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Carbon Dynamics for Biofuels Produced From Woody Feedstocks

Energy Systems Division

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Carbon Dynamics for Biofuels Produced From Woody Feedstocks

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ABSTRACT

Growing biomass incorporates atmospheric carbon and stores it as biogenic carbon. In a biorefinery, some portion of this biogenic carbon is converted into a biofuel, which then emits biogenic CO_2 through the biofuel combustion. In the Life Cycle Analysis (LCA) of biofuels, it is generally assumed that this biogenic CO_2 emission is offset by atmospheric carbon uptake during biomass growth, establishing the so-called carbon neutrality of biogenic carbon. When the elapsed time between biomass growth and biofuel combustion is short, this assumption is defensible. In the case of slower-growing forestry-derived bioenergy feedstocks, however, this time window may be significantly longer and the assumption of carbon neutrality is weaker. To address the carbon neutrality issue of woody-biomass-derived biofuels, this study investigated the carbon dynamics of producing bioenergy from woody biomass. Specifically, key factors affecting the net GHG emissions results, such as biomass species, land analysis framework, and the sequencing of the planting and harvest steps, were examined.

This study examined two different types of analysis frameworks: stand-level and landscape-level analyses. A stand-level analysis examines the impacts of temporal carbon dynamics of carbon emissions/sequestration over time, which is a critical issue in LCAs of woody biomass products. The stand-level analysis is based on a narrowly defined biomass growth scenario and harvest geographic boundary. The specific growth scenario may have high variability, especially with long growth cycles. A landscape-level analysis, on the other hand, is appropriate for conducting LCAs of products from managed forest assuming sustainable forestry management, e.g., the overall carbon fluxes associated with forest growth and harvest/mortality are balanced. A landscape-level analysis can represent managed (or private) forests that are intended to provide a constant supply of biomass to their customers, including bioenergy plant operators.

This study included two general types of forest biomass: managed softwoods, represented by Douglas fir, loblolly pine, and spruce/fir mixtures, and dedicated short-rotation woody crops (SRWCs), represented by poplar, willow and eucalyptus. The softwoods were selected to represent the dominant wood species found in the Pacific Northwest (Douglas fir), the southern United States (loblolly pine), and the northeastern U.S. (spruce/fir). The SRWCs were selected to represent systems that have been commercially deployed in the Pacific Northwest (poplar), the southern U.S. (eucalyptus), and the northeastern U.S. (willow).

The sequencing of the planting and harvest, and biogenic carbon release steps, also had a major impact on the carbon accounting. One analysis framework (Cycle 1) starts with 1) the “harvest” of standing trees, followed by 2) the production and use of the biofuels, and 3) replanting, and recapture of the released carbon. An alternative framework (Cycle 2) starts with 1) the planting of the wood and the capture of atmospheric carbon, followed by 2) harvesting of the trees, and 3) release of the biogenic carbon in the production and use of the biofuel. With Cycle 1, the carbon emissions released from biofuel production and combustion are allocated before biomass growth and harvest, and handled accordingly by the CO_2 emission-discounting method; the slow growth of softwoods (especially Douglas fir and spruce/fir) results in a large portion of the upfront carbon debt being recovered slowly. With discounting, the

carbon uptake during biomass regrowth becomes less significant. Cycle 2 is appropriate for SRWCs because these will be established dedicatedly for bioenergy or bioproducts production, which starts with the silviculture, and Cycle 1 is more appropriate for softwoods because it is more realistic to collect the thinnings and residues when they are readily available for bioenergy production than to wait for decades to grow a mature softwood stand when the thinnings and residues could be made available.

Using both stand- and landscape-level analyses, this work shows that biofuels derived from woody biomass with longer growth cycles and slower growth rates, e.g., Douglas fir and spruce/fir, have much larger variations in GHG emissions depending on the land analysis framework and CO_2 emission cycle compared to biofuels derived from woody biomass with shorter growth cycles and faster growth rate, e.g., SRWCs. For example, the GHG emissions associated with renewable gasoline from eucalyptus, poplar, and willow range from 40 to 47, 37 to 41, and 45 to 50 g CO_2e/MJ, respectively, depending on the analysis cycles, in comparison to 94 g CO_2e/MJ for petroleum gasoline. On the other hand, the renewable gasoline from loblolly pine, Douglas fir, and spruce/fir generate GHG emissions ranging from 19 to 42, 13 to 67, and -10 to 56 g CO_2e/MJ, respectively, depending on the analysis cycles. Thus, much caution is needed to handle the temporal carbon dynamics issue for biofuels from woody biomass with long growth cycles and slow growth rates.

1. INTRODUCTION

This report provides the approach and preliminary results for the life-cycle analysis (LCA) of six woody feedstocks that are converted into biofuels. This work was conducted by a team at Argonne National Laboratory and the Consortium for Research on Renewable Industrial Materials (CORRIM) in FY 2016 and FY 2017. This report documents the team's approach to selecting the tree species and production regions, the energy flows during the forest growth and harvest cycles, forestry growth models, and carbon accounting methods to handle carbon dynamics of woody feedstock growth and removal.

The material and energy flows, forestry growth models, and carbon accounting methods are incorporated into the Greenhouse gases, Regulated Emissions and Energy use in Transportation (GREET®) model to produce a cradle to grave LCA of biofuels derived from woody feedstocks. GREET is a publicly available LCA model developed by Argonne National Laboratory with support from several programs in the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy, including the Bioenergy Technologies Office, Vehicle Technologies Office, and Fuel Cell Technologies Office.

GREET is structured to systematically examine the well-to-wheels (WTW) energy use and emissions associated with a wide range of vehicle technologies and feedstock sources for producing alternative fuels. The previous versions of GREET included various woody biomass feedstocks, such as willow, poplar, and forest residue. This report expands the woody feedstock module to include four additional woody biomass feedstocks (loblolly pine, Douglas fir, spruce/fir, and eucalyptus) and updates the details for two existing woody biomass feedstocks (i.e., willow and poplar). In addition, the report provides two appendices explaining the woody feedstock module configured in GREET, and additional results from the module.

1.1. MOTIVATION

Growing biomass incorporates atmospheric carbon and stores it as biogenic carbon. In a biorefinery, some portion of the biogenic carbon is converted into a biofuel, then re-emitted to the atmosphere during the combustion process. Considering corn ethanol as an example, about one-third of the carbon in the corn grain that enters the ethanol plant ends up in ethanol, another third is emitted during fermentation, and the final third ends up in an animal feed co-product. When the biofuel is combusted for end use, biogenic CO_2 is emitted. In biofuel LCA, it is generally assumed that this biogenic CO_2 emission is offset by atmospheric carbon uptake during biomass growth. In other words, it is assumed that combustion of the biofuel is carbon-neutral. When the time elapsed between biomass growth and biofuel combustion is short, this assumption is defensible. In the case of forestry-derived feedstocks, where the growth period of the woody biomass may be significantly longer, the assumption of carbon neutrality is weak.

Several studies have called into question the carbon neutrality of forest-derived biofuels and examined their so-called carbon debt (Repo, Tuovinen, and Liski 2015; Repo, Tuomi, and Liski 2011; Holtsmark 2012; McKechnie et al. 2011; Cherubini et al. 2011). Most of these studies consider forest management practices, i.e., establishment, silviculture and growth rates, outside the U.S. For example, Repo et al. (2015; 2011), Holtsmark (2012), and McKechnie et al. (2011) focused on wood feedstocks in Finland, Norway, and Canada, respectively. As shown in these publications, the material and energy flows associated with forestry as well as forest growth itself vary widely by region. The present report considers the production of forestry-derived feedstocks in the United States, examining woody feedstocks produced in three different regions as defined by the U.S. Forest Service (USFS) (see FIGURE 1): the Eastern U.S., Southern U.S., and Pacific Northwest. For each of these commercially important forest regions, the forest growth and harvest cycles, and the associated carbon and energy flows associated with bioenergy production, are tracked.

The LCA studies mentioned above assumed that the woody biomass feedstocks are used for bio-power (Repo, Tuovinen, and Liski 2015; Repo, Tuomi, and Liski 2011), second generation biofuel production (Holtsmark 2012), or combined ethanol and bio-power production (McKechnie et al. 2011). In all these cases, the biogenic carbon is rapidly emitted, while the carbon is slowly recaptured by the growing biomass. Cherubini et al. (2011) did not carry out a formal LCA but developed a modified global warming potential (GWP) method that could be used in LCA of woody feedstocks. As shown by McKechnie et al. (2011), the final products, e.g., biofuels, biopower, and bioproducts, have a significant impact on the life-cycle results. The present study calculates life-cycle energy consumption and GHG emissions for biofuels produced from forest-derived feedstocks via either a thermo- or biochemical biomass conversion process. This study also considers carbon dynamics in terms of temporal variations in carbon uptake and emissions.

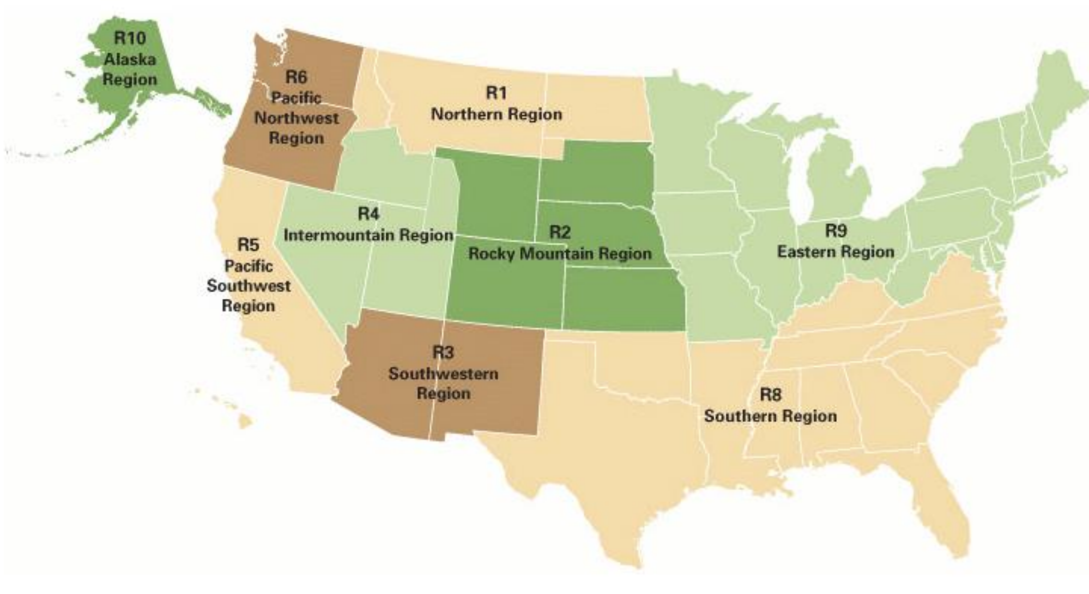


FIGURE 1 U.S. Forest Service region locations (USDA 2017)

1.2. FOREST RESOURCES

The United States contains over 765 million acres of forest (U.S. Forest Service 2014), which amounts to 34% of the total area of the country (Oswalt et al. 2017). Alaska contains the largest forest area, at 129 million acres, followed by Texas, California, Oregon and Montana at 41, 32, 30, and 26 million acres, respectively. Relative to the area of each state, Maine, New Hampshire and West Virginia have the largest percentage of forest, at 89%, 83% and 79%, respectively, while North Dakota has the lowest, at 2%. About 58% of U.S. forest land (443 million acres over 765 million acres) is privately owned. Agencies including the USFS, the National Park Service, the Bureau of Land Management, and the Department of Defense manage federally owned forested land. All 50 states and many counties and cities also own and manage forest lands. Approximately 81 million acres (11%) of forest is reserved (Oswalt et al. 2017), meaning it can't be accessed for wood production (Smith et al. 2009). These reserved lands include National Parks and Monuments, as well as wilderness areas. Most of these reserved forests are located in the western part of the country, with Alaska having the largest reserve area at 33 million acres, followed by California at 6.3 million acres (Oswalt et al. 2017). The states with the highest percentage of forest reserves are Hawaii and Wyoming at 49% and 34%, respectively.

Forests in the United States are separated into nine different management regions, as shown in FIGURE 1. Within each region, there are a wide variety of different ecosystems and tree species, and there are even greater differences between the regions. The total aboveground mass of trees, and predominant species for each region, are presented in Table 1. There are approximately 29 billion tons of aboveground biomass in U.S. forests (U.S. Forest Service 2014). The average biomass density for the entire country is 8,360 tons/mi^2. As for individual states, those on the West Coast contain the largest amount of aboveground biomass at 2.10, 2.07, and 1.79 billion tons for Oregon, California, and Washington, respectively. On a per-area basis, West Virginia has the most biomass at 34,600 tons/mi^2 and North Dakota has the lowest at 287 tons/mi^2.

Trees can be classified into two categories, softwoods and hardwoods. Hardwoods are deciduous, while softwoods retain their leaves (needles) year-round. There are significant chemical and morphological differences between hardwoods and softwoods, and these differences are particularly important for biochemical conversion processes. Both hardwoods and softwoods have commercial value, but the overall production is dominated by softwoods. With 10.3% of the aboveground biomass, the softwood Douglas fir is the most common tree species in the country (U.S. Forest Service 2014). This species is widespread in the West and is common in Regions 1–6, although more than 60% of Douglas fir trees are found in Region 6. The second most dominant species is loblolly pine, which comprises 8.2% of the total aboveground biomass (U.S. Forest Service 2014). Almost all of this species (98%) is located in Region 8, with the rest in Region 9. Both of these species are commercial trees used to produce durable wood products (DWPs), pulp and paper products, and process energy. Other species making up a noticeable amount of the total tree biomass include hardwoods like maples, white and red oaks, and hickory. However, this work focuses on short-rotation woody crops (SRWC) or "dedicated bioenergy plantations" to avoid concerns about using ecologically valuable hardwood forests.

TABLE 1 Predominant Tree Species and Aboveground Biomass for Each Region (U.S. Forest Service 2014; Oswalt et al. 2017)

Region	Predominant Tree Species	Total Aboveground Biomass (billion tons)	Biomass Density (tons/mi^2)
1	Douglas-Fir, Fir, Lodgepole Pine, Engelman Spruce	0.79	3,670
2	Aspen, Cottonwood, Fir, Lodgepole Pine, Engelman Spruce	1.0	2,410
3	Jeffery Pine, Ponderosa Pine	0.59	2,500
4	Douglas-Fir, Fir, Woodland Softwood	1.2	4,550
5	Douglas-Fir, Jeffery Pine, Ponderosa Pine, Fir, Oak	2.1	13,300
6	Douglas-Fir, Fir, Western Hemlock	3.9	24,000
8	Loblolly Pine, Mixed Hardwoods	9.9	11,900
9	Spruce/Fir, Maple	8.9	13,800
10	Sitka Spruce, Western Hemlock	1.0	1,760

1.3. SCOPE OF THE WORK

This study examines woody biomass feedstocks from managed forests, and dedicated SRWCs. With the exception of spruce/fir, all the forest systems use seedlings with improved genetic traits, are grown with vegetation control, and, where needed, are provided additional nutrients. As a result, the productivity on managed lands is generally higher than in natural forests (Frederick Jr. et al. 2008; Adams et al. 2005). Managed, as opposed to unmanaged, stands respond better to weather stress, insects, and disease (Cunningham, Barry, and Walkingstick 2008). They also have shorter rotation lengths, and can be efficiently thinned and harvested in many different ways (Andreu, Zobrist, and Hinckley 2008; Cunningham, Barry, and Walkingstick 2008). Another benefit of managed forests is that the management regime can be modified to respond to new market opportunities or changing landowner objectives. For example, forest harvest residues and pre-commercial thinnings may be collected and used for bioenergy production if a market exists. Mill residues are already commonly used for in-mill energy applications, e.g., dry kilns, or heat and power. There is increasing interest in using wood for pellets that are then used for commercial power production or residential heating. Bark from the final harvest may be used for biopower and heating applications. Also, lignin isolated during the pulp-and-paper process is a major source of process energy, and greatly enhances the energy efficiency of this industry.

Among the nine forest service regions (FIGURE 1), this study focuses on the three regions with the largest amount of aboveground biomass: Regions 8, 9 and 6 (Table 1). For each region, one softwood and one SRWC species (see TABLE 2) are considered. For the softwoods, more than half of all of the growing stock removed in Region 8 in 2013 was loblolly pine (U.S. Forest Service 2014). Similarly, Douglas fir and spruce/fir are the dominant softwoods for Regions 6 and 9, respectively. Among SRWCs, eucalyptus, willow, and poplar are considered as high-potential bioenergy crops for Regions 8, 9 and 6, respectively. These SRWCs have all been commercially deployed on tens of thousands of acres in their respective regions, and exhibit fast growth rates and high biomass yields in short rotations. They can also be efficiently harvested as single "stems" or with "whole tree" harvesting methods. These plantations can be established as seedlings or with coppice methods. GREET currently includes data for two of the most studied SRWC species, willow and poplar (Wang et al. 2013).

TABLE 2 Tree Species for Each Region Examined in This Study

Region	Softwood	SRWC
8 (Southern)	Loblolly Pine (*Pinus Taeda)*	Eucalyptus (*Eucalyptus spp.*)
9 (Eastern)	Spruce/Fir (*Picea/Abies*)	Willow (*Salix alba L.*)
6 (Pacific Northwest)	Douglas-Fir (*Pseudotsuga menziesii*)	Poplar (*Populus spp.)*

The following questions are addressed in this study:

- How can woody biomass from different regions and species, e.g., with different growth rates and management practices, be used as a feedstock for liquid biofuels?
- How does the energy, material, and carbon intensity of growing and harvesting different types of woody feedstocks vary by region?
- Under what conditions is the carbon neutrality assumption (that carbon uptake during biomass growth offsets carbon emissions from biofuel combustion) for biofuels produced from SRWCs and softwoods valid?
- How does the "starting" point for the analysis, e.g., planting the trees or harvesting the trees, impact the carbon cycle?
- How does approaching forestry systems from a stand level versus a landscape level influence woody biofuel LCA results?
- How do different emissions-discounting approaches influence LCA results for woody biofuels?

