do so, we focus our efforts on the American West, a region defined for the purposes of this whitepaper to include California, Idaho, Nevada, Oregon, and Washington.

In the following section, we present the methodology and results for four model scenarios of biomass availability based on Forest Inventory and Analysis (FIA) datasets. The four scenarios are built from different base assumptions about biomass use and accessibility, presenting a range of conservative to liberal predictions. We address key limitations to our study and conclude by providing recommendations for next steps of work.

3.1 Methods

For our forest biomass model, we used published data sourced from the FIA Evalidator tool [34] a custom query database that allows for segmenting, exploring, and summarizing current carbon stocks in the U.S. To select and quantify biomass availability based on limiting criteria and/or assumptions, we submitted a selection of custom queries to the Evalidator tool to report and record results on a county-level.

Key assumptions relevant to all scenarios included the following:

Region

We included biomass available from California, Idaho, Nevada, Oregon, & Washington. The rationale for including these states is that they are at significant risk of severe wildfire and have the largest quantities of overstocked biomass compared to other regions in the U.S.

Reserved Status

The FIA provides distinctions between available and reserved forest land, with the lat ter defined as land permanently reserved from wood products utilization through statute or administrative design. Examples include but are not limited to National Forest wilderness areas and National Parks and Monuments. We elected to remove reserved forest land from our considerations of available biomass.

Wildfire Hazard Potential

Wildfire Hazard Potential refers to an index that quantifies the relative potential for wildfire that may be difficult to control. This value can be used as a measure to help prioritize where fuel treatments may be needed. For the purposes of the model, we selected only counties that are in the top 35% of highest wildfire hazard potential nationally, as reported by USDA[35].

Desired Stocking Level

The FIA provides a prescriptive level of biomass which it considers to be a “full” level of stocking to individual trees, forest types, stand sizes, and stocking classes in all Forest Inventory and Analysis plots nationwide. These are assigned using species specific functions of diameter developed from normal yield tables and stocking charts. Plots are designated as fully stocked if they are 60-100% of the value considered to be full. In practice, depending on characteristics of the forest plot of interest, mechanical thinning efforts reduce biomass to as low as 40% of full stocking. However, as a conservative estimate, we set all model scenarios to remove biomass to 80% of full stocking levels.

Standing Deadwood

Defined as remnants of once living trees that are still self-supported and leaning less than 45 degrees from vertical, standing deadwood is a large pool of biomass potentially available for use by BECCS facilities. Given lower structural stability of advanced decay classes, we conservatively limit the inclusion of deadwood to those pools that are standing and in Decay Class 1[36] to ensure safety of removal efforts. We anticipate that the pools of deadwood available for use, both standing and downed, may in fact be much larger.

Accessibility

For our final restriction across all scenarios, we removed all areas with a slope greater than 40%. Our reasoning for this final limitation to the dataset was to focus on areas that were accessible and safe to operate machinery on.

For the four model scenarios, the following two metrics were varied to represent conservative and liberal approaches (see Table 2):

Biomass Types

The aim of forest restoration treatments is to remove the low value, small diameter biomass. However, some forest plots will require removal of larger diameter trees to reach desired stocking levels. Given that larger boles are potentially merchantable, we set the following strategy; on all overstocked plots, the smallest diameter biomass was removed first, with removal occurring in ascending order until the desired stocking level was achieved.

For the conservative estimate, we included only the overstocked biomass under 9-inches in diameter in the analysis (assuming that all larger diameter classes would be removed for use in other industries).

Meanwhile, for the more liberal estimate, we included woody biomass <12inches in diameter as well as the tops of larger trees removed (to meet optimal stocking of 80%). Tops, by FIA definition, are the wood of a tree above merchantable height, or above the point on the stem 4.0 inches diameter outside bark, including the usable material in the uppermost stem.

Distance from Road

The FIA reports biomass availability at seven distances from existing road structures: ≤100-ft., ≤300-ft., ≤500-ft., ≤1000-ft, ≤½ mile, ≤1 mile, ≤3 miles, and ≤5 miles. Selection of one of these distances restricts the area considered to those where the straight-line distance to the nearest improved road (a road of any width that is maintained as evidenced by pavement, gravel, grading, ditching, and/or other improvements) is within the given range.

For the conservative estimate, we limit the calculation to include only biomass available within 1000-ft. from existing road structures.

For the liberal estimate, we permit any biomass that meets all other criteria with no limitation on distance from roads.

Table 2

Scenario 1 (Conservative)	Biomass Type: <9-in diameter wood (no tops) Distance from Road: 1000 ft
Scenario 2	Biomass Type: <12-inch diameter and tops Distance from Road: 1000 ft
Scenario 3	Biomass Type: <9-in diameter wood (no tops) Distance from Road: All
Scenario 4 (Liberal)	Biomass Type: <12-inch diameter and tops Distance from Road: All

3.2 Results

The locations included are forestlands from our selected region, on non-reserved land, and in a county in the top 35% of wildfire hazard risk. Within these selected locations, we quantify the amount of biomass that would be available if stocking levels were brought from current reported values to 80% of full stocking levels. We additionally assume that Decay Class 1 standing deadwood is available and safe for harvest. Finally, we removed all areas with a slope greater than 40% to account for accessibility limitations. Within this selection of locations and available biomass, we then applied each of our four scenarios ranging from conservative (scenario 1) to liberal (scenario 4).

We estimate that there is between *265 million and 1.07 billion bone dry tons of woody biomass available* to support the development of a BECCS industry. This is equivalent to between 487 million and 1.96 billion tons of carbon dioxide (see Table 3 for full model results, below).

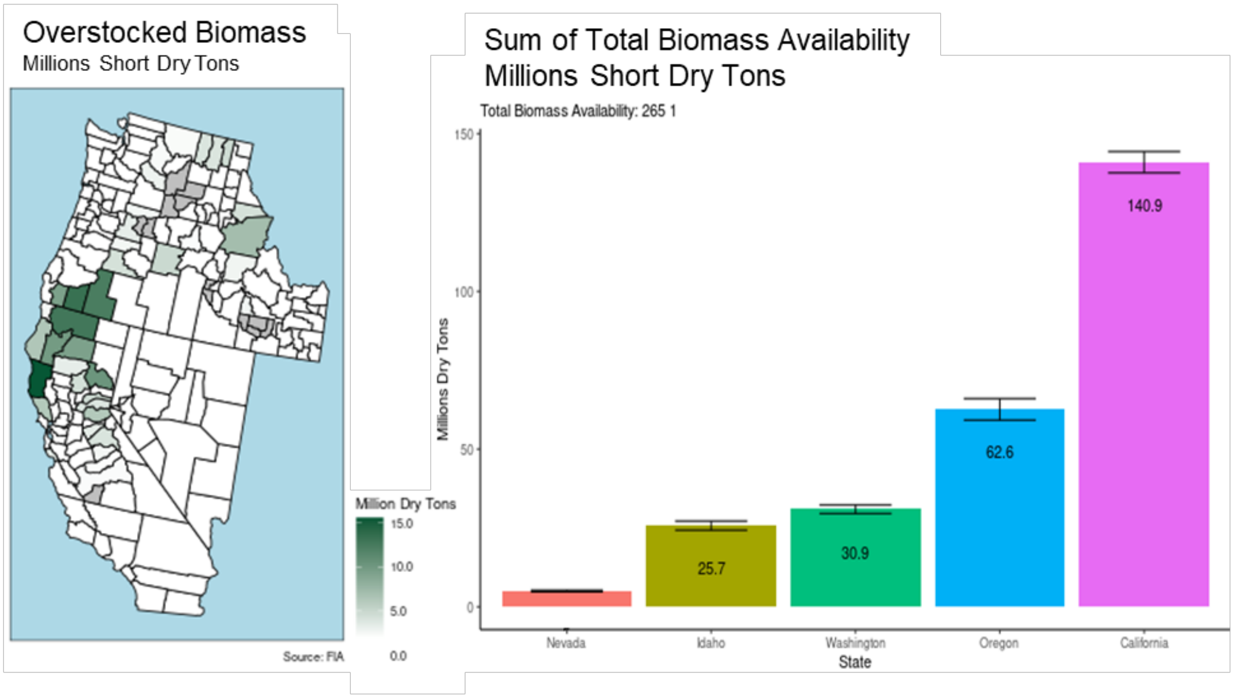
Table 3

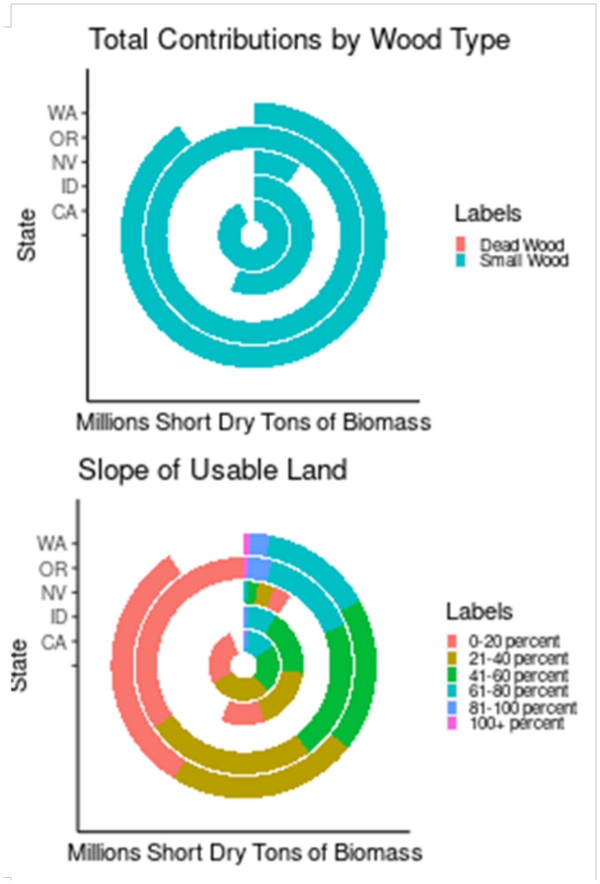
Scenario 1 (Conservative)	Bone dry tons: 265 million CO2 equivalent: 487 million
Scenario 2	Bone dry tons: 424 million CO2 equivalent: 778 million
Scenario 3	Bone dry tons: 642 million CO2 equivalent: 1.18 billion
Scenario 4 (Liberal)	Bone dry tons: 1.01 billion CO2 equivalent: 1.96 billion

