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Project Title:	**Carbon Cycling, Environmental & Rural Economic Impacts of Collecting & Processing Specific Woody Feedstocks in Biofuels**	
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Final Report –

Carbon Cycling, Environmental & Rural Economic Impacts of Collecting & Processing Specific Woody Feedstocks in Biofuels

Executive Summary

Woody biomass will be an essential feedstock for a large-scale cellulosic biofuel industry. The life cycle carbon accounting for the production of biofuels from woody feedstocks is complex and has engendered significant controversy. Issues such as below ground carbon, carbon debt, varied regional forest practices, multiple parallel forest product lines, and development of realistic counterfactual scenarios all contribute to the complexity. DOE funded CORRIM to develop comprehensive and definitive lifecycle inventories and assessments on the production of fuels from woody feedstocks. CORRIM brought together expertise in forest practices, short rotation woody crops, bioconversion of woody biomass, process modeling, and life cycle assessment to successfully accomplish this goal.

The CORRIM team has developed data on forest productivity, fuel usage, and fuel production for six regionally specific forest systems. These six forest systems include three current commercial systems; southern pine plantations, Douglas-fir plantations, naturally regenerated Northeastern (NE) spruce/fir, and three 'short rotation woody crops', poplar, eucalyptus and willow, which are at different stages of demonstration in the US. The fuel production systems include cellulosic ethanol and bio-oil based hydrocarbons. The project was successfully reviewed at the BETO Program review in March 2015, 2017, and 2019 and has resulted currently in 19 publications and reports and 35 presentations at both national and international conferences, with more in the pipeline. See publications and presentations for links to each document.

Finally, *and most importantly*, CORRIM has gone beyond the scope of the original DOE proposal to work closely with GREET at Argonne National Laboratory (ANL) to incorporate all the life cycle data and scenario models into their modeling system. GREET is the most widely used and definitive information source for evaluating lifecycle carbon emissions for fuels. The incorporation of CORRIM data from this project guarantees the results of the research will be extensively used and widely disseminated.

Technical process improvements and policy relevant accomplishments are detailed in the relevant programmatic sections in the full report including citations therein. Highlights are summarized here for easy reference.

Technical Process Improvements

Highlights for technical process improvements and accomplishments include:

- Robust tools have been developed to estimate the range and distribution of key woody biomass characteristics to better inform yield and recovery assumptions. **(Task 1)**.

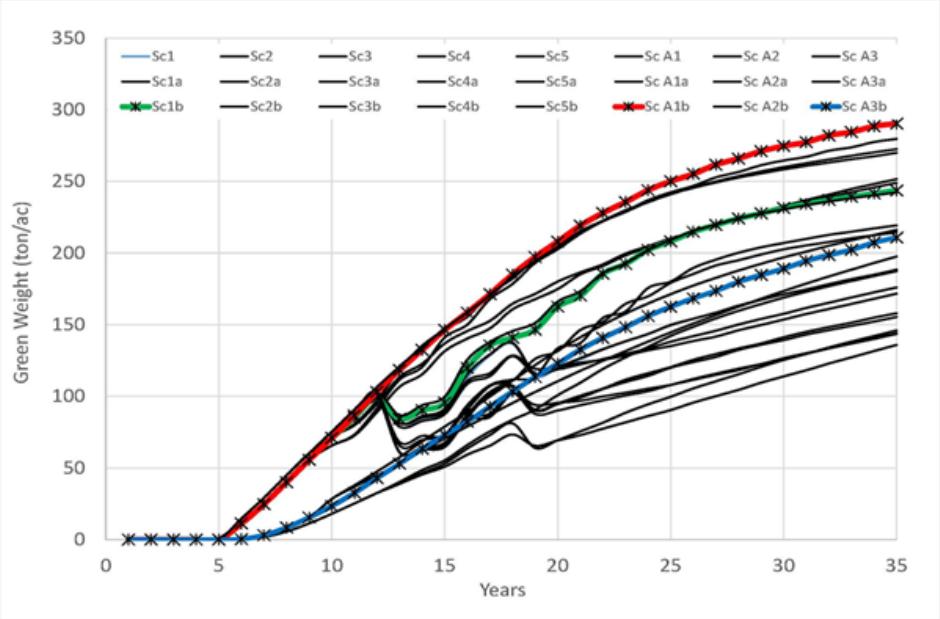

Figure 1ES Variations in biomass production for southern loblolly pine plantations for a variety of growth conditions and management regimes. The modeling was conducted with the LOBDSS forest growth and yield modeling tool. (Task 1 LCI – SE Softwoods)

- The pyrolysis to hydrocarbon ASPEN process model was modified to 1.) separately track both the biogenic and fossil carbon, 2.) relate the moisture content to the overall heat balance of the biorefinery and 3.) correlate the ash and carbon content of the biomass with the yield of the intermediate bio-oil and the associated demand for hydrogen for the reforming process. This improved model was used in this project to determine the relationship between the composition of the different woody feedstocks, and the production of the final hydrocarbon fuel. This improvement is applicable to all types of biomass. **(Task 3)**

- Biomass quality matters. Using the improved ASPEN process model, we show that the volume and quality (e.g., ash and carbon content, and moisture content) of the forest residues have a significant impact on the life cycle assessment (LCA) burdens for the alternative woody feedstocks. **(Task 4)**

Table 1ES A subset of the results from the ASPEN modeling that shows the impact of changes in the feedstock carbon, ash, and moisture content. The impact of these feedstock variables the yield of the final biofuel product, the natural gas demand for the reforming process and the co-production of electricity from the combustion of the residue streams are detailed[1/]. (Task 3 – Conversion – Pyrolysis).

Carbon (%)	Ash (%)	Moisture (%)	Gasoline yield (MM liter/yr)	Diesel yield (MM liter/yr)	NG usage (kg/hr)	Net power (MW) *	TCI (MM$)	MFSP ($/L)
44	3	35	86.04	86.94	9603	10.0	595	1.08
46	3	35	84.22	87.92	9618	15.5	598	1.07
48	3	35	81.96	88.95	9779	21.3	601	1.06
50	3	35	79.91	89.96	9859	26.9	604	1.05
46	**1**	35	97.56	96.55	10978	10.4	620	1.00
46	**3**	35	84.22	87.92	9618	15.5	598	1.07
46	**5**	35	85.63	79.17	9122	17.1	588	1.09
46	**7**	35	88.98	72.82	8661	17.8	581	1.10
46	3	**15**	84.22	87.92	9618	24.6	598	1.04
46	3	**25**	84.21	87.92	9618	20.6	598	1.05
46	3	**35**	84.22	87.92	9618	15.5	598	1.07
46	3	**45**	84.22	87.91	9618	8.6	598	1.09

[1/] Modeled for 2,000 ODT/day of woody feedstocks

- Primary data from poplar, willow, and 'frost hardy' eucalyptus plantations were used to develop growth and yield curves reflective of actual growth conditions across a range of sites in the PNW (poplar), NE (willow) and SE (eucalyptus) regions of the US. These data, and the data for collection and processing were used to develop robust LCI models of biomass yield and characteristics for input into bioconversion process models. **(Task 2)**

- An ASPEN based bioconversion process model was used to estimate the overall conversion yield of 303, 275 and 282 liters of ethanol per tonne of feedstock for willow, hybrid poplar, and eucalyptus. **(Task 3)**

- The yield of gasoline and diesel varied with the quality of the woody biomass feedstocks, e.g., moisture content, and ash and carbon content. For the feedstocks studied in this work that equated to 231 to 277 liters of hydrocarbon per ODT of biomass, or approximately 61-73 gal/ODT.

- Sensitivity analysis indicates that variation in glucan and lignin content directly affects ethanol yield and the heat balance, and the associated CO_2 emissions during bioconversion of poplar. **(Task 3)**

- All the short rotation woody crops (SRWC) analyzed in this research to produce ethanol via bioconversion showed a better environmental performance when compared to conventional gasoline, with GWP reductions for biohydrocarbon vs gasoline ranging from 70 to 105%. **(Task 3)**.

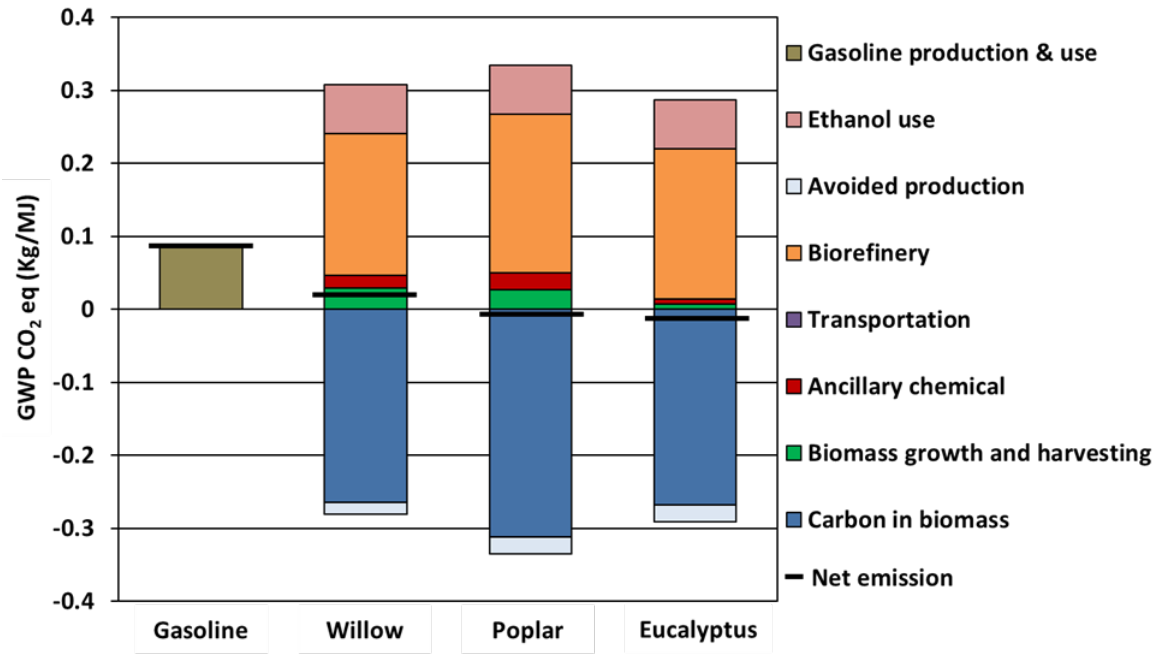

Figure 2ES Global warming potential of SRWC and gasoline per MJ of fuel. (Task 3 – SRWC Biochemical)

Policy Relevant Accomplishments

Analysis of the interaction between current markets and bioenergy uses for commercial softwoods identified many barriers to bioenergy development. These barriers are manifest at all scales. Some barriers have technical solutions, while others require systemic change including changes to relative value of co-products, markets, and at the policy and accounting framework levels.

- Commercial softwoods provide the greatest carbon benefit and economic benefit when placed in durable wood products. Residues from durable wood products (DWP) production are suitable for an array of purposes including bioenergy uses.
    - A nuanced examination at the stand level shows how current commercial practices in softwood forestry interact with forest growth, and durable wood products markets, to provide the highest financial return to the landowner. This leaves forest residues and, in some cases, thinnings and mill residues for bioenergy products. These biomass steams provide modest supply volumes, and thus transportation distance must increase or biorefinery size must decrease if residues are the sole source of feedstock supply. Specifically, about 20% of above ground biomass from commercial forests in the PNW and NE regions and 28% in the SE are available for bioenergy production. The supply constraint is particularly noticeable in the NE region, and also material in the PNW. In the SE, changes to forest management practices would be required to ensure adequate supply at scale **(Details in Tasks 1-4)**.

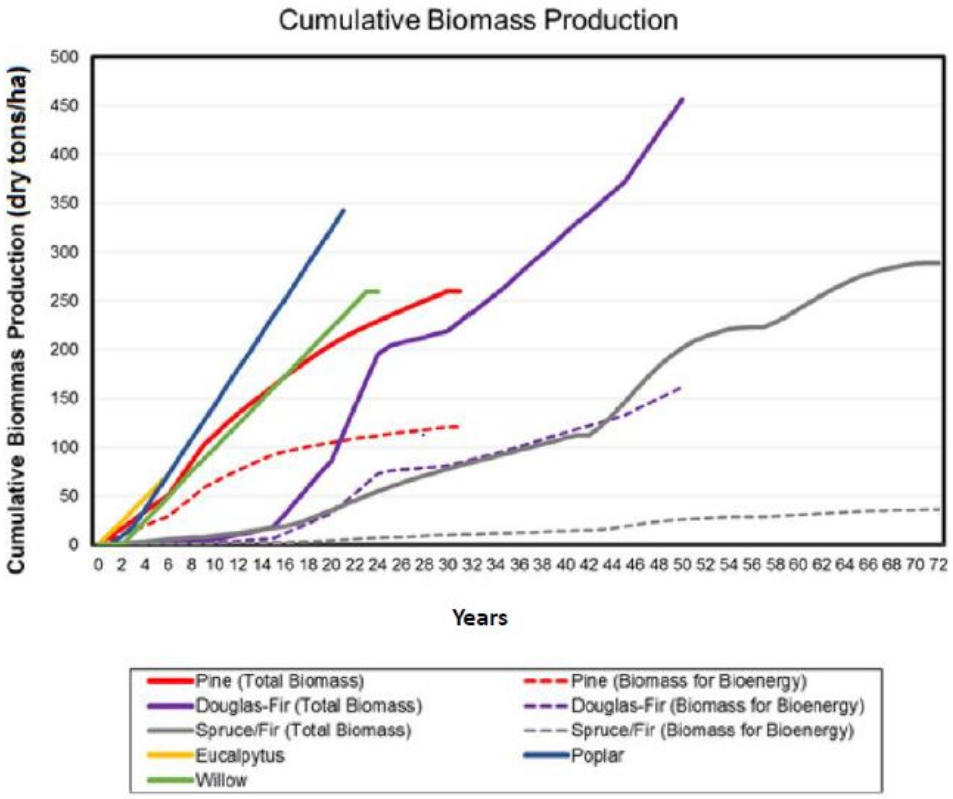

Figure 3ES Summary of the six alternative biomass production scenarios completed as part of this work. These biomass production scenarios were used as inputs for the biofuels production modeling, and for the ANL GREET analysis. Note, in the three softwood cases the woody biomass would be split between durable wood products and biofuels, and each of these allocations are also provided in Figure 3ES. (Task 1 and 2) (Han et al. 2018)

- Re-allocation of biomass from other commercial uses is possible, but the economic costs are high and there is rarely a carbon benefit from diverting biomass from durable wood products to biofuels **(Task 5)**.

Table 2ES Comparison of carbon benefits between wood composite products (WCP) and ethanol generated from identical wood residues. (Task 5 Hierarchies of wood use)

Carbon Emissions Displaced: Carbon Stored in Product		
	Displacement (carbon NOT emitted) kg carbon/kg of wood fiber used	
	If wood residues are used for WCP and not for ethanol	**If ethanol from wood residues is used in place of fossil fuels**
Particleboard: Ethanol	7.78	
MDF: Ethanol	5.13	
Ethanol: Gasoline		0.43

- Counterfactual scenarios that assume up-front management with no expectation of harvest are not realistic given landowner expectations for a financial return. More appropriate counterfactuals were developed for this project that estimate forest growth and yield when forests are not managed for commercial purposes. While the outcomes are highly variable, common outcomes in the Douglas-fir region show four times more biomass in managed forests than unmanaged forests over a 100-year period. This biomass from managed forests is used in durable wood products that keep carbon out of the atmosphere for extended periods of time, thus doubling the carbon benefit of the forest sequestration alone **(See Task 1).**

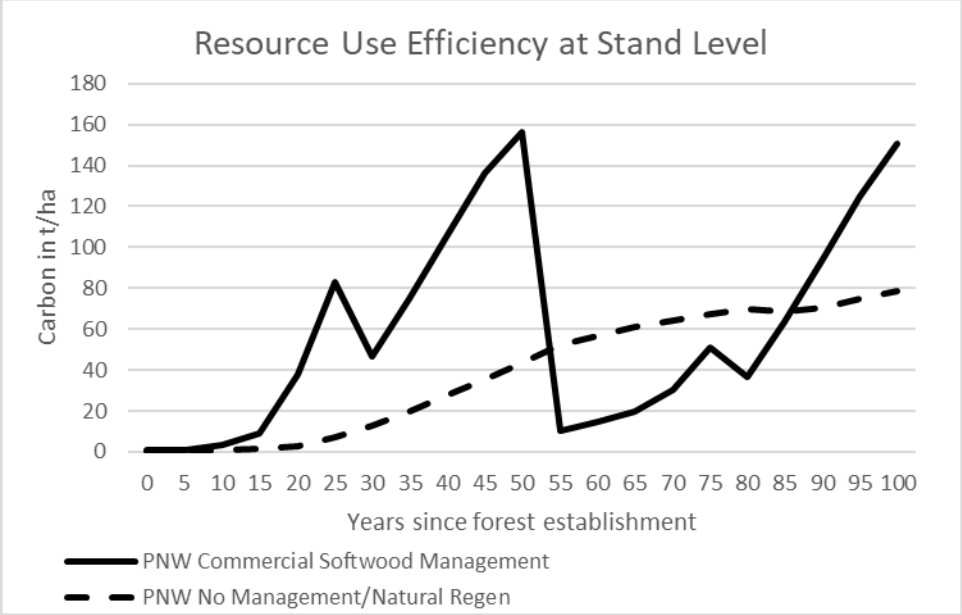

Figure 4ES Comparison of Natural regeneration and Douglas-fir plantation growth and yield in the PNW region. (Task 1 LCI Softwoods PNW)

- An analysis of the barriers to biomass to bioenergy initiatives arrived at eight key recommendations. **(Task 5)**
  1. Biases that have evolved from the man/nature dichotomy discount the benefits of the sustainable use of forests. They can and should be openly discussed.
  2. IPCC guidance considers deforestation responsible for almost 90% of global estimated C emissions due to land-use change yet sustainable harvest activities have been incorrectly labeled as 'degradation' by this same authoritative body. A paradigm shift is required that recognizes the role of forestry in supplying bio-based goods and services from the fast domain of the carbon cycle, and which specifically addresses the differences between degradation and managed forest outcomes.
  3. To accurately characterize the benefit and hierarchy of using forests to mitigate climate change, carbon accounting systems must include the whole life cycle at a temporal and spatial scale that is relevant to the questions being asked. Attributional LCA (ACLA) has a significant role to play at specific scales but using ACLA to inform land use and broad policy questions can produce unintended negative consequences. Different tools are required to characterize needs at broad scales, including integrative tools being developed within the rubric of the circular economy.