To address these questions, this report presents the LCA system boundary and key assumptions of the selected woody feedstocks in Sections 1 and 2. The carbon dynamics associated with the timing of planting and harvesting are discussed in Section 0. Section 4 presents and discusses key LCA results for biofuels produced from woody feedstocks, followed by the conclusions in Section 5.

2. LCA SYSTEM BOUNDARY AND KEY PARAMETERS FOR BIOFUELS PRODUCED FROM WOODY FEEDSTOCKS

2.1. SYSTEM BOUNDARY

The system boundaries for softwood and SRWC systems are presented in FIGURE 2. For commercial forest systems based on softwoods, there are tremendous variations depending on the objectives of the landowner and local market conditions. For example, the presence of a pulp wood market or wood composite production plant will influence the planting density and thinning practices. The system boundary used for softwoods in this work is shown in Figure 2A. It is assumed that the forest experiences at least one thinning event during the growth cycle. Later, the forest is harvested to produce sawlogs and pulp chips, as well as harvest residues. The timing of this harvest, and the allocation of the softwood biomass to these different products, are dependent on the region studied. Sawlogs are sent to the mill, where lumber and pulp/paper products are produced. Mill residues are also produced at the mill and are sent to the biorefinery, along with thinnings and harvest residues. Fuel is produced in the biorefinery, which has its own additional process inputs, e.g., enzymes or hydrogen, and outputs, e.g., electrical energy sold back to the grid. The biofuel is combusted in a vehicle, with the release of CO_2 to the atmosphere. This CO_2 is eventually taken up by the regrowth of the biomass. The volume and allocation of the pre-commercial thinnings, harvest residues, and mill residues are further explained in Sections 2.1.1, 2.1.2, and 2.1.3, respectively.

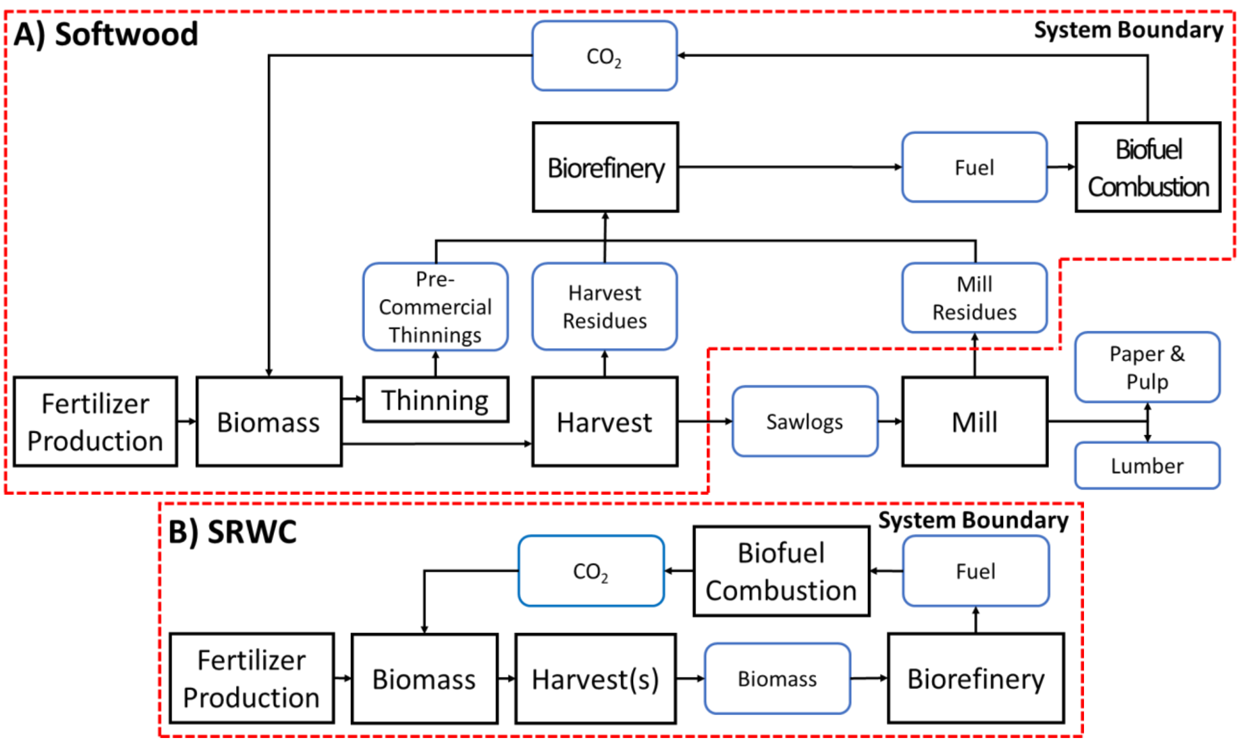


FIGURE 2 LCA system boundary diagrams, designated by red dashed lines, for A) softwood and B) SRWC systems. Unit processes are represented by the black boxes and material flows are represented in blue.

The SRWC (Figure 2B) is a purpose-grown or dedicated energy crop and thus its only use is as a feedstock for the biorefinery. The SWRC may be replanted or coppiced after a harvest. The resulting fuel is also combusted, producing CO_2, which is then taken up during the next growth cycle.

Both the softwood and SRWC systems include any needed fuel, fertilizer or chemical products required for biomass production and biorefinery operation. N_2O emissions from nitrogen fertilizer application are also considered via the default GREET emission rate of 1.525% of the nitrogen in the fertilizer lost as N_2O from soil (Wang et al. 2012). Carbon emissions or sequestration due to biomass decay or soil carbon changes on forest lands is excluded. Note that several studies suggested increases in soil organic carbon (SOC) caused by SRWC systems (Pacaldo, Volk, and Briggs 2013; Gregory et al. 2018).

Biomass production was modeled for one rotation for each tree species, and was based on common forestry practice in that region. Nursery practices were excluded from this analysis, as it has been shown that they generally have very little impact on LCA results (Caputo et al. 2014). To account for the temporal carbon dynamics of woody biomass, the carbon content of woody biomass is critical. For the species whose carbon contents are specified in GREET (i.e., loblolly pine, poplar, and willow), the GREET default values are used. The carbon contents for the other feedstocks were found by averaging experimental values (Energy Research Centre of the Netherlands 2011), as shown in TABLE 3.

TABLE 3 Carbon Content on an Ash-Free Dry Weight Basis for Each Species

	Loblolly Pine	Douglas Fir	Spruce/Fir	Eucalyptus	Poplar	Willow
Data Source	(Dunn et al. 2014)	(Energy Research Centre of the Netherlands 2011)			(Wang et al. 2013; Pacaldo et al. 2013)	
Average Carbon Content Used in This Study	50.1%	51.3%	49.9%	50.6%	50.1%	49.1%

2.1.1. Thinnings

Thinning forests that produce loblolly pine, Douglas fir, and spruce/fir is a dominant practice and has multiple benefits, depending on the mix of desired products. During thinning, rows of trees in the plantation are harvested. As a result, the remaining trees have less competition for water and soil resources, and growth rate and log quality increase. Thinning can also compensate for the effects of seedling mortality, damage to young trees, and poor tree form. After thinning, both the height and diameter of the remaining trees will increase (Johnson et al. 2015). The year and frequency of thinning will depend on the productivity of the site, local market conditions, and the desired final product. For southern pines, it is recommended that the first thinning be done between years 12 and 15 of the growth cycle. The thinning may be delayed if there is a market for chip-n-saw logs or pulp wood. A second thinning may be performed if there is a market for small-diameter logs or if the landowner is targeting poles or veneer logs as the product of the final harvest (Andreu, Zobrist, and Hinckley 2008; Cunningham, Barry, and Walkingstick 2008). Thinning of Douglas fir in the Pacific Northwest is done around year 25, while thinnings for spruce/fir occur at around years 42 (pre-commercial thinnings or "release") and 57 (commercial thinnings). In all cases, diseased trees or trees with poor form can be selectively removed to maximize the value of the trees available at final harvest.

The demand for bioenergy feedstocks may alter conventional harvesting scenarios and could alter the fate of wood harvested at different points in the forestry cycle. According to USDA, the fraction of logging residues to the total harvested forest materials has been increasing in the 1976-2011 period in various parts of the U.S. As a result, residue volume has the potential to be a significant resource for wood energy even after leaving a portion of residues for nutrient cycling and soil protection, and logging residues are being increasingly considered by companies as a possible resource for bioenergy use (USDA, 2014). Therefore, logging residues including pre-commercial thinnings could potentially be used for bioenergy production, given appropriate bioenergy market circumstances and the proximity of manufacturing operations. Meanwhile, the residues may be left in the forest to decay and to satisfy objectives related to maintaining site productivity, minimizing erosion, and preserving ecological values (USDA, 2016), especially when there is no local bioenergy market for them.

2.1.2. Harvest Residues

In addition to pre-commercial thinnings, the forest residues generated at harvest, e.g., the limbs, tops, and cull trees (unsuitable for the production of lumber or other DWPs because of decay, poor form, limbiness, or splits) from the final harvest, are also available as a biofuel feedstock (Oak Ridge National Laboratory 2011). In the U.S., if these residues are to be converted into fuels eligible for renewable identification number (RINs), they can only come from nonfederal land and tree plantations cleared/cultivated prior to December 2007 and can only be used to produce a transportation fuel, like ethanol or a hydrocarbon-based biofuel, or for electricity generation (Oak Ridge National Laboratory 2011; Daystar et al. 2013; Thakur, Canter, and Kumar 2014). If residues aren't collected, they are either left in the forest to decompose or burned as part of the site preparation work conducted before replanting. The decomposition rate depends on the litter type (e.g., stumps, roots, branches, needles), precipitation, and temperature (Zanchi, Pena, and Bird 2012; Haus, Gustavsson, and Sathre 2014). Depending on how the harvest residues are collected, different proportions of the nutrients they contain may also be removed, although on a mass basis these effects are small (Repo, Tuovinen, and Liski 2015). Approximately 50–65% of the residues can be collected from the forest, depending on the equipment used (Daystar et al. 2012). They can be collected with a forwarder and can either be bundled together for transportation to a processing facility as bales, or chipped in the woods and trucked to the conversion facility (Thakur, Canter, and Kumar 2014).

Treatment of forest residue from an LCA perspective depends on whether one is considering residue from pre-commercial thinnings or from whole-tree harvesting. In the former case, the residues are responsible for the full energy consumed in felling, skidding, and chipping. In the second case, the residues could be considered either a forestry waste product or co-product. If logging residues are treated as a waste product, only the energy used to chip the collected residues will be attributed to the biofuel feedstock. Alternatively, if they are treated as a co-product, the energy consumption and environmental burdens can be allocated between the primary wood product and residues by mass fraction. An economic allocation approach could also be taken. However, in all cases, the actual collection of the residues has only a small impact on the overall LCA burden of the biofuel.

2.1.3. Mill Residues

Sawmills produce a variety of wood products from sawlogs (logs with a large enough diameter to produce dimension lumber). The main product from these facilities is dimension lumber, which comes in a variety of sizes and has greater value than chips, particles or flakes. Four main processes occur at mills: 1) a series of sawing operations, 2) heat and steam generation, 3) drying, and 4) planing/finishing (Milota 2004; Milota, West, and Hartley 2004). The first step removes the bark and cuts the sawlogs to a desired length (Milota, West, and Hartley 2004). The logs are then cut into planks and the planks into rough lumber. Other outputs from this process can include pulp chips, which can have meaningful economic value, and bark and sawdust, which are only useful for process heat. In the second step, energy is generated in boilers and used throughout the mill. Wood, diesel, or natural gas can be used to power these boilers (Milota 2004). In the case of wood boilers, bark, sawdust and hog fuel (a mixture of bark, sawdust and shavings) produced in the sawing process are used as fuel. The energy balance for a specific mill is heavily dependent on the efficiency of the boiler and wood-drying operations. Steam generated from the boiler is used to dry the rough lumber in the third step. Drying can take 2–4 days, depending on the type of wood, the cross-sectional dimensions, and the type of dryer. In the final step, the dry lumber is planed to provide a smooth surface and accurate final dimensions, and the planar shavings can also be used in the biomass boiler.

Wood products from sawmills are most commonly dry dimension lumber; chips or shavings; sawdust; and bark and hog fuel. Chips can be sent to pulp mills or used for composite manufacturing, and bark can be used for landscaping (Milota 2004). Mill residues can also be used for energy generation at a power plant, pressed into wood pellets for combustion, or used to produce liquid biofuels.

2.2. FOREST BIOMASS PRODUCTION AND DELIVERY TO THE BIOREFINERY

As part of this project, forestry and growth cycles are modeled with careful attention to the growth rates relevant to the specific regions and species (Section 0). This modeling yields information about the mass of wood available at different points in the forest growth cycle. It informs assumptions about the timing of thinnings and final harvest. The model selected for this purpose is the Forest Vegetation Simulator (FVS), which was developed by the USFS (USDA 2013) and verified by extensive field work. The CORRIM team has used the FVS for a variety of woody tree species and scenarios.

One key output of the FVS model is the increase in stem diameter and tree height over time. This can vary widely depending on the site, tree spacing, and early management practices. The FVS model does not directly provide whole-tree biomass, which is of interest here. In this work, whole-tree biomass is estimated with the National Biomass Equations (Jenkins et al.

2003), which relate stem biomass to whole-tree biomass. It should be noted that the choice of techniques used to relate stem biomass to whole-tree biomass can significantly influence the total biomass available for bioenergy applications. This project relies on CORRIM's expertise in converting stem biomass to whole-tree biomass. CORRIM assisted with the development of the biomass growth models for some of the species and regions described in TABLE 2. Also, fertilizer, lubricant, and fuel consumption rates were obtained from field trials/measurements/data from CORRIM.

2.2.1. Loblolly Pine (Region 8: Southern Region)

Loblolly pine, which is grown on almost 40 million acres in the southern U.S., was used to represent the softwood species in Region 8. This species is modeled with a 31-year rotation and a thinning at year 15. CORRIM provided the aboveground stock for the loblolly pine management scenario in mass per area, which is converted to carbon per area using a carbon content of 50.1% (Dunn et al. 2014). FIGURE 3 provides a schematic of loblolly pine carbon stocks over a growth cycle. Note that FVS models provide the total carbon stock grown each year, and this study allocates the carbon stock to each product on the basis of the final product slate. For example, the total biomass at final harvest is allocated to lumber, pulp/paper, mill residues, and harvest residues as 45%, 27%, 15%, and 13%, respectively. Conversely, 100% of the pre-commercial thinnings in year 16 are allocated to the biofuel application.

The energy consumption for the thinning and harvesting of loblolly pine, and the energy used to produce the fertilizer and herbicide used in site preparation and establishment, are provided in

TABLE 4. The total biomass removed for the biorefinery is summarized in TABLE 5. In the bioenergy scenario, 86.2 and 51.4 dry tons/ha of lumber and pulp/paper, respectively, are also produced. The thinnings and harvest residues are treated as wastes; therefore, energy and materials attributed to their production are based on attributional allocation. That is, when considering the use of fertilizers and pesticides, their burden is assigned to DWPs because forest biomass is grown in a specific management style to increase the yields of those products, not thinnings and residues. Diesel consumption during harvest and collection of thinnings and residues is assigned to these biofuel feedstocks, and not to other forestry products. Again, it is important to note that the GHG burdens associated with the planting, fertilization, and harvesting steps are a very small portion of the overall GHG burdens of the resulting biofuel.

TABLE 4 Annual Fertilizer, Herbicide and Energy Consumption for a 31-Year Loblolly Pine Rotation

Year	Nitrogen* (kg-N/ha)	P_2O_5* (kg-P_2O_5/ha)	K_2O* (kg-K_2O/ha)	$CaCO_3$* (kg-$CaCO_3$/ha)	Herbicide* (kg-herb/ha)	Diesel Consumption (mmBTU/ha)
1					23.9	
2	132	113	105	2,001		
3	83	23	60			
16						5.77
31						2.52

* These are allocated to DWPs.