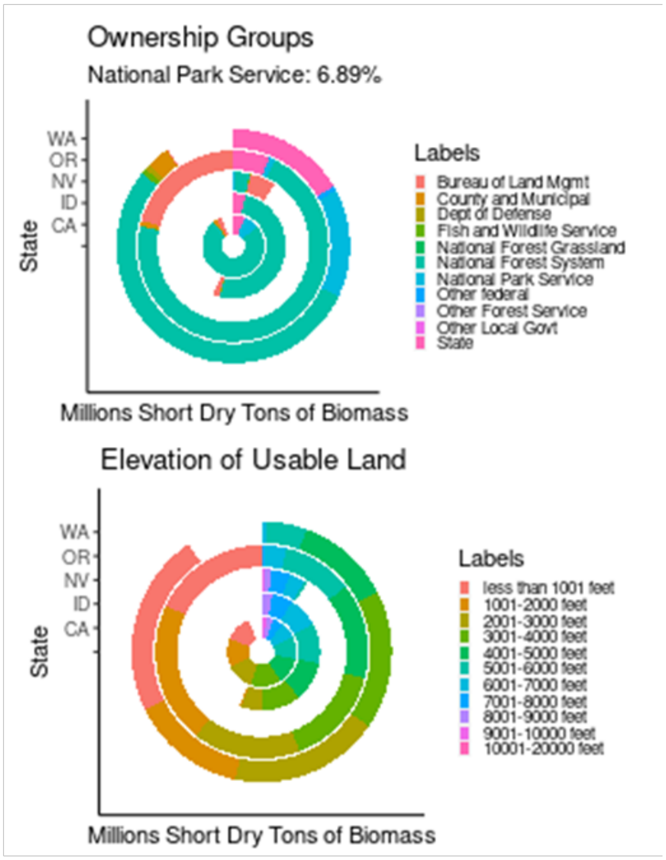
In the following pages, we present finer resolution data for the most conservative (scenario 1) and liberal (scenario 4) scenarios. Specifically, we first provide a map of available biomass from counties that met the wildfire hazard potential cutoff (top 35%), as well as the sum totals across states in a bar plot. Error bars are provided in scope with the uncertainty attached to the underlying calculations on generalized FIA data. Counties with missing data are grayed out and removed from consideration. White counties represent regions that do not meet the criteria, or where there is no available biomass that fit within the customized restrictions.

The bottom panels further describe the available biomass and characteristics of the forestland and ownership groups. The top-left plot highlights the breakdown by wood type. The top-right plot gives the dry tons of biomass by ownership group. The bottom two panels report the amount of biomass available across slopes and elevations.

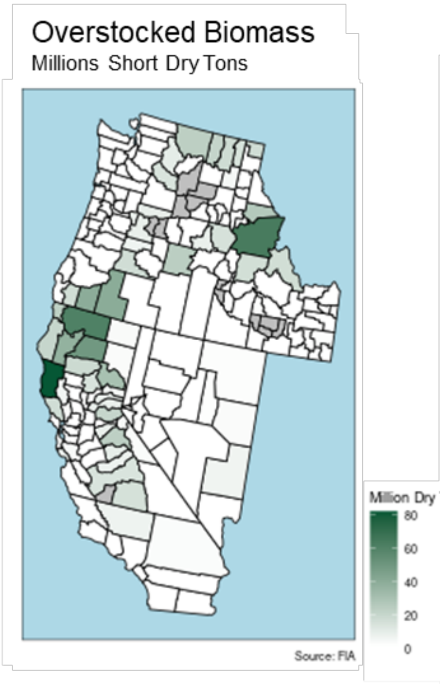
SCENARIO 1

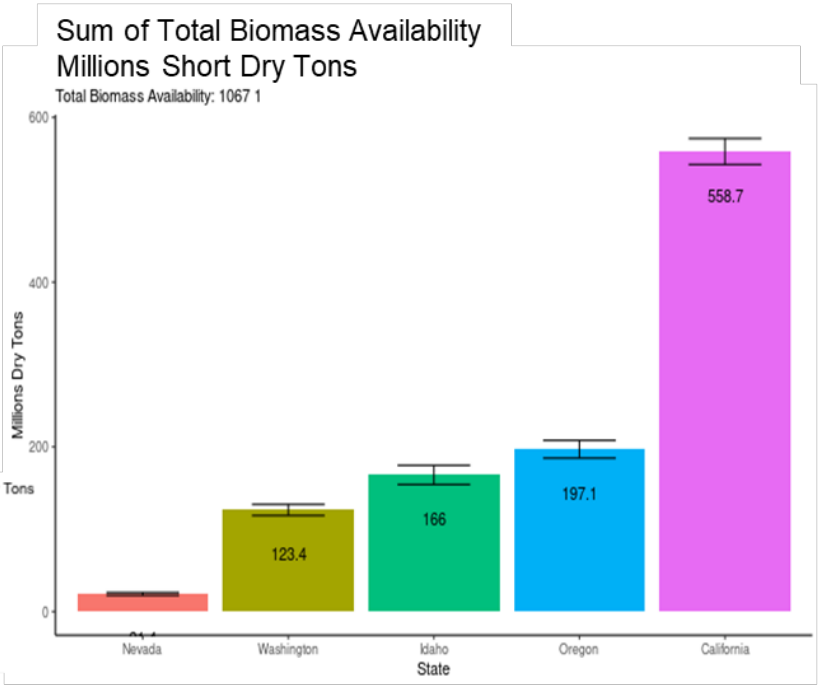

Overstocked Biomass
Millions Short Dry Tons
Million Dry Tons
15.0
10.0
5.0
0.0
Source: FIA
Sum of Total Biomass Availability
Millions Short Dry Tons
Total Biomass Availability: 265 1
150
100
50
0
Millions Dry Tons
25.7
30.9
62.6
140.9
Nevada
Idaho
Washington
Oregon
California
State

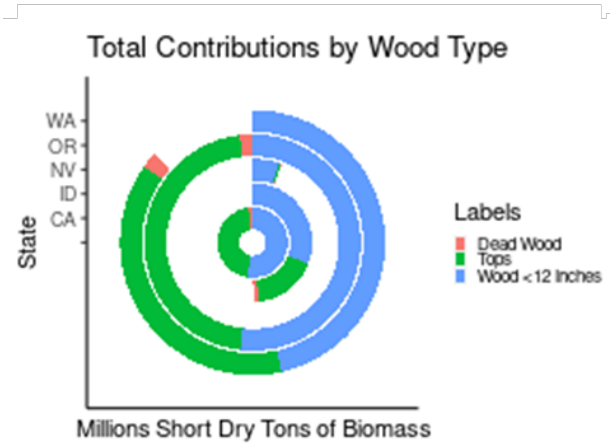

Total Contributions by Wood Type
WA
OR
NV
ID
CA
State
Labels
Dead Wood
Small Wood
Millions Short Dry Tons of Biomass
Slope of Usable Land
WA
OR
NV
ID
CA
State
Labels
0-20 percent
21-40 percent
41-60 percent
61-80 percent
81-100 percent
100+ percent
Millions Short Dry Tons of Biomass

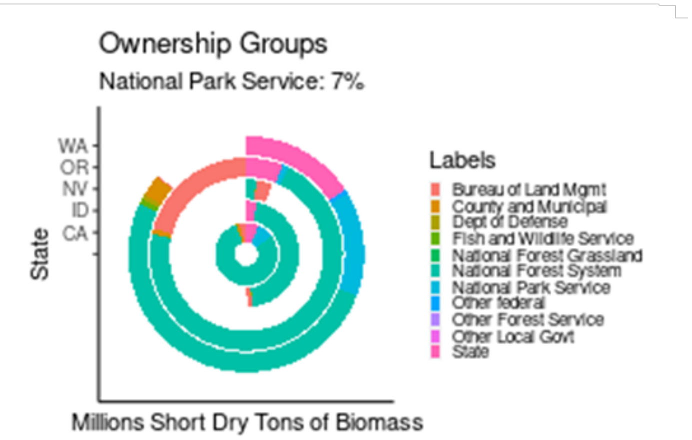

Ownership Groups
National Park Service: 6.89%
WA
OR
NV
ID
CA
State
Labels
Bureau of Land Mgmt
County and Municipal
Dept of Defense
Fish and Wildlife Service
National Forest Grassland
National Forest System
National Park Service
Other federal
Other Forest Service
Other Local Govt
State
Millions Short Dry Tons of Biomass
Elevation of Usable Land
WA
OR
NV
ID
CA
State
Labels
less than 1001 feet
1001-2000 feet
2001-3000 feet
3001-4000 feet
4001-5000 feet
5001-6000 feet
6001-7000 feet
7001-8000 feet
8001-9000 feet
9001-10000 feet
10001-20000 feet
Millions Short Dry Tons of Biomass