4. Private forest land provides the greatest potential for mitigating climate change of all forest lands in the US.
5. Maintain viable markets that maintain forest lands in forest and produce durable wood products.
6. To maximize carbon uptake, grow trees efficiently, harvest using economic recovery systems, and manufacture timber into products according to a product hierarchy that prioritizes long-lived products. Following harvest, trees must be re-planted. Note that genetic improvements, conducted with traditional breeding programs, can increase the productivity of the new trees by 30-50%.
7. Implement cascading use policies that follow a hierarchy of optimal uses favoring long lived products over short term products.
8. Whenever possible the combustion of waste streams to provide onsite factory energy (for example, heat and electricity) will maximize conversion efficiencies.

- A re-framing of the carbon debt question that has plagued biofuel development in the US is required. Specifically, that the analysis be expanded from a single acre, or stand, to the landscape in order to account for the time dimension in analysis of carbon debt. When taken at this appropriate analysis scale, carbon debt becomes a meaningless construct on a sustainably managed landscape **(See Task 5)**.

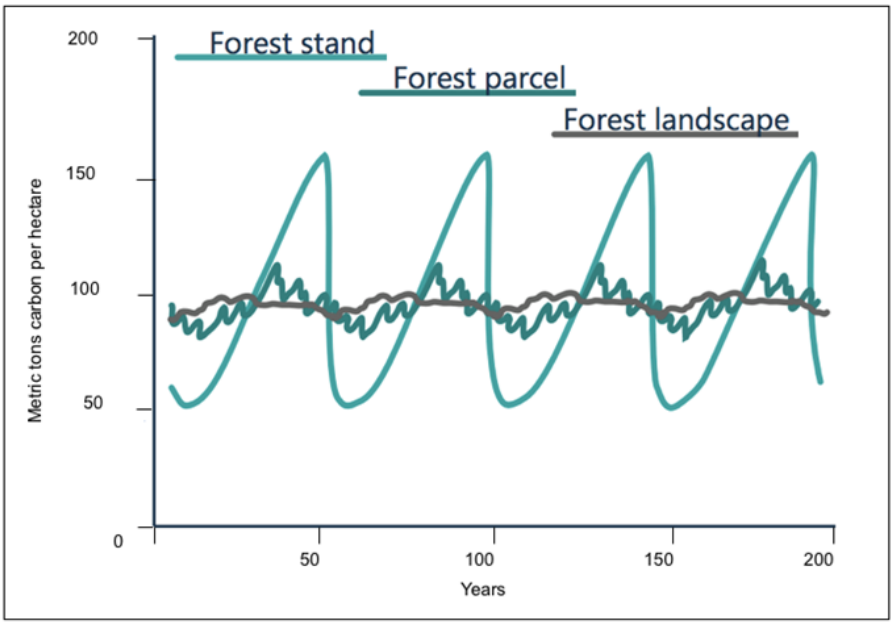

Figure 5ES Graphic representation of the spatial and temporal dynamics of C storage for a typical PNW forest managed on 45-year rotations presented as: the growth and harvest cycles of one forest stand (in turquoise), an average per ha for 10 forest stands harvested in sequential intervals (in teal), and an average for 100 stands harvested sustainably as part of a "normal" forest (in brown). (Task 5 - Supply chain barriers)

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Definition of Terms and Abbreviations

ALCA – attributional LCA - estimates what share of the global environmental burdens belongs to a product -

ANL /Argonne– Argonne National Laboratory

Basal area - is the cross-sectional area of trees at breast height (1.3m or 4.5 ft above ground). It is a common way to describe stand density. In forest management, basal area usually refers to merchantable timber and is given on a per hectare or per acre basis.

BDT – bone dry metric tons

CLT – cross laminated timber - are made by laminating dimension lumber orthogonally in alternating layers.

CO2 – carbon dioxide

CORRIM – the Consortium for Research on Renewable Industrial Materials, a non-profit corporation of currently 20 Research Based Organizations, mostly universities devoted to measuring all of the environmental impacts for growing and using renewable resources such as wood.

DOE – Department of Energy

DWP – Durable wood product.

ECD – emission control device limits release of particulates and volatile organic compounds.

EH – enzymatic hydrolysis

EROI – energy return on investment

ESF - SUNY College of Environmental Science and Forestry (ESF)

Feedstocks - raw material, unprocessed material, is a basic material that is used to produce goods, finished products, energy, or intermediate materials that are for future finished products.

Ferm - fermentation

GHG – Greenhouse Gas Emissions

Glu - glucan

GREET – Greenhouse gases, Regulated Emissions, and Energy use in Transportation Model

GWP – Global Warming Potential measured in kg CO2 eq.

Ha – Hectare

KD lumber – wood studs or dimension lumber that has been dried to standards (<19% moisture content, dry basis)

L - liter

LCI - Life Cycle Inventories of all energy and material inputs and outputs for a product

LCA – Life Cycle Assessments is a multi-step procedure for calculating the lifetime environmental impact of a product or service. The complete process of LCA includes goal and scope definition, inventory analysis, impact assessment, and interpretation.

LCIA – life cycle impact assessment - the inventory is analyzed for environmental impact. For example, manufacturing a product may consume a known volume of natural gas (this data is part of the inventory); in the LCIA phase, the global warming impact from combustion of that fuel is calculated

LOBDSS – Loblolly Pine Decision Support for Silviculture

Long L Products – long live products, e.g. wood products (plywood, wood, CLT etc.)

MDF – medium density fiberboard - is an engineered wood product made by breaking down hardwood or softwood residuals into wood fibres, often in a defibrator, combining it with wax and a resin binder, and forming panels by applying high temperature and pressure

MJ – megajoule

MW - megawatt

N - nitrogen

NCSU – North Carolina State University

NE – Northeast US

NREL – National Renewable Energy Laboratory

ODT – oven dry tons

OSB – oriented strandboard

P - Phosphorous

PB – particleboard - is an engineered wood or composite material product manufactured from wood chips, sawmill shavings, or even sawdust, and a synthetic resin or other suitable binder, which is pressed and extruded.

Ply- plywood

PNW- Pacific Northwest US

SE – Southeast US

Short L. Products – short lived products e.g. paper

Site index – a single value that combines the annual temperature and rainfall, and land quality into an indicator of the productivity of the land

SOC – soil organic carbon

SOPO – Scope of Project Objectives

SRWC – Short Rotation Woody Crops (Willow, Poplar, Eucalyptus)

Sustainable forest management - The stewardship and use of forests and forest lands in a way, and at a rate, that maintains their biodiversity, productivity, regeneration capacity, vitality and their potential to fulfill, now and in the future, relevant ecological, economic and social functions, at local, national, and global levels, and that does not cause damage to other ecosystems.

Thinnings – A selective removal of trees to improve growth rate or health of remaining trees. Can be pre-commerical (no economic value) or commercial (sawlogs)

Tonne or t – metric tonne

UM – University of Maine

Uncertainty analysis - investigates the uncertainty of variables that are used in decision-making problems in which observations and models represent

Unmanaged forest - forests which have been excluded from forest management by legal status and left to develop undisturbed by man while tolerating all kinds of natural disturbances

USDA – United States Department of Agriculture

WCP – wood composite panel -an engineer wood product made to fibers, sawdust, strands, or flakes.

Wood I-joist - is an engineered wood product that has great strength in relation to its size and weight designed to eliminate problems that occur with conventional wood joists.

Yield – measure of tree volume or weight at a point in time. Growth in yield is the growth in volume or weight

Acknowledgement

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History, Timeline, and Project Structure

This project is divided into two phases to reflect the lapse in DOE funding between June 2012 and December 2015. This lapse had a fundamental impact on the project, which is reflected throughout this final report.

Phase I

The project was awarded in December 2009, with work commencing in late 2010 after all contracting conditions were in place. The Principal Investigator was Professor Bruce Lippke at the University of Washington College of Forest Resources, and President of CORRIM, the prime recipient of this grant. The University of Washington held the contract for the CORRIM management function at that time. On June 28, 2011 we were notified that funding would be withdrawn due to DOE budget shortfalls, effective June 30, 2011. CORRIM subrecipients were notified immediately and all sub-contracts were cancelled due to the funding lapse. All funds remaining at that time were used to cover costs expended to June 30, 2011 and to present an initial set of results the following June in a special session of the Forest Products Society International Convention. The contract between DOE and CORRIM was not cancelled as DOE leadership indicated that the project had value but ranked lower on their funding scale than the funds that were available. A total of $399,802 in federal award money and $123,000 in cost share was spent prior to the funding withdrawal. For purposes of this final report all activities that occurred during this period will be referred to as Phase I. See Appendix A.2. Project Management Plan for details.

In 2015, the project was re-established in what we will refer to as Phase II of this project. By 2015, Professor Lippke had been retired for several years and leadership was assumed by Dr. Stephen Kelley at NCSU and Dr. Rick Gustafson at the University of Washington. In addition to the new leadership, there were also a new set of deliverables that aligned CORRIM skill sets with research needs at Argonne National Labs pertaining to the life cycle of cellulosic feedstocks for biofuel production. This new set of deliverables was finalized in a SOPO approved by DOE in December 2015. In 2017, due to leadership changes in CORRIM, the CORRIM management function was moved to Corvallis Oregon and placed under Dr. Maureen Puettmann of WoodLife Environmental Consultants. Dr. Puettmann was assigned the position of Director of Operations for CORRIM by the Board of Directors, including the then CORRIM President, Dr. Stephen Kelley. The remaining grant monies, totaling $1,030,733 in federal award and $246,000 in cost share were expended during phase II of the project which started in December 2015 and closed on September 30, 2019.

In A.2. Project Management Plan we have provided the details on the sub-award recipients, core team members, and disbursements for Phase I of the project. As Phase II has a fundamentally different structure and substantially revised SOPO, the remainder of the final report will focus on Phase II SOPO deliverables, and results.

Presentations

View or download in the Publications and Presentation sections of this report.

Biomass Feedstock Supply: Cost and Life Cycle Analysis. 2012. Han-Sup Han. 66th Forest Products Society International Convention. June 3, 2012 Washington D.C.

Pellets Production Alternatives and their Impacts. 2012. Adam Taylor. 66th Forest Products Society International Convention. June 3, 2012 Washington D.C.

Comparison of Bio-oil Produced from Southern Pine Slash to that from Clear Pine Wood. 2012. Maureen Puettmann. 66th Forest Products Society International Convention. June 3, 2012 Washington D.C.

Bioethanol from Lignocellulosic Feedstocks: A Life Cycle Assessment of Thermochemical Conversion Pathways. 2012. Jesse Daystar. 66th Forest Products Society International Convention. June 3, 2012 Washington D.C.

Impact of Feedstock on Lifecycle Carbon and Water Usage in Producing Ethanol from Wood Feedstocks using Bioconversion Processes. 2012. Rick Gustafson. 66th Forest Products Society International Convention. June 3, 2012 Washington D.C.

Summary of LCI/LCA Impacts for a Wide Range of Available Collection and Processing Alternatives Including Unintended Consequences 2012. 66th Forest Products Society International Convention. June 3, 2012 Washington D.C.

Phase II

The Phase II SOPO realigned the CORRIM work to reflect DOE updated priorities when the project was re-initiated. Core to the realignment was to work closely with the DOE ANL GREET Team to provide woody biomass LCI data for their next generation GREET model. There were three original overriding goals:

1.) providing life cycle inventory (LCI) data for six regionally specific woody biomass production systems to ANL for the GREET model,

2.) evaluate the interaction between the chemical characteristics of the woody biomass, and its production through thermochemical and biochemical biofuels production systems, and

3.) evaluate the interactions and trade-offs between the production of biofuels and durable wood products (DWP). We were able to accomplish these goals while also contributing significant advances to the understanding of uncertainties from the process scale to the global scale when evaluating the carbon consequences of using woody biomass for biofuel production.

There was significant detail required to accomplish each of these three goals, and these details are outlined by task and subtask in the body of this report.

The six regionally specific woody biomass scenarios included three commercially harvested softwood species, specifically southern loblolly pine plantations, Douglas-fir plantations common to the Pacific Northwest, and naturally regenerated northeastern spruce/fir. The three short rotation woody crops (SRWC) were poplar, eucalyptus and willow.

The fuel production systems include cellulosic ethanol and bio-oil based hydrocarbons. Liquid biofuel production from the three softwoods was modeled using the thermochemical conversion process that produces an intermediate bio-oil, and then a final hydrocarbon fuel. The biochemical conversion of sugars to ethanol was used with the three SRWC.

Analysis of the three softwoods included the co-production of DWP, which can serve as an important intermediate sink for the biomass carbon, and also limit the amount of biomass available within a financially reasonable collection radius. The DWP can have major impact on the atmospheric carbon, especially in the near-term.

Figure 6 outlines the major unit operations in the integrated biorefinery processes, including the feedstock ‘production’ and biomass conversion processes, and in the case of the softwoods production of DWP.

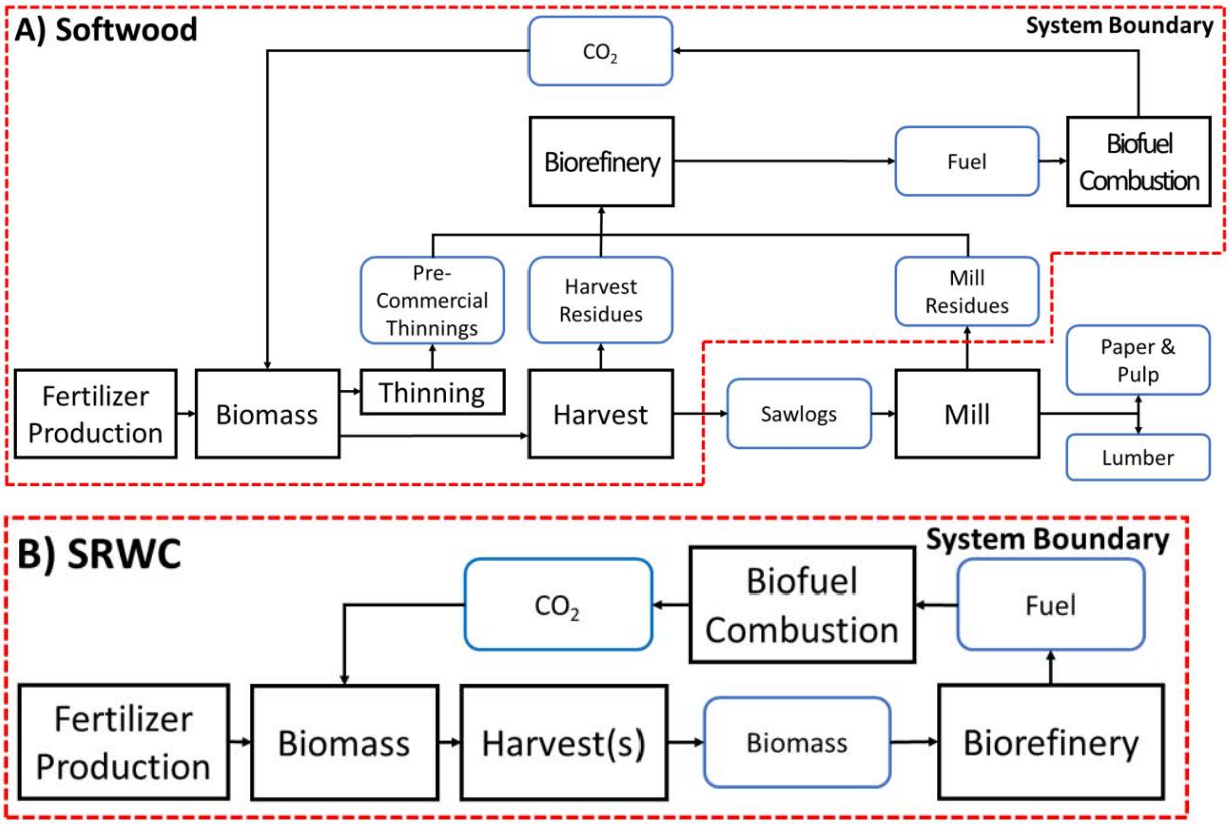

Figure 6 A) Block flow diagram that outlines the entire process for utilization of the softwood biomass including both the production of the biofuel, and the durable wood product. Only the biofuel (dashed red line) was considered in the ANL GREET analysis, B) block flow diagram that outlines the entire process cycle for utilization of the hardwood short rotation woody crops (SRWC) that used 100% of the biomass for biofuels production.

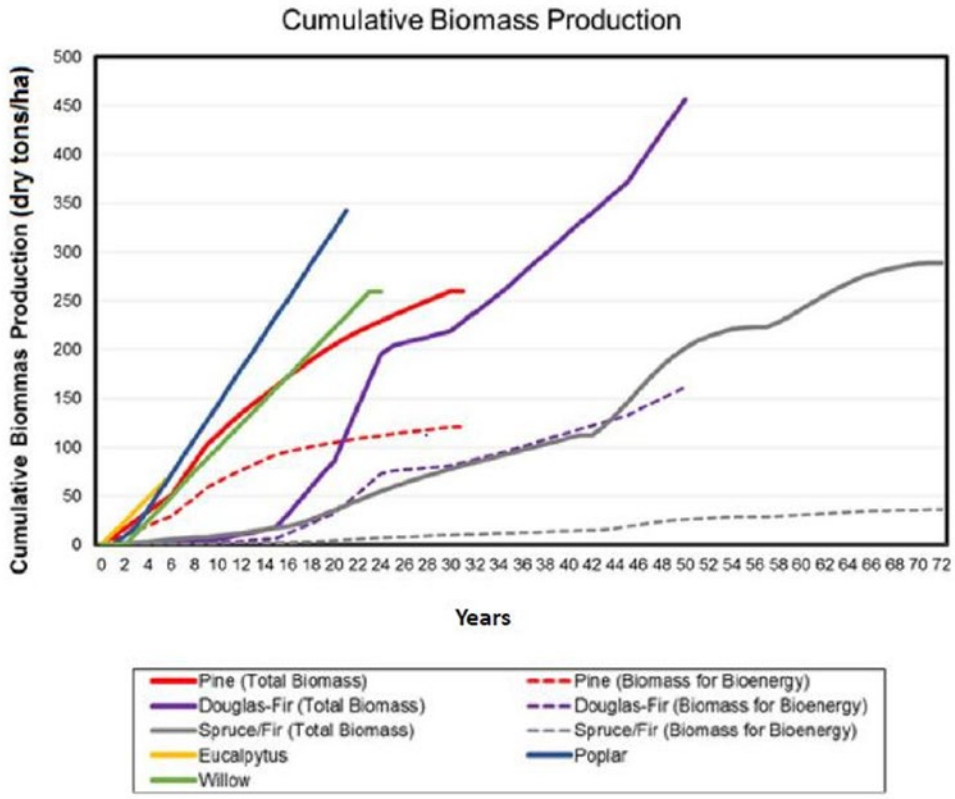

Figure 7 Summary of the six alternative biomass production scenarios completed as part of this work. These biomass production scenarios were used as inputs for the biofuels production modeling, and the ANL GREET analysis. Note, in the three softwood cases the woody biomass would be split between durable wood products and biofuels, and each of these allocations are also provided in Figure 7 (Han et al. 2018).