TABLE 5 Biomass Removal for Biofuel Production Based on a 31-Year Loblolly Pine Rotation

Biomass Removal Type	Year	Biomass Removal Rate (dry tons/ha)
Pre-Commercial Thinnings	16	64.2
Forest Residues	31	28.0
Mill Residues	31	28.5

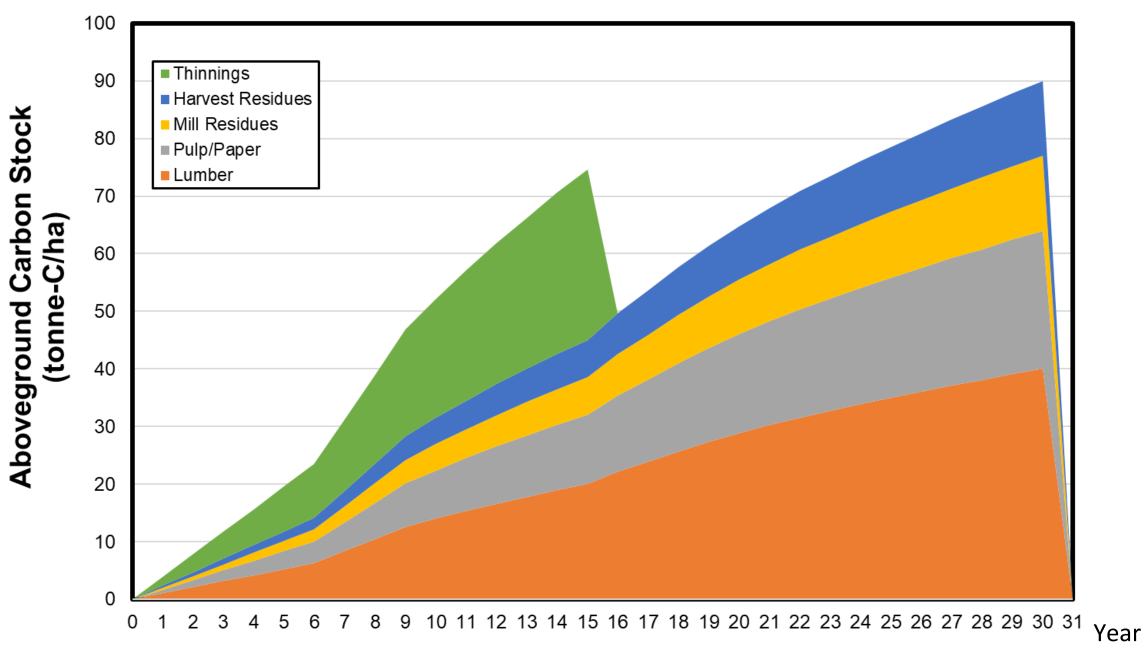


FIGURE 3 Loblolly pine forest aboveground carbon stock in lumber, pulp/paper, thinnings, and harvest and mill residues

2.2.2. Douglas Fir (Region 6: Pacific Northwest)

Douglas fir grown in the Pacific Northwest region of the U.S. (Region 6) is modeled with a 50-year rotation. Commercial thinnings and the resulting forest and mill residues are removed at year 25, while final harvest and resulting forest and mill residues are generated at year 50. The aboveground biomass for this feedstock is supplied by CORRIM on a mass-of-carbon-per-area basis at five-year intervals and was interpolated linearly by Argonne to generate yearly biomass stocks. The aboveground carbon stock for Douglas fir is provided in FIGURE 4.

The energy required for the collection of harvest residues is presented in TABLE 6. The total biomass removed for the biorefinery is summarized in Table 7. The majority of the biomass produced in this forest is used to produce DWPs (295 dry tons/ha), and this initial scenario assumes no pulp and paper production. Fertilizer and herbicides are used during stand establishment, with another fertilizer application after the pre-commercial thinning, but their burden is assigned to the DWPs. Mill residues are treated as a waste from the lumber mill and carry no burden from upstream processes.

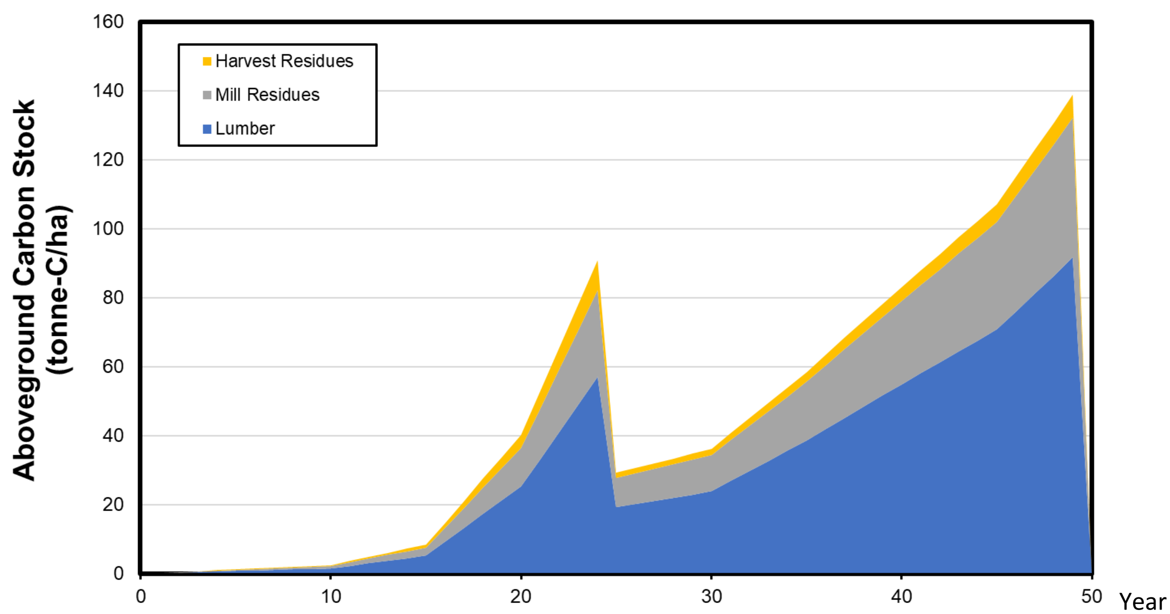


FIGURE 4 Douglas fir forest aboveground carbon stock over the 50-year modeling period

TABLE 6 Annual Energy Consumption for a 50-Year Douglas Fir Rotation

Year	Diesel and Lubricant* (mmBTU/ha)	Gasoline (mmBTU/ha)
25	1.97	0.027
50	1.82	0.025

* Lubricant accounts for 2% of total diesel and lubricant consumption

TABLE 7 Biomass Removal by Year for Biofuel Production Based on a 50-Year Douglas Fir Rotation

Biomass Removal Type	Year	Biomass Removal Rate (dry tons/ha)
Pre-Commercial Thinnings	25	16.5
Mill Residues	25	38.1
Harvest Residues	50	15.2
Mill Residues	50	91.7

2.2.3. Spruce/Fir (Region 9: Eastern)

Spruce/fir is a mixture of softwood species grown in the Eastern U.S. with a 72-year rotation. This forest is modeled with one pre-commercial and one commercial thinning and harvest residue collection in years 42, 57, and 72, respectively. Mill residues are available from the commercial thinnings and final harvest in each of those years as well. The aboveground biomass was provided by CORRIM on a yearly basis in mass of carbon per area. The aboveground carbon stock of spruce/fir is provided in Figure 5.

The energy consumption values for thinnings and harvest residues are listed in TABLE 8. The mass of biomass removed from the forest is shown in TABLE 9. The total mass of biomass removed for lumber and pulp/paper are 91.3 and 38.1 dry tons/ha, respectively. Owing to its much slower growth rate than the other softwoods, the spruce/fir mixture produces much less biomass for bioenergy and has a much longer rotation for the production of commercial sawlogs. For this region, it is uncommon to replant seedlings, and thus no fertilizer and herbicide are used during the growth cycle. As with other softwoods, mill residues are treated as a waste at the lumber mill and carry no burden from upstream processing.

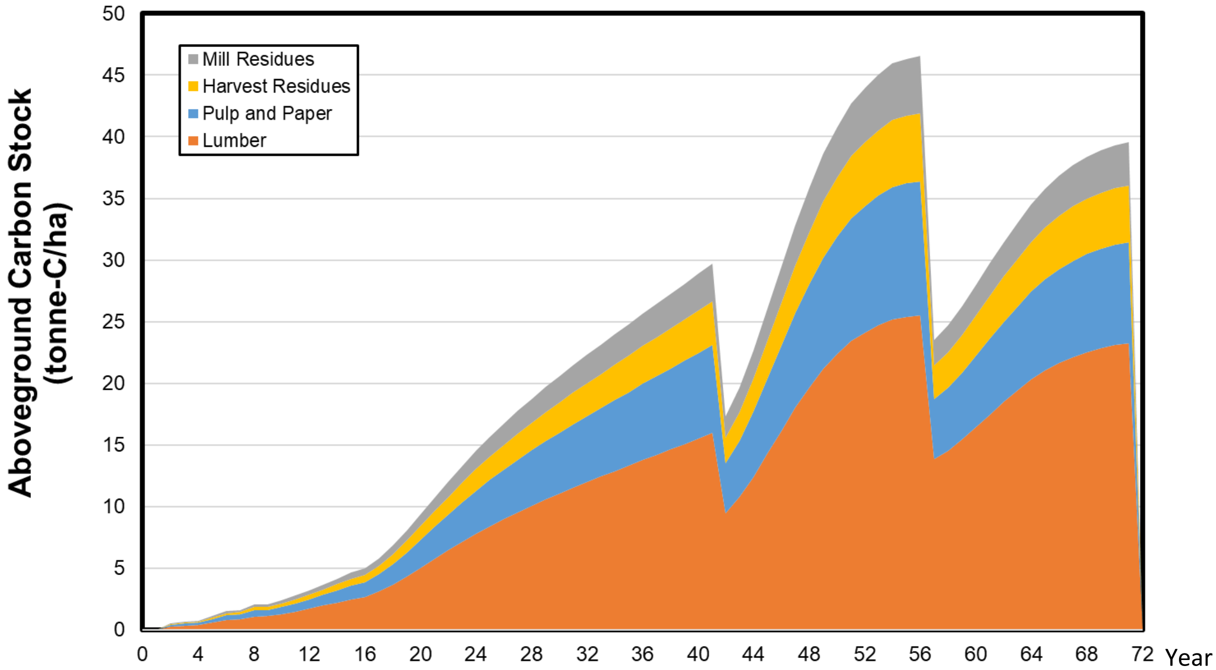


FIGURE 5 Spruce/fir forest aboveground carbon stock

TABLE 8 Annual Energy Consumption for a 72-Year Spruce/Fir Rotation

Year	Diesel (mmBtu/ha)
42	0.278
57	0.501
72	0.847

TABLE 9 Biomass Removal for Biofuel Production Based on a 71-Year Spruce/Fir Rotation

Biomass Removal Type	Year	Biomass Removal Rate (dry tons/ha)
Pre-Commercial Thinnings	42	3.3
Mill Residues	42	2.9
Commercial Thinnings	57	6.0
Mill Residues	57	5.7
Harvest Residues	72	10.2
Mill Residues	72	7.7

2.2.4. Eucalyptus (Region 8: Southern Region)

For the three fast-growing SRWCs, a linear growth rate between establishment and harvest is assumed. The SRWCs are also assumed to have been established and harvested specifically for use in the biorefinery, and thus all establishment and harvesting burdens are allocated to the biomass. Only aboveground carbon was tracked for this analysis, and the effects of decay were not considered in this first analysis.

Eucalyptus, a hardwood species, is commonly used for production of pulp, and is modeled with a six-year rotation for the Southern U.S. Rather than modeling annual growth, the final harvested biomass (69 dry tons per ha) is linearly interpolated to a yearly stock value. This system is modeled with a single-stem harvest and collection scenario, and thus new seedlings are replanted after every harvest. With the single-stem harvest assumption, a portion of the biomass will be left in the field; this portion is assumed to be 3.0 dry tons per ha, or about 5 wt.% of the biomass. Carbon impacts of the decomposition of these residues are not considered in this analysis. The harvest is provided on a mass-per-area basis, which is converted to carbon using an average carbon content of 50.6 wt.% (Energy Research Centre of the Netherlands 2011). An example of the aboveground carbon stock for eucalyptus is given in FIGURE 6, showing steady uptake until harvest. Fertilizers and herbicide are used during the first two years of growth, as shown in

TABLE 10, while diesel is used for biomass harvesting.

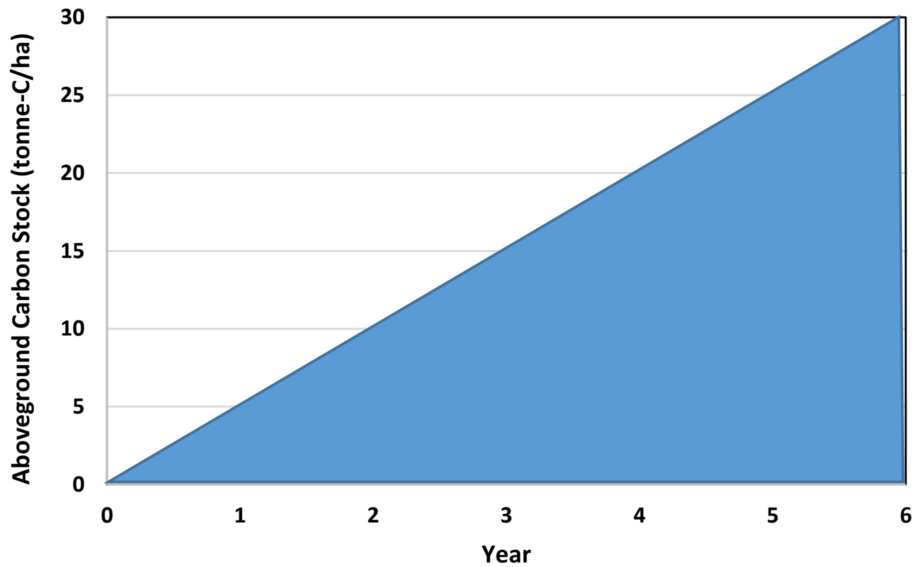


FIGURE 6 Aboveground carbon stock over a rotation period of eucalyptus in the Southern U.S.

TABLE 10 Annual Fertilizer, Herbicide and Energy Consumption for a 6-Year Eucalyptus Rotation.

Year	Nitrogen (kg-N/ha)	P_2O_5 (kg-P_2O_5/ha)	K_2O (kg-K_2O/ha)	$CaCO_3$ (kg-$CaCO_3$/ha)	Herbicide (kg-herb/ha)	Diesel (mmBtu/ha)
1	132	113	105	2,000	21.3	6.1
2	205	23	60			
6						

2.2.5. Poplar (Region 6: Pacific Northwest)

Poplar for bioenergy is modeled for the Pacific Northwest U.S. In this work, a 21-year rotation was used before replanting. The poplar was harvested every three years, with coppice regeneration. Similarly to eucalyptus, the harvested biomass is linearly interpolated with the annual growth, along with the poplar carbon content of 50.1%, to determine yearly uptake (Wang et al. 2013). A schematic of the aboveground carbon stock is provided in FIGURE 7. Only 18 dry tons per ha are harvested after the first three years, while 51 dry tons per ha are removed at every subsequent harvest. At the first harvest, 1.3 dry tons per ha is uncollected and left to decompose, while 3.7 dry tons per ha remains after the subsequent harvests. The fuel, lubricants, herbicides,

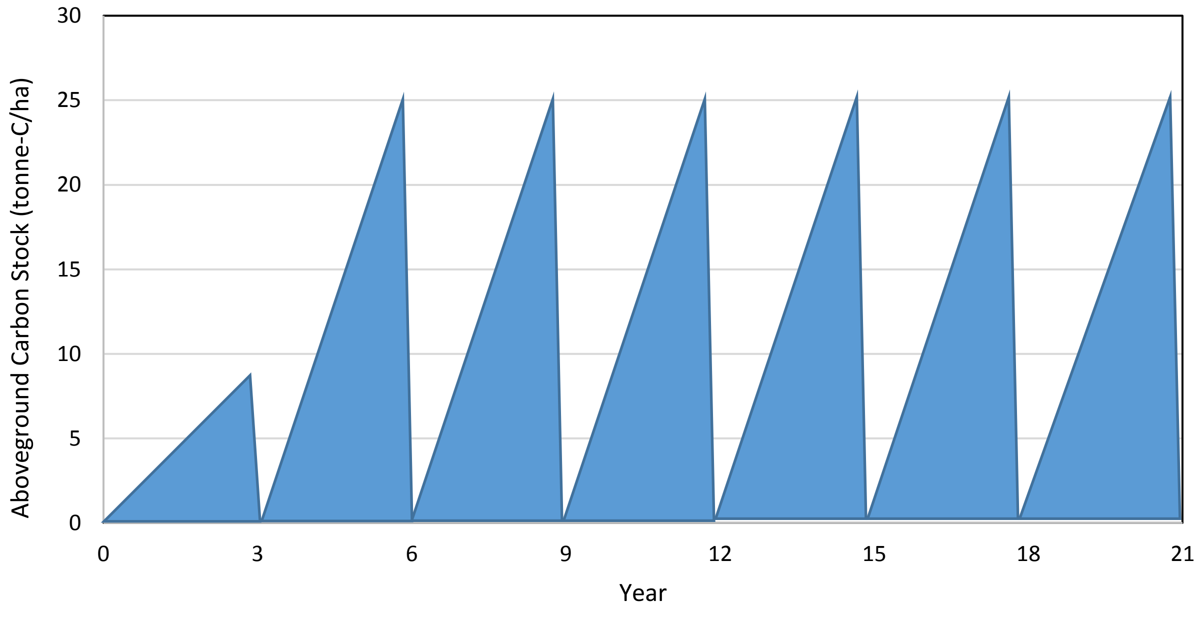


FIGURE 7 Aboveground carbon stock over a 21-year poplar rotation in the Pacific Northwest U.S.

and insecticides used for poplar production are provided in TABLE 11. For the first three years, fuel and chemical consumption varies owing to establishment activities. After the first harvest, though, the inputs remain relatively constant on a three-year cycle, until the last year, in which additional fuel and herbicide are consumed to remove the stumps/stools and restore the field for a new rotation.

TABLE 11 Fuel, Fertilizer, and Chemical Use for the Production of Poplar

Year(s)	Diesel and Lubricant (mmBtu/ha)	Herbicides (kg/ha)	Insecticides (kg/ha)
1	5.01*	9.5	0.030
2	0.01¶	2.5	0
3	6.41*	1.9	0
4,7,10,13,16,19	0.20†	7.0	0
5,8,11,14,17,20	0.30‡	3.5	0
6,9,12,15,18	10.1*	3.5	0
21	11.8*	16.1	0

*Lubricant accounts for 2% of total diesel and lubricant consumption; lubricant accounts for 100% of total diesel and lubricant consumption; †lubricant accounts for 0.5% of total diesel and lubricant consumption; and ‡lubricant accounts for 1% of total diesel and lubricant consumption.

2.2.6. Willow (Region 9: Eastern)

Willow used as a SRWC can be modeled with a 24-year rotation. The first two years are dedicated to site preparation and the initial growth phase, and the plot can be harvested every three years after that. As with the other SRWC feedstocks, only the biomass yield during every harvest is provided (Wang et al. 2013). The harvest yields are 30.9, 33.3, and 30.3 dry tons per ha for years 5, 8, and 11, respectively. The remaining harvests have the same yield, at 31.2 dry tons per ha. For every harvest, 1.8 dry tons per ha remains uncollected. The aboveground carbon stock, shown in FIGURE 8, is calculated with linear interpolation and the carbon content of willow at 48.7%. No willow is grown in the first two years owing to site preparation and initial establishment. The fuel and herbicide consumption for this unit operation, as well as fuel and nitrogen fertilizer consumption in the following years, is provided in TABLE 12. Additional diesel and lubricant are consumed with the final harvest to eliminate the stools.