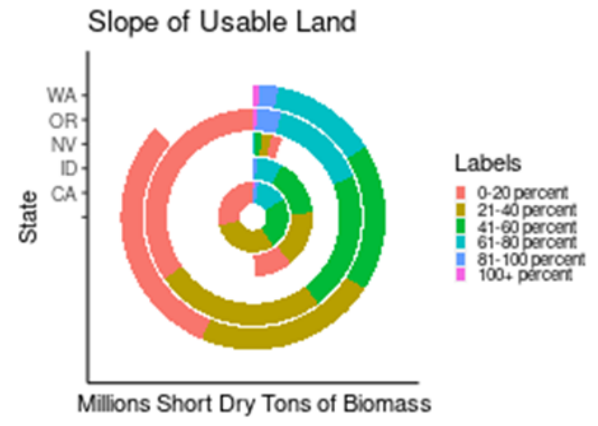
SCENARIO 4

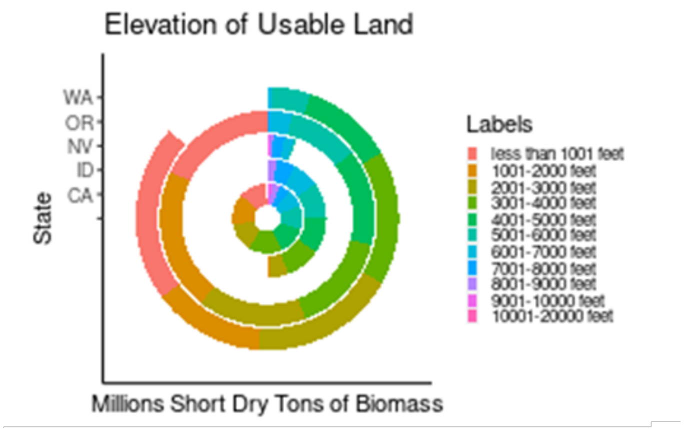

Overstocked Biomass
Millions Short Dry Tons
Million Dry Tons
80
60
40
20
0
Source: FIA


Sum of Total Biomass Availability
Millions Short Dry Tons
Total Biomass Availability: 1067.1
Millions Dry Tons
600
400
200
0
123.4
166
197.1
558.7
Nevada
Washington
Idaho
Oregon
California
State


Total Contributions by Wood Type
State
WA
OR
NV
ID
CA
Labels
Dead Wood
Tops
Wood < 12 Inches
Millions Short Dry Tons of Biomass


Ownership Groups
National Park Service: 7%
State
WA
OR
NV
ID
CA
Labels
Bureau of Land Mgmt
County and Municipal
Dept of Defense
Fish and Wildlife Service
National Forest Grassland
National Forest System
National Park Service
Other federal
Other Forest Service
Other Local Govt
State
Millions Short Dry Tons of Biomass


Slope of Usable Land
State
WA
OR
NV
ID
CA
Labels
0-20 percent
21-40 percent
41-60 percent
61-80 percent
81-100 percent
100+ percent
Millions Short Dry Tons of Biomass


Elevation of Usable Land
State
WA
OR
NV
ID
CA
Labels
less than 1001 feet
1001-2000 feet
2001-3000 feet
3001-4000 feet
4001-5000 feet
5001-6000 feet
6001-7000 feet
7001-8000 feet
8001-9000 feet
9001-10000 feet
10001-20000 feet
Millions Short Dry Tons of Biomass

3.3 Discussion and Limitations

- Scenario 1: In the most conservative scenario, we see that the largest quantities of overstocked biomass are located in northern California and southern Oregon, while Eastern Washington, Oregon, and central Idaho have the smallest quantities. When summed across states, we see that California contributes the greatest amount of overstocked biomass, with over 140 million bone dry tons. No standing dead biomass is included in this material. The major landowner was the National Forest System, and two-thirds of the available area was on slopes <40%.

- Scenario 4: In the most liberal scenario, we again see large amounts of overstocked biomass in northern California and southern Oregon. Eastern Washington, Oregon, and California as well as central Idaho exhibit far larger quantities than in the more conservative scenario. When summed across states, we again see that California contributes the greatest overall amount of overstocked biomass, over 558 million bone dry tons. Small amounts of standing dead biomass were included in this material, and approximately 40% of the available biomass was derived from tops of larger diameter trees. Again, the major landowner was the National Forest System, and two-thirds of the available area was on slopes <40%.

- While imperfect as an exact measure of available biomass, this model demonstrates that there are hundreds of millions of bone dry tons of biomass available in the American West. It highlights geospatial hotspots of available biomass in areas where wildfire hazard potential is highest, and it demonstrates that the majority of this material is on accessible land. The majority of the thinned biomass is on USFS land however, so addressing this issue with thus require federal buy-in.

- Finally, we discuss some limitations inherent in the model's data sources in order to provide a framework for how it can be improved for future use:

- FIA county level data provides estimates of carbon pools using a select number of monitored plots to extrapolate wider estimations. At a high level, these values are robust and benefit from the generalization of modeling. However, as we narrow our fields of interest, we reduce the relevant sample size and produce less robust estimates.

- Due to the complexity of calculation for reserved forest land, the project adjusts available biomass by a proportion of the land in each county that is "reserved" by the FIA definition. This limits the granularity, and leaves open the possibility that all candidate land does not have equal proportions of reserved forest land.

- The project relies on relatively coarse measures of forest health delineated by the USFS FIA program. These measures are imperfect and not universally accepted. Distinctions about full stocking status are highly dependent on specific environmental conditions, and a multitude of prescriptive analyses might provide a range of possible values. Any results based on these measures may generate controversy, particularly in the context of bioenergy technologies.

- The project uses wildfire hazard data that describe current and historic conditions, which may not best represent projected conditions for forest health and wildfire risk. As population dynamics, flood and draught patterns, and active management schemata alter the growth and wellbeing of forests, so too will the climactic conditions and relative rates of risk evolve.

- While efforts were made to adjust for accessible lands by removing National Park Service forests and biomass on extreme slopes, other potential and undocumented factors such as unwilling ownership groups (Fish and Wildlife Service, Department of Defense, small landowners), additional protections, and geographic inaccessibility may interrupt access to lands.

- The actual implementation of these forest treatments is highly dependent on economics and, subsequently, the financial viability of BECCS technologies is highly dependent on delivered feedstock cost. We were unable to capture these economic factors in this report.

- While fuel reduction treatments (i.e., mechanical thinning) are likely to reduce fire risk if conducted on a large spatial scale, they need to be maintained regularly by prescribed fire (or further mechanical thinning) in order to have effects that last beyond the first 5-10 years.

4. RESEARCH QUESTION 2: What are the potential net emissions benefits from removal and utilization of overstocked biomass at scale in the region?

Given the large volumes of biomass available, we investigate the life cycle carbon benefits of different biomass use pathways. Pathways can vary across three important metrics: carbon physically stored in a product (e.g., biochar), carbon emitted in the production process of a product (e.g., smokestack emissions), and the potential carbon benefits from substituting a low-carbon product for a carbon-intensive one (e.g., substitution of low-carbon fuel for diesel). Characterizing the carbon benefits of forest biomass utilization requires careful comparison of these metrics across potential technology pathways.

To answer this research question, we model cradle-to-grave life cycle carbon outcomes for a suite of conventional and innovative biomass-based energy products. These products were chosen to represent a range of technically and economically feasible biomass uses in the near term. The intent of this exercise is to quantify the life cycle carbon benefits associated with each product on a per-unit basis (here, per BDT). These values can then be applied to biomass feedstock flows to estimate net carbon benefits associated with different management and biomass utilization scenarios.

4.1 Methods

For each biomass use pathway considered, we aggregate values from several published Life cycle Assessments (LCAs) and adjust those values where necessary to achieve consistency, largely following the methods used in Cabiyo et al., (2021).[37] We use a harvest-to-grave system boundary for the life cycle accounting of forest residue products over 40 years. Given the complexity of modeling in-forest carbon fluxes associated with growth, harvest, and disturbance, we assume biomass is carbon neutral. We include harvest and transport, production emissions, product substitution, and end-of-life. We consider one BDT of harvested wood as the primary unit of analysis. The assumptions and methods for each product are described below. For every product, we rely on LCA studies that have either a wells-to-wheels or cradle-to-grave system boundary. We normalize harvest and transport emissions for all products to be consistent with values used in The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model.[38] Where necessary, we adjust values so that forest residues are carbon neutral. We assume a travel distance of 145 km (90 mi) with backhaul. We test the effect of varied regional electric grid carbon intensities (Table 4) but, due to low sensitivity of results to grid carbon intensity, we assume the grid intensity of the WECC for all states.[39] Cumulative carbon benefits for each product pathway are given in Table 5. Extended descriptions of the methods used for each biomass use pathway are included in Appendix A.