Figure 7 highlights the six woody biomass production scenarios developed and detailed in this work. In addition to the growth and yield models shown in Figure 7 a complete LCI was developed for the biomass production and harvesting for these six woody biomass scenarios. In all three of the softwood systems, the woody biomass is allocated between the more valuable DWP (solid line), and a biofuels feedstock (dashed line) and this allocation is shown schematically in Figure 7. This allocation is detailed in the reporting to the ANL GREET team.

Figure 8 shows a schematic of the ASPEN based thermochemical conversion process used to model the bio-oil to hydrocarbon production system.

The ASPEN thermochemical engineering process model considers key ‘characteristics’ of the woody biomass feedstock, e.g., delivered moisture content, ash content and carbon content. The biochemical model considers the cellulose and hemicellulose sugar content as the most important biomass characteristic (Figure 9). This is critical since a ton of biomass with differing ‘characteristics’, e.g. composition or moisture content, yield very different amounts of final products, have different demands for process heat, and use differing amounts of chemicals in the process.

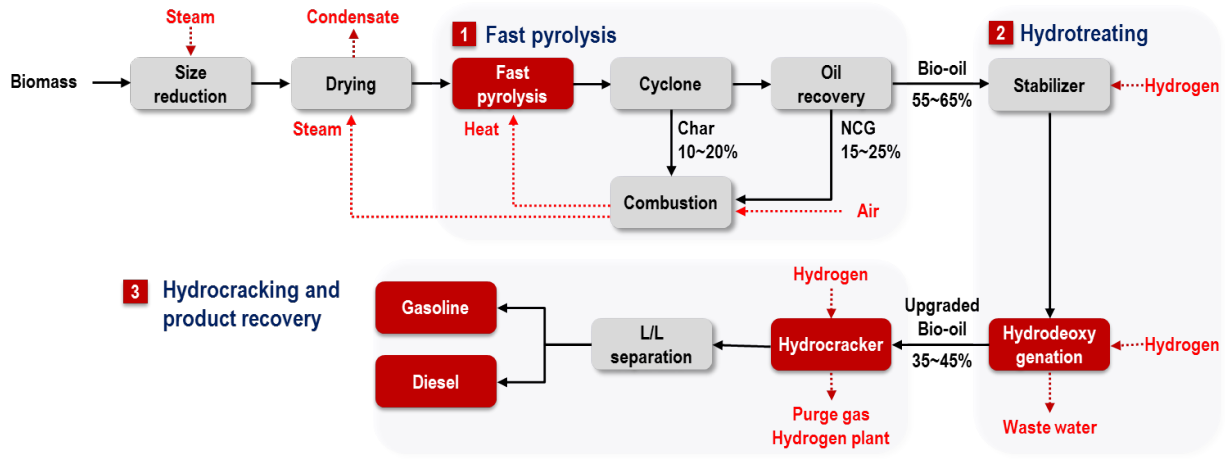

Figure 8 Schematic of the ASPEN-based, engineering process model for the thermochemical conversion process used for this work, e.g., fast pyrolysis to an intermediate bio-oil to a final hydrocarbon fuel.

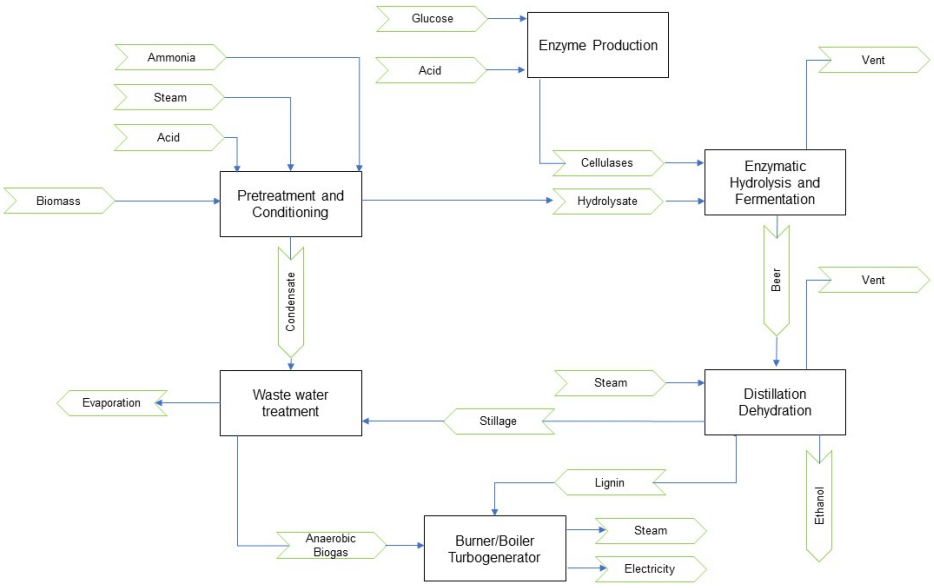

Figure 9 Schematic of the ASPEN-based, engineering process model for the biochemical conversion process used for this work.

The production of the DWP adds a very important, and variable carbon sink to the biomass carbon cycle. This is because the carbon in the woody biomass is 'stored' in a structure, e.g., as a 2x4 in the wall of a house, and it also displaces a fossil-fuel intensive building material. **Task 5** elucidate the complexities of the DWP biomass carbon sink using comparative analysis of a range of DWP and biofuel production processes. This work clearly shows a hierarchy of carbon benefits. The greatest carbon and financial benefit come from using wood in DWP, with opportunities for cascading uses that have lower carbon benefit but extend the useful life of the wood fiber through multiple cycles. When framed within the larger context of the global carbon budget, demand and supply for wood products, extant markets, and the hierarchy of carbon benefits from using wood in a myriad of ways, using wood to directly replace fossil fuel use does not provide as great a carbon mitigation benefit as using wood in place of other materials

that require large amounts of energy in their manufacturing and construction. This 'substitution' carbon benefit can be as much as nine times greater than the displacement benefit of using woody biomass to produce renewable fossil fuel alternatives. To demonstrate variation in carbon benefits, a carbon efficiency metric was developed (Figure 10) to allow comparisons across fuels and durable wood products. This efficiency metric places fuels and durable wood products on the same basis as their LCA do not use the same functional unit.

That is not to say that bioenergy development has no role in commercial softwood forestry operations. There are significant opportunities for improvement in utilization that could produce a reliable volume of high-quality bioenergy feedstocks in some regions of the US. The challenges will remain in the domain of technical recovery, and particularly in the economics of recovery. If there were sufficient demand for bioenergy feedstocks, the upstream forest management activities could be modified to generate the supply of residues needed to meet that feedstock demand. **(Task 1.)**

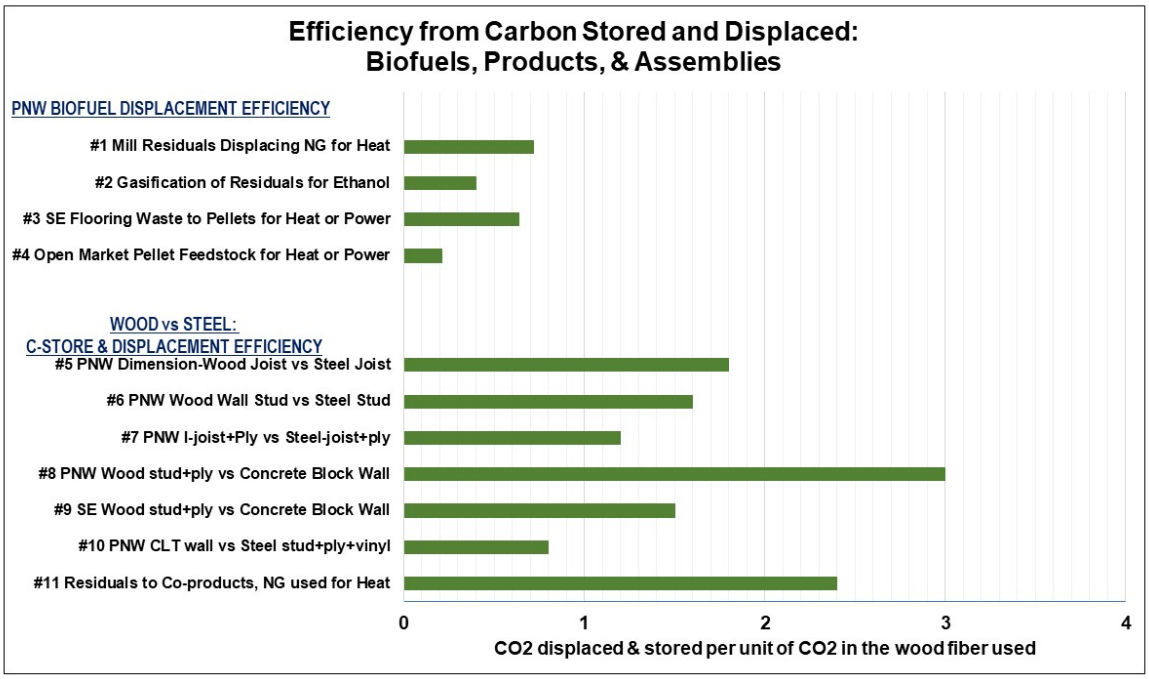

Figure 10 A cross section of different displacement efficiencies from substitution: #1-4 for biofuels, #5-6 floor & wall components, #7-10 floor & wall assemblies, #11 mill residuals for co-products & NG for drying.

Presentations

View or download in the Publications and Presentation sections of this report.

Carbon cycling, environmental & rural economic impacts of collecting & processing specific woody feedstocks into biofuels – SOPO, ANL, Nov 16, 2015

Deliverable and Accomplishments

Task 1 - An analysis of the carbon storage implications of using woody feedstocks for the production of both biofuels and the current commercial suite of short-lived and durable wood products

In Task 1 three commercially relevant, regional woody biomass production systems that are dominant in their respective regions were studied. These include softwood Douglas-fir (*Pseudotsuga menziesii*) and western hemlock (*Tsuga heterophylla*) systems common west of the Cascade mountain range in the Pacific Northwest (PNW), plantation southern pine (loblolly pine, *Pinus taeda*) systems common in the southeast (SE), and fir (*Abies spp.*) and spruce (*Picea spp.*) forestry systems common in the Northeast (NE) U.S. The three regions are substantially different in terms of growth rate, yield, common harvesting techniques, competing markets, and silvicultural practices. These differences result in substantial differences in forest biomass recovery, both in terms of yield, quality, and time. For each region, life cycle inventory data sets were developed based on current commercial practice and one or more alternatives. The regional outputs are reported individually below.

In general, feedstocks that require few chemical inputs and grow very fast are preferred. The composition of the biomass can impact the efficiency of the conversion process as well as the addition demand for power and process chemicals.

Biomass production data from each region (PNW, SE, and NE) and an alternative were delivered to Argonne National Lab (ANL) for inclusion in their GREET model for producing cellulosic biofuels (Han et al. 2018). CORRIM team members collaborated with ANL scientists to ensure they had a clear understanding of the data and its limitations. The current commercial operations life cycle inventory (LCI) data and assumptions were relatively straight forward but demanded special effort to address the 'time dimension' of emissions given the 25-65-year time periods between stand initiation and final harvest. Using CORRIM input, the ANL scientists generated alternative methodologies for accounting for the time dimension in their report (Han et al. 2018), which is cited as a companion to the work completed under this project.

An analysis of stand volumes, forest cover, management, recovery challenges, and reasonable transportation distances for the woody biomass suggested that the opportunity for developing a large scale biorefinery is possible at a number of locations in the SE, at very few locations in the PNW, and is not reasonable for the NE. In the case of the NE, this conclusion is driven by the slow growth rate and modest stand volumes, which result in an excessive transportation distances, (e.g., 150-200 mile one-way hauls) in order to accumulate sufficient biomass to support a modest sized biorefinery, e.g., 500-1,000 ODT/day. These comparisons between the three regions identified the SE region as the best candidate for further sensitivity analysis of bioenergy feedstock recovery. Reporting on this key deliverable is found in **Task 1 – LCI Softwoods SE**.

Counterfactual scenarios that assume no-harvest as an alternative were considered as a special case that was explored to address biomass carbon debt related research questions. In general, forests are either managed for profit or not managed at all. Commercial forestry operations typically include an initial stand investment that is only economically viable if there is an expectation of harvest. If there is no plan to harvest forests, they are left to develop on their own. In most cases the result is a forest that is partially stocked, which has a range of species that may or may not grow quickly, and will typically not

Counterfactual scenarios that assume up front management with no expectation of harvest are not realistic given forest land values and the need to ensure return on investment (ROI).

reach anywhere near the carbon sequestration potential of a managed forest (See Figure 11) for an example **Task 1- LCI softwoods PNW**). In no case would landowners invest in regenerating a forest without the opportunity to recover those costs and make a profit in the future from their management activities.

> The introduction of a temporal aspect to the lifecycle analysis requires that the analysis be expanded from a single acre, or stand, to the landscape in order to account for the time dimension in analysis of carbon debt on a managed landscape.

There are significant challenges in characterizing the time dimension of carbon dynamics over a rotation that is 25, 35, 50 or more years using the activities that accrue on an 'average acre'. Unlike the analysis for agricultural crops, for forests the average or representative acre without considering time is not analogous to the average acre when we do incorporate the rotation length into the scenario. A single acre example can be used as representative of the carbon impacts of forest operations only if we ignore the time dynamics (Figure 11), but it cannot be used if we consider them. That is because it takes 25, 35, 50+ years to produce a harvested crop, therefore the actual representative acre in any given year is a conglomerate of 25, 35, 50+ average "acres" representing the weighted average of the forest stands in a wood basket with each on a different year of their trajectory. The size of the 'wood basket' is driven by the total yearly volume needed to keep the mills operational. In a real-world scenario, when the infrastructure and demand are stable, the carbon changes on the landscape balance out to near zero (see **Task 5 – Supply Chain Barriers**) as harvest is equal to the growth increment only. The shift to something other than near zero is a function of either over harvesting or under harvesting in response to shifts in infrastructure (e.g. loss of mills because forests are removed from production as happened in the west); shifts in demand; changes in retention policies in the forest which removes forest land from harvest and puts it in reserved status; or loss of timber land to alternate uses. A more nuanced discussion of counterfactuals and carbon debt can be found in **Task 5 – Supply Chain Barriers**.

Current biofuels production scenarios are focused on collecting forest residue and in some regions, recovery of forest thinnings. The LCI input data provided both estimates of timing and mass of biomass available for biofuels production, in conjunction with the continued production of paper and durable wood products for the business as usual case. Re-allocation of thinned material, or lower value logs, were considered in a bioenergy intensive case (Table 3). Because the current commercial wood production systems have long production cycles that vary from 25-65 years, average yearly input values were derived using forest inventory simulation data for each region to generate the quantity and timing of the inputs. Variability within regions was incorporated into the yield estimates.

LCI – Softwoods PNW (University of Washington)

Summary

The LCI of PNW softwoods generated volume and yield assessments for three alternative harvest scenarios in the PNW: 1.) current commercial operations with recovery of forest residues (i.e. non-commercial logs, tops and branches) for bioenergy feedstocks, 2.) current commercial operations with re-allocation of small pulp logs to bioenergy, and 3.) a no-management alternative representing an example condition if the forest is not used for commercial forestry activity (Table 3). As the no-management alternative generates no feedstocks as inputs to the biorefinery, the scenario was limited to the development of growth and yield outputs that could serve as a counterfactual for comparison to the bioenergy scenarios.

Table 3 Scenario alternatives for PNW and NE region commercial softwood analysis

Scenario	PNW	NE
Business as Usual Bioenergy Scenario (wood products, pulp & paper, thinnings, harvest residues to bioenergy)	X	X
Bioenergy Scenario B (all thinnings and residues go towards bioenergy)	X	X
No Action Alternative (do not site prep, plant, or harvest)	X	X

For the PNW, the business as usual and bioenergy scenarios used the identical growth and yield variables but varied in their allocation of biomass to durable wood products and bioenergy feedstocks. Thus, they follow the same carbon yield curve in Figure 11. The no – management example was based on natural regeneration of forest canopy after harvest estimated from harvest volumes from naturally regenerated stands.

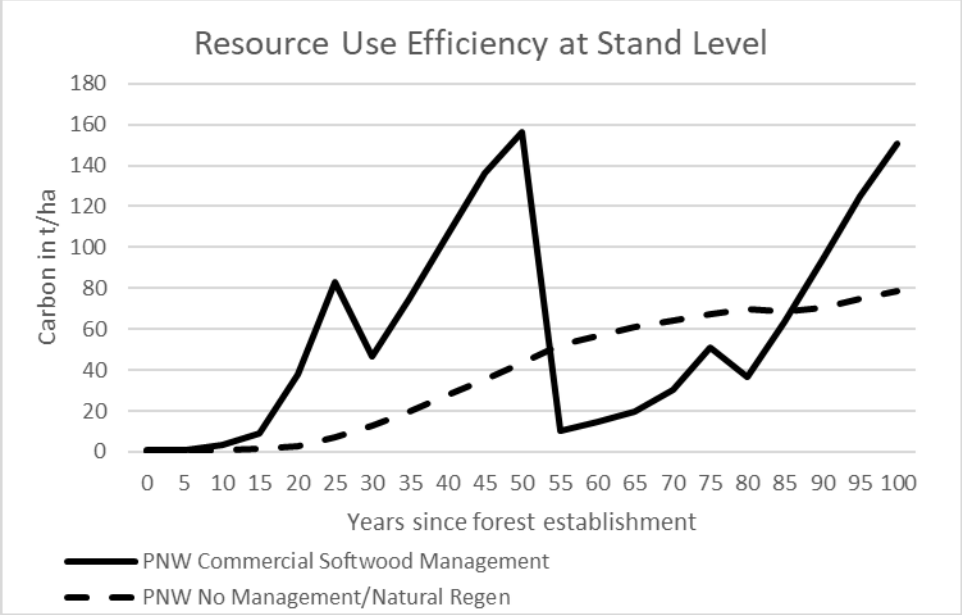

Figure 11 Comparison of natural regeneration and Douglas-fir plantation growth and yield in the PNW region.