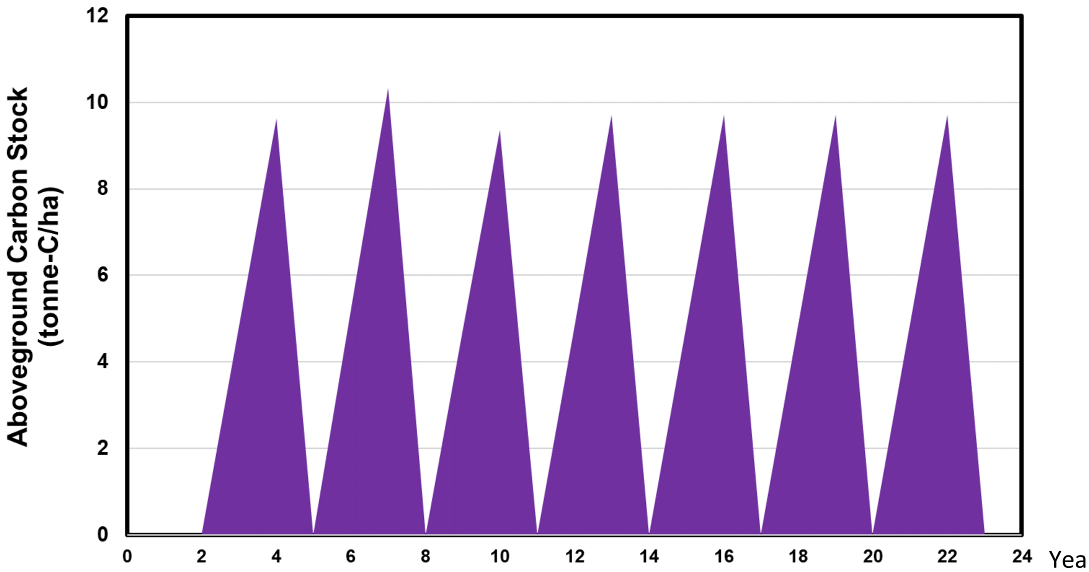


FIGURE 8 Aboveground carbon stock for a 24-year willow rotation in the Eastern U.S.

TABLE 12 Fuel, Fertilizer, and Chemical Use for the Production of Willow

Year	Diesel and Lubricant (mmBtu/ha)	Nitrogen (kg/ha)	Herbicide (kg/ha)
1	4.23*		5.0
2	7.32¶		3.7
3	7.81†	112	
4	2.60†		
5	58.2‡		
6,9,12,15,18,21	6.71‡	112	
7,10,13,16,19,22	2.60†		
8,11,14,17,20,23	58.2‡		
24	7.32†		

*Lubricant accounts for 0.7% of total diesel and lubricant consumption; ¶lubricant accounts for 0.3% of total diesel and lubricant consumption; †lubricant accounts for 0.2% of total diesel and lubricant consumption; and ‡lubricant accounts for 0.1% of total diesel and lubricant consumption.

2.2.7. Biomass Transportation to Biorefinery

CORRIM provided information on transportation of each feedstock to the biorefinery (TABLE 13). For softwoods, logistics are only considered for thinnings and harvest residues, as it is assumed the lumber mill that provided mill residues is co-located with the biorefinery. Transportation distance is determined by the area required to supply a 500-dry-tons-per-day facility in each specific region. The load capacity and fuel consumption are based on current logistics in each region. It is assumed that each feedstock is transported at a moisture content of 45%.

TABLE 13 Parameters for Feedstock Transportation to the Biorefinery

	Loblolly Pine	Douglas Fir	Spruce/ Fir	Eucalyptus	Poplar	Willow
Transportation Distance (mi)	14, 32*	48.5	87.5	28	39.8	44.1
Load Capacity (dry ton/load)	12.5	10.7	11.3	22.5	20.7	20.7
Fuel Consumption (gal/mi)	0.2	0.2	0.2	0.2	0.26	0.17

* 14 miles for thinnings, 32 miles for harvest and mill residues

2.3. BIOMASS CONVERSION TO FUELS

2.3.1. Thermochemical Conversion to Gasoline and Diesel

CORRIM used an updated Aspen-based engineering process model to estimate the conversion of the six types of biomass to a final hydrocarbon fuel based on previous modeling (Jones et al. 2013; Oasmaa et al. 2010; Mahadevan et al. 2016; Howe et al. 2015). However, this updated Aspen model had three important modifications. First, the amount of intermediate bio-oil, char and permanent gases varied according to the carbon and ash content of the biomass. Second, all the hydrogen was produced from natural gas with well-development technology, which would be a much lower-cost alternative to a biomass gasification unit. Third, all the char, permanent gases, and heavy cuts from the hydrogenation and distillation processes were burned in a biomass boiler and used to generate the heat and energy needed. Any excess heat was used to generate electricity, which was sold back to the grid and taken as a credit in the LCA.

TABLE 14 Energy Balance Information for Thermochemical Conversion Process (mmBtu/dry ton of woody biomass)

	From CORRIM						
	Loblolly Pine	Douglas Fir	Spruce/ Fir	Eucalyptus	Poplar	Willow	GREET Value
Inputs							
Natural Gas	6.17	6.41	5.96	5.77	5.79	5.52	2.72
Outputs							
Co-Produced Electricity	0.47	0.61	0.59	0.74	0.60	0.63	0.51
Renewable Gasoline	4.19	4.24	4.05	3.91	3.99	3.90	5.16
Renewable Diesel	5.29	5.56	5.05	4.83	4.86	4.54	5.19

As shown in Table 14, biorefinery conversion data included gasoline and diesel fuel product yields, natural gas consumption, electrical energy consumption (or production), and biogenic and non-biogenic carbon release to the atmosphere. The biogenic carbon release to the atmosphere included carbon emissions from the conversion processes as well as combustion of off-gas and char to produce electricity. The biogenic carbon emissions were calculated from the balance of carbon in the biomass input feedstock (TABLE 3) and carbon in the final fuels. The carbon contents of the renewable diesel and gasoline are 87.1% and 84.0%, respectively (Han et al. 2011). The co-produced electricity is estimated to have a GHG credit based on replacement of the U.S. average electricity.

In addition to the thermochemical conversion modeling by CORRIM, this study examined the conversion parameters from Argonne's past research assuming constant energy inputs, surplus electricity, and total fuel produced for all species, and compared the results (Han et al. 2011).

2.3.2. Biochemical Conversion to Ethanol

CORRIM also used an ASPEN-based biochemical process model to estimate the production of ethanol from the three SRWC feedstocks[1], based on previous work (Humbird et al. 2011). Note that the eucalyptus pretreatment conditions, conversions, and enzymatic hydrolysis yields were chosen from the work of Emmel et al. (2003), which used considerably less severe pretreatment conditions than for poplar and willow. Thus, the sulfuric acid and lime usage is much lower than for the other two feedstocks. The SRWC feedstocks are converted to ethanol using the cellulosic ethanol conversion information already available in GREET. This process uses diesel, along with a variety of chemicals, to produce ethanol and surplus electricity. All process parameters are the same for SRWCs, except for biogenic carbon emissions, which are determined with a mass balance for the carbon contents in input feedstocks and output products. It is assumed that all the carbon in the woody feedstock is converted to ethanol or is released to the air at the facility, either through fermentation or combustion/electricity generation. The carbon content of each feedstock, as presented in TABLE 3, determines the incoming carbon, while the carbon content of the ethanol product is 52.2%. Biochemical conversion parameters to produce ethanol are provided in

[1] Because of the well-known recalcitrance of softwoods, they were not considered as a useful feedstock for a biochemical-based biorefinery.

TABLE 15. Similarly to thermochemical conversion, a displacement credit is estimated for the co-produced electricity by assuming replacement of the U.S. average electricity.

TABLE 15 Biochemical Conversion Parameters for All SRWC Feedstocks

	From CORRIM			
	Eucalyptus	Poplar	Willow	GREET Value
Diesel Consumption (Btu/gal ethanol)	0	0	0	337
Co-Produced Surplus Electricity (Btu/gal ethanol)	9,977	10,022	7,243	8,200
Ethanol Yield (gal ethanol/dry ton)	68	66	73	85
Ammonia Use (g/gal ethanol)	113	265	199	42
Corn Steep Liquor Use (g/gal ethanol)	180	201	183	132
Diammonium Phosphate Use (g/gal ethanol)	19	22	20	14
Sulfuric Acid Use (g/gal ethanol)	22	304	277	346
Sodium Hydroxide Use (g/gal ethanol)	201	525	383	117
Lime (CaO) Use (g/gal ethanol)	13	122	93	76
Urea Use (g/gal ethanol)	11	11	11	21

3. TEMPORAL AND SPATIAL ASPECTS OF CARBON DYNAMICS OF WOODY FEEDSTOCK GROWTH AND HARVEST

The temporal and spatial aspects of forest growth can have a large effect on the total biomass production and the overall carbon cycle. In a healthy forest ecosystem, the carbon stocks are relatively constant over time (Haus, Gustavsson, and Sathre 2014), barring forest fires or other disasters. If a "mature" forest were undisturbed (no management or harvesting), then there would be a continuous uptake of carbon due to forest growth, and also a slow release of carbon from the forest over time due to the decomposition of dead biomass (Repo, Tuomi, and Liski 2011).

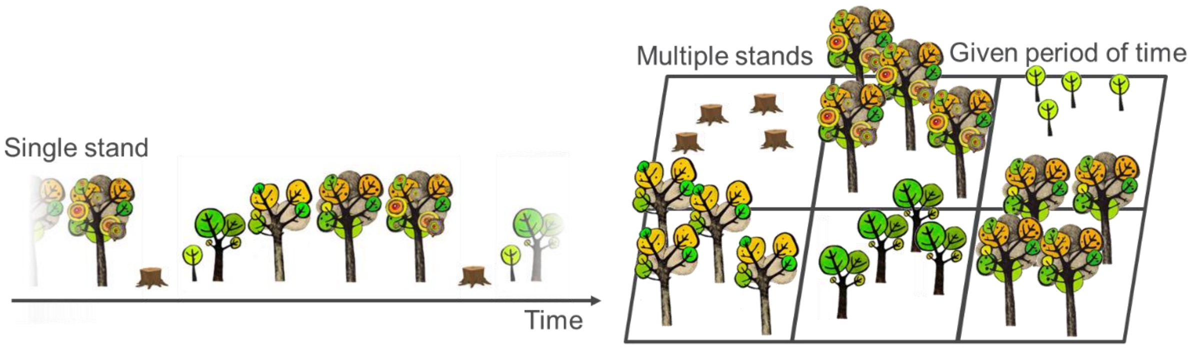
In a managed forest, on the other hand, a series of activities take place at different times during a growth cycle, and the time period between planting and harvest cycles also varies widely. As a result of these inputs that occur at specific times during the cycle, the associated GHG emissions are released in distinct bursts, instead of continuously over time (Repo, Tuomi, and Liski 2011).

Biogenic carbon emissions upon combustion of woody biomass-derived biofuels are also affected by temporal aspects of the carbon cycle. For many biofuels, biogenic carbon emissions upon combustion are usually considered to be net zero because it is assumed the combustion releases carbon that is removed from the atmosphere and incorporated into the biomass. As mentioned previously, this assumption has been challenged for woody biomass, especially for the slower-growing softwoods with long growth cycles (Zanchi, Pena, and Bird 2012; Holtsmark 2012; Jonker, Junginger, and Faaij 2014; Lamers and Junginger 2013). This challenge is due to the time lag between the carbon release from biofuel combustion and the carbon uptake during biomass growth in the next cycle. This time lag between the carbon emissions and recapture/sequestration from the regrowth of the biomass would result in differences in atmospheric carbon over the time frame of one to two growth cycles.

In the following section, three specific issues concerning the carbon tracking protocols are examined. First is the question of a "stand-level" or "landscape-level" analysis. A second issue, which applies to "stand-level" analysis, is the timing for the start of the analysis; does the analysis start with the planting of seedlings or the harvesting of the trees? The final issue is the temporal issue of tracking carbon over extended periods of time.

3.1. STAND-LEVEL VS LANDSCAPE-LEVEL CARBON ACCOUNTING METHODS

Carbon accounting of woody biomass feedstock can be conducted with different analysis scopes: stand-level and landscape-level analyses (see **Error! Reference source not found.**Figure 9). A tree stand can be defined as a contiguous community of trees that is uniform enough (in terms of composition, structure, age- and size-class distribution, etc.) to distinguish it from adjacent communities, e.g., a 20-hectare loblolly pine plantation that has been harvested and replanted. Thus, the stand-level analysis takes into account the emissions and sequestration of carbon over a cycle of forest operation that occurs from the point of view of a relatively small, defined land area, e.g., tens to hundreds of hectares. On the other hand, a landscape-level analysis is conducted on a forest made up of hundreds of stands, each at a different point in its growth cycle. Sustainable forest management would assume that the same amount of carbon is removed in one part of the forest as is absorbed by trees in other parts of the forest, maintaining a constant carbon stock for the whole forest. With landscape-level analysis, carbon emissions and sequestration do not have temporal effects, since forest biomass stock in a landscape remains constant with annual biomass harvest for bioenergy production.



(a) Stand-level analysis (b) Landscape-level analysis

FIGURE 9 Illustrative examples of stand-level and landscape-level analysis

3.2. HARVEST-PLANTING CYCLE FOR STAND-LEVEL ANALYSIS

Since the stand-level analysis considers the carbon dynamics over the forest operation cycle, the selection of the “start” and “end” of the analysis is critical. In this study, the stand-level analysis starts immediately after the final harvest for the previous forest operation cycle, and ends at the final harvest of the resulting forest operation cycle.

Since a forest operation generates a large amount of biomass at the end of a cycle, tracking the carbon fluxes is an important factor. For example, the final harvest of a softwood stand results in forest and mill residues, and the final harvest of SRWCs results in dedicated biomass feedstock. This biomass could be allocated to the post-harvest cycle of the analysis (Cycle 1 in FIGURE 10) or the pre-harvest cycle of the analysis (Cycle 2 in FIGURE 10). In other words, Cycle 1 considers the forest operation to regrow the carbon stock that has been lost in the harvest at the beginning, while Cycle 2 considers the forest operation to harvest biomass at the end of the cycle. This study examines both Cycles 1 and 2 to demonstrate how growth rate and forest operations (thinnings) impact changes in atmospheric carbon.

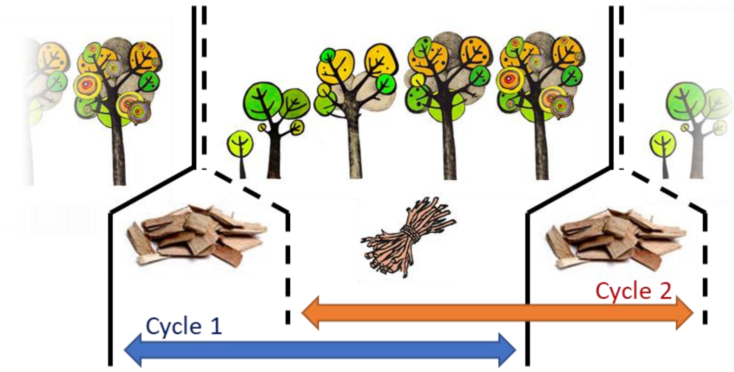


FIGURE 10 Illustrative forest operation cycles for bioenergy production

3.3. CARBON ACCOUNTING METHOD FOR TEMPORAL CARBON DYNAMICS FOR STAND-LEVEL ANALYSIS

Another key issue is how to account for future GHG emissions. Owing to delays in GHG emissions/sequestration as the feedstock grows, the global warming impacts of delayed GHG emissions/sequestration observed at the end of a given analysis horizon would be reduced gradually. A widely accepted method to address the impacts of delayed GHG emissions/sequestration is to estimate cumulative global warming effects using discounted GWPs over time.

During a cycle of forest operations, GHG emissions and sequestration occur in different years. The carbon accounting method used in this study estimates the cumulative global warming effects of these emissions at the 100th year from the start of the forest operation cycle. The cumulative global warming effects in g CO_2e (E_{total}) are estimated by the sum of the production of emissions *i* in a given year *t* in grams, $E_i(t)$, and discounted global warming potential (dGWP) of the emissions *i* in year *t* to the 100th year, $dGWP_i(100\text{-}t)$, as follows:

$$E_{total} = \sum_{t=0}^{100} \left(E_i(t) \times dGWP_i(100 - t)\right).$$

The dGWP of the emissions in year *t* to the 100th year (or over 100 – *t* years) is the ratio of the absolute global warming potential (AGWP) of the emissions *i* over 100 – *t*, $AGWP_i(100 - t)$, and CO_2 emissions over 100 years, $AGWP_{CO_2}(100)$, calculated as follows:

$$dGWP_i(100 - t) = \frac{AGWP_i(100 - t)}{AGWP_{CO2}(100)}.$$

Note that the dGWP uses the AGWP of CO_2 over 100 years as a denominator, while a general GWP uses the AGWP of CO_2 over the same period as a denominator and a numerator. For example, with a 100-year time horizon, a general GWP is calculated as follows:

$$GWP_i(100) = \frac{AGWP_i(100)}{AGWP_{CO2}(100)}.$$

AGWP in W m^{-2} kg^{-1} year is the integration of radiative forcing of a gas *i* at a given time horizon. For CO_2, the AGWP can be calculated as follows:

$$AGWP_{CO_2}(H) = 1.759e^{-15}\left[a_0\, H + \sum_{i=1}^{3} a_i \tau_i \left(1 - \exp\left(-\frac{H}{\tau_i}\right)\right)\right].$$

where 1.759e^{-15} is the radiative efficiency for CO_2 in W m^{-2} kg^{-1}, a_i are weighting factors for the effect of each perturbation time scale, and τ_i are perturbation time scales for three modes of redistribution of CO_2 following release (IPCC 2007). The a_i and τ_i are estimated by average values of a set of climate models, summarized in TABLE 16.