Table 4. Grid carbon intensity of different regions within the study area

Grid region	*Grid carbon intensity (lbs CO_2e/MWh)*
WECC	953
California	422
Idaho	161
Nevada	747
Oregon	314
Washington	200

The LCA of *biochar production* relies on data from Roberts et al. (2010) and Woolf et al. (2010).[40] Roberts et al. (2010) analyze feedstocks most like the forest residues from thinning Western forests, and Woolf et al. (2010) provide general characteristics of biochar. We assume that biochar is produced from the slow pyrolysis of forest residues. The LCA of the *electricity with CCS* pathway relies on data from Sanchez et al. (2015) and Xie et al. (2011)[41]. We rely on the biomass integrated gasification combined cycle (IGCC) with CCS scenario in Sanchez et al. (2015).

The LCA of p*yrolysis fuels, with and without biochar co-production* primarily relies on Li et al. (2017), who present a techno-economic assessment of a 2000 t/day facility with red-oak (*Q. rubra)* feedstock[42]. In the default scenario, the non-condensable gas and biochar burnt for process heat is assumed to displace natural gas. We also model an alternative process in which biochar is reserved. The reserved biochar is assumed to be the same as described by Woolf et al. (2010), although it may have different properties given that it is produced via fast pyrolysis instead of slow pyrolysis.

For the LCA of *lignocellulosic ethanol with CCS* we rely on modeling done by McKechnie et al. (2011) and Liu et al. (2011).[43] We obtain relevant process information about forest biomass harvesting and operations from McKechnie et al. (2011), and fuels production with CCS from Liu et al. (2011). We analyze an E85 (85% ethanol, 15% gasoline) pathway from forest biomass.

For the LCA of *Fischer-Tropsch (FT) liquids production with CCS*, we rely on Xie et al. (2011)[44], who document various combinations of feedstocks for FT liquids generation, including 100% forest biomass. Xie et al. (2011) use GREET for their LCA using a well-to-wheels boundary: from biomass collection to tailpipe emissions. We harmonize this analysis with the assumptions used in other pathways, for example the regional power grid intensity.

For *hydrogen production with CCS*, we rely on the LCA conducted by Antonini et al. (2021) of hydrogen gas produced from wood waste[45]. We model their entrained flow gasifier with pre-combustion CO_2 capture and storage and harmonize it with the rest of the pathways modeled here. This process was chosen because it has the highest rate of carbon capture amongst all modeled hydrogen production processes. To model substitution benefits, we assume this hydrogen displaces conventional hydrogen produced from natural gas via steam reforming in California, which has a carbon intensity of 120 g/MJ.[46]

4.2 Results

We find a wide range of carbon benefits across potential biomass use pathways. We present these values using the comparable units of carbon benefit per BDT (tCO_2/BDT), or the amount of CO2 that is stored or avoided for each ton of dry feedstock used in a given biomass pathway. The potential climate benefits associated with the technologies we assess range from 0.40 tCO_2/BDT (biopower) to 3 tCO_2/BDT (hydrogen with CCS), inclusive of substitution benefits. When considering only net storage of carbon (i.e., storage minus process emissions), this range drops to -0.37 tCO_2/BDT (pyrolysis fuels) to 1.54 tCO_2/BDT (hydrogen with CCS). The products with the greatest carbon benefits are those that store most carbon in long-term sinks, particularly those with CCS. As a result, technology pathways with durable carbon storage may be essential to maximizing the carbon benefits associated with biomass utilization.

When applied to the biomass available in the region, we find a cumulative range of net carbon storage for BECCS technologies from 223-408 Mt CO2e for all years in Scenario 1, the most conservative scenario. This range represents the atemporal amount of carbon benefit attainable through use of all forest residues modeled in Scenario 1. The inclusion of substitution benefits increases this range to 310-797 Mt CO2e. In Scenario 4, net carbon storage ranges from 848-1555 Mt CO2e, or 1182-3040 Mt CO2e when substitution benefits are included. In Figures 7 and 8, we show the potential total carbon benefits if all biomass from forest treatments were used in each technology pathway for scenarios 1 and 4 presented in the previous section.

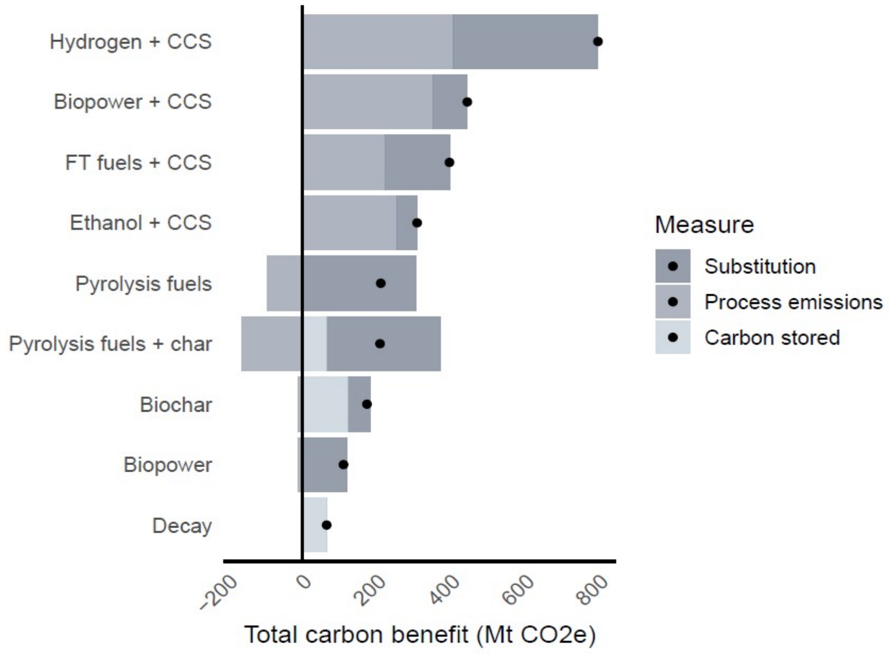
Across this mix of biomass-use pathways, there is a wide range of potential carbon outcomes. Some emerging technologies, like biomass-based hydrogen with CCS, show significant potential because of high substitution benefits and sequestration of nearly all carbon in biomass. Conversely, biopower without CCS has very low carbon benefits because nearly all biomass carbon is emitted. Biopower without CCS is relatively widely deployed today, but significant carbon gains could be achieved through the deployment of CCS on these existing facilities. In general, the pathways with high rates of CCS have the greatest carbon benefits, which precludes liquid transportation fuels from achieving maximal carbon benefits. Some of these, like FT-fuels with CCS, still have significant carbon benefits when substitution is accounted for, though. In reality, a mix of these technologies would likely be necessary to accommodate such a large supply of biomass.

Table 5. Life cycle carbon benefits for nine forest residue product pathways, in terms of tons CO2 benefit/BDT in feedstock.

Forest residue pathway	*Substitution*	*Process emissions*	*Carbon storage*	*Net storage*	*Key references*
Pyrolysis fuels	1.17	-0.37	0.00	-0.37	41, 44, 46
Pyrolysis fuels + char	1.17	-0.62	0.26	-0.36	44
Biopower	0.44	-0.04	0.00	-0.04	42
Decay	0.00	0.00	0.26	0.26	37
Biochar	0.22	-0.04	0.48	0.44	40, 41
FT fuels + CCS	0.66	0.84	0.00	0.84	49
Ethanol + CCS	0.22	0.95	0.00	0.95	47, 50
Biopower + CCS	0.37	1.32	0.00	1.32	42
Hydrogen + CCS	1.47	1.54	0.00	1.54	51, 52

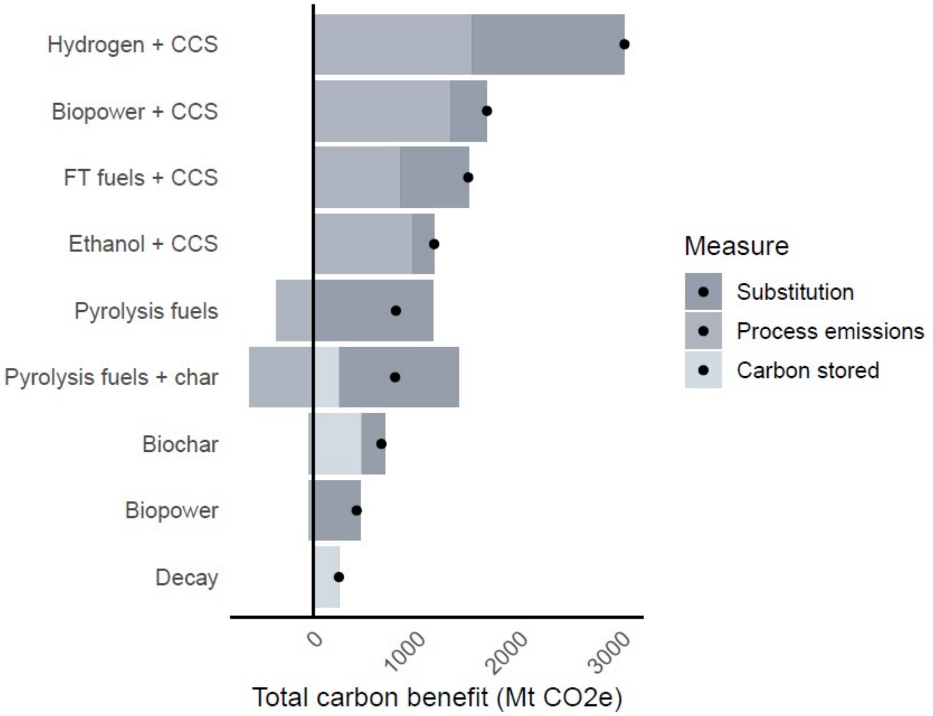
Storage includes carbon in decaying wood and biochar, but does not include storage from CCS, which is included in process emissions. Net storage is the net of process emissions and carbon storage. Values below use the average WECC grid carbon intensity.