The average volume differences between managed stands and unmanaged stands, when converted to biomass or carbon equivalents shows that managed stands produce nearly 4 times the biomass in a 100-year period to an unmanaged stand. That calculation is based on two 50- year rotations that each generate over 150 metric tons per hectare (t/ha) of carbon (C) sequestration for Douglas-fir forests vs. 78 t/ha for naturally regenerated stands at 100 years.

The life cycle impact assessment (LCIA) and LCI of commercial forestry operations were used in a comparative assessment of the regional differences between the PNW and the NE for woody feedstocks that could be used for biofuel production (Oneil et al. 2019). This comparative analysis of PNW and NE forestry data shows a nearly 5-fold difference in forest productivity and a four-fold difference in available residues, assuming all pulp quality material is redirected for energy production. These differences result in significant differences in the LCIA results as show in Table 4. LCA results on specific process details are shown in Table 5 for the PNW and Table 6 for the NE. Results are indicative of the relative differences in regional ability to scale up production to meet bioenergy goals using forest residues from commercial softwood production.

Table 4 Comparison of LCA results per allocated bone-dry metric ton (BDT) of biomass at the facility for the PNW and NE regions

LCA impact per BDT of biomass at Facility Gate			
Impact category	**Unit**	**PNW**	**NE/NC**
Ozone depletion	kg CFC-11 eq	0.00	0.00
Global warming	kg CO2 eq	38.46	55.91
Smog	kg O3 eq	14.15	22.20
Acidification	kg SO2 eq	0.44	0.70
Eutrophication	kg N eq	0.03	0.04
Respiratory effects	kg PM2.5 eq	0.01	0.01
Ecotoxicity	CTUe	79.48	131.98
Fossil fuel depletion	MJ surplus	56.13	93.21

Table 5 LCA results per allocated bone-dry metric ton (BDT) of biomass at the facility for the PNW region

PNW, all available biomass, at plant gate								
Impact category	**Unit**	**Residue Recovery**	**Pulp logs from thinning**	**Transport - pulp logs**	**Transport ground residues (from ground-based locations)**	**Transport ground residues (from cable-based locations)**	**Chipping pulp logs at facility**	**Total**
Ozone depletion	kg CFC-11 eq	2.77E-10	1.53E-10	2.20E-10	1.36E-10	1.57E-10	2.46E-10	1.19E-09
Global warming	kg CO_2 eq	6.63E+00	3.67E+00	1.03E+01	6.35E+00	5.58E+00	5.90E+00	3.85E+01
Smog	kg O_3 eq	2.91E+00	1.58E+00	3.17E+00	1.95E+00	1.96E+00	2.58E+00	1.41E+01
Acidification	kg SO2 eq	9.17E-02	4.99E-02	9.79E-02	6.03E-02	6.12E-02	8.15E-02	4.42E-01
Eutrophication	kg N eq	5.48E-03	2.98E-03	5.87E-03	3.61E-03	3.66E-03	4.87E-03	2.65E-02
Respiratory effects	kg $PM_{2.5}$ eq	1.89E-03	1.01E-03	1.89E-03	1.16E-03	1.21E-03	1.68E-03	8.83E-03
Ecotoxicity	CTUe	1.85E+01	1.02E+01	1.47E+01	9.10E+00	1.05E+01	1.65E+01	7.95E+01
Fossil fuel depletion	MJ surplus	1.31E+01	7.22E+00	1.04E+01	6.43E+00	7.39E+00	1.16E+01	5.61E+01

Final report, publications, and presentations

View or download in the Publications and Presentation sections of this report.

Oneil, E.E., J. Puhlick, A. Weiskittel. 2019. Regional variations in the lifecycle assessment of softwood residue recovery for biofuel production for the Pacific Northwest and northeast regions of the USA, CORRIM report, 52 pp.

Carbon cycling, environmental & rural economic impacts of collecting & processing specific woody feedstocks into biofuels – Harvest systems, ANL, Nov 16, 2015

Regional variations in the lifecycle assessment of softwood residue recovery for biofuel production for the Pacific Northwest and northeast regions of the USA. Elaine Oneil (presenter), et al. Forest Products Society Annual Meeting, Madison WI June 11-14, 2018

Carbon Cycling, Environmental & Rural Economic Impacts of Collecting & Processing Specific Woody Feedstocks into Biofuels. 2016. Oneil, E., R. Morales-Vera, and N. Rajagopalan. Agronne National Lab. December 5, 2016

LCI – Softwoods Northeast/Northcentral (University of Maine and University of Washington)

Summary

Growth and yield modeling estimates of tree mortality, and the impact of partial cutting on future stand composition and stocking in spruce-fir stands has not been well documented in the past, especially with model data comparisons to actual inventory. The University of Maine (UM), School of Forest Resources provided key data on simulated forest growth and yield under different forest management and tree utilization scenarios for the spruce-fir forest type in Maine that incorporated state of the art modeling for the region. That growth and yield modeling was coupled with experience of the common current practices to generate the most realistic scenarios of biomass recovery in the spruce/fire forests to date. The modeled scenarios included:

- management and tree utilization according to the common current practice (whole-tree harvesting with tops and branches of trees left on-site (base-case scenario),
- no-management (managed lands that would not be harvested for wood products in the future) (counterfactual 1), and
- management according to the current practice but intensive utilization of trees (use of pulpwood-sized material as well as the tops and branches of cut trees for bioenergy) (counterfactual 2).

Simulations generated estimates of live tree biomass and carbon (C) stocks over the timeframe of an entire rotation. For each commercial harvest, harvested wood yield (volume, biomass, and C) by product type (e.g. sawlogs and pulpwood) was provided to CORRIM and ANL for inclusion in the GREET model of cellulosic biofuels. In addition to providing CORRIM and ANL with growth and yield values, the UM was tasked with assembling information on C emissions related to residue recovery machinery and transportation of wood products to mill facilities. Data provided by the UM were used by the University of Washington to generate LCI results for the GREET model and to generate LCIA results Table 6 for comparison with PNW regional outcomes by the University of Washington.

Table 6 LCA results per allocated bone-dry metric ton (BDT) of biomass at the facility for the NE Region

NE region all available biomass at plant gate							
Impact category	**Unit**	**Residue Recovery**	**Pulp logs from thinning**	**Transport - pulp logs**	**Transport ground residues**	**Chipping pulp logs at facility**	**Total**
Ozone depletion	kg CFC-11 eq	1.29E-10	1.14E-09	2.62E-10	1.02E-10	3.41E-10	1.97E-09
Global warming	kg CO_2 eq	3.08E+00	2.76E+01	1.23E+01	4.74E+00	8.17E+00	5.59E+01
Smog	kg O_3 eq	1.35E+00	1.20E+01	3.78E+00	1.45E+00	3.58E+00	2.22E+01
Acidification	kg SO_2 eq	4.26E-02	3.79E-01	1.17E-01	4.50E-02	1.13E-01	6.97E-01
Eutrophication	kg N eq	2.55E-03	2.27E-02	7.02E-03	2.70E-03	6.75E-03	4.17E-02
Respiratory effects	kg $PM_{2.5}$ eq	8.76E-04	7.76E-03	2.26E-03	8.66E-04	2.32E-03	1.41E-02
Ecotoxicity	CTUe	8.60E+00	7.62E+01	1.76E+01	6.80E+00	2.28E+01	1.32E+02
Fossil fuel depletion	MJ surplus	6.07E+00	5.38E+01	1.24E+01	4.80E+00	1.61E+01	9.32E+01

Critical differences between the NE and PNW that drive the LCA outcomes include:

- Marked differences in forest productivity. Managed Douglas-fir stands yield 500-700 cubic meters per hectare (m^3/ha) in 50 years whereas NE spruce/fir stands yields 155 m^3/ha in 70 years.
- There are few markets in either region and those that exist are constrained by difficult terrain, long haul distances, and low-quality roads in the PNW and low volume, mixed species stands on small acreages in the NE.

Final report, publications, and presentations

View or download in the Publications and Presentation sections of this report.

Oneil, E.E., J. Puhlick, A. Weiskittel. 2019. Regional variations in the lifecycle assessment of softwood residue recovery for biofuel production for the Pacific Northwest and northeast regions of the USA, CORRIM report, 52 pp.

Shaler, S., A. Weiskittel, J. Puhlick, and P. Heisl. 2018. Forest carbon stocks and emissions from harvesting operations in spruce-fir forests of Maine, USA. CORRIM Final Report. 20pp.

Regional variations in the lifecycle assessment of softwood residue recovery for biofuel production for the Pacific Northwest and northeast regions of the USA. Elaine Oneil (presenter), et al. Forest Products Society Annual Meeting, Madison WI June 11-14, 2018.

LCI – Softwoods Southeast (North Carolina State University)

Summary

Researchers at the North Carolina State University were tasked with simulating forest growth and yield of southern loblolly pine plantations managed with different forest practices and on differing 'quality' of sites. These forest growth and yield models were conducted with LOBDSS model (Forest Productivity Cooperative), and common commercial tool that have been benchmarked against a number of different commercial plantations and is used by commercial forest managers, and researchers. Our scenarios included:

1.) two different site indexes. (Site index is single value that combines the annual temperature and rainfall, and land quality into an indicator of the productivity of the land)

2.) different establishment practices, e.g., planting density (stems per acre), and the presence or absence of fertilization two years after establishment

3.) management of the thinning, e.g., no thinning, precommercial thinning to two basal areas, or commercial thinning to two different basal areas

These different cases are shown in Table 7.

.

Table 7 The conditions used for modeling southern loblolly pine production.

Scenario	Site Index	Planting Density (trees/ac)	Fertilization	Precomm Thinning (Yr.)	Precomm Thinning (Basal area)	Comm Thinning (Yr.)	Comm Thinning (Basal area)	Green tons/Ac
Sc 1	High	871	Yes	12	90	18	90	188
Sc 1a	High	871	No	12	90	18	90	176
Sc 1b	High	871	Yes	12	90	None	NA	243
Sc 2	High	871	Yes	12	70	18	70	158
Sc 2a	High	871	No	12	70	18	70	144
Sc 2b	High	871	Yes	12	70	None	NA	219
Sc 3	High	680	Yes	12	90	18	90	188
Sc 3a	High	680	No	12	90	18	90	172
Sc 3b	High	680	Yes	12	90	None	NA	242
Sc 4	High	680	Yes	12	70	18	70	155
Sc 4a	High	680	No	12	70	18	70	144
Sc 4b	High	680	Yes	12	70	None	NA	214
Sc 5	Low	871	Yes	12	90	18	90	146
Sc 5a	Low	871	No	12	90	18	90	136
Sc 5b	Low	871	Yes	12	90	None	NA	187
Sc A1	High	871	Yes	9	90	None	NA	273
Sc A1a	High	871	No	9	90	None	NA	252
Sc A1b	High	871	Yes	None	NA	None	NA	290
Sc A2	High	680	Yes	9	90	None	NA	270
Sc A2a	High	680	No	9	90	None	NA	249
Sc A2b	High	680	Yes	None	NA	None	NA	280
Sc A3	Low	871	Yes	9	90	None	NA	216
Sc A3a	Low	871	No	9	90	None	NA	198
Sc A3b	Low	871	Yes	None	NA	None	NA	211

The purpose of this modeling was to estimate total biomass, the biomass in thinnings and forest residues that could be allocated to biofuels, and the biomass the is available for DWP. Examples of the data generated by the forest growth and yield modeling is shown in Figure 12.

As seen in Figure 12 there are large variations in the biomass produced over a single 25-35-year rotation. It is also worth noting that rotation age alone has a large impact on the total biomass, and the biomass that can be allocated to DWP. It is not the purpose of this summary to detail every case, but it is useful to note that the original planting density, and the timing and intensity of the precommercial thinning both have a significant impact on the total biomass production. It is worthwhile to note that case Sc1b (marked on Figure 10) and Sc2b (not marked on Figure 12) both generate a useful combination of biomass for biofuels production and biomass for DWP.

The relationship between the total biomass production and the total lumber produced for DWP is shown in Figure 13a. As expected, there is a strong relationship, and that the ‘site index’ plays a dominate role in this relationship. A less obvious relationship is the changes in stand density (trees per acre) over time, as shown in Figure 13b. There are two significant observations taken from Figure 13b:

1.) the expected reductions in stand density due to pre-commercial thinning, and

2.) the reductions due to mortality. The effects of tree mortality significantly impact the total biomass carbon, and that biomass carbon is left on the site because it cannot be cost-effectively collected. It becomes a source of carbon emissions that are typically not accounted for in the tracking of emissions from forest decay.

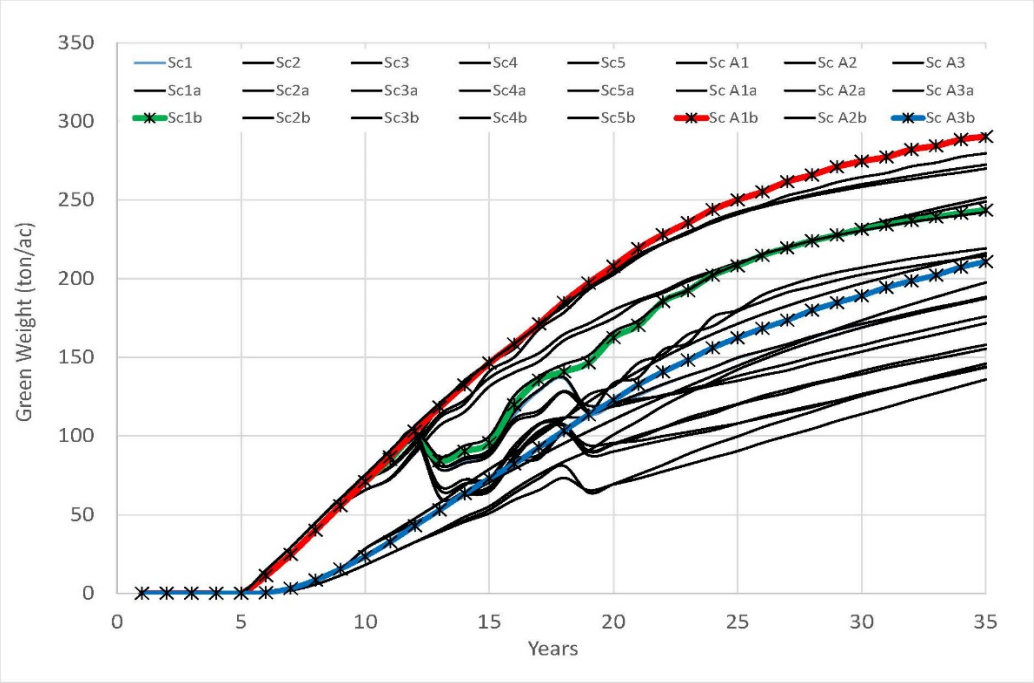

Figure 12 Variations in biomass production for southern loblolly pine plantations for a variety of growth conditions and management regimes. The modeling was conducted with the LOBDSS forest growth and yield modeling tool.

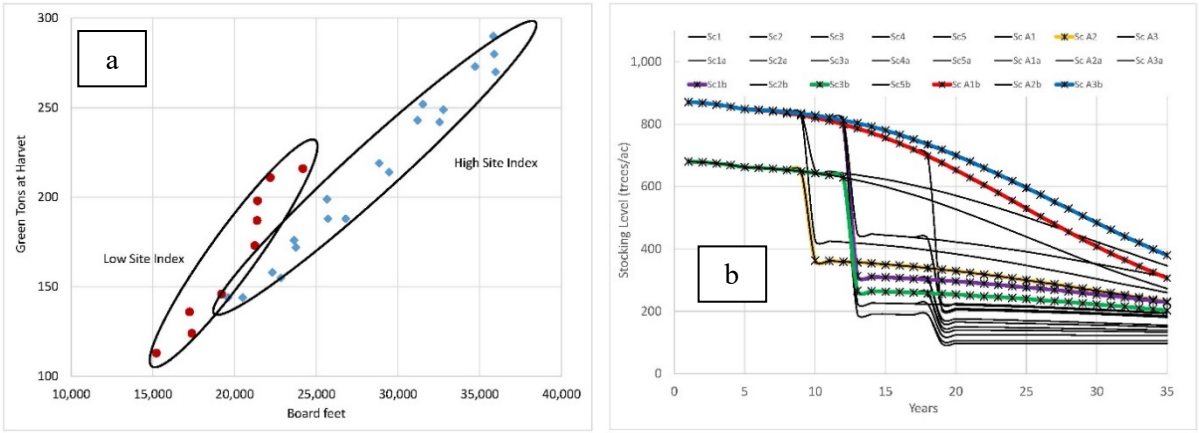

Figure 13 (a) The relationship between the total biomass production and the total lumber produced for DWP; (b) the relationship between stand density (trees per acre) and time (years). The sharp drops in stocking at years 9, 12 and 18 are due to pre-commercial and commercial thinning. The gradual declines in between are due to stand morality.

Final report, publications, and presentations

View or download in the Publications and Presentation sections of this report.