TABLE 16 Parameter Values for the Sum of Exponentials Describing the Fraction of CO_2 Remaining in the Atmosphere after a Pulse Emission of CO_2

	0	1	2	3
Coefficient, a_i (unitless)	0.2173	0.2240	0.2824	0.2763
Time scale, τ_i (years)		394.4	36.54	4.304

FIGURE 11 shows the dGWP and AGWP of CO_2 over 100 years. For AGWP (blue line), the time horizon indicates how long the radiative forcing is estimated to continue after a pulse emission of CO_2. AGWP increases from 0 to 9.209 x 10^{-14} W m^{-2} kg^{-1} year in 100 years. In the context of this study, emissions that occur in the 0th year have 9.209 x 10^{-14} W m^{-2} kg^{-1} year of cumulative radiative forcing impacts because the effective time horizon for the emissions is 100 years. On the other hand, the emissions that occur in the 100th year or after would have zero cumulative radiative forcing impacts. In other words, the dGWP of the CO_2 emissions is 1 in the 0th year and is gradually reduced (or discounted) to 0 in the 100th year. Thus, this approach truncates the effect of emissions and sequestration over the 100-year analysis period at 100 years, and does not account for any residual effects of these carbon flows beyond the 100-year analysis period. As the residual GWP is cut off at the end of the analysis horizon (100 years in this study), this method is referred to here as the "GWP cutoff" method.

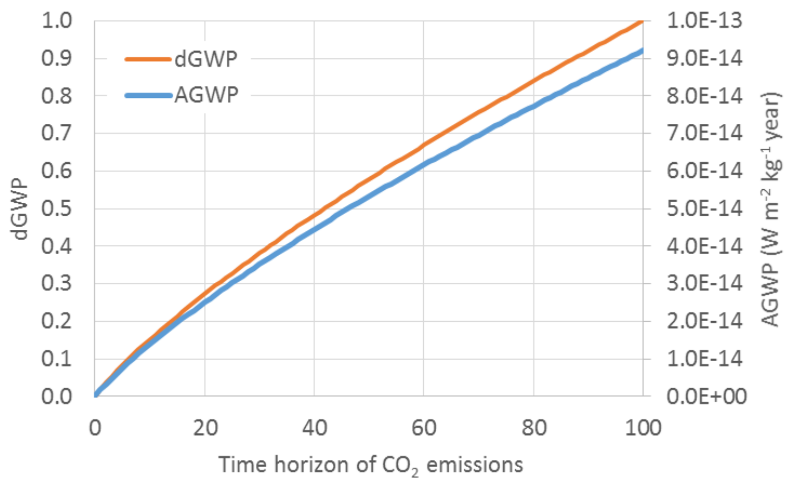


FIGURE 11 dGWP and AGWP of carbon emissions or sequestration

4. RESULTS

4.1. CUMULATIVE BIOMASS PRODUCTION

FIGURE 12 presents the cumulative biomass growth of the six woody biomass feedstocks evaluated in this study. The SRWC species (i.e., eucalyptus, poplar, and willow) show much faster growth rates and a shorter planting-to-harvest cycle than the softwoods. Note that the softwood species produce additional higher-value products (i.e., lumber and pulp/paper), and thus only a portion of the total is available for bioenergy (dotted lines). For example, the biomass for bioenergy feedstock, comprised of pre-commercial thinning, harvest residues and mill residues, accounts for only 46%, 35%, and 24% of total biomass from loblolly pine, Douglas fir and spruce/fir, respectively, over the entire rotation period.

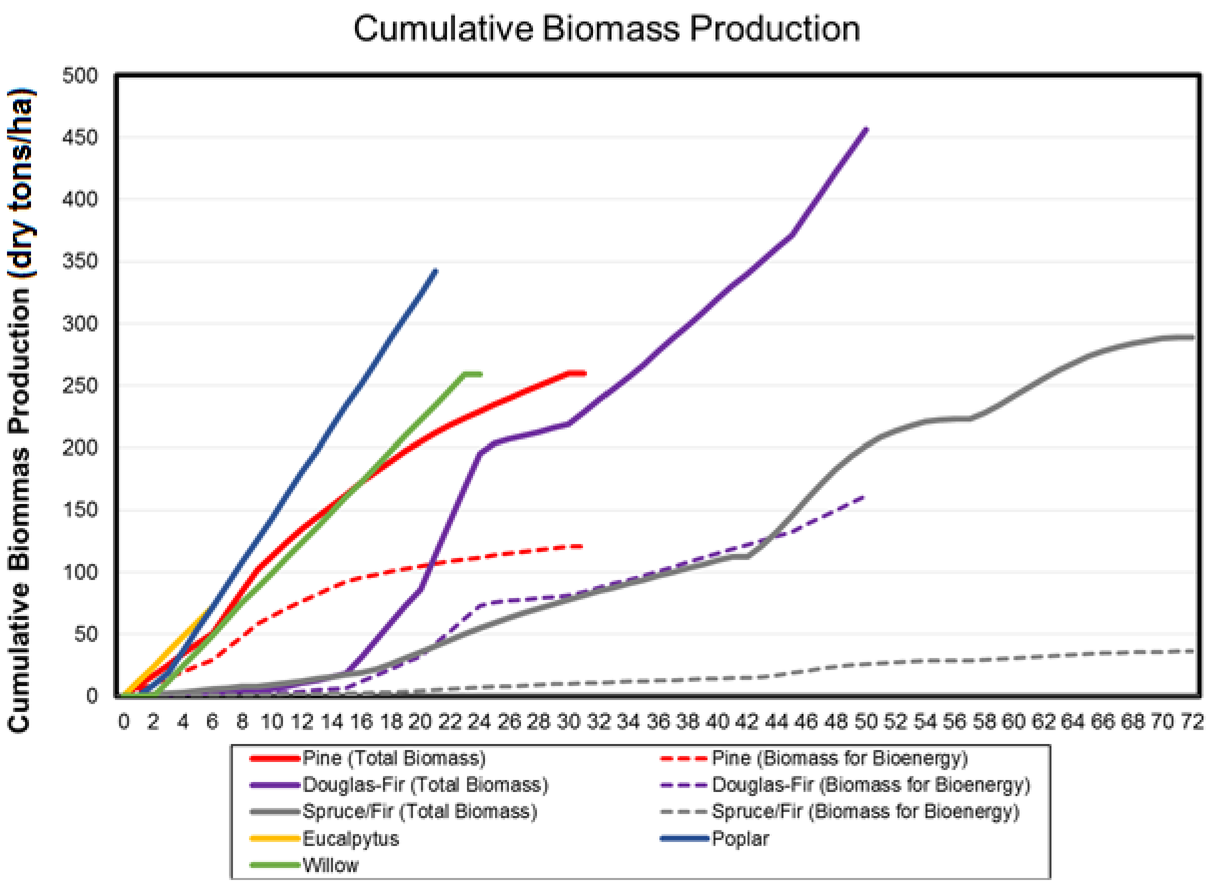


FIGURE 12 Cumulative biomass production of six species examined in this study

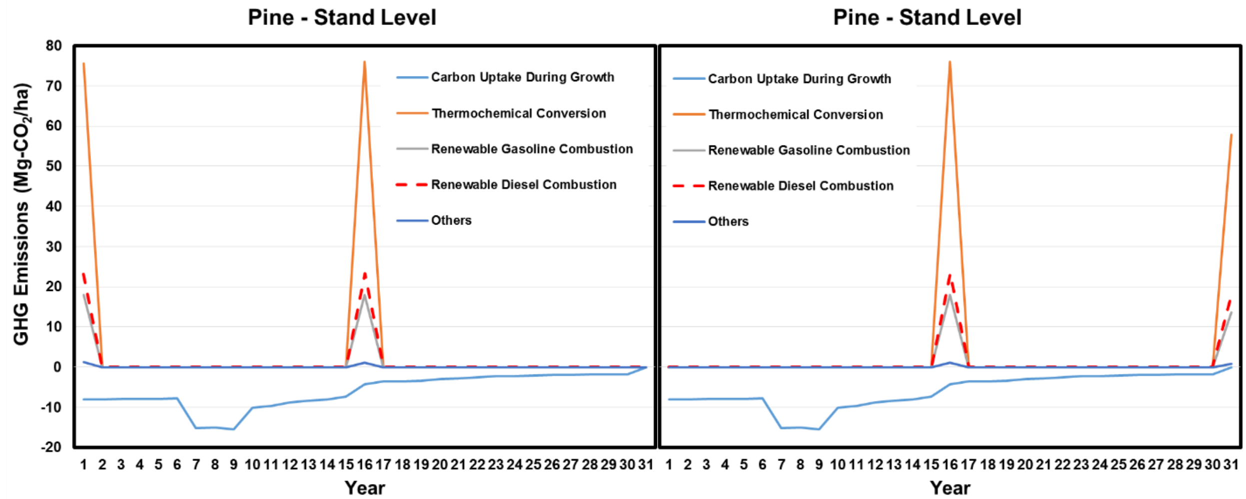
4.2. LIFE-CYCLE GHG EMISSIONS OVER TIME AT THE STAND LEVEL

4.2.1. Softwood

FIGURE 13 presents GHG emissions in Mg CO_2e/ha over time for the stand-level analysis for loblolly pine grown in the Southern region with two planting/harvest cycles (Cycles 1 and 2). Carbon uptake during growth occurs every year. The largest emission comes from the thermochemical biorefinery conversion process, followed by renewable gasoline and diesel combustion. Other emission sources, including the sum of forest operations, logistics, and renewable gasoline and diesel transportation and distribution, together make a very minor contribution. The dominant sources of the GHG emissions from the thermochemical conversion process are the combustion of the renewable gasoline and diesel, and the fuel production process. Following the growth curve in FIGURE 3, the rate of carbon uptake peaks between years 8 and 10, then tapers off as the growth rate slows, the number of stems per hectare is reduced during thinning, and the additional carbon uptake is discounted by the accounting methods. If the future emissions were not discounted (as in the landscape-level analysis), these GHG emissions would be almost canceled out by the carbon uptake during growth.

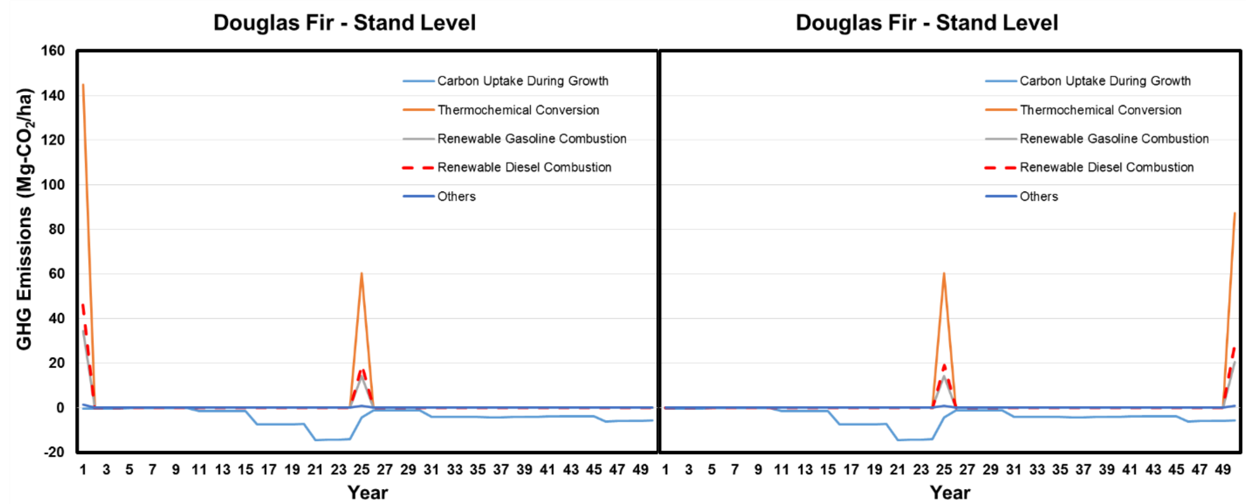
As shown in FIGURE 13, the only difference between Cycles 1 and 2 is that all emissions occurring in Cycle 1 (from thermochemical conversion, renewable gasoline and diesel combustion, and other sources) occur in years 1 and 16. Since Cycle 2 starts with the establishment of the trees, the emissions take place in years 16 and 31, delaying the global warming impacts. Note that, without the discount of global warming impacts, the amounts of GHG emissions occurring in year 1 of Cycle 1 and year 31 of Cycle 2 are the same. With the discount, the global warming impact of the GHG emissions occurring in year 31 of Cycle 2 is reduced by 23% relative to that occurring in year 1 of Cycle 1. The effects of the reduced global warming impacts on the overall GHG emissions associated with renewable gasoline and diesel are discussed in the next section (Section 4.3).

Figures 14 and 15 show GHG emissions in Mg CO_2e/ha over time at the stand level for Douglas fir grown in the Pacific Northwest region and spruce/fir grown in the Eastern region, respectively. Compared to loblolly pine, there is a much larger carbon debt allocated in the first year using the Cycle 1 accounting framework. Using the Cycle 2 framework pushes the major emission at harvest out to year 50 and 72 for Douglas fir and spruce/fir, respectively. Similarly to the loblolly pine cases, the only difference between Cycles 1 and 2 is that the emissions occurring in year 1 in Cycle 1 occur in the last year of the growth cycle in Cycle 2, with significant discounts. Since the biomass growth cycles of Douglas fir and spruce/fir are much longer than that of loblolly pine, the magnitude of the global warming impacts of the delayed emissions occurring in year 50 and year 72 in Cycle 2 is reduced by 39% and 60% for Douglas fir and spruce/fir, respectively, relative to that occurring in year 1 of Cycle 1 due to the accounting method; these reductions are much greater than in the loblolly pine case (23%).



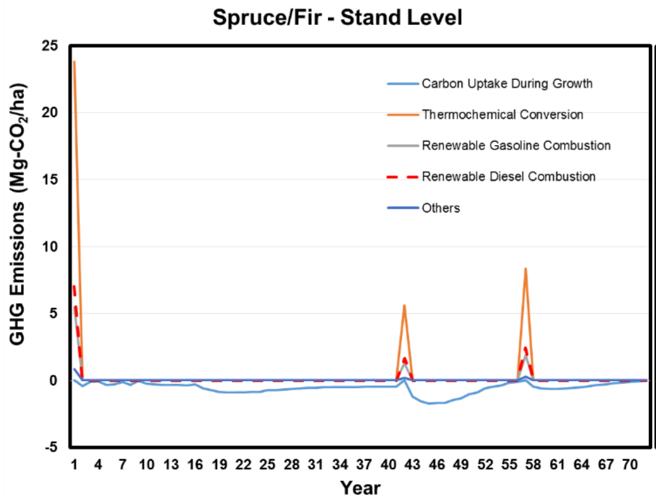
(a) Cycle 1 (b) Cycle 2

FIGURE 13 GHG emissions (Mg CO_2e/ha) over time for loblolly pine (Southern region) using a stand-level analysis, with a Cycle 1 or a Cycle 2 framework

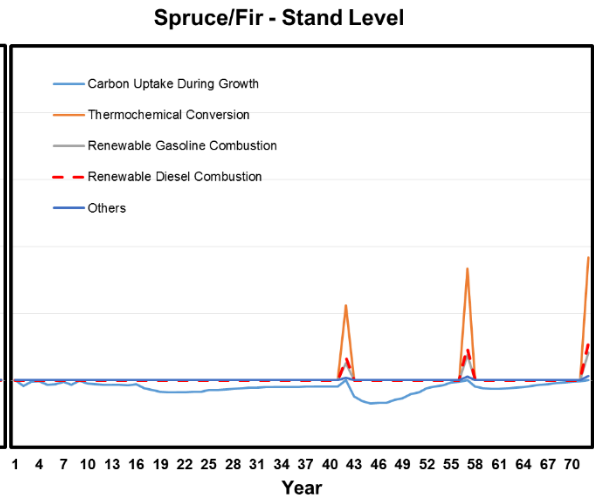


(a) Cycle 1 (b) Cycle 2

FIGURE 14 GHG emissions (Mg CO_2e/ha) over time for Douglas fir (Pacific Northwest Region) using a stand-level analysis, with a Cycle 1 or a Cycle 2 framework



(a) Cycle 1



(b) Cycle 2

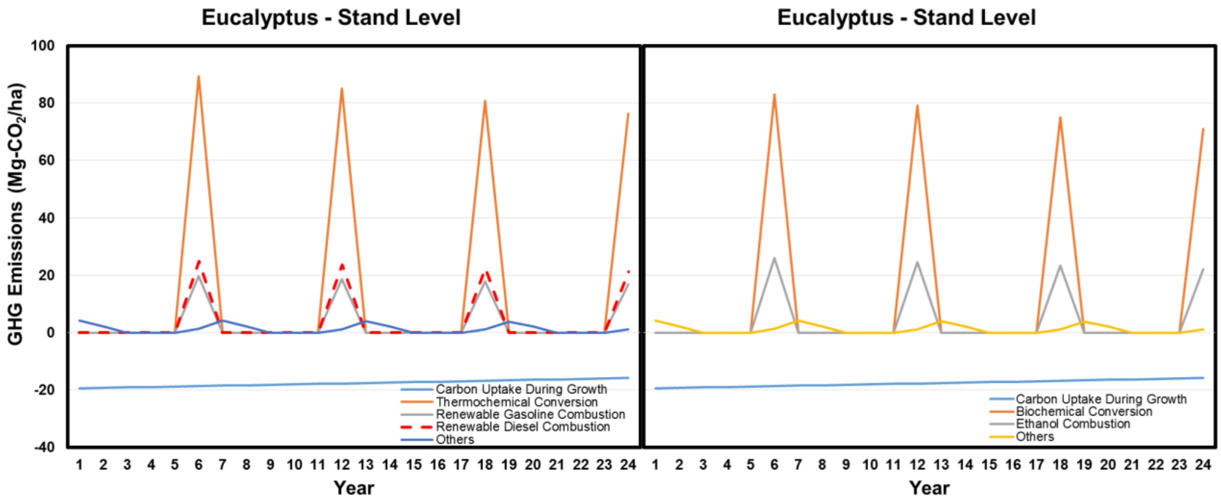
FIGURE 15 GHG emissions (Mg CO2e/ha) over time for spruce/fir (Eastern Region) using a stand-level analysis, with a Cycle 1 or a Cycle 2 framework

4.2.2. SRWCs

This section presents GHG emissions for biofuels produced thermochemically and biochemically from SRWCs. Since the SRWCs are planted for the expressed purpose of producing feedstock for the biorefinery, only Cycle 2 is a reasonable biomass production scenario. To better understand the impacts of using the three alternative SRWCs, this study examined four consecutive growth cycles (a total of 24 years) so that the overall analysis cycles of the three SRWCs are relatively consistent.