Figure 3. Total potential carbon benefits associated with biomass availability Scenario 1, across multiple biomass use technology pathways.



Black dots represent net carbon benefit for each technology pathway.

Figure 4. Total potential carbon benefits associated with biomass availability Scenario 4, across multiple biomass use technology pathways.



Black dots represent net carbon benefit for each technology pathway.

5. RESEARCH QUESTION 3: Which policies would help expand BECCS contribute to State and Federal climate and forest management goals?

Carbon-negative fuels from low-value forest biomass can help the western states attain greenhouse gas (GHG) reduction targets and offer an opportunity to support sustainable forest restoration activities to reduce wildfire risk. Development and deployment of these innovative products can help the U.S. increase the pace and scale of forest restoration efforts, strengthen regional capacity, support innovation, reduce vulnerability to wildfire, and promote carbon storage in long-lived products, including geologically sequestered CO_2.

In this section we describe established policies and programs that could incentivize BECCS, as well as recommendations to extend the use of large volumes of biomass that could potentially be available due to wildfire mitigation/forest restoration activities. We do not discuss federal or state forestry or wildfire policy in any detail, but these policies may change the volume of biomass available, its location, and when it would potentially become available.

The states of California, Oregon and Washington all have adopted broad-reaching climate and energy policies, commitments, incentives and programs to help reach these goals. Some of these incentives and programs could directly support BECCS installations, while others may indirectly help BECCS approaches through supporting an aspect of a BECCS value chain. Existing state and federal policies provide generous support for carbon-negative transportation fuel production. These include low-carbon fuels standard (LCFS) policies in states like California and Oregon, the federal Renewable Fuels Standard (RFS), and federal the Section 45Q tax credits for carbon oxide sequestration.

A LCFS is a market-based policy instrument that specifies declining standards for the average life cycle fuel carbon intensity of transportation fuels sold. California has the most established and broad reaching LCFS program; and Washington adopted a similar program in 2021. The primary goals of LCFS are to: (i) reduce the average carbon intensity for all transportation fuels used in a state, as measured on a life cycle basis; (ii) incentivize innovation, technological development, and deployment of low-carbon and carbon-negative fuels; and (iii) provide a framework for regulating transportation sector GHG emissions within a broader portfolio of climate policies.[47] Recent LCFS credit prices in California are roughly \$75/tCO_2e abated but have exceeded \$200/tCO_2e.[48]

Federal policy also supports carbon-negative fuel production. A Renewable Identification Number (RIN) is a credit under the Renewable Fuels Standard that is generated each time a gallon of renewable fuel is produced. Forest biofuels qualify as a “cellulosic” biofuel (D3/D7 RIN), with recent prices around \$3.5/gallon-of-gasoline-equivalent.[49] These RIN credits are only generated from forest biomass from private landowners, rather than the U.S. Forest Service, as discussed later in this section.

Another federal incentive intended to incentivize investment in carbon capture and sequestration is “45Q”, administered as a tax credit. Tax credits are available for the first 12 years of the plant life at up to \$180/ton CO2 (for DAC-sourced CO2) sequestered (depending on the size and type of the facility).

Additional policy support is needed to realize the opportunity for BECCs in western states.

Successful commercialization of carbon-negative fuels from forest biomass is far from certain, despite existing policy support. Barriers include securing long-term feedstock contracts from public lands (where the majority of biomass sources are found in western states), the exclusion of forest biomass from public lands under the federal Renewable Fuels Standard, competing supply from municipal and agricultural biomass markets, a lack of biofuels infrastructure situated near forested communities, and the high cost and technical risk of some of the technical systems deployed, including CCS technologies and gasification approaches. Without meaningful effort from relevant state and federal policymakers, the U.S risks missing the opportunity to develop and deploy these fuels.

To successfully commercialize carbon-negative fuels under federal policy, we propose six recommendations:

1. Update the federal Renewable Fuel Standard's rules to allow biomass from forests at high risk of wildfire to reflect the modern-day threat of catastrophic wildfire in the American West
2. Allocate existing resources within the Department of Energy aimed at supporting BECCS, and expand future appropriations for BECCS programs
3. Enhance USDA's BECCS portfolio in the 2023 Farm Bill
4. Support market development and enhancement within the U.S. Forest Service
5. Enhance federal policy stability
6. Leverage federal and state procurement to catalyze market development for biomass derived products and bioenergy

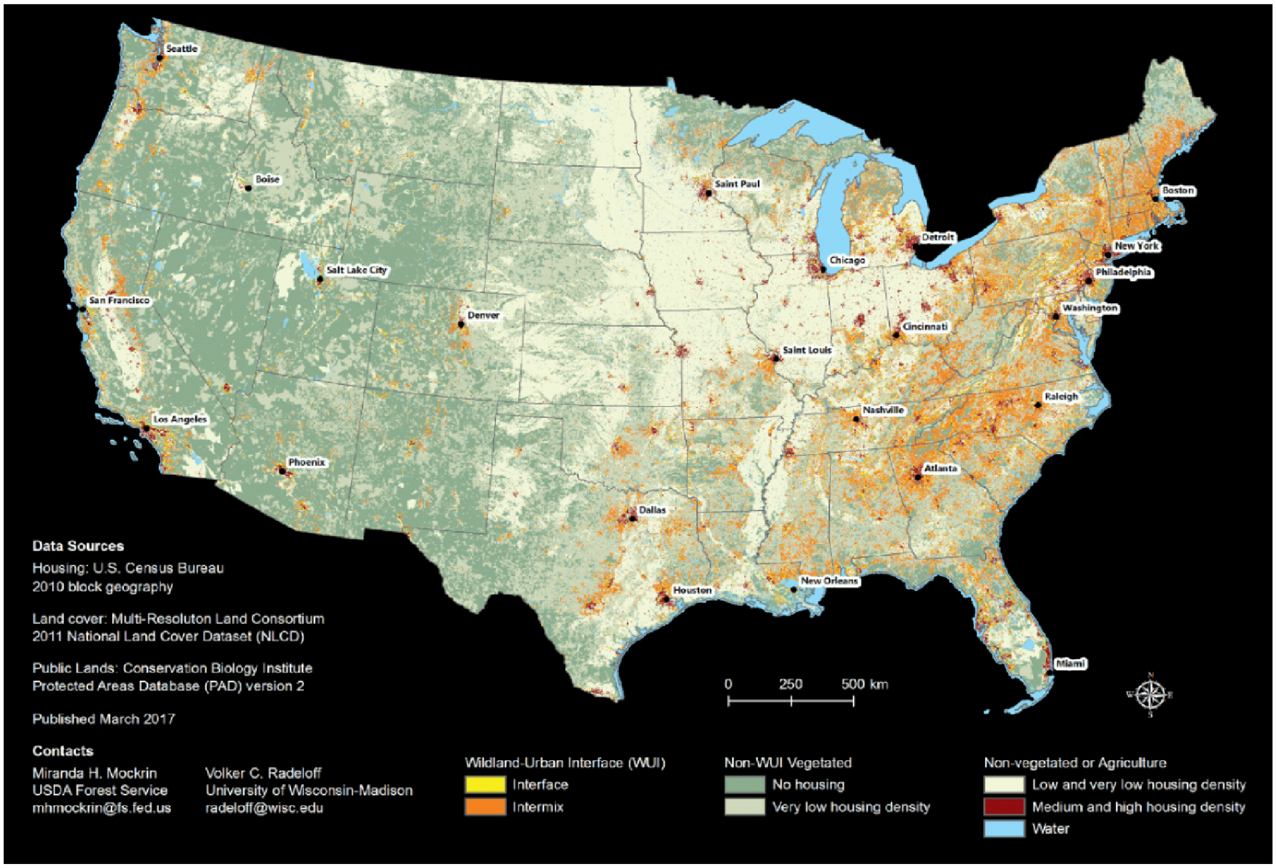
1. Update the federal Renewable Fuel Standard's rules to allow biomass from forests at high risk of wildfire to reflect the modern-day threat of catastrophic wildfire in the American West[50]

The Renewable Fuel Standard (RFS) is a market-based federal program that provides incentives to low carbon biofuels projects. The incentives are awarded in categories (called "D-Codes") based on the type of feedstock used and renewable fuel produced, provided the life cycle carbon accounting is below a certain threshold. For example, D-3 cellulosic biofuel pathways must demonstrate at least a 60% life cycle GHG reduction.