Lan, K., L. Ou, S. Park, S.S. Kelley, and Y. Yao 2019. Life cycle analysis of decentralized pre-processing systems for fast pyrolysis biorefineries with blended feedstock in the southeastern United States. Energy and Technology, early access, doi.org/10.1002/ente.201900850

Carbon cycles in US wood-based bioenergy systems. 2017. Seminar at Tampere University of Applied Sciences, Kelley, S.S. (presenter), Tampere, Finland, Nov. 1, 2017

Woody biomass in energy cycles. 2017. Kelley, S.S. S. Park, N. Rajagopalan, L. Ou. Presentation to USDA NIFA staff, and SE Foresters, Auburn University, Nov 14-15, 2017

Southern pine and short rotation woody biomass for production of bioenergy. 2017. Kelley, S.S., S. Park, N. Rajagopalan, L. Ou, and M. Herrera. Seminar at the University of Concepcion Technology Center, Concepcion, Chile, Dec 18, 2017

Task 2 of SOPO- LCI of Regionally specific, Dedicated to SRWC for Production of Biofuels

LCI of PNW Poplar (University of Washington)

Summary

Short rotation woody crops (SRWC) present an attractive option for diversifying and expanding biomass available for biofuels production. Most of the SRWC LCI data available have been collected using publicly available research papers. In this study, the hybrid poplar growth and operational data are provided by a primary source, GreenWood Resources. GreenWood has been growing poplar for more than 30 years in the PNW and has four experimental tree farms to assess poplar growth and environmental impacts. In the coppice system, the first year of feedstock production includes growing poplar trees at a nursery and preparing the plantation site for poplar to be planted the following year. The first coppicing of the poplar trees takes place in year 2 and the trees are harvested every 3 years for 6 cycles. We used data from the experimental tree farms to construct a detailed inventory of the material and energy inputs required to operate the tree farms. Some of the results include 8 liters of diesel fuel that are consumed for each bone-dry metric ton (BDT) of poplar over the 20-year growth. Glyphosate was the main chemical input for growing the trees, with 320 g/BDT used over the growing cycle.

Poplar feedstock production and harvesting

The feedstock production and harvesting model was developed using operational data from industry[1]. Table 8 shows poplar growth, harvesting and silvicultural activities, in summary, the first 3 years of feedstock production include growing poplar trees at a nursery and preparing the plantation location for poplar to be transplanted the following year. Nursery operations include herbicide, fertilizer, and pest control application. Once large enough, the poplar trees are turned into cuttings and transported to cold storage. Preparing the plantation location for the cuttings will depend on the site-specific characteristics, but in general the land will undergo heavy and finish disking, smoothing, row marking, and herbicide application. The cuttings are planted the following year and are grown for two years before the first coppicing, which will promote the growth of multiple stems per stump. Following the first coppicing the trees are harvested every 3 years for 6 cycles. The poplar trees are harvested with a forage harvester and forage wagons are towed alongside the harvest to collect the chips. The chips are loaded into a chip van using a silage blower and transported to the biorefinery. No storage of the poplar biomass is needed at the tree farm or biorefinery as the trees will be harvested year-round, following a just-in-time harvest management scheme. Herbicide is used every year. No pesticides and fertilizers are used during the growing cycles.

[1] Jose Zerpa, Brian Stanton, Rich Shuren from GreenWood Resources, oral & written communication) and literature for lubricant estimation (Caputo et al. 2014)

Table 8 Silvicultural activities to grow hybrid poplar in the Pacific Northwest (PNW)

	Year										
Hybrid Poplar Growth	Nursery		Crop establishment			Cycle 1,2,3,4,5			Cycle 6		
Activities	-1	-2	0	1	2	3	4	5	18	19	20
Nursery operation*	■	■									
Site preparation			■								
Machinery use	■	■	■		■	■	■	■	■	■	■
Application of herbicides	■	■	■	■	■	■	■	■	■	■	■
Application of pesticide	■										
Plant cuttings			■								
Cultivation**				■	■		■	■		■	■
Growth				■	■	■	■	■	■	■	■
Harvest***					■			■			■
Post harvest clean up						■			■		
Restoration (disking)											■
Transport to mill					■			■			■

*Nursery operations include herbicide, fertilizer and pest control application

**Includes soil overturning to eliminate weeds

***The first harvest is to promote the growth of multiple stem per stump

Table 9 summarizes biomass yields obtained during crop establishment, 3 years cycle, annually and after the total growth period of 20 years. Yields of 15.8 BDT/ha were obtained using short rotation coppice silviculture.

Table 9 Poplar yields after 20 years poplar plantation lifespan.

Item	Yield
Crop establishment	16.6 BDT/ha
3 years poplar (per cycle)	47.7 BDT/ha
3 years poplar (per yr)	15.8 BDT/ha/yr
Total biomass after 20-year growth	301 BDT/ha

Fossil fuel and chemical use per BDT of hybrid poplar are shown in Table 10. Diesel fuel and lubricants are used for machinery utilized during silvicultural activities. Harvesting activities such as cutting and offloading are the main diesel consumers. Electrical cold storage is used to maintain the quality of the poplar cuttings in the nursery. Most of the chemical use of nitrogen (urea) and pesticides (imidacloprid and oust) are applied during nursery activities. Herbicide as glyphosate is used every year to control weed growth.

Table 10 Fossil fuel and chemical use per BDT of hybrid poplar.

Energy consumption per BDT		Chemical consumption per BDT	
Diesel (gal/BDT)	2.0	N (gal/BDT)	0.02
Lubricant (kg/BDT)	0.1	Glyphosate (gr/BDT)	320
Electricity (kg/BDT)	0.1	Pesticides (gr/BDT)	1.5

The detailed information of this study was delivered to ANL) for inclusion in their GREET models. A technical report entitled "Carbon dynamics for biofuels produced from woody feedstocks" was published in 2018 by ANL (Han et al. 2018).

Final report, publications, and presentations

View or download in the Publications and Presentation sections of this report.

Han, Jeongwoo, Christina E. Canter, Hao Cai, Michael Wang, Zhangcai Qin, Jennifer B. Dunn, Richard Gustafson, Stephen S. Kelley, Rodrigo Morales, Elaine E. Oneil, Longwen Ou, Sunkyu Park, Maureen Puettmann, Neethi Rajagopalan, Timothy Volk, and Aaron Weiskittel. 2018. Carbon dynamics for biofuels produced from woody feedstocks, Technical Report #: ANL/ESD-18/10, Argonne National Laboratory, Chicago. IL. 72 pp

Carbon Cycling, Environmental & Rural Economic Impacts of Collecting & Processing Specific Woody Feedstocks into Biofuels. 2016. Oneil, E., R. Morales-Vera, and N. Rajagopalan. Agronne National Lab. December 5, 2016

Poplar biomass using short rotation coppice silviculture for acetic acid production: techno-economics assessment and environmental impacts. 2017. Morales et al. Brazil, Biofuels, Bioenergy, & Bioeconomy, 2017.

LCA for environmental assessment: The case of poplar to ethanol. Morales, Vera, R. (presenter), R. Gustafson, and R. Shuren. 2018. 3° Coloquio de Investigación UCM Curicó-Los Niches. Sustentabilidad desde la transdisciplinariedad: Propiciando diálogos colaborativos para el desarrollo sustentable. Curicó Region del Maule, Chile, Sept 2018.

Poplar to ethanol production using short rotation coppice silviculture: Life cycle assessment. 2018. Morales Vera, R. (presenter), R. Gustafson, and R. Shuren. 2018. II Conferencia Chilena de Análisis de Ciclo de Vida. Santiago, Chile, August 2018.

LCI of Northeast Willow (SUNY College of Environmental Science and Forestry (ESF))

Summary

Data were collected and assembled for an LCI for willow biomass crops. Data were collected from commercial scale operations in northern New York (NY) including information on planting, maintenance and harvesting operations. Data were provided to ANL and their final report was reviewed, and feedback was provided.

In addition to updating LCI data, information on key quality parameters of willow (ultimate and proximate analysis) needed to run the ASPEN model were provided. These data were based on samples collected from fields harvested with a single pass cut and chip harvester and are therefore more representative of the material that will be delivered to an end user than hand harvested samples that have been used in the past.

This study uses a spatial life cycle assessment (LCA) model that incorporates GIS data in Central and Northern New York to provide spatially specific estimates of greenhouse gas (GHG) emissions and energy return on investment (EROI). The model accounts for land use conversion and willow biomass production and includes soil organic carbon (SOC) change. Ninety-two percent of 9,718 suitable parcels for willow biomass production had negative GHG emissions in willow biomass production indicating climate change mitigation potential. The average life cycle GHG emissions in the region were -126.8 kg CO_2eq Mg^{-1} biomass on cropland or pastureland and ranged from -53.2 kg to -176.9 kg CO_2eq Mg^{-1} across the region. However, for grassland converted to willow biomass crops, there was a modeled

decrease in SOC resulting in a slightly positive (27.7 kg CO_2eq Mg^{-1} biomass) GHG balance. Land use change, willow crop yield, and transportation distance had the greatest impact on GHG emissions. The uncertainty analysis showed large variations of probability distributions of GHG emissions in the five counties arising from differences in these key parameters. The average EROI was estimated at 19.2 and was not affected by land use change. The results showed substantial potential to reduce GHG emissions in the region by growing willow biomass crops as well as potential to provide bioenergy with a high EROI for certain land use change and transportation scenarios. Furthermore, these results suggest that willow biomass can serve as a low carbon and high EROI energy source in other regions of the world with similar infrastructure and growing conditions such as soil conditions, land cover types, and climate.

Final report, publications, and presentations

View or download in the Publications and Presentation sections of this report.

Han, Jeongwoo, Christina E. Canter, Hao Cai, Michael Wang, Zhangcai Qin, Jennifer B. Dunn, Richard Gustafson, Stephen S. Kelley, Rodrigo Morales, Elaine E. Oneil, Longwen Ou, Sunkyu Park, Maureen Puettmann, Neethi Rajagopalan, Timothy Volk, and Aaron Weiskittel. 2018. Carbon dynamics for biofuels produced from woody feedstocks, Technical Report #: ANL/ESD-18/10, Argonne National Laboratory, Chicago. IL. 72 pp

Frank, J., Brown, T. Volk, T.A. Heavey, P., Malmsheimer, R. 2018. A stochastic techno-economic analysis of shrub willow production using EcoWillow 3.0S. Biofpr. DOI: 10.1002/bbb.1897

Yang S. 2017. Understanding land use and land cover change: national forest dynamics and regional willow crop environmental impacts based on spatial modeling and spatial life cycle assessment. A dissertation submitted in partial fulfillment of the requirements for the Doctor of Philosophy Degree State University of New York College of Environmental Science and Forestry Syracuse, New York, June 2017. 172pp.

Spatially explicit life cycle assessment of willow biomass production in northern New York. Yang, S., T. Volk, M-O. Fortier. 2016.. Short Rotation Woody Crops Operations Working Group meeting, St. Petersburg, FL, Oct. 11 – 13, 2016.

Greenhouse gas and energy balance of willow biomass crops are impacted by prior land use and distance from end users. Volk, T.A., S. Yang, M-O Fortier, and O. Therasme. 2018. 2018 Woody Crops International Conference, July 23-25, 2018, Rhinelander, WI.

LCI of Southeast Eucalyptus (North Carolina State University)

Summary

Researchers at the North Carolina State University (NCSU) were tasked with simulating forest growth and yield of managed Eucalyptus plantations. Eucalyptus is an extraordinarily fast-growing hardwood, that is the basis of a dominate pulp and paper industry in the southern hemisphere. While there are millions of acres of Eucalyptus in Brazil, Chile, South Africa, and Australia, commercial plantations in the US are limited to the southern tip of Florida. This is due to a lack of 'cold tolerance' in Eucalyptus. Freezing temperatures will stunt or even kill most Eucalyptus varieties. However, there are a number of tree improvement programs in the SE US focused on identification of 'cold tolerant' Eucalyptus.

This DOE project leveraged a series of Eucalyptus trials that were separately funded by USDA and companies under the umbrella organization of the NCSU Forest Productivity Cooperative program. The scope of these trials funded by USDA and private companies are shown in Figure14. Examples of the results from these trials are shown in Figure 15.

The unique investment made by this project was focused on connecting the Eucalyptus growth rates and LCI attributes to its composition. The composition data was then used to explore the interaction between the wood composition and biofuels production.

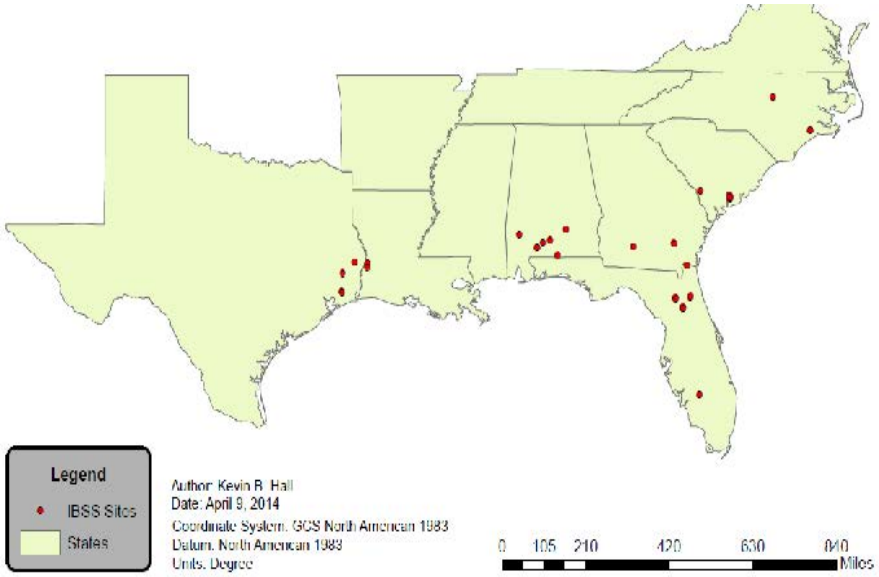

Figure 14 Location of Eucalyptus trials managed by the NCSU Forest Productivity Cooperative program.

Age (year)	Number of plots	Stocking (TPH)	Basal area (m^2 ha^{-1})	Dom. height (meter)	Volume (m^3 ha^{-1})
1	1	2078	4.5	7.6	14.6
2	63	1621	4.6	7.6	15.6
3	25	1502	9.0	9.6	39.8
4	8	1549	13.6	12.2	70.6
7	1	637	17.0	20.4	125.4
8	1	864	19.5	19.2	144.9
13	1	732	24.4	21.5	192.9

Figure 15 Examples of the results of Eucalyptus trials managed by NCSU. The data from these trials, was combined with biomass composition data (uniquely funded by this project) provide the LCI input data

Specific LCI attributes considered for the evaluation of eucalyptus as a SRWC included the chemical and fuel inputs needed for the establishment of plantations (Table 11 and Table 12).

Table 11 Site preparation equipment and fuel use for SE establishment and harvesting of Eucalyptus plantatins

Activity	Equipment	Equipment power (hp)	Diesel consumption (gal/acre)
Establishment	Tractor	225	4.7
Harvest	Feller Buncher	175	4.7
	Skidder	225	4.7
	Chipper	100	2.6

Table 12 Fertilizer and herbicide use for SE Eucalyptus plantations

Year	N (kg/ha) (Urea)	P (kg/ha) (Triple Superphosphate)	Herbicide (kg/ha) (Flumioxazin – 100% active)
0	225	200	0.58
1	225	200	None

Final report, publications, and presentations

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Han, Jeongwoo, Christina E. Canter, Hao Cai, Michael Wang, Zhangcai Qin, Jennifer B. Dunn, Richard Gustafson, Stephen S. Kelley, Rodrigo Morales, Elaine E. Oneil, Longwen Ou, Sunkyu Park, Maureen Puettmann, Neethi Rajagopalan, Timothy Volk, and Aaron Weiskittel. 2018. Carbon dynamics for biofuels produced from woody feedstocks, Technical Report #: ANL/ESD-18/10, Argonne National Laboratory, Chicago. IL. 72 pp

Hall, Kevin. 2016 MS Thesis, Assessing and modeling the growth of *Eucalyptus benthamii*in the Southern United States, North Carolina State University

Task 3 of SOPO – LCA of the impacts of using woody biomass as a feedstock for different biochemical and thermochemical biofuels production processes

LCA of Conversion- Biochemical: (University of Washington)

Uncertainty and Sensitivity

Summary

A sensitivity analysis was incorporated into the poplar to ethanol conversion model to understand the influence of the chemical composition of the feedstock and conversion factors on ethanol yields and carbon emissions. Chemical composition of poplar as glucan and lignin content affected directly ethanol yields, and CO_2 emissions during the bioconversion of poplar to ethanol in the ASPEN modeling. More glucan content will yield more ethanol per tonne of feedstock. Lignin influences the production of electricity in the biorefinery which impacts directly in the CO_2 emissions of the system. An uncertainty tool was defined and incorporated into our aspen modeling to understand the probabilities of achieving a base case scenario with values of 275 L of ethanol per tonne of biomass, 17.8 megawatt (MW) net electricity generated, and 5 kg of CO_2 emitted per liter of ethanol.

Sensitivity methods and results

Adapted ASPEN biorefinery model done by NREL (Humbird et al. 2011)[2] was used to develop 8 different scenarios varying glucan (gluc) content, enzymatic hydrolysis (EH) conversion rates, and fermentation (ferm) yields to determine the influence of those factors in ethanol yields, net power and CO_2 emissions (Table 13).

The glucan (gluc) content, enzymatic hydrolysis (EH) and fermentation (ferm) yields influences directly the production of ethanol. The availability of glucan content as well as higher conversion of glucan to glucose via saccharification and better fermentation yields increase the production of ethanol per tonne of biomass. Low lignin content shows higher ethanol yields per tonne of biomass, less excess power and the lowest CO_2 emissions, due to the lignin combustion that is the main contributor to the CO_2 emissions.

[2] Humbird, D. R. Davis, L.Tao, C. Kinchin, D. Hsu, and A. Aden. 2011. Process design and economics for biochemical conversion of lignocellulosic biomass to ethanol – Dilute-acid pretreatment and enzymatic hydrolysis of corn Stover. Technical Report NREL/TP-5100-47764. May 2011. 147pp.

Table 13 Ethanol yields (l/tonne), net power (MW) and CO_2 emissions for the different modeled scenarios.