FIGURE 16 provides GHG emissions in Mg CO_2e/ha over time based on a stand-level analysis using Cycle 2, for eucalyptus grown in the Southern Region producing (a) renewable gasoline and diesel and (b) ethanol. While the actual emissions in years 6, 12, 18, and 24 are the same, their global warming impacts decrease gradually over time owing to lower GWPs for delayed emissions.

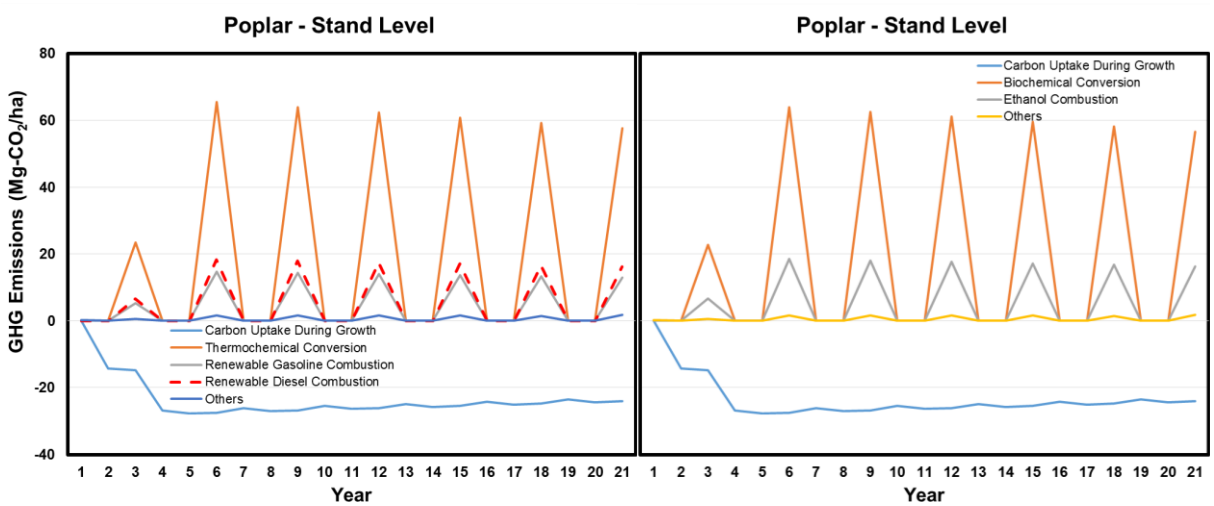
Thermochemical conversion consumes a large amount of hydrogen, which is GHG-intensive. Thus, the GHG emissions from thermochemical conversion are larger than those from biochemical conversion even if the carbon efficiency of thermochemical conversion is higher than that of biochemical conversion. Also, owing to the higher carbon efficiency of thermochemical conversion, renewable-gasoline and diesel combustion combined produce larger emissions of carbon per hectare than ethanol combustion, although fewer hectares of land are needed to produce the biofuel.



(a) Thermochemical Conversion (b) Biochemical Conversion

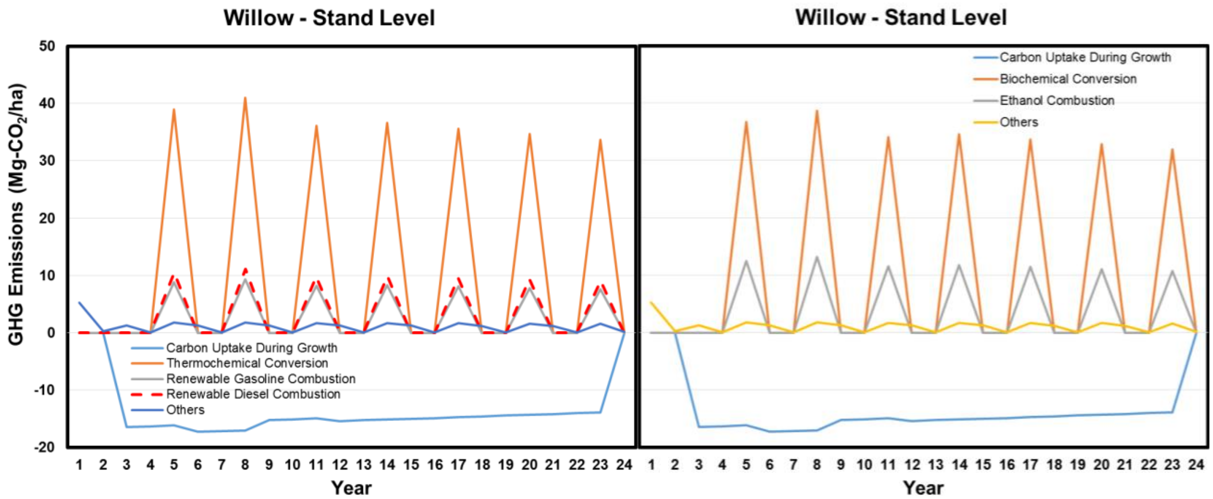
FIGURE 16 GHG emissions (Mg CO_2e/ha) over time for eucalyptus (Southern Region) producing (a) renewable gasoline and diesel and (b) ethanol, using a stand-level analysis with a Cycle 2 framework

FIGURE 17 shows the GHG emissions in Mg CO_2e/ha over time based on a stand-level analysis using Cycle 2, for poplar grown in the Pacific Northwest Region producing (a) renewable gasoline and diesel and (b) ethanol. FIGURE 18 shows the analogous results for willow grown in the Eastern Region. The same observations noted for eucalyptus can be made for poplar and willow.



(a) Thermochemical Conversion (b) Biochemical Conversion

FIGURE 17 GHG emissions (Mg CO_2e/ha) over time for poplar (Pacific Northwest Region) producing (a) renewable gasoline and diesel and (b) ethanol, using a stand-level analysis with a Cycle 2 framework



(a) Thermochemical Conversion (b) Biochemical Conversion

FIGURE 18 GHG emissions (Mg CO_2e/ha) over time for willow (Eastern Region) producing (a) renewable gasoline and diesel and (b) ethanol, using a stand-level analysis with a Cycle 2 framework

4.3. COMPARING GHG EMISSIONS USING LANDSCAPE-LEVEL AND STAND-LEVEL ANALYSES

To estimate and compare the GHG emissions associated with biofuels, the results on a hectare basis over time need to be converted into g CO_2e/MJ of biofuel produced. To this end, the results shown in Figures 13 to 18 are summed over time and then divided by the total energy in biofuel produced. Since the thermochemical conversion process co-produces both renewable gasoline and diesel, emissions/sequestrations associated with the carbon uptake during growth, thermochemical conversion, and forest operations are allocated to these two components (i.e., renewable gasoline and diesel) on the basis of their energy shares.

This section presents the GHG emissions of renewable gasoline in g CO_2e/MJ, using the landscape-level and stand-level analyses. The landscape-level analysis, which addresses an entire forest in which there are numerous individual stands, assumes sustainable forest management and a steady-state inventory of carbon. The stand-level analysis, which follows the emissions and sequestration of carbon over a cycle of an individual stand, accounts for temporal effects of carbon dynamics. Therefore, the definition of an analysis cycle (Cycle 1 vs. Cycle 2) is critical, as a large amount of biomass is only generated at harvest. This section provides the results using both Cycle 1 and Cycle 2 for softwood-derived renewable gasoline, while SRWC results are based on Cycle 2 only.

FIGURE 19 shows the GHG emissions (g CO_2e/MJ) of renewable gasoline from the three alternative softwoods at both the landscape and stand levels. For the stand-level analysis, results with both Cycle 1 and Cycle 2 are presented. Note that the biogenic carbon emissions (green bars) are the sum of biogenic CO_2 emissions from both the thermochemical biorefinery and the combustion of the renewable fuel. Across all the scenarios, the biogenic carbon emissions and biogenic carbon uptakes dwarf the other GHG emissions. Moreover, the magnitudes of these two dominate operations, and the overall net carbon emissions vary significantly depending on the forest type.

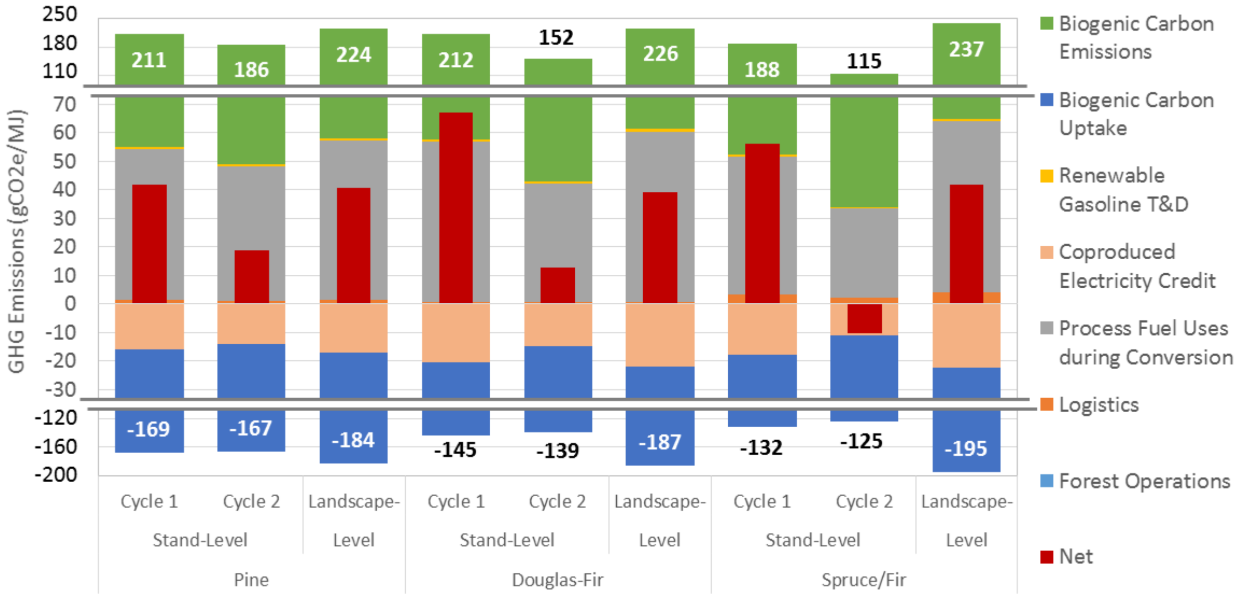


FIGURE 19 GHG emissions of renewable gasoline from softwoods in landscape- and stand-level analyses

The net GHG emissions of softwood-based renewable gasoline estimated in the landscape-level analysis are 41, 39, and 42 g CO_2e/MJ for loblolly pine, Douglas fir, and spruce/fir, respectively. In this landscape-level analysis, the GHG emissions and carbon uptake (i.e., carbon uptake during biomass growth, and biogenic CO_2 emissions during both thermochemical conversion and renewable gasoline combustion) largely cancel each other out, since in the landscape-level analysis, the temporal effects of carbon emissions and sequestration are not critical. These three wood sources also have similar chemical and ash composition, and thus perform similarly in the biorefinery, e.g., with respect to yield of intermediate crude bio-oil, hydrogen demand, and final renewable-fuel yield.

In the stand-level analysis, on the other hand, the choice of the analysis cycle has a significant effect on the outcome. With Cycle 1, where the analysis starts with emissions from the harvest, the net GHG emissions estimated by the stand-level analysis are 42, 67 and 56 g CO_2e/MJ for loblolly pine, Douglas fir, and spruce/fir, respectively. With Cycle 2, where the analysis starts with the growth of the trees and sequestration of carbon, the net GHG emissions are 19, 13 and -10 g CO_2e/MJ for loblolly pine, Douglas fir, and spruce/fir, respectively. With Cycle 1, the carbon debt at the beginning of the cycle is recovered by the carbon uptake as biomass re-grows. The impacts of the carbon uptake are discounted with the stand-level analysis, which makes the initial, large biogenic carbon emissions more impactful than the later recapture of the biogenic carbon. With Cycle 2, on the other hand, the biogenic carbon emissions follow the biomass carbon uptake, resulting in negative GHG emissions across all cases.

Loblolly pine, with its relatively short rotation, shows smaller temporal impacts of delayed emissions/sequestration compared to Douglas fir and spruce/fir, across the different analysis schemes. Thus, the differences between the stand- and the landscape-level analyses in the loblolly pine case (23 g CO_2e/MJ) are much smaller than those in the Douglas fir (54 g CO_2e/MJ) and spruce/fir (66 g CO_2e/MJ) cases.

Besides the biogenic carbon emissions and uptake, the GHG emissions from process fuel used during conversion are the most significant, since the thermochemical conversion process consumes a large amount of natural gas for H_2 production, which is used to upgrade the intermediate bio-oil into renewable gasoline and diesel.

Figure 20 presents the net GHG emissions of renewable hydrocarbon biofuels from softwoods at the stand level with different analysis cycles and conversion parameters. The analysis cycle (i.e., which cycle does the biomass belong to?) is most critical for the LCA results of softwood-based renewable gasoline. The impact of the analysis cycle becomes stronger when the growth cycle of woody biomass gets longer because the discounts associated with the delayed emissions become larger.

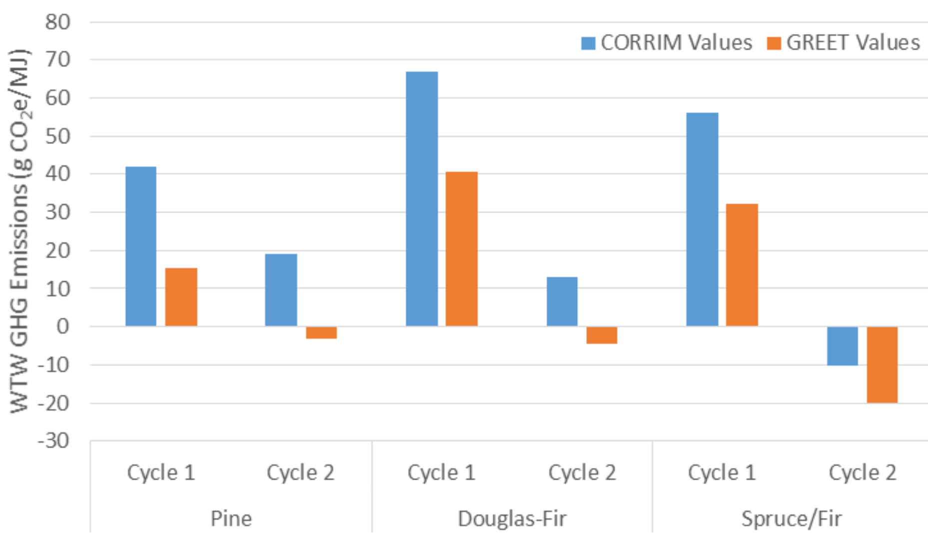


FIGURE 20 Net GHG emissions of renewable gasoline from softwoods in stand-level analysis with different analysis cycles and conversion parameters

The differences in the conversion assumption between CORRIM's modeling and GREET values also have large impacts on the LCA results. The key differences between the CORRIM and GREET default models are 1) composition sensitivity to the carbon and ash content of the biomass, which impacts the yield of renewable gasoline and diesel, 2) the exclusive use of natural gas for H_2 production, and 3) the combustion of all the residual streams for production of process heat and power, with the sale of residual electricity as a credit. The production of hydrogen from natural gas is particularly important, ranging between 5.5 and 6.4 mmBtu/dry ton biomass from CORRIM's modeling, and 2.7 mmBtu/dry ton biomass in the GREET default. It is important to note that both these modeling assumptions produce the same amount of hydrogen, but the CORRIM models consider the current low capital and operating costs of making hydrogen from natural gas, and its positive impact on the overall cost of the renewable-fuel product. The GHG emissions associated with natural gas use in biorefineries are the largest GHG emissions source other than biogenic carbon emissions and uptake, as shown in FIGURE 19. Thus, the reduction of natural gas use by half in the GREET default reduces the WTW GHG emissions significantly.

FIGURE 21 shows the GHG emissions of renewable gasoline for the three SRWC species in g CO_2e/MJ in landscape- and stand-level analyses. Similarly to FIGURE 19, the biogenic carbon emissions (green bars) are the sum of biogenic CO_2 emissions from thermochemical conversion and renewable-gasoline combustion. Other than the biogenic carbon emissions and uptake, the process fuel used during thermochemical conversion (gray bars) is the GHG emissions source, as in the softwood cases.