The RFS program was created under the Energy Policy Act of 2005, and further amended under the Energy Independence and Security Act of 2007 (EISA). EISA requires that cellulosic biofuels be derived from "renewable biomass". As it relates to forestry residues, EISA defines renewable biomass as "slash and pre-commercial thinning that is from non-federal forest lands", as well as "biomass obtained from the immediate vicinity of buildings and other areas regularly occupied by people, or of public infrastructure, at risk from wildfire". The latter definition is especially relevant to California, given the majority of the state's forests are federal lands (almost 60%), with the key qualifying term being "areas at risk from wildfire”. This term is not defined in statute and is instead defined in the Code of Federal Regulations (CFR) as “those areas in the wildland-urban interface”.

Areas deemed to meet this criterion are determined based on modeling performed by the University of Wisconsin-Madison (2017). This modeling, which is based on historic data up to 2010 only, excludes large swathes of the American West, which faces a severe, contemporary threat of wildfire (Figure 5). In other words, by virtue of this historic modeling the accessibility of RFS incentives is limited in states like California.

Figure 5. The 2010 Wildland Urban Interface of the Conterminous U.S.



The US EPA should revise the definition of “areas at risk of wildfire” to instead provide the public agencies that are responsible for wildfire management in a given region the authority to determine areas at risk of wildfire. As the responsible entity with much more intimate knowledge of the landscape as well as on-the-ground experience, these agencies (i.e., USFS, other federal agencies, tribal authorities, state, and local fire agencies) are better placed to make such assessments. These agencies include USFS, other federal agencies, tribal authorities, state and local fire agencies.

In addition, we recommend that clarifying amendments be made to the definitions of “renewable biomass” and “slash” in the CFR. Specifically, we recommend that the preclusion of biomass beyond 200 feet be removed, which is arbitrary and can limit what would otherwise constitute an ecological forest treatment in certain circumstances. By adding access roads and utility lines, agencies will also be incentivized to address these high-risk areas. In addition, we recommend that the US EPA incorporate “whole dead and dying trees” into the definition of slash. A limited number of whole dead or dying trees per acre can provide ecological value in the form of habitat, but otherwise may create an important wildfire risk and limitations on the effectiveness of possible reforestation efforts. In California (notably the southern Sierra Nevada), hundreds of millions of dead and dying trees are present on the landscape, largely the result of overgrown and unhealthy forests, pest infestations (bark beetle), and drought. This addition would provide an incentive to perform ecological forest treatments in such forests.

Box 1.

The US Environmental Protection Agency (EPA) should undertake the following administrative actions related to the Renewable Fuels Standard (RFS) program.

1- Revise definitions as contained in Title 40, Section 80.1401 (Renewable Fuel Standard) of the Code of Federal Regulations as follows:

- *Areas at risk of wildfire:* By wholly revising this definition, as “Areas at risk of wildfire are determined on an ongoing basis by the government agency with primary authority for managing wildfire risk, including the United States Forest Service, other federal agencies, tribal authorities, and state and local fire agencies. Eligible renewable biomass can be gathered from areas at risk of wildfire so long as the biomass is obtained in compliance with an approved wildfire risk management activity approved by the responsible government agency.”
- *Renewable biomass:* By partly revising paragraph (5), as “Biomass obtained from the immediate vicinity of buildings and other areas regularly occupied by people, or of public infrastructure including access roads and utility lines, at risk of wildfire.”
- *Slash:* By partly revising this definition, as “Slash is the residue including treetops, branches, and bark, left on the ground after logging or accumulating as a result of a storm, fire, delimbing, or other similar disturbance, as well as whole dead or dying trees determined by the government agency with primary authority for managing wildfire risk to provide limited ecological benefit and otherwise create a high wildfire risk”.

2- Develop new guidance that outlines a pathway for sawmill residues from sawmills that purchase non-qualifying wood and therefore incur a blanket disqualification under the RFS, to qualify as renewable biomass under the RFS. This could be achieved through the use of inventory accounting methods that provide RIN crediting for the portion of the finished fuel that has been produced from qualifying renewable biomass.

Finally, mill residues such as sawdust and shavings could be used to make renewable fuels under the RFS. However, sawmills that obtain any non-qualifying wood in their operations (e.g. from federal lands deemed not at risk from wildfire) may be disqualified from participating. The US EPA could provide an administrative statement showing a path for sawmills that buy federal or other non-qualifying wood to sell RFS-qualifying residuals to biofuel facilities. For example, a mill could use an accounting system to show the percentage of qualifying wood they process, similar to what some mills already do for third party certification and establish a qualifying threshold on this basis. Similarly, a fraction of their residues proportional to the amount of qualifying wood they receive could be certified for this purpose.

Other actions under the RFS could also support further development of biomass fuels, such as pathways for hydrogen, electricity, and other emerging biomass-derived fuels. However, they are not further contemplated here.

2. Allocate existing resources within the Department of Energy aimed at supporting BECCS, and expand future appropriations for BECCS programs

The Infrastructure Investments and Jobs Act (IIJA), signed into law on November 15, 2021, provides funding for four major policy areas: carbon capture, utilization & storage (CCUS) research, development, and demonstration (RD&D); carbon transport and storage infrastructure & permitting; carbon utilization market development; and carbon removal.[51] Of these provisions, several are relevant to commercial scale deployment of carbon-negative forest biofuels:

- $2.54 billion for carbon capture demonstration projects (FY22-25)
- $100 million for carbon capture front end engineering and design (FEED) studies (FY22-26)
- $2.1 billion for carbon dioxide transport infrastructure finance and innovation (FY22-26)
- $2.5 billion for CO2 storage commercialization program (FY22-26)
- $75 million for CO2 storage permitting

Each of these funds or others could be used to support BECCS. For instance, the U.S. Department of Energy could provide grants or cost-share for carbon capture demonstrations, fund FEED studies for nearly commercial technologies, or develop CO_2 transport and storage locations with an emerging bioeconomy in mind.

Future large-scale BECCS deployments can also be supported through the U.S. Department of Energy. Two of DOE’s applied science offices, Fossil Energy and Carbon Management (FECM) and the Biomass Technologies Office (BETO), bring relevant expertise to these emerging technologies. Further, DOE's Loan Program Office and Office of Clean Energy Demonstration can provide further support for commercialization through debt financing or cost-sharing.

3. Enhance USDA's BECCS portfolio in the 2023 Farm Bill[52]

The U.S. Department of Agriculture plays a similarly important role in supporting the bioeconomy in the U.S.. Several offices and programs provide limited support for research, development, and demonstration (RD&D) activities relevant to carbon dioxide removal.

The primary legislation authorizing USDA funds is the 2018 Agriculture Improvement Act—known colloquially as the 2018 Farm Bill. the "2018 Farm Bill," is an omnibus bill composed of twelve titles, providing roughly half a trillion dollars in funding for various USDA functions over a period of 5 years. The titles include (1) Commodities, (2) Conservation, (3) Trade, (4) Nutrition, (5) Credit, (6) Rural Development, (7) Research and Extension, (8) Forestry, (9) Energy, (10) Horticulture, (11) Crop Insurance, and (12) Miscellaneous. The bill is renewed roughly every 4 years. While roughly 80% of the funds appropriated through the 2014 Farm Bill were allocated to the Nutrition title, the Bill also provides billions of dollars in financial support to America's rural constituencies through crop insurance, conservation payments, and loan support (Monke, 2018).

Given its broad remit and semi-regular authorization, future Farm Bills are promising legislative vehicles to support carbon-negative fuels. Opportunities span conversation, rural development, research, extension, forestry, and energy programs (Table 6).

Table 6. Relevant Sections of 2018 Farm Bill for BECCS innovation and deployment

Title	Section(s)
2 – Conservation	Secs. 2201-2209. Conservation Reserve Program
6 - Rural Development	Sec 6303. Rural Energy Savings Program
7 - Research, Extension, and Related Matters	Sec. 7132. Agriculture advanced research and development authority pilot.
7 - Research, Extension, and Related Matters	Sec. 7308. Forestry products advanced utilization research.
8 – Forestry	Sec. 8643. Wood innovation grant program.
8 – Forestry	Sec. 8644. Community wood energy and wood innovation program.
9 – Energy	Sec. 9002. Bio-based markets program
9 – Energy	Sec. 9003. Biorefinery assistance.
9 – Energy	Sec. 9004. Repowering assistance program
9 – Energy	Sec. 9010. Biomass Crop Assistance Program
9 – Energy	Sec. 9011. Carbon utilization and biogas education program

Improving Commercialization Support Within USDA Agencies

To accelerate the commercialization of the technologies and processes needed to supplement and support the R&D efforts occurring at USDA agencies, additional entrepreneurial and tech-to-market support will likely be necessary. While ARS laboratories and FFAR and NIFA grant programs have effectively delivered impactful discoveries at the research stage, these processes and technologies must rapidly scale and mature beyond the laboratory in order provide benefits to land managers.

In addition to the funding provided through USDA extramural grant programs, mentorship, market intelligence, facilities, and professional development trainings could all help to accelerate the transition of academic research projects into commercial technologies. In order to rapidly develop the research occurring at ARS laboratories and land grant universities and colleges into scalable technologies, researchers will need to acquire the skills necessary to secure private investment.

Specifically, proven curriculums from national lab and university technology incubator and accelerator programs could provide excellent models for the creation of a similar program embedded within REE agencies. Broadly, incubators and accelerators are structured programs intended support early-stage companies and technologies in order to expedite the commercialization process. While the difference between accelerators and incubators is not well-established, incubators generally operate on an open timeline, whereas accelerators have a strict timeline and intensive curriculum. With laboratories located across the US in close proximity to national laboratories, ARS could establish a federal technology incubator program to accelerate the maturation of promising research to commercialized technologies with the capacity for wide-spread deployment.