Scenarios	Gluc content (%)	Liters EtOH/tonne	Net power (MW)	CO2 emissions (Kg/L of EtOH)
Based case scenario	38.5	275	17.8	5.0
Scenario 1	41.5	283	17.0	4.9
Scenario 2	46.5	317	13.5	4.3
	EH conversion	Liters EtOH/tonne	Net power (MW)	CO2 emissions (Kg/L of EtOH)
Based case scenario	0.9	275	17.8	5.0
Scenario 1	0.8	255	20.9	5.6
Scenario 2	0.7	234	23.9	6.2
	Ferm yields	Liters EtOH/tonne	Net power (MW)	CO2 emissions (Kg/L of EtOH)
Based case scenario	0.95	275	17.8	5.0
Scenario 1	0.85	254	20.8	5.6
Scenario 2	0.75	233	23.6	6.2
	Lignin content (%)	Liters EtOH/tonne	Net power (MW)	CO2 emissions (Kg/L of EtOH)
Low lignin (66.4% sugar cont)	18.5	299	10.5	4.4
Based case scenario (60.2% sugar cont)	24.2	275	17.8	5.0
High lignin (51.4% sugar cont)	33.2	230	30.3	6.6

A surrogate modeling approach was selected (Scott et al. 2017)[3] due to the large number of scenarios to include in the simulation (5,000 total). The number of scenarios is selected to produce a reasonable coverage of the three-dimensional space of the variables in the analysis: enzymatic hydrolysis yield, glucose fermentation yield and glucan content (dry basis). In this approach, instead of solving a complete Aspen Plus simulation, in each scenario a surrogated representation of the Aspen Plus flowsheet is solved. The surrogated model was built using mass and energy balances relationships and chemical and thermophysical data from the 2011 NREL biochemical conversion of lignocellulosic biomass to ethanol report (Humbird et al. 2011). Other design considerations and simplifications can be found in Scott et al. (2017).

The surrogate model was used to perform a Monte Carlo analysis calculating the plant ethanol yield in L of ethanol per metric ton of dry poplar biomass, the net electricity production (plant electricity production minus plant consumptions) and the specific CO_2 production (kg of CO_2 emitted per L of ethanol produced), including emissions from the fermentation and distillation scrubbers, aerobic lagoons in wastewater treatment and the emissions from burner (including the CO_2 in the combusted biogas). Each of the 5,000 scenarios represents an instance, this is, a realization of the three random parameters (enzymatic hydrolysis yield, glucose fermentation yield and glucan content) sampled from three triangular distributions defined in (Table 14).

[3] Scott F, Aroca G, Caballero JA, Conejeros R. A generalized disjunctive programming framework for the optimal synthesis and analysis of processes for ethanol production from corn stover. Bioresour Technol 2017;236:212–24. doi:10.1016/j.biortech.2017.03.180.

Table 14 Triangular distribution parameters for the random variables used in the analysis

Parameter	Minimum	Base Scenario	Maximum
Glucan to glucose yield in enzymatic hydrolysis	0.70	0.90	0.95
Glucose to ethanol yield in fermentation	0.75	0.95	0.97
Glucan content in poplar (wt. fraction, dry basis)	0.350	0.385	0.465

The surrogate model was implemented as a system of non-linear equations in GAMS 27.3. Each instance of the problem was solved using the non-linear solver CONOPT 3 using default options. The agreement between the Aspen Plus simulations and the surrogate model was verified by comparing the values of the analyzed variables for extreme instances of the parameter values one at a time (the maximum and minimum values and the base case "peak values" in Table 14). The largest difference between both models was less than 2% for the variables under analysis. Results from the Monte Carlo simulation using 5,000 scenarios defined by combinations of the triangular distributions defined in Table 14 are presented as cumulative distributions and relative frequency distributions in Figure 16.

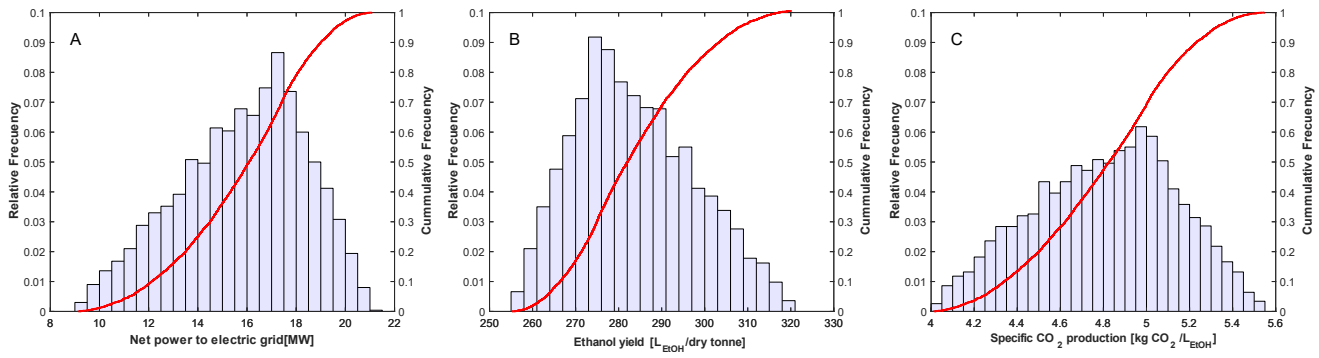

Figure 16 Cumulative (red solid line) and relative frequency (bars) distribution of enzymatic hydrolysis yields, plant ethanol yield and specific CO2 production under the 5,000 Monte Carlo scenarios.

The analysis reveals that, under the assumed triangular distributions of the random parameters, the probabilities of achieving or surpassing the base case scenario values of 17.8 MW of net electricity production and 275 L tonne^{-1} of ethanol yield are 23.8% and 70.1%, respectively. Regarding the specific CO_2 production, there is a 69.2% probability of attaining a value lower or equal than 5.0 kg CO_2/L_{EtOH}

LCA Comparison of Short Rotation Woody Crops to Ethanol

Summary

The bioconversion processes were modeled with an Aspen simulation which estimates an overall conversion yield of 303, 275 and 282 liters of ethanol per tonne of feedstock for willow, hybrid poplar, and eucalyptus. Greenhouse gases, regulated emissions, and energy use in transportation (GREET) is used to model combustion of ethanol from each woody crop in an ethanol dedicated car. All necessary chemicals, transportation, and processes required by each bioconversion process are included within the LCAs. The impacts of bioconversion produced ethanol are compared with those of gasoline on an equivalent energy basis. Results of the LCA show that the life-cycle global warming potential (GWP) of

ethanol is slightly negative for willow and hybrid poplar. Carbon emissions from ethanol production and use are balanced by carbon absorption in the growing willow feedstock and the displacement of fossil fuel produced electricity with renewable electricity produced in the bioconversion process. The fossil fuel input required for producing 1 megajoule (MJ) of energy from ethanol were willow, hybrid poplar, and eucalyptus; 70, 101 and 105 percent less than that from gasoline respectively.

System boundaries for the study arise from the establishment of the site for SRWC production to the combustion of the ethanol product. The product stages in this life cycle are feedstock production and harvesting, transport to biorefinery, the bioconversion process, ancillary chemicals, avoided production, and fuel use. Modules were developed in SimaPro v.7.3.0 (PRé Consultants 2011) using the US LCI (NREL 2011) and EcoInvent (Swiss Centre for Life Cycle Inventories [SCLCI] 2009) databases for materials and processes that were not user generated. EcoInvent was used only when no appropriate data were available from the US LCI. Biochemical conversion was modeled using Aspen Plus. Willow, hybrid poplar, and eucalyptus growth and harvesting data were provided by Tim Volk (ESF), Greenwood Resources, and Steve Kelley (NCSU).

In this study the functional unit used is 1 mega joule (MJ). Using a unit of energy is a common practice in biofuel LCAs as it allows for the comparison of different types of fuels regardless of their respective energy densities. The energy densities for ethanol and gasoline were assumed to be 29.6 MJ/kg and 47.9 MJ/kg, respectively.

The net GWP values as well as the contributions from each area from biomass growth, ethanol bioconversion and ethanol use in a dedicated car are shown in Figure 17 for willow, hybrid poplar, eucalyptus and gasoline. A net of GWP of 27 grams per MJ was estimated for the conversion of willow. Both hybrid poplar and willow showed a negative net value of 1 and 5 grams respectively. A net reduction of 70%, 101% and 105% in GWP per MJ of fuel were observed to gasoline for willow, hybrid poplar, and eucalyptus respectively. For all the SRWC, the main contributors to the GWP are the biorefinery and ethanol use. In the biorefinery, CO_2 is emitted during combustion of lignin to produce steam, fermentation and enzymes production vents, distillation and decomposition of organic matter in the wastewater treatment. Combustion of ethanol in a dedicated car produces CO_2 and other GHG. Both biorefinery and fuel use CO_2 emissions were originated from the different trees analyzed (biogenic sources). Carbon dioxide stored as carbon in the harvested wood offset the CO_2 emissions produced during the bioethanol life cycle.

Biomass growth and harvesting is only responsible for 6%, 7% and 3% of total GWP per MJ for willow, hybrid poplar, eucalyptus. Most of these emissions are related with diesel involved during machinery usage for crop harvesting, herbicide and fertilizers manufacturing. Avoided production of electricity which displaced electricity generated by natural gas in the US, resulted in a small GWP credit ranging from 16 to 23 gram per MJ of fuel, representing in average 7% of the total GWP credits.

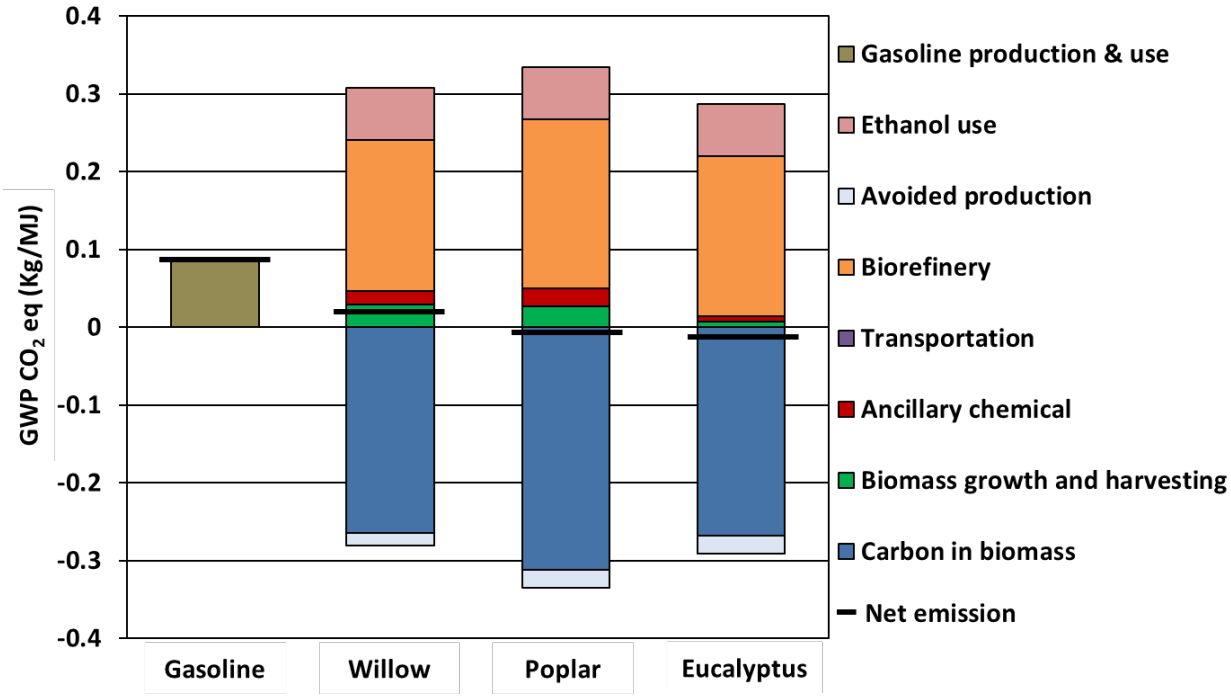

Figure 17 Global warming potential of SRWC and gasoline per MJ of fuel.

As expected, all the SRWC analyzed in this research to produce ethanol via bioconversion showed a better environmental performance when compared to conventional gasoline, with GWP reductions ranging from 70 to 105%. Significant carbon sequestration by fast-growing feedstock and the displacement of fossil fuel electricity generated on the national grid are the largest contributors to ethanol's low carbon footprint. Eucalyptus was the SRWC that presented the lowest negative net value emission followed by hybrid poplar. Willow showed a slightly positive net emission, however willow-based ethanol could be considered virtually carbon neutral.

The detailed LCI of this study was delivered to ANL for inclusion in their GREET models. A technical report entitled "Carbon dynamics for biofuels produced from woody feedstocks" was published in 2018 by ANL (Han et al. 2018).

Final report, publications, and presentations

View or download in the Publications and Presentation sections of this report.

Han, Jeongwoo, Christina E. Canter, Hao Cai, Michael Wang, Zhangcai Qin, Jennifer B. Dunn, Richard Gustafson, Stephen S. Kelley, Rodrigo Morales, Elaine E. Oneil, Longwen Ou, Sunkyu Park, Maureen Puettmann, Neethi Rajagopalan, Timothy Volk, and Aaron Weiskittel. 2018. Carbon dynamics for biofuels produced from woody feedstocks, Technical Report #: ANL/ESD-18/10, Argonne National Laboratory, Chicago. IL. 72 pp

LCA of Poplar to Ethanol Production Using Short Rotation Coppice Silviculture. Rodrigo Morales (presenter) and Rick Gustafson. Forest Products Society International Conference. June 2018. Madison, WI. USA.

Morales-Vera, R., M. Puettmann, T. Volk, S. Kelley, and R. Gustafson. 2020. Life cycle assessment of short rotation woody crops for production of bioethanol. The case of Eucalyptus, Willow, and Poplar grown in USA. *Environmental Science and Technology* (in preparation).

LCA of Conversion – Thermochemical (North Carolina State University)

Summary

The DOE as invested heavily in ASPEN engineering process models, and this work leveraged that investment, and also made substantial improvements. This project, and a related DOE project (*Next Generation Logistics Systems for Delivering Optimal Biomass Feedstocks to Biorefining Industries in the Southeastern US*) both invested in an improved ASPEN engineering process model that was sensitive to the moisture content and composition of the biomass feedstock, e.g., the ash content and carbon content. This improved model then allowed this project to determine the relationship between the composition of the different woody feedstocks, and the production of the final hydrocarbon fuel. This modified process model was able to 1.) separately track both the biogenic and fossil carbon, 2.) relate the moisture content to the overall heat balance of the biorefinery, and 3.) correlate the ash content of the biomass with the yield of bio-oil and the associated demand for hydrogen for the reforming reaction.

The compositionally sensitive ASPEN process model is a gate-to-gate model for the biorefinery and is shown schematically in Figure 18. This model is intentionally structured to be 'independent' of the sources of the biomass, e.g., it can be used for softwoods, SWRCs or even crop residues, and is focused on the composition of the biomass.

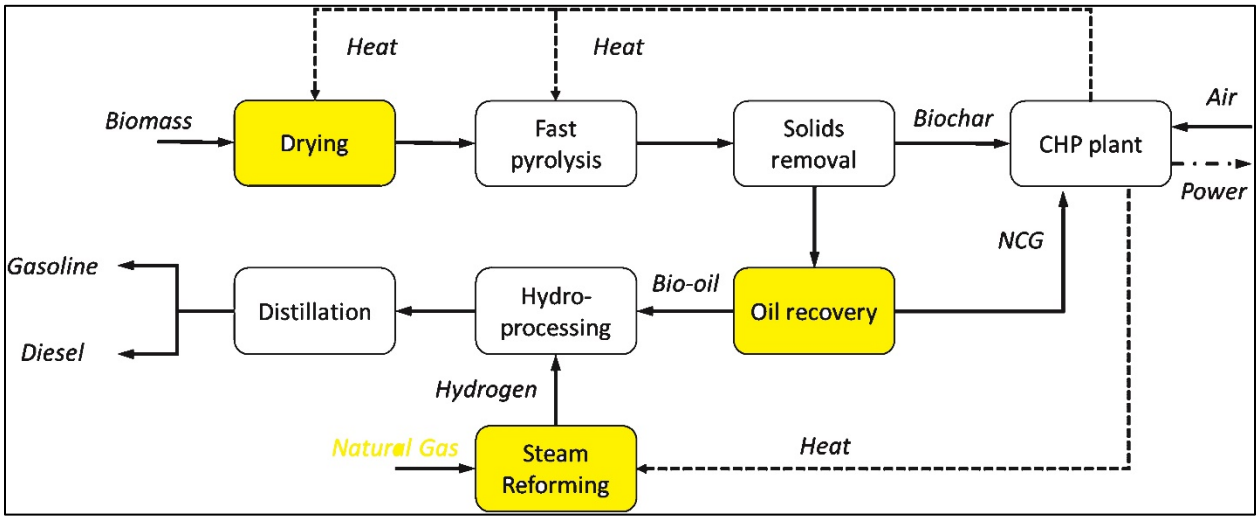

Figure 18 A schematic of the major unit operations of the ASPEN thermochemical process model. This model is based on the PNNL process model, with the highlighted blocks updated to make the model sensitive to the moisture content, and ash and carbon content of the

It is important to note this process model includes the demand for natural gas used in the hydroprocessing/reforming as it is impacted by the yield of intermediate bio-oil. In addition, this model uses system expansion to include the co-production of electricity generated by the combustion of several biorefinery waste streams.

Final report, publications, and presentations

View or download in the Publications and Presentation sections of this report.