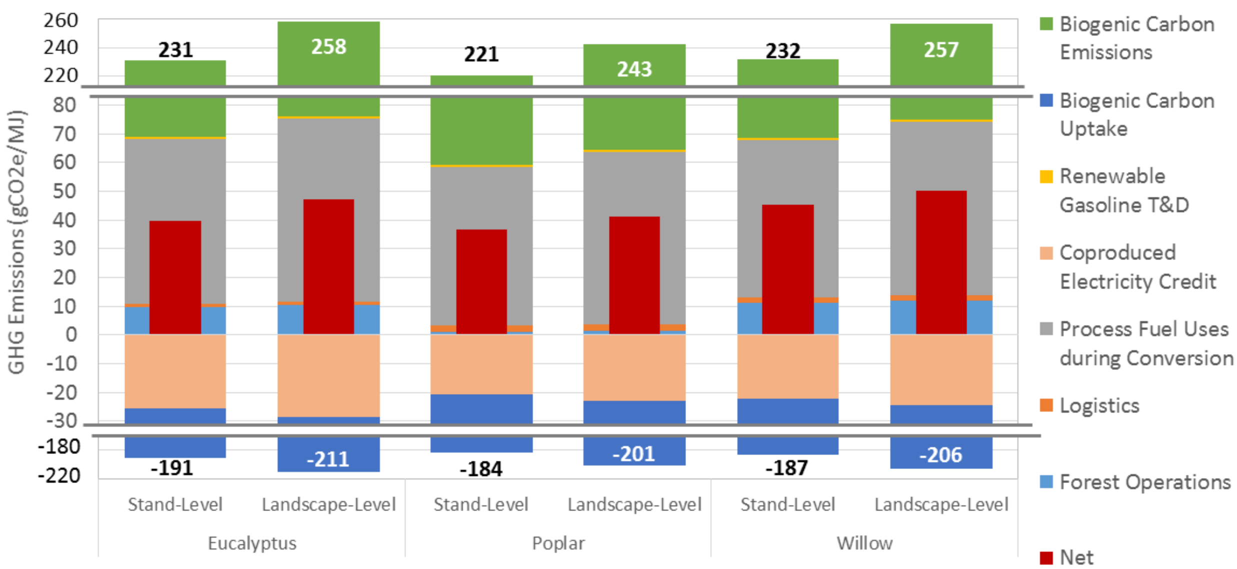


FIGURE 21 GHG emissions of renewable gasoline from SRWCs in g CO_2e/MJ, in landscape- and stand-level analyses

The net GHG emissions of SRWC-based renewable gasoline estimated in both stand- and landscape-level analyses show much smaller variation than those of softwood-based renewable gasoline. The differences between the two analysis cycles range from 5 to 7 g CO_2e/MJ, compared to 23–66 g CO_2e/MJ in the softwood-based renewable-gasoline cases. The small variations result from the much shorter growth cycles and similar annual productivity for the SRWCs relative to the softwoods.

Additional results on renewable diesel and ethanol are presented in Appendix B, from which similar observations can be made.

5. CONCLUSIONS AND FUTURE WORK

Managed forests are complex systems, and analysis of their carbon flows requires specific definitions of the region, the species and the allocation of woody biomass to DWPs, pulp and paper, and bioenergy. To provide insight into the question of carbon neutrality of woody feedstocks for biofuels, Argonne has collaborated closely with CORRIM to investigate regionally relevant examples and common forest management practices, and has conducted LCAs for three softwood species (loblolly pine, Douglas fir, and spruce/fir) and three SRWC species (eucalyptus, poplar, and willow) grown in three U.S. regions (Southeast, Pacific Northwest and Northeast), taking into account the temporal carbon distribution.

The results show that biofuels derived from the three SRWC biomass species exhibit relatively narrow GHG emission ranges: 40–47 g CO_2e/MJ for eucalyptus, 37–41 g CO_2e/MJ for poplar, and 45–50 g CO_2e/MJ for willow, depending on analysis cycles, with the conversion parameters from CORRIM's modeling of biomass conversion to biofuels. If the GREET default conversion parameters are used, the net GHG emissions decrease to 17–22 g CO_2e/MJ for eucalyptus, 13–15 g CO_2e/MJ for poplar, and 21–23 g CO_2e/MJ for willow. Since the majority of the GHG emissions are associated with conversion, the impacts of the analysis cycles and accounting methods are relatively small.

On the other hand, biofuels derived from softwood thinnings and residues with longer rotations have larger variations in GHG emissions: 19–42 g CO_2e/MJ for loblolly pine, 13–67 g CO_2e/MJ for Douglas fir, and -10–56 g CO_2e/MJ for spruce/fir, depending on analysis cycles, with the conversion parameters from CORRIM's modeling. With the GREET default conversion parameters, the GHG emissions decrease to -3–15 g CO_2e/MJ for loblolly pine, -5–41 g CO_2e/MJ for Douglas fir, and -20–32 g CO_2e/MJ for spruce/fir. The main driver for the large variations is the analysis cycle, e.g., does the accounting start with the emission of carbon from harvested wood or the growth of trees?

Cycle 1 starts with the biomass harvest, followed by the conversion of the biomass to biofuels and emission of biogenic CO_2 from combustion of the biofuel. Cycle 2 starts with the sequestration of carbon into the growing trees. With large differences between initial tree growth and harvest, 30–72 years for the three softwoods in this study, selection of the starting point is critical. For these longer growth cycles, the discounting of carbon also becomes material.

In summary, this study investigated carbon dynamics over time with bioenergy production to develop results of net GHG emissions of the system itself, and examined key factors affecting the net GHG emissions results, such as biomass species, analysis cycles, and accounting methods. Key observations are summarized as follows:

- *Biomass species and growth cycle:* Biofuels from woody biomass with longer growth cycles and slower growth rates (such as Douglas fir and spruce/fir) have much larger variations in GHG emissions, depending on analysis cycles and CO_2 emission accounting methods, compared to those with shorter growth cycles and faster growth rate (i.e., SRWCs). Thus, much caution is needed to handle the temporal carbon dynamics issue for biofuels from woody biomass with long growth cycles and slow growth rates.

- *Stand-level vs. landscape-level analysis:*
    - A stand-level analysis examines the impacts of temporal carbon dynamics on carbon emissions/sequestration from a plot over time, from harvest to regrowth, which is a critical issue in LCAs of woody biomass products. The stand-level analysis, however, is based on specific growth projections, which are subject to large variations based on the productivity of the site and the objectives of the landowner, especially with long growth cycles.
    - A landscape-level analysis is appropriate for conducting LCAs of products from managed forest with sustainable forestry management goals, i.e., a steady supply of forest biomass to customers and steady revenue to the landowner.
- *Analysis cycle (Cycle 1 vs. Cycle 2):* The impacts of the analysis cycle become greater as the growth cycle becomes longer. For the SRWCs examined in this study, it is appropriate to consider the biomass for biofuels as the sole product of the forestry operation. In other words, SRWCs are considered dedicated biomass feedstocks for bioenergy production, and there would be no SRWCs available without purposefully growing them in the first place. Therefore, Cycle 2 is recommended for SRWC feedstocks. For the softwoods, which are managed for DWPs and pulp and paper, the biomass used for renewable fuel is a residue that would otherwise be left to slowly decay and produce emissions to the atmosphere if not collected. Cycle 1 is recommended for softwood feedstocks because it is more realistic to collect the thinnings and residues when they are readily available for bioenergy production than to wait for decades to grow a mature softwood stand when the thinnings and residues could be made available.

An important question in woody biomass LCA is how to compare forest systems with bioenergy production and without bioenergy production (the so-called counterfactual scenarios). These counterfactuals are not included in this work. From the analytic basis built in the current study, therefore, reliable counterfactual scenarios (or business-as-usual [BAU] cases) should be developed and compared with the bioenergy scenarios. For example, the forest operations for softwood currently leave thinnings and residues on the ground. In a counterfactual scenario, this biomass would either decay or be burnt or sequestered in soil, changing the level of SOC. But these processes vary widely between different regions, and even within a region.

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APPENDIX A: ALTERNATIVE CARBON ACCOUNTING METHOD

The carbon accounting method used in this study, the "GWP cutoff" method, captures the climate impacts of CO_2 emissions in relation to their atmospheric residence time over the time horizon selected for the analysis, e.g., 50, 100 or 200 years. One drawback of the GWP cutoff method is that it ignores the global warming impacts after the analysis horizon, which for this study was 100 years. It should be noted, however, that AGWP contains three exponential decay terms representing three modes of redistribution of CO_2 following release, and their time scales are 4.3, 36.5 and 394 years (IPCC 2007). Thus, in the 100th year, the CO_2 redistribution processes that occur over 4.3 and 36.5 years are essentially "complete" over 100 years. These processes taper off significantly, even for biomass with moderate growth cycles (such as loblolly pine), alleviating the drawback.

An alternative approach to accounting for the temporal effects of carbon dynamics is to consider discounted emissions over time with a given discount rate. Similarly to financial discounting, this "discounted emission" method calculates the "net present emissions" of all emissions and sequestration that occur over a 100-year analysis period (E_{total}) by discounting future emissions, $E_i(t)$, between the year the emissions occur, t, and year 0 of the analysis with a given yearly discount rate (*discount*%), as follows:

$$E_{total} = \sum_{t=0}^{100} E_i(t) \times (1 - discount\%)^t.$$

This study sets the yearly emission discount rate at 2%, which is equivalent to the average yearly atmospheric decay rate of CO_2 emissions, as simulated by IPCC AR4 (IPCC 2007). Emissions intensity per "average" ton of biomass using the "discounted emissions method" can be estimated as follows:

$$EI = \frac{E_{total}}{Tonnage_{total}}.$$

While this "discounted emissions" method accounts for the global warming effects of emissions over a 100-year time horizon, the results are highly dependent on the discount rate, which has no physical relation to global warming effects. Thus, this study examines two sensitivity cases: 0% and 4% discount rates.

Figure A1 presents the GWP of CO_2 emission in a given year of emissions relative to that in year 0 calculated with the GWP cutoff method, and with the discounted-emissions method with 0%, 2% and 4% discount rates. The ratio of GWP of CO_2 relative to that in year 0 with the GWP cutoff method decreases from 1, in year 0, to 0 in year 100. After that, the GWP is set to 0. On the other hand, the GWP of CO_2 with the discounted-emissions method depends on the discount rate. With a 0% discount rate, the ratio of GWP of CO_2 remains at 1, meaning the results would be the same as the landscape-level analysis results. With a 2% discount rate, the

GWP ratio decreases to about 0.15 in year 100, while a 4% discount rate reduces the GWP ratio sharply, to near 0 in year 100.

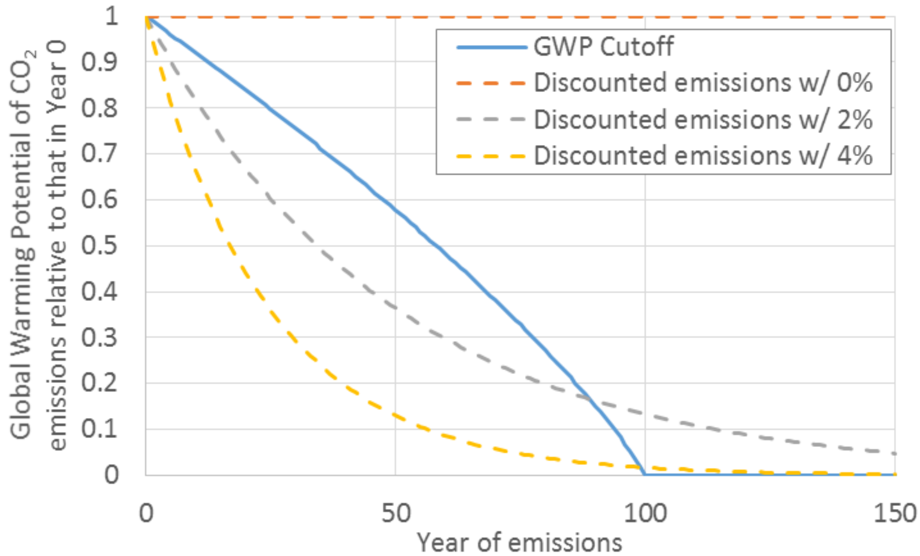

FIGURE A 1 GWP of CO_2 emissions in a given year of emissions relative to that in year 0 with the two accounting methods

The impacts of discounting vary depending on the carbon account cycle, e.g., Cycle 1, which starts with emission at harvest followed by carbon capture by the new growing trees, vs Cycle 2, which starts with carbon capture by the growing trees and the growth rate of the woody biomass. To illustrate this point, two extreme examples are shown in **Error! Reference source not found.** These examples show the net GHG emissions of renewable gasoline from spruce/fir and poplar in stand-level analysis with different accounting methods. For a slow-growing softwood like spruce/fir, the carbon accounting method and the discount rate are critical factors, especially with Cycle 1. On the other hand, the GHG emissions of renewable gasoline from fast-growing SRWCs like poplar are not that sensitive to the carbon accounting method and the discount rate.

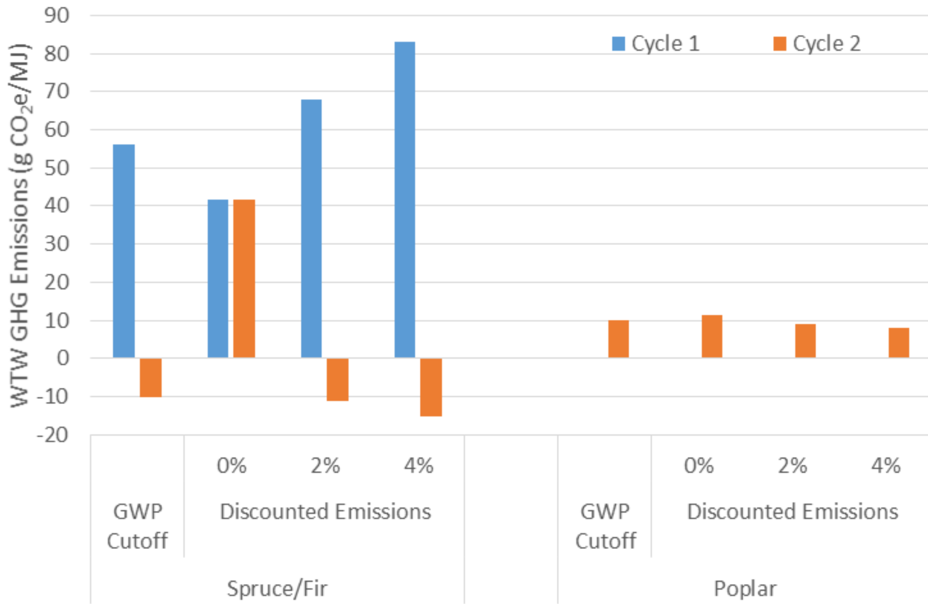

FIGURE A 2 Net GHG emissions of renewable gasoline from spruce/fir and poplar in stand-level analysis with different accounting methods

APPENDIX B: ADDITIONAL RESULTS

B.1 RENEWABLE GASOLINE

Figure B 1 presents the GHG emissions for renewable gasoline produced from SRWCs. This figure shows the effects of the assumptions in the modeling of the thermochemical conversion process, primarily the effects of ash on the renewable-fuel yield, and the use of natural gas to produce the hydrogen needed in the hydrotreating process. Relative to the biorefinery assumptions, the details of the production of SRWCs have a modest impact on the final GHG emissions.