Several national laboratories already have incubator or accelerator programs, including Argonne National Laboratory, National Renewable Energy Laboratory, and Lawrence Berkeley National Laboratory. Notably, Cyclotron Road at Lawrence Berkeley Laboratory has demonstrated particularly strong results. Since 2015, the program has provided $15 million in financial support to 41 fellows who have gone on to attract over $80 million in support for their projects. The Cyclotron Road model could allow ARS to recruit and mature nascent technologies crucial to measuring, increasing, and enhancing carbon dioxide removal deployment in agricultural, natural, and working lands in the US. A similar program within USDA could leverage a small amount funding to drastically expand the impact of ongoing intramural and extramural research occurring through the department's agencies.

Second, USDA can benefit from enhanced research capabilities that have proven successful in other portions of the federal government. For instance, USDA does not have many authorities granted to certain offices of the DOE and U.S. Department of Defense known as the "Advanced Research Projects Agency" (ARPA) model. These include organizational flexibility on an administrative level and significant authority given to program directors to design programs, select projects, and actively manage projects (Azoulay et al., 2019). Below, we propose an independent research office within USDA to focus on carbon dioxide removal and other climate-related research. We describe the goals, means, role of the director, personnel, and coordination authorities of a new research office, based largely off of legislation establishing ARPA-E within DOE (Gordon, 2007):

Goals: The new office should focus on two primary goals: (1) to overcome the long-term and high-risk technological barriers in the development of agricultural and land management technologies related to climate change and CDR, and (2) to ensure that the U.S. maintains a technological lead in developing and deploying advanced agricultural and land management technologies that increase economic opportunities.

Means: Much like ARPA-E, this new agency may (1) identify and promote revolutionary advances in fundamental sciences, (2) translate scientific discoveries and cutting-edge inventions into technological innovations, and (3) accelerate transformational technological advances in areas that, due to technical and financial uncertainty, industry is not likely to undertake without federal assistance.

4. Support market development and enhancement within the U.S. Forest Service

To meaningfully address wildfire risk, large scale forest restoration efforts are needed on federal and state-owned lands. If mechanical thinning is used, wildfire mitigation efforts will generate large quantities of biomass as slash piles, which will emit the stored CO2 either when burned, or slowly as they decay. Federal and state funds to address and mitigate wildfire risks in the region have been woefully inadequate to the scale of the problem, and are caught in a spiral of being spent on immediate fire suppression, rather than preventative approaches.[53]

A newly released USDA strategy for wildfire mitigation seeks to increase forest restoration treatments from 2-3 million acres nationwide, to treating up to an additional 20 million acres on the National Forest System in the West, over and above current treatment levels over the next 10 years, and developing a plan for long-term maintenance beyond the 10 years.[54] While this infusion of funds is laudable, it will be more effective if supported by market-based mechanisms that support sustainable business models to utilize the end products of the biomass gathered, such as for bioenergy and/or wood products.

Market-based mechanisms can help drive forest restoration efforts in the western states region. They are also needed to develop the forest feedstock supply chain for forest biofuels production facilities. Likewise, securing long-term forest feedstock supply agreements from a variety of investment-grade feedstock suppliers is key to securing project financing.

Box 2.

Issue longer-term contracts for harvesting and restoration.

Developing or commitment to developing long-term (up to 20 year) stewardship contracts to facilitate investment in expanding biomass harvesting and utilization capacity. Working towards these contracts would increase reliability and confidence in biomass markets and help project proponents gain access to project finance.

Use of Share Stewardship Agreements: In August 2020, the state of California and the USFS signed a Shared Stewardship Agreement (SSA) to increase the pace and scale of forest restoration by treating 1 million acres of forest per year across forest land ownerships in the state of California. Major tenants of the SSA include development of a 20-year project plan (across all forest ownerships) by 2021 and increased vegetation treatments targeting 1 million acres/year of forestland by 2025. Approximately 500,000 acres/year of treatments will be conducted on federal lands. Implementation of the SSA could produce significant volumes of by-product potentially available as feedstock for bioenergy production.

Improving USFS Business Practices and Appraisal methods. There is a pressing need to reform and improve current USFS business practice. In particular, agreements need to be structured to better define fair market value and that USFS appraisal processes should be reformed to allow for partnership agreements, which allows for contractors to inform their own procurement policy and ensure fair market value.

Improving Permitting Processes, especially NEPA. The length and complexity of permitting process to complete forest restoration on federally owned lands is a key barrier. Expanded the use of third party National Environmental Policy Act (NEPA) subcontractors, could reduce permitting time.

We recommend that a streamlined process for conducting resource surveys and reporting be adopted, supported by clearer policies and best practice guidance. Protocol level resource surveys and reporting requirements have been established but are not always conducted consistently. This recommendation includes beginning surveys months earlier if resources are available to determine if the species of concern is present in the area, or if other changes have occurred (e.g., species has raised young and left the area). The use of streamlined options and flexibility in determining Limited Operating Periods could significantly improve project timelines.

Securing long-term forest feedstock supply agreements from federal forest lands appears to be a significant barrier in USFS Region 5, (which includes California) as well as in USFS Region 6 (which includes Oregon and Washington). Several organizations have proposed solutions to address these institutional barriers, including the Joint Institute for Wood Products Innovation in California.[55]

5. Enhance federal policy stability

Policies that seek to engage and encourage private sector investments – especially those that require significant capital expenditures – need to be stable and coherent to be successful. While biomass incentives have been more stable over time than, for instance, many other renewable energy policies like solar tax production credits, greater policy certainty on key aspects of how “bioenergy” is defined in incentives programs such as renewable fuel standards are important. Likewise, incentives aimed at encouraging negative emissions technologies and long-term geologic sequestration such as 45Q should be adapted to explicitly include injection of biomass- generated CO_2, and be open for long time periods so that other permits and approvals like NEPA and Class VI permits for CO2 injection can be granted, and investment decisions can be made to support these efforts. Existing permitting infrastructure is complex and costly, and incentives must match these timelines or else remain under-utilized.

6. Leverage federal and state procurement to catalyze market development for biomass derived products and bioenergy

In addition to policy coherence and stability, federal and state governments can use the power of their own procurement actions to support and encourage bioenergy and or the greater use of forest products. The federal government, via the General Services Administration and US military, is the single largest purchaser and landlord in the U.S. federal contracts, not only to conduct forest restoration and wildfire mitigation, but also to utilize the energy and products being generated, can provide an effective “market pull” to enhance existing forest policy.

In December 2021, President Biden signed Executive Order 14057 “Catalyzing America’s Clean Energy Industries and Jobs through Federal Sustainability”56 which commits the government to a “whole-of government effort to tackle the climate crisis in a way that creates well-paying jobs, grows industries, and makes the country more economically competitive”. The E.O. directs the federal government to use its scale and procurement power to achieve five goals, each of which could use biomass-derived products such as electricity, fuels, and construction materials:

1. 100 percent carbon pollution-free electricity (CFE) by 2030, at least half of which will be locally supplied clean energy to meet 24/7 demand;
2. 100 percent zero-emission vehicle (ZEV) acquisitions by 2035, including 100 percent zero emission light-duty vehicle acquisitions by 2027;
3. Net-zero emissions from federal procurement no later than 2050, including a Buy Clean policy to promote use of construction materials with lower embodied emissions;
4. A net-zero emissions building portfolio by 2045, including a 50 percent emissions reduction by 2032; and
5. Net-zero emissions from overall federal operations by 2050, including a 65 percent emissions reduction by 2030.

Purchasing policy can build on this new policy as well as decades of experience by states and the Federal government in buying greener and more sustainably[57] by:

- Recognizing existing standards for renewable and biomass energy and biomass products
- Rewarding the procurement of products sourced from biomass materials generated through forest restoration efforts in regions with high wildfire risk
- Requiring suppliers of bioenergy or forest products to incorporate carbon accounting and standardizing how such carbon accounting is measured and communicated
- Adopting technology that enables better traceability and ensures independent verification

- Streamlining state and federal purchasing requirements and policies
- Encouraging private sector purchasing requirements to follow federal and state leads.

6. Conclusion

There is a unique opportunity to make use of the energy and CO_2 embedded in forests with very high fuel loads and those considered overstocked and at high risk for severe wildfire. Other uses for this material and/or CO2 also exist, such as mass timber, and in some cases, can be complementary to bioenergy systems. This paper investigated and sought to give a range of the total potential pool of CO_2 from western forests with high wildfire risk, on an absolute and net emissions basis, and compared to other potential uses. While our analysis is indicative and excludes many more localized factors, it does provide an indication of the large scale of the opportunity (and the challenge ahead for wildfire mitigation).

As modelled in Scenario 1, the most conservative mechanical thinning scenario, we estimate that there is a stock of some 487 million tons of CO_2e within excess waste biomass generated from necessary fuel reduction treatments. In contrast, as modeled in the most aggressive thinning regime, Scenario 4, we estimate a stock of some 1,960 million tons of CO_2e. When we factor in net emissions in a use case of this biomass for bioenergy, we find that some 310-797 Mt CO2e is available at the low end, or 1182-3040 Mt CO2e at the higher end. If CCS is included, and the vast majority of the CO2 is stored in geologic formations in the region, such as in saline aquifers or mineralized in basalts, the problem of overstocked, high fire risk forests in the western states instead becomes a negative emission or carbon removal solution.