Lan K., L. Ou, S. Park, S.S. Kelley, and Y. Yao 2019. Life cycle analysis of decentralized preprocessing systems for fast pyrolysis biorefineries with blended feedstock in the southeastern United States. Energy and Technology, early access, doi.org/10.1002/ente.201900850

Ou L., H. Kim, S.S. Kelley, and S. Park. 2018. Impacts of feedstock properties on the process economics of fast pyrolysis biorefineries, BioFPR, 12(3), 442-452

Aizpurua, Carlos Ernesto. 2016. Process Simulation and Techno-Economic Evaluation of Alternative Biorefinery Scenarios. NCSU PhD Dissertation, 2016

Introduction of Bioenergy Systems in the US. Ou L., H. Kim, S. Park, S.S. Kelley. Tampere Applied Sciences University (TAMK), Tampere Finland, Sept 20, 2016

Life Cycle Analysis of Forest Carbon Sinks. Ou L., H. Kim, S. Park, S.S. Kelley. T3 Consortium meeting, Tampere, Finland, Oct. 13, 2016

Introduction of Bioenergy Systems in the US. Ou L., H. Kim, S. Park, S.S. Kelley. JAMK, Jyvaskyla, Finland, Nov. 12, 2016

LCA of Conversion – Pyrolysis (North Carolina State University)

Summary

Working with the GREET team, the LCI data for the three commercial softwoods were combined with the process model and incorporated in the GREET analysis for the GHG per MJ of fuel. This analysis showed that slow growth rates and low of levels forest residues significantly increases the biomass transportation for the NE forest. While the PNW Douglas fir growth rate is faster and can capture significant amounts of carbon, in many cases the most common forest management practices do not include precommercial thinning which limits the total mass of carbon can be delivered to the biorefinery. For a biorefinery with a fixed size, (e.g., 2,000 OD tons per day) this lack of readily available mass increases the transportation distances for the biomass supply beyond an economic recovery radius. The southern pine plantations, with available precommercial thinning and forest residues, were able to deliver more biomass in close proximity to the biorefinery. This has both LCA and financial advantages. As discussed below, all three of the softwoods have very similar ash and carbon contents, and in all cases the moisture content can be managed within a large range. The details of these variations are discussed in detail in Task 4.

Final report, publications, and presentations

View or download in the Publications and Presentation sections of this report.

Lan, K., L. Ou, S. Park, S.S. Kelley, and Y. Yao 2019. Life cycle analysis of decentralized preprocessing systems for fast pyrolysis biorefineries with blended feedstock in the southeastern United States. Energy and Technology, early access, doi.org/10.1002/ente.201900850

Ou L., H. Kim, S.S. Kelley, and S. Park. 2018. Impacts of feedstock properties on the process economics of fast pyrolysis biorefineries, BioFPR, 12(3), 442-452

Aizpurua, Carlos Ernesto, Process Simulation and Techno-Economic Evaluation of Alternative Biorefinery Scenarios. NCSU PhD Dissertation, 2016

Introduction of Bioenergy Systems in the US. Ou L., H. Kim, S. Park, S.S. Kelley. Tampere Applied Sciences University (TAMK), Tampere Finland, Sept 20, 2016

Life Cycle Analysis of Forest Carbon Sinks. Ou L., H. Kim, S. Park, S.S. Kelley. T3 Consortium meeting, Tampere, Finland, Oct. 13, 2016

Introduction of Bioenergy Systems in the US. Ou L., H. Kim, S. Park, S.S. Kelley. JAMK, Jyvaskyla, Finland, Nov. 12, 2016

Task 4 of SOPO – An Analysis of the Impacts of Natural Variations in Wood Composition and Production Scenarios on the LCA of Wood Based Biofuels

Summary

The ASPEN Model developed in **Task 3** for the thermochemical production of intermediate bio-oil and the final hydrocarbon fuel was then used to assess the effects of variations in the quality of the feedstock.

It is important to note this process model includes the demand for natural gas used in the hydroprocessing/reforming as it is impacted by the yield of intermediate bio-oil. In addition, this model uses system expansion to include the co-production of electricity generated by the combustion of several biorefinery waste streams.

At total of 64 cases of moisture content, ash content, and carbon content were modeled. In all cases demand for natural gas in hydroprocessing, and the co-production of electricity were tracked. An example of these interactions is shown in Table 15.

Table 15 A subset of the results from the ASPEN modeling that shows the impact of changes in the feedstock carbon, ash content, and moisture content. The impact of these feedstock variables, the yield of the final biofuel product, the natural gas demand for the reforming process, and the co-production of electricity from the combustion of the residue streams are detailed.

Carbon (%)	Ash (%)	Moisture (%)	Gasoline yield (MM liter/yr)	Diesel yield (MM liter/yr)	NG usage (kg/hr)	Net power (MW) *	TCI (MM$)	MFSP ($/L)
44	3	35	86.04	86.94	9603	10.0	595	1.08
46	3	35	84.22	87.92	9618	15.5	598	1.07
48	3	35	81.96	88.95	9779	21.3	601	1.06
50	3	35	79.91	89.96	9859	26.9	604	1.05
46	**1**	35	97.56	96.55	10978	10.4	620	1.00
46	**3**	35	84.22	87.92	9618	15.5	598	1.07
46	**5**	35	85.63	79.17	9122	17.1	588	1.09
46	**7**	35	88.98	72.82	8661	17.8	581	1.10
46	3	**15**	84.22	87.92	9618	24.6	598	1.04
46	3	**25**	84.21	87.92	9618	20.6	598	1.05
46	3	**35**	84.22	87.92	9618	15.5	598	1.07
46	3	**45**	84.22	87.91	9618	8.6	598	1.09

It is important to note the complex interactions between the quality of the woody feedstock and the outputs from the biorefinery. Decreasing the moisture content of the delivered biomass has a significant impact on the overall heat balance for the biorefinery. Specifically, lower moisture content increases the amount of electricity generated in the biorefinery. However, changing the moisture content does not change the bio-oil production or hydrotreating conditions.

Increasing the ash content of the biomass decreases the bio-oil yield, while increasing the yield of char and pyrolysis gases. Decreasing the bio-oil production also decreases the natural gas usage since there is less hydrogen needed for hydrotreating the intermediate bio-oil. With the higher yield of char and gas there is an increase in the residues, and thus and increase in the electrical power production.

Increasing the carbon content of the woody biomass results in a counter-intuitive decrease in the bio-oil yield. This is due to an increase in char forming reactions with increasing biomass carbon. Thus, there is a decrease the natural gas (hydrogen) needed for hydrotreating. With the higher char and gas yields there is an increase in the biorefinery residues, and corresponding increase in the electrical power production.

Final report, publications, and presentations

View or download in the Publications and Presentation sections of this report.

Lan K., L. Ou, S. Park, S.S. Kelley, and Y. Yao 2019. Life cycle analysis of decentralized preprocessing systems for fast pyrolysis biorefineries with blended feedstock in the southeastern United States. Energy and Technology, early access, doi.org/10.1002/ente.201900850

Ou L., H. Kim, S.S. Kelley, and S. Park. 2018. Impacts of feedstock properties on the process economics of fast pyrolysis biorefineries, BioFPR, 12(3), 442-452

Scouse A., K. Lan, P. Nepal, Y. Yao, S. Kelley. 2019. The influence of forestry practices, manufacturing variables, and end-of-life decisions on softwood lumber CO_2 emissions (submitted to Forest Policy and Economics)

Edmunds C.W., N. André, C. Hamilton, E. Molina Reyes, S. Park, S.S. Kelley, O. Fasina, S. Adhikari, J. Tumuluru Shankar, T.G. Rials, and N. Labbé. 2018. Blended Feedstocks for Thermochemical Conversion: Biomass Characterization and Bio-Oil Production from Switchgrass-Pine Residue Blends, Frontiers in Energy Research, vol 6, UNSP 79

Ren X., J. Meng, J. Chang, S.S. Kelley, H. Jameel, H., and S. Park. 2017. Effect of blending ratio of pine wood and bark on the properties of pyrolysis bio-oils, Fuel Processing Technology, 167, pg. 43

Process simulation of fast pyrolysis into transportation fuels: Model sensitive to variations in biomass chemical composition, Aizpurua C., J. Kim, H. Jameel, S. Park, S.S. Kelley. ACS annual meeting, 249, Denver, CO, March 22, 2016

Optimization of financial, environmental and social attributes in a biorefinery. Aizpurua C., J. Daystar, T. Hays, H. Kim, R. Radics, N. Rajagopalan, C. Reeb, E. Reyes, L. Xiao, R. Gonzalez, S. Park, R. Venditti, and S. Kelley. November 17, 2016. IFM^{2}E.

Effects of biomass composition on the economics and life cycle impacts of bio-oil biorefinery. Longwen Ou, Hoyong Kim, Maria Herrera, Yuan Yao, Sunkyu Park and Stephen S. Kelley (presenter). 2018. Forest Products Society Annual Meeting, Madison WI June 11-14, 2018

Task 5 of SOPO - an analysis of the carbon storage implications of using woody feedstocks for the production of both biofuels and the current commercial suite of short-lived and durable wood products.

Regional Scale Analysis (North Carolina State University)

Summary

The implications of allocating woody biomass to DWP or biofuels is complex since there are large regional variation that dictate the potential volumes. For this work it was assumed that biofuels could not 'compete' on a costs basis for the wood that goes to solid wood products. It was also assume assumed that the pre-commercial thinning residues and forest residues from DWP harvest were all allocated to biofuels. Mill residues were analyzed in two alternative cases, 1.) to the biofuel, or 2.) to a durable wood product such as particleboard or medium density fiberboard. The process is shown schematically in Figure 19.

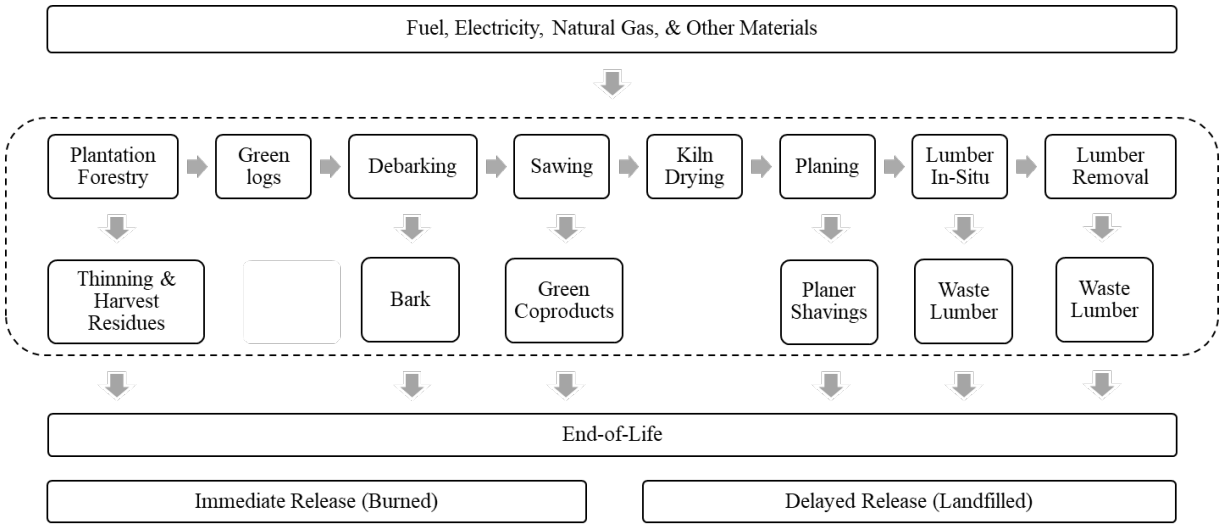

Figure 19 Schematic of the cradle to grave flows for southern pine plantation forestry.

Plantation establishment and management both have a significant impact on the volumes of woody biomass available for these two processes. As highlighted by the work outlined in Task 1C there are large variations in the total amount of southern pine biomass, and subsequently large variations in the amount available for DWP and biofuels. These differences are shown for the case used in the Task 5 in Figure 20.

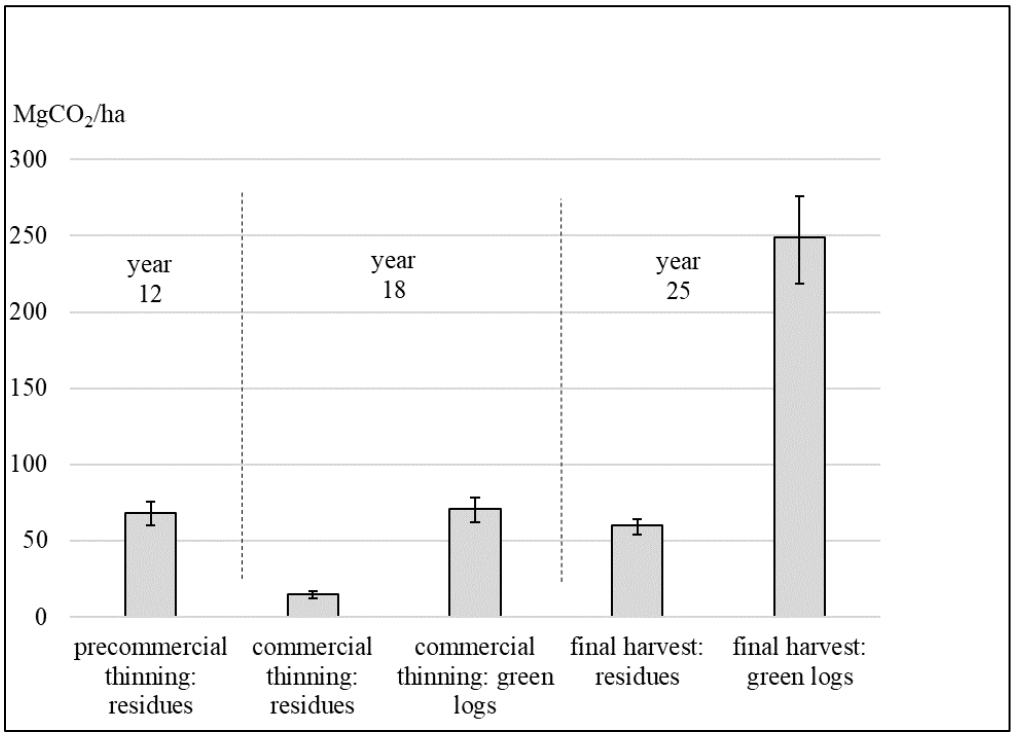

Figure 20 Relative amounts of southern pine plantation biomass (measured in Mg CO_2/ha) available for DWP and biofuels. The error bars are an indication of natural variation for a single plantation management regime.

Using the process diagram in Figure 19 and the southern pine plantation forest management outlined in Figure 20, the immediate and delayed carbon emissions can be tracked. Examples of the carbon flows for a cubic meter of DWP is shown in Figure 21.

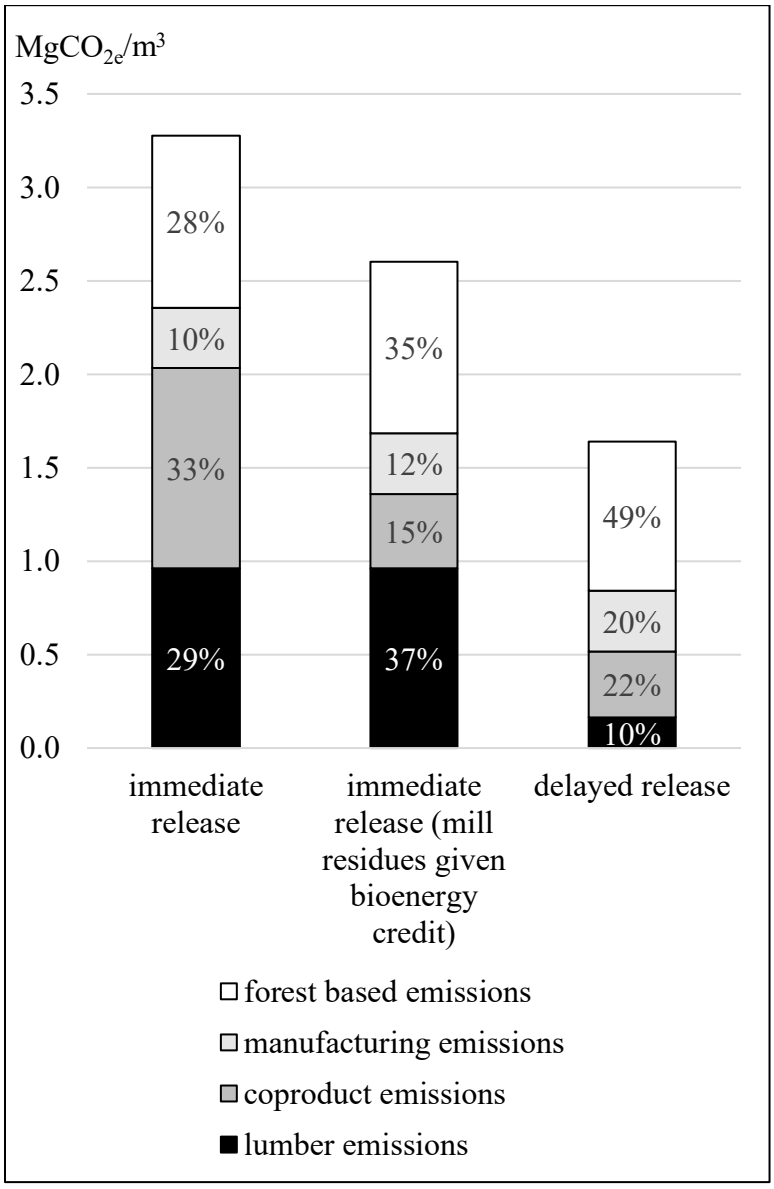

Figure 21 Carbon emissions for three alternative biomass allocation scenarios. Immediate release maximizes bioenergy production, while delayed release allocates mill residues to DWP instead on biofuel.

Final report, publications, and presentations

View or download in the Publications and Presentation sections of this report.

Scouse, A., K. Lan, P. Nepal, Y. Yao, S. Kelley. 2019. The influence of forestry practices, manufacturing variables, and end-of-life decisions on softwood lumber CO2 emissions (submitted to Forest Policy and Economics)

Modeling silvicultural and process variation and its influence of life-cycle carbon emissions for durable wood products. Scouse, A. (presenter), K. Lan, P. Nepal, Y. Yao, S. Kelley. International Society of Wood Science and Technology Annual Convention. Yosemite, CA, 2019

Hierarchies of wood use (Lippke and Associates, WoodLife Environmental Consultants, and Elaine Oneil)

Summary

Carbon emissions can be compared across products and materials, production processes, and end-uses. Life cycle inventory and life cycle impact assessment (LCI/LCIA) data measures all the inputs and outputs across all life cycle stages important to carbon mitigation strategies and policies. The Consortium for Research on Renewable Industrial Materials has recently updated primary survey data on life cycle measurements for many wood products and processes that were first collected in 2000. Energy consumption in processing mills has increased up to 66% largely because of broad adoption of environmental control devices (ECD) to reduce non-carbon emissions such as particulate matter. Biofuel use has also increased, offsetting most fossil fuel increases. This report reviews the impact on emissions across each stage of production and end-of-product-life, providing critical information on how and why wood use can more efficiently reduce fossil carbon emissions and consequently carbon in the atmosphere-- thus reducing GWP. This report updates the many ways to improve CO_2 emissions reductions by both using wood to displace fossil-intensive products as well as store more carbon in wood products for extended periods.

The updated hierarchy of wood use efficiencies for reducing CO_2 emissions results in a range from 0.2 (20% efficient use of wood to displace and store carbon**)** for displacing some products or fuels, to 4.0 (400%), a high leverage carbon negative technology. The interaction of many different processes and products reveals many complexities that, if not understood, contribute to unintended consequences which are counterproductive to carbon mitigation objectives.

This analysis describes a suite of examples to demonstrate the hierarchy of uses of wood resources. It includes durable wood products (DWP) that substitute for non-wood products, and biofuels that substitute for fossil fuel alternatives. The analysis provides clarity on how to obtain the highest possible efficiency in the displacement of fossil carbon emissions and to increase the long-term storage of carbon removed from the atmosphere. ***The primary focus is on the joint production of wood products, co-products, and biofuels recovered from sustainably managed forests.*** We present examples of alternative wood uses to highlight comparative outcomes and alternative scenarios to illustrate the impact of the changes in LCI data over time. A subset of results is listed here, the full results can be found in (Lippke et al. 2019, Puettmann 2019).

Integrated Carbon Impacts

Forest Carbon from Unmanaged Forests and Sustainably Managed Forests –

The importance of managed forests relative to atmospheric CO2 emission reductions derives from the relatively large amount of carbon dioxide removed from the atmosphere through photosynthesis which is then stored in the trees. While the rotation for growing trees for the best economic return varies with site productivity and climate, as forests age they grow more slowly, which translates into removing less CO_2 from the atmosphere per unit of land. As forests age some trees die from overcrowding thus releasing CO_2 through decay, while other trees grow larger.

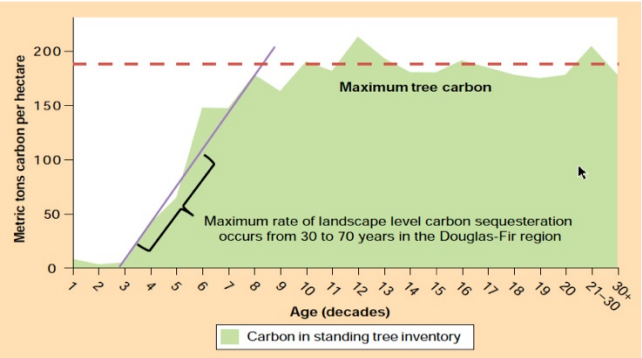

Figure 22 Forest carbon growth rates decrease with age in Western Washington (From US Forest Service Forest Inventory & Analysis inventory plot data, Bolsinger et al. 1997)

These changes in forest stand structure are driven by the site carrying capacity which creates an upper limit in forest carbon stores per unit of land (Figure 22)[4] referred to as saturation or senescence (Smith et al. 2014).

Removals allocated to short and long-lived products and the use of residuals

From Puettmann "Life cycle assessment can improve decisions to optimize wood residue use (white paper)": Historically, coproducts are sold as feedstock for pulp and paper or for wood panel products such as medium density fiberboard (MDF), particleboard (PB), and hardboard. Recent surveys of wood industries estimate the softwood residue demand at 8.6 million BDT per year. In addition, softwood lumber producers use about 3.8 million BDT per year of coproduct for energy. This self-generated biofuel not only comes at a low environmental and economic cost but is a direct substitution of fossil fuels with a direct reduction in carbon emissions. Recent surveys found that 22 percent of wood residues generated during lumber production in the PNW were used for onsite energy, a direct displacement of fossil fuels (Figure 23). The remaining 78 percent could be used for pulp and paper, wood composite panels (WCP), or for conversion to energy products such as ethanol.

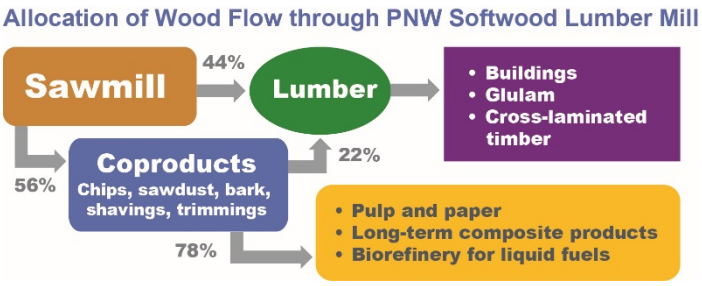

Figure 23 Flow of wood material through a PNW sawmill (Milota 2015)

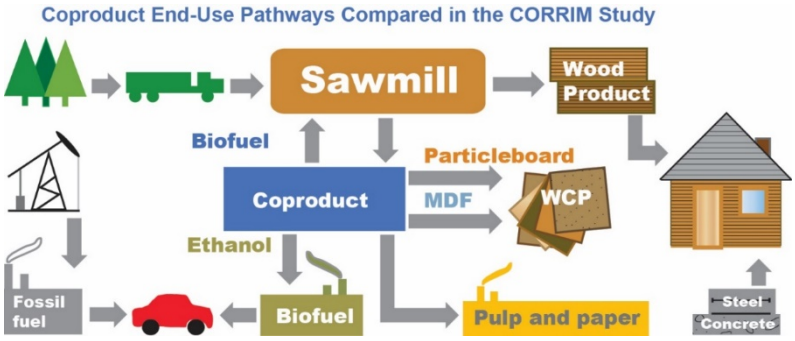

Figure 24 Biomass pathways generated in a sawmill

[4] Bolsinger C., N McKay, D Gedney, C Alerich C. 1997. Washington's Public and Private Forests. Resource Bulletin. PNW-RB-218, Portland, OR: USDA Forest Service. Pacific Northwest Research Station

Life cycle assessment methodologies were used to determine the carbon impacts of using wood residues for producing WCP or ethanol (Figure 22). Full results show the "best pathway" for optimal carbon mitigation (Figure 24) (Puettmann 2019).

- It is up to 50% more efficient (mass of feedstock to mass of product) to use wood residues to produce WCP than ethanol (Figure 25).
- Less carbon is emitted during the production and use of WCP than of ethanol for biofuel.
- Using residues for WCP and not for ethanol for biofuel provides the greatest displacement of carbon emissions (Table 16).

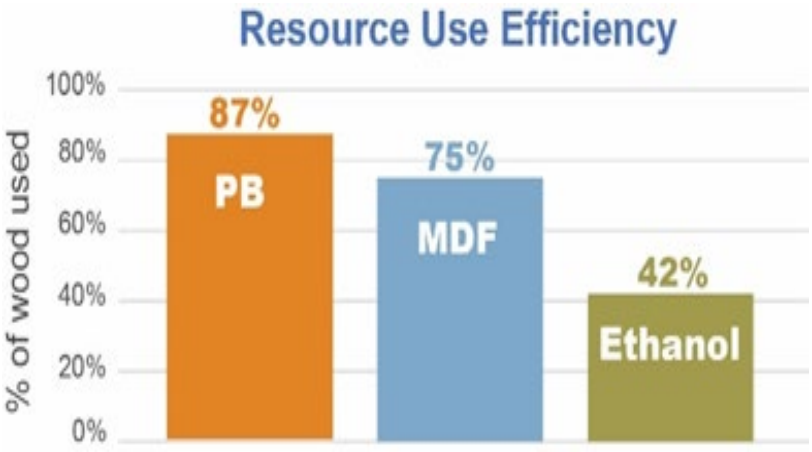

Figure 25 Efficiency use based on wood inputs into production of particleboard, medium density fiberboard, and ethanol

Table 16 Carbon displacement efficiencies for comparison between wood composite products and ethanol and ethanol and gasoline

Carbon Emissions Displaced: Carbon Stored in Product		
	Displacement (carbon NOT emitted), kg C emission / kg of wood fiber used	
	If wood residues are used for WCP and not for ethanol	If ethanol from wood residues is used in place of fossil fuels
Particleboard: Ethanol	7.80	
MDF: Ethanol	5.15	
Ethanol: Gasoline		0.43

Carbon stores and Displacement from Substituting wood for non-wood materials

Including a substitution parameter that accounts for the differential in emissions from using wood in place of non-wood products like steel and concrete (Table 17), raises the total carbon stored and displaced to 3.06 Ct/h/yr, or more than 100% better than no substitution. The substitution parameter used in this

example is from a broad meta-analysis of substitution impact studies from Sathre and O Connor (2010)[5] as they found an average benefit in carbon reductions from using wood in place of other fossil intensive products of 2 units of carbon displaced and stored for every unit of wood used. The 50% increase in energy to support ECD's has little impact on total carbon stored per hectare when the increased energy is derived from forest residuals (Table 17{b}). However, the carbon stored from using forest residuals is 10.5% higher than diverting energy from co-product production (Table 17{c}). Similarly, it is 4% better than by using natural gas {Table 17{d}).

Table 17 Trendline of Net Carbon displaced and stored with substitution- - Sensitivity Analysis

	t C/hectare/year
(a) Total product carbon trend growth with historic fuel use and mix	3.06
(b) 50% Energy increase from an increase in forest or mill residual feedstock	3.07
(c) 50% Energy increase redirecting feedstock away from co-products	2.78
(d) 50% Energy increase by using natural gas instead	2.95

EXAMPLE: Component Substitution of the Efficiency of using wood to displace CO2 in fossil intensive fuels and building products –

A typical use of a wood component in residential structures is to substitute wood studs and/or floor joists for steel studs or joists. Steel floor joist per m^2 of floor = net floor joist production of GWP 42.3 kg CO_2 eq + CO_2 stored in wood products (32.3 kg CO_2) reduced by GWP fossil emissions from wood production (2.3kg CO_2) = 72.3 kg CO_2 displaced and stored as the output; divided by 32.3 kg CO_2 in the wood product used = 2.24 efficiency of Carbon displaced & stored per unit of carbon in the wood product used (Table 18).

The high efficiency results from the fact that solid wood fiber can displace fossil intensive products while also storing carbon. The use of biofuel for the energy to produce wood products has a much lower leverage to displace a fossil fuel such as 0.7 C units of natural gas per 1.0 unit of C in the biofuel fiber used (Lippke et al. 2012). In contrast to 2.24 efficiency from steel floor joists, when not including biofuel, the efficiency drops to 1.78 when the much lower valued biofuel is included.

Table 18 Efficiency of carbon displacement & net carbon store per unit of carbon in the wood used in a square meter of floor

	t C displaced & stored per C in wood used
a. Valuing biofuel as a zero valued waste:	2.24
b. Valuing biofuel the same as product carbon	1.78
c. Eliminate biofuel by substituting natural gas.	2.13
d. Using biofuel feedstock for co-products with 2:1 meta average displacement	2.4

[5] Sathre, R., J. O'Connor. 2010. Meta-analysis of greenhouse gas displacement factors for wood product Substitution. *Environ. Sci. Policy* 13:104-114.

Emission displacement information to improve carbon mitigation and avoid unintended impacts

It is important to understand the wide range of efficiencies with each different use of wood to displace fossil intensive product emissions while also storing carbon in products. Clearly when a wood is in use as a DWP it is no longer available for other uses during its useful life but may be collected and reprocessed after its first life cycle in a system of cascading uses. Woody feedstock may be equally suitable for solid wood co-products like composite panels and biofuel inputs. But composite panels have much higher displacement efficiencies than biofuel energy, and can have cascading uses, including for bioenergy once their useful life is over. Carbon efficiency in terms of carbon stored and displaced per unit of carbon in the wood used are displayed in Table 19 for wood wall components and Table 20 for floor components as calculated from life cycle data.

Table 19 Wood wall stud efficiency to store carbon & displace steel stud or concrete block

Net CO2 emissions displaced per wood product fiber used			+ biofuel used
SE Steel Stud	SE KD Wood Stud	1.87	1.39
SE Concrete Blocks	SE KD Wood Stud	2.39	1.77
PNW Steel Stud	PNW KD Wood Stud	1.93	1.54
PNW Concrete Blocks	PNW KD Wood Stud	2.46	1.97
PNW Concrete Blocks	CLT-Oregon	1.02	0.84

Table 20 Wood floor dimension joist or I-joist efficiency to displace steel joist or concrete slab

Net CO2 emissions displaced per wood product fiber used			+ biofuel used
SE Steel joist	SE Dimension joist	2.11	1.56
SE Steel joist	SE Wood I joist	2.79	2.15
SE concrete slab	SE Wood I joist	2.24	1.72
SE concrete slab	SE Dimension joist	1.79	1.33
SE Wood I joist	SE Dimension joist	0.52	0.38
PNW Steel Joist	PNW Dimension Joist	2.24	1.79
PNW Steel Joist	PNW Wood I joist	2.95	1.77
PNW Concrete slab	PNW Wood I joist	2.36	1.77
PNW Concrete slab	PNW Dimension Joist	1.89	1.51
PNW Wood I joist	PNW Dimension Joist	0.48	0.38

The PNW kiln dried wood stud component displacing a PNW steel stud component displaces 1.54 units of carbon for every unit of carbon in the wood stud used including the biofuel it used (Table 19). The efficiency per unit of carbon in the wood stud only is 1.93, 25% higher. By comparison, the SE wood stud component efficiency at displacing the SE steel stud is about 1.39, or 1.88 based on the carbon in the wood stud only, or 35% higher. More biofuel is used in the SE wood production resulting in slightly lower efficiency than the PNW when the biofuel carbon is included.

Cross laminated timber (CLT) is more like a wall assembly than a component so comparative analysis of CLT is to other wall assemblies. Table 21 shows that CLT is less efficient than other wood-based wall assemblies, largely because it uses much more wood and much more energy in production. However, it

still shows a positive displacement of 1 unit of carbon for every unit of carbon in the wood used when displacing a concrete block wall. While CLT provides a future opportunity to displace concrete and steel in high rise buildings under new building codes, using it in low rise residential buildings results in lower efficiencies than traditional wood uses.

EXAMPLE: Construction Assembly Substitution

The PNW wood stud and plywood sheathing wall displacing a steel stud with similar sheathing provides a 1.17 efficiency of displacement relative to the wood-product fiber used (Table 21). The additions of plywood in both the carbon stored output and wood carbon input lowers the efficiency relative to single component comparisons. As the non-wood share of products approaches zero the efficiency ratio converges to just less than 1.0 as the net carbon stored is slightly less than the carbon in the wood used to offset the emissions from wood product manufacturing.

Table 21 Efficiency of wall assemblies per product fiber used

Wall Assemblies (components + hardware + coverings)		
Net CO2 emissions displaced per wood product fiber used		
PNW: Steel Stud + OSB	PNW Wood Stud + OSB	1.04
PNW: Steel Stud + Ply	PNW Wood Stud + Ply	1.17
PNW: Steel Stud + Ply	CLT + Gypsum	0.95
PNW: Concrete Block Gypsum	PNW Wood Stud + OSB	3.60
PNW: Concrete Block Gypsum	PNW Wood Stud + Ply	3.94
PNW: Concrete Block Gypsum	CLT + Gypsum	1.38
SE: Steel Stud + OSB	SE Wood Stud + OSB	1.04
SE: Steel Stud + Ply	SE Wood Stud + Ply	1.13
SE: Concrete Block Gypsum	SE Wood Stud + OSB	1.89
SE: Concrete Block Gypsum	SE Wood Stud + Ply	1.93

Comparing a PNW wood stud and plywood wall to a concrete block wall results in a much higher efficiency (3.94) because the concrete wall assembly in the PNW must meet west-coast seismic codes that demand much stronger materials. Without a seismic requirement in the building code in the SE the efficiency of displacement is only 1.93 or about half of the efficiency in the PNW.

Using CLT for multiple storied buildings, which can displace steel and concrete assemblies in non-residential high-rise buildings, is now being allowed with updated building codes. This provides a significant new opportunity for CLT wood assemblies to displace non-wood assemblies. However, if used only in conventional low-rise residential walls it can be less efficient in carbon displacement. This comparative analysis does not consider the plethora of potential applications in high rise buildings that use more steel and concrete, nor a potentially longer product life for a CLT wall due to easier re-use, disassembly and reassembly in a second life building application. Hybrid assemblies may include more steel components than wood in which case the wood can serve an additional function of reducing the overall amount of steel and concrete emissions. Laurent et al. (2018)[6] demonstrated that using more wood even when less than the amount of steel used, reduced carbon emission 40%.

[6] Laurent, Achille-B., Yvonne van der Meer, Claude Villeneuve. 2018. Comparative Life Cycle Carbon Footprint of Non-Residential Steel and Wooden Building Structures. *Current Trends Forest Research* Vol. 2018 Issue 4:1-10

One can expect many innovations in how the CLT wall will be used given it is just at the beginning of a technology driven growth curve. However, using it to displace primarily wood residential walls in not as efficient as conventional residential wood frame walls.

Cradle to Grave considerations (end of 1st product life disposition including re-use, reprocessing, recovery for biofuel use, and landfill decomposition alternatives)

The same kind of efficiencies to displace carbon emissions are relevant to end of life alternatives. In a circular carbon economy construct, wood may be reused such that the product remains in service across several harvest cycles providing continued displacement of fossil carbon and embodied carbon storage. Some products may be directly reused without additional reprocessing energy, though such high-quality demolition wood from recycling may be very limited. In the future CLT may provide such opportunities.

Lippke and Puettmann (2013)[7] provided carbon impact estimates of product reuse, recovery and reprocessing, or biofuel displacement of natural gas, and landfill management options. Re-processing reduced the 2nd life yield of long-lived products relative to the first life, increased the energy used, and reduced the biofuel available relative to first life. The rate of substitution was also reduced by the reduction in product yield resulting in a 44% increase over the initial first life baseline trend.

A futuristic scenario with a more likely rate of wood recovery and reprocessing of 40% instead of 100%, and the use of 100% natural gas for reprocessing assuming a lack of biofuel available to reprocessing plants, still results in sustained growth in carbon pools of 4.15 tons C/ha/year (Figure 26). Primary assumptions included using updated LCI data with increased biofuel to provide energy for ECD but no sustained benefit from feedstock for paper or other co-products. This provided a 36% increase in carbon pool growth from 40% wood product recovery for reprocessing relative to no product recovery. See Lippke et al. 2019b for more detail.

[7] Lippke, B., M.E. Puettmann. 2013. Life-Cycle Carbon from Waste