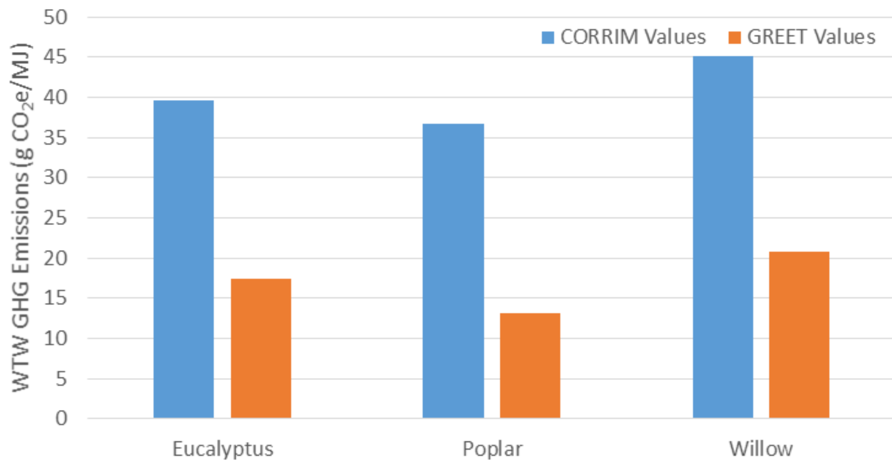

FIGURE B 1 Net GHG emissions of renewable gasoline from SRWC in stand-level analysis with different conversion parameters

B.2 RENEWABLE DIESEL

Figures B 2 and B 3 present the GHG emissions for renewable diesel from the three softwoods and the three SRWCs, respectively, in g CO_2e/MJ, by landscape- and stand-level analyses. These results are very similar to the results for the renewable-gasoline cases (Figures 19 and 21). The only differences are in the renewable-diesel transportation and distribution, which are minuscule. _Figures B 4 and B5 show GHG emissions of renewable diesel from the three softwoods and the three SRWCs, respectively, in g CO_2e/MJ, in stand-level analysis with different analysis cycles and conversion parameters. _______________

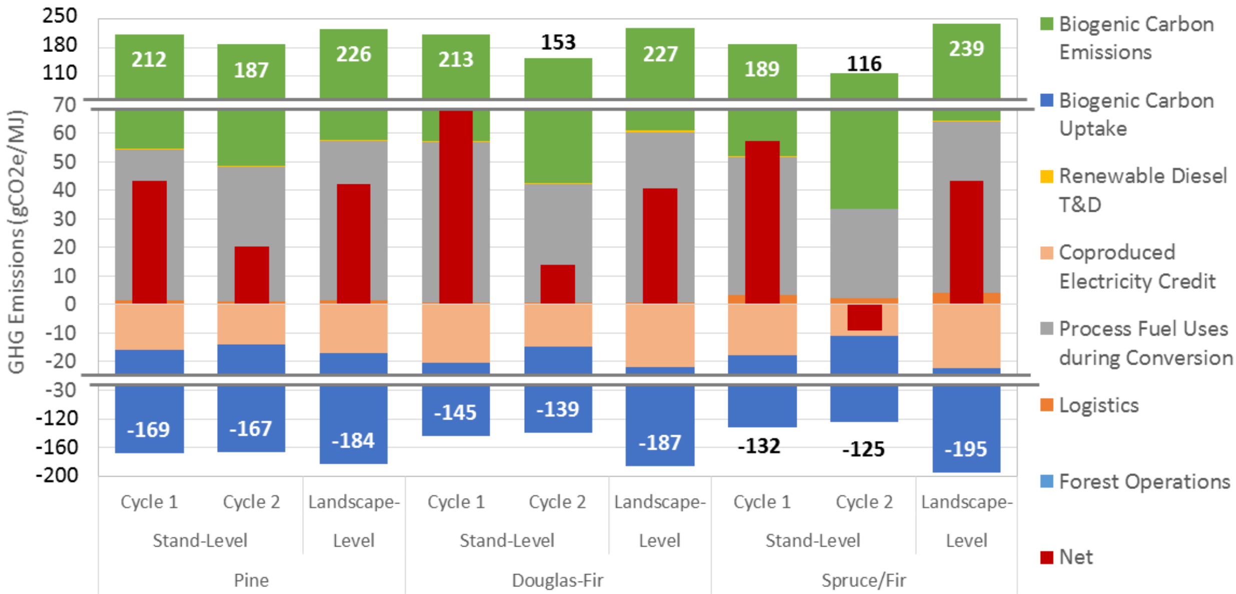

FIGURE B 2 GHG emissions of renewable diesel from softwoods in g CO_2e/MJ by landscape- and stand-level analyses

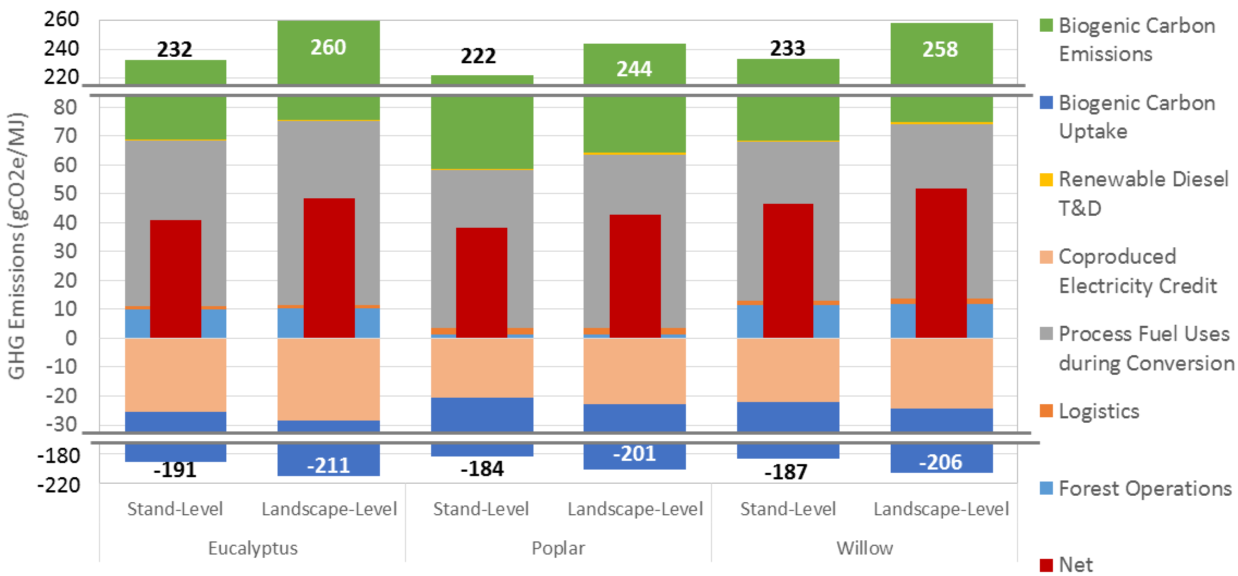

FIGURE B 3 GHG emissions of renewable diesel from SRWCs in g CO_2e/MJ by landscape- and stand-level analyses

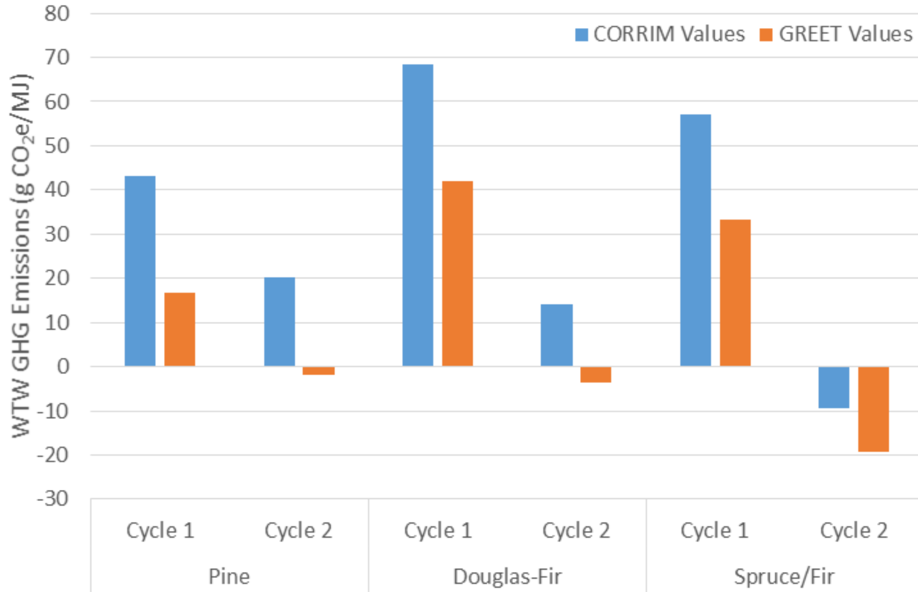

FIGURE B 4 GHG emissions of renewable diesel from softwoods in stand-level analysis with different analysis cycles and conversion parameters

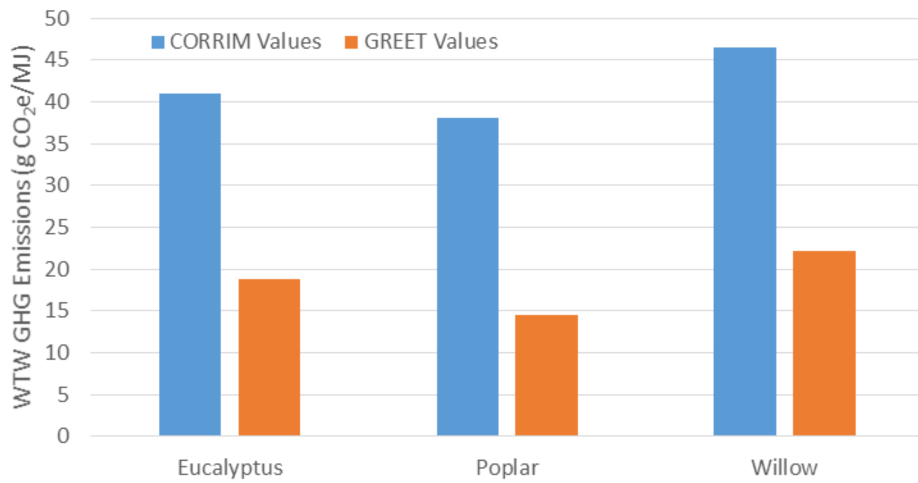

FIGURE B 5 GHG emissions of renewable diesel from SRWCs in stand-level analysis with different conversion parameters

B.3 ETHANOL

FIGURE B 6 shows the GHG emissions (g CO_2e/MJ) for ethanol produced from the three SRWCs using landscape- and stand-level analyses. A key difference between ethanol production and the production of renewable gasoline and diesel is the greater displacement credits by co-produced electricity in the process fuel used during biochemical conversion. Figure B 7 shows the GHG emissions of ethanol from SRWC in stand-level analysis.

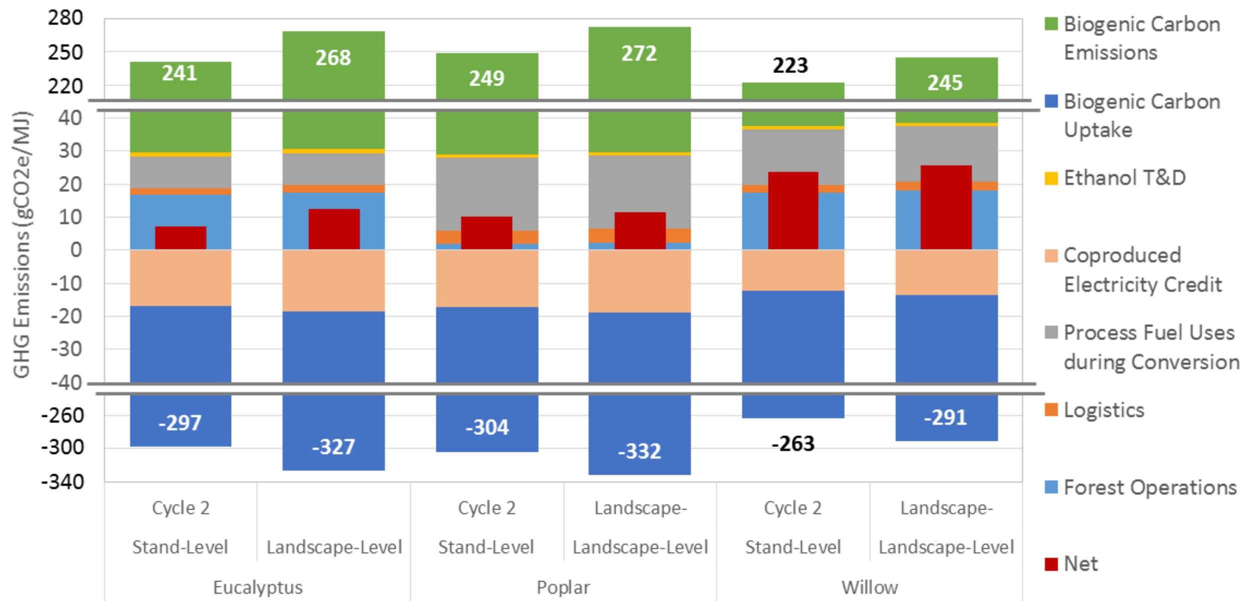

FIGURE B 6 GHG emissions of ethanol from SRWCs in g CO_2e/MJ by landscape- and stand-level analyses

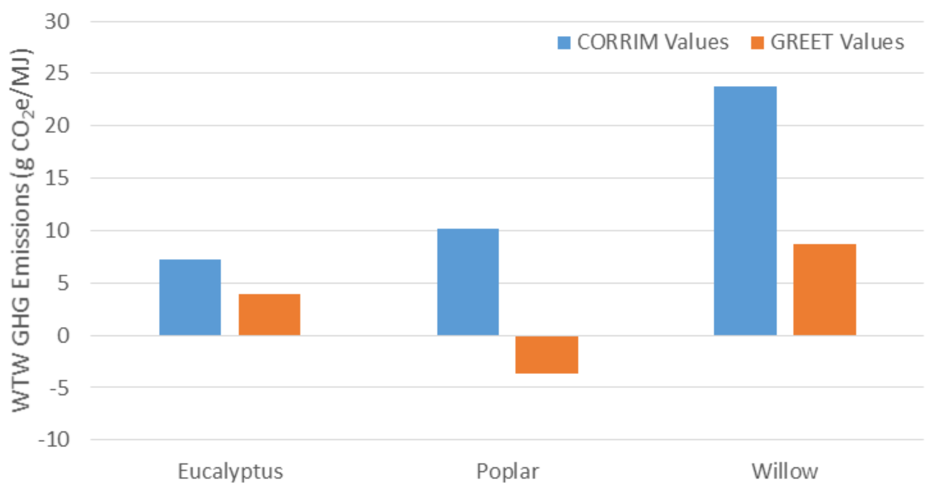

FIGURE B 7 GHG emissions of ethanol from SRWC in stand-level analysis with different conversion parameters

APPENDIX C: GREET WOODY MODULE CONFIGURATION

This section describes the addition of a new module named "Woody" that addresses the temporal aspects of woody biofuel production. GREET is a tool that uses LCA to determine the WTW GHG emissions, water consumption, and energy inputs for various transportation fuels. Before the addition of this module, the GREET tool already included a few woody biomass feedstocks, specifically poplar, willow, and forest residues. The most recent data inputs for willow and poplar were based on the 2016 Billion-Ton analysis (U.S. Department of Energy 2016), with county-level data adapted to a national average for input into GREET (Canter et al. 2016). The latest data for forest residues, with biomass produced from either thinnings or harvest residues, were added in 2013 and did not separate the forest feedstock by softwood type (e.g., Douglas fir vs. loblolly pine) (Wang et al. 2013). These analyses are presented in the ETOH tab of GREET and will not be updated using work presented in this report.

C.1 MODULE SECTION 1 – SCENARIO CONTROL AND KEY PARAMETERS

This section contains relevant selections for analysis, including the wood species evaluated, the analysis starting point, the carbon accounting method, how the fertilizer and pesticide use is allocated for loblolly pine, and whether or not to include avoided decomposition emissions for softwoods.

The first table in *Section 1.1) Biomass Production and Logistics* contains the biomass inputs and outputs (i.e., forest carbon uptake, bioenergy removals, biomass left in the forest, annual SOC change), as well as the farming energy and chemical use. Information from this table is populated from the data tables to the right of this table on the basis of the wood species selected. The next table, *Biomass Characteristics*, and some later tables contain information for all the species, but populate the last column as the species evaluated. For the softwoods, the *Decomposition of Biomass Left in Forest* table calculates the avoided CO_2 and N_2O emissions from utilizing the thinnings and residues that would normally be left in the forest in the BAU scenario. For the SRWCs, this table determines the decomposition emissions from any biomass left after harvest. The *Biomass Transportation* table includes all key parameters to determine biomass transportation.

Section 1.2) Fuel Production, Transportation, Distribution contains all the inputs for thermochemical conversion, which include energy consumption, fuel production, and carbon emissions. All results are presented on a per-dry-ton basis. Carbon emissions include the biogenic emissions, which come from combustion products generated during combined heat and power (CHP) production. There is also fossil energy released during CHP production, which comes from utilization of byproducts from hydrogen production. Also included in this section is a menu to select the type of electricity that is displaced by the co-produced electricity during the thermochemical conversion process.

Section 1.3) Temporal Carbon Dynamics contains information on the carbon-accounting method, which is based on the time-integrated AGWP and GWP, was calculated on the basis of equations in Section 3.3.

C.2 MODULE SECTION 2 – SHARES OF COMBUSTION PROCESSES FOR EACH STAGE

This section contains a breakdown, by wood species type, of the equipment used during forest activities and conversion. Forest production only considers off-road diesel, and conversion natural gas combustion comes from steam methane reforming. Also considered in this section is the urban share of conversion emissions.

C.3 MODULE SECTION 3 – CALCULATIONS OF ENERGY CONSUMPTION, WATER CONSUMPTION, AND EMISSIONS FOR EACH STAGE

This section calculates the yearly energy consumption, water consumption, and emissions on the basis of unit process. All values are calculated on a per-area basis to allow conversion to a per-amount-of-biofuel-produced basis (i.e., per mmBtu of biofuel) in later sections. The first table in this section, *Carbon Uptake During Growth,* determines the amount of CO_2 sequestered during tree growth each year. *Forest Operations* considers the energy, fertilizer, and pesticide use during growth. SOC changes for poplar and willow are also included. *Logistics* determines the impact of transporting the harvested biomass to the biorefinery. Calculations are based on the selected species and consider how far the biomass is transported, the load capacity, and fuel consumption. Back-haul is also considered by multiplying the results by two. *Conversion* multiplies both the natural gas use and the electricity generation credit by the total biomass transported to the biorefinery. CO_2 calculations in this table add the biogenic and fossil carbon emissions. *Renewable Gasoline T&D and Renewable Diesel T&D* determines the yearly transportation emissions generated in delivering these products for consumer consumption. *Renewable Gasoline Combustion and Renewable Diesel Combustion* calculates the yearly emissions for gasoline and diesel combustion in a baseline gasoline vehicle and a compression ignition direct injection vehicle using conventional diesel.

C.4 MODULE SECTION 4 – CARBON TEMPORAL CALCULATIONS

This section calculates the effect of the time when the carbon is released after the start of the analysis. The CO_2 yearly calculations from each table in Section 3 are multiplied by the GWP of either carbon-accounting method 1 or 2, based on the selection at the top of the spreadsheet.

C.5 MODULE SECTION 5 – SUMMARY OF ENERGY CONSUMPTION, WATER CONSUMPTION, AND EMISSIONS CONSIDERING TEMPORAL EFFECTS

Final values for the selected feedstock are calculated in this section. For all variables, except CO_2 and GHGs, results are found by summing the relevant emissions in Section 3 and dividing by the total biomass produced during the analysis period. Feedstock emissions for both renewable gasoline and renewable diesel consider the forest operations and logistics, divided by the total biomass production, then divided by the total energy produced per dry ton. CO_2 emissions use the carbon temporal calculations in Section 4, including the carbon uptake during growth. Fuel emissions include the conversion, transportation and distribution, and biofuel combustion. For both renewable gasoline and diesel, the conversion emissions are divided by the total energy produced, while the transportation and distribution and the combustion emissions are divided only by their respective energy produced (i.e., renewable-gasoline or renewable-diesel production). This section also provides a combined fuel result, which is the summation of the results of each biofuel type multiplied by their percentage of total energy produced.

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