Without significant policy and market incentive support, however, these CO2 sources will likely remain in forests and at high risk of emission due to wildfire. Climate change and land-use changes could exacerbate the situation, exposing forests, wildlife and human populations in the region to increasingly significant health, environmental, and economic damages. Alternatively, if adequately addressed, the responsible, safe, and sustainable utilization of this resource could help to mitigate wildfire risk, generate local non-fossil sources of energy, and generate needed economic development and employment in the region.

In many western forests, the CO2 embedded is at high risk of near-term release due to wildfire, and/or through exposure to pests, diseases, and decomposition—natural processes that may accelerate due to climate change. Stronger and more stable policies and incentives are needed to act and ensure that these negative externalities are mitigated. We make several policy recommendations in the whitepaper, including the need to collaborate with local communities and with industry partners, in order to advance implementation. Better coordination between government agencies is also urgently needed.

The whitepaper uncovered some additional avenues for future research that could further our understanding of the scale of the problem and opportunity and deepen our understanding of how to best implement various solutions. These include:
Including more regional and local forestry and wildfire mitigation plans into modelling in order to enhance predictive capacity, inform future management plans, and complete gap analysis.

- Researching how climate change may alter the availability, both in terms of quantity and quality, of BECCS forest feedstocks and net emission benefits, especially from the increased fire, pest, and other threats to forests and forest carbon storage.
- Researching the relationship of BECCS and bioenergy systems to other policy objectives federally and in the region, such as contributing to state-level GHG emission reduction targets, low-carbon fuels policies, and achieving “30 by 30” land preservation targets.
- Scoping from a life cycle perspective both short-term and long-term prospects for carbon utilization and storage in the region, and other innovative uses of the biomass resources that may become available. For example, understanding of smaller scale biomass gasification systems, new approaches to biochar and torrefaction, wood burial and other techniques to delay decomposition.

- Undertaking a full cost benefit analysis of different policies and interventions at different scales. Such studies should include multiple factors, such as understanding economic costs and benefits over time, job creation, human health, damages and avoided damages due to wildfire, biodiversity and ecosystem health, conservation goals, and other priorities for the region.
- Understanding health impacts of action and inaction, as well as environmental justice considerations in the region.

Finally, all research should seek to meaningfully engage with local stakeholders in the region, to address their priorities, concerns, and vision for a sustainable, resilient, and healthy forestry economy and ecosystem in the west.

7. Appendix A. Extended Methods

Biochar production

The LCA of biochar production and use from forest residues relies on data from Roberts et al. (2010) and Woolf et al. (2010).[40] Roberts et al. (2010) analyze feedstocks most like the forest residues from thinning western forests, and Woolf et al. (2010) provide general characteristics of biochar. We assume that biochar is produced from the slow pyrolysis of forest residues.

Roberts et al. (2010) use a cradle-to-grave system boundary, which begins from feedstock handling to carbon sequestered by biochar. We assume that the char yield is 29.6% (by weight) of the feedstock input in a slow pyrolysis process. The net stable C in char is 574 kgCO_2e/ton feedstock, which includes emissions from pyrolysis. Roberts et al. (2010) assumes that transport and residue collection emits 19 kgCO_2e/ ton feedstock, but we modify this assumption to be consistent with other pathways. Lastly, Roberts et al. (2010) estimate a natural gas substitution benefit of 229 kgCO_2e/ton feedstock. For end-of-life, we assume that the biochar has a labile fraction of 15% with a half-life of 20 years and a recalcitrant fraction of 85% with a half-life of 300 years.[40]

Biopower with and without CCS

The LCA of the electricity with CCS pathway using forest residue feedstock relies on data from Sanchez et al. (2015) and Xie et al. (2011).[41] While Sanchez et al. (2015) consider electricity generation from a blend of lignocellulosic biomass, we supplement this with the LHV of forest residues from Xie et al. (2011) to be consistent across scenarios. We use the biomass integrated gasification combined cycle (IGCC) with CCS scenario in Sanchez et al. (2015).

Sanchez et al. (2015) consider the growth of the biomass until the generation of the electricity and the subsequent CO_2 storage to be its system boundary. Since forest carbon is accounted previously in our model, we remove the agricultural phase (0.004 tCO_2/mmBtu) from the total carbon intensity (-0.0802 tCO_2/mmBtu). Instead of an LHV of 17 mmBtu/BDT, we assume 13.2 mmBtu/BDT from Xie et al. (2011) to be consistent with the Fischer-Tropsch diesel pathway. We use a heat rate of 16.32 mmBtu/MWh, implying a facility with a 21% efficiency. For the biopower without CCS pathway, we use a heat rate of 12.5 mmBtu/MWh.[58] We also assume that the generated electricity displaces the average California grid electricity in 2016. We update the transportation assumptions in Sanchez et al. (2015) to our common assumptions, given above.

Pyrolysis fuels, with and without biochar co-production

The LCA of biofuels production and use from forest residues relies on Li et al. (2017), who present a techno-economic assessment of a 2000 t/day facility with red-oak (Q. rubra) feedstock.[42] This facility produces 50.73 gallons (192L) of gasoline/BDT feedstock and 37.01 gallons (140L) of diesel/BDT, which we assume replace conventional gasoline and diesel. The facility burns the non-condensable gas and biochar for process heat, but natural gas and electricity are also used for the bio-oil stabilization process. This process has a reported carbon intensity of 31.8 gCO_2e/MJ.[59] The non-condensable gas and biochar burnt for process heat is assumed to displace natural gas.

We model an alternative process in which biochar is reserved. Pyrolysis of loblolly pine residue yields 50.7 (wt%) bio-oil, 10% char, and 25.3% non-condensable gas.[60] Meanwhile, the facility still produces the same amount of gasoline and diesel as above. Li et al. (2017) use an HHV of biochar of 23.05 MJ/kg, and we assume for this to be the same for the biochar that is produced from loblolly pine instead of red oak. We calculate the energy produced from combustion of biochar and replace it with the equivalent amount of energy from natural gas combustion. We use a natural gas carbon intensity of 50 gCO_2/MJ.[2] The reserved biochar is assumed to be the same as described by Woolf et al. (2010), although it may have different properties given that it is produced via fast pyrolysis instead of slow pyrolysis.

Lignocellulosic ethanol with CCS

For the LCA of lignocellulosic ethanol production with carbon capture and storage (CCS) from forest residue we rely on modeling done by McKechnie et al. (2011) and Liu et al. (2011).[43] We obtain relevant process information about forest biomass harvesting and operations from McKechnie et al. (2011), and fuels production with CCS from Liu et al. (2011). We analyze an E85 (85% ethanol, 15% gasoline) pathway from forest biomass, which allows for more direct substitution of gasoline relative to E100. To account for the efficiency loss when switching from conventional gasoline to E85, we assume an efficiency of 5 km/L for E85 and 7.69 km/L for gasoline.[61] McKechnie et al. (2011) also include a coproduct credit from natural gas-fired sources for electricity, which we modify to assume displacement of average grid electricity (see above).

Fischer-Tropsch diesel with CCS

For the LCA of Fischer-Tropsch (FT) liquids production with CCS from forest residue, we rely on Xie et al. (2011)[44], who document various combinations of feedstocks for FT liquids generation, including 100% forest biomass. Xie et al. (2011) use GREET for their LCA using a well-to-wheels boundary: from biomass collection to tailpipe emissions. Forest residues are assumed to have an LHV of 13.243 mmBtu/BDT and the FT process has a 0.5 LHV efficiency, with 92% are FT liquids and 8% is electricity by LHV. In their BTL-CCS case, they assume 89.9% CO_2 capture ratio with a recycling design, the well-to-wheels emission factor is -150 $kgCO_2e$/mmBtu. Xie et al. (2011) assume that the coproduced electricity displaces the average US grid electricity in 2009 (554 gCO_2e/kWh). We update this assumption so that the coproduced electricity displaces the average California grid electricity in 2016. We also update the forest operation and transportation emissions, using data from[62] as discussed above. While the FT process produces a mixture of diesel and gasoline, we assume a constant baseline carbon intensity (CI) of 100.45 gCO_2e/MJ (diesel's CI, as compared to 100.82 gCO_2e/MJ for gasoline) for all FT liquids produced since Xie et al. (2011) do not report a breakdown by fuel type.

Hydrogen production with CCS

For hydrogen production, we rely on the LCA conducted by Antonini et al. (2021) of hydrogen gas produced from wood waste.[45] We model their entrained flow gasifier with pre-combustion CO_2 capture and storage, which has a CI of -130 gCO_2/MJ. This process was chosen because it has the highest rate of carbon capture amongst all modeled hydrogen production processes. We adjust this CI to account for using West Coast grid electricity, which has a lower CI than the EU grid used in their analysis (400 gCO_2/kWh). We further adjust this CI to include harvest operations and transportation to a processing facility, consistent with our other pathways. To convert the functional unit from MJ to BDT-feedstock, we use an energy conversion efficiency of 70%. To model substitution benefits, we assume this hydrogen displaces conventional hydrogen produced from natural gas via steam reforming in California, which has a carbon intensity of 120 g/MJ.[46]

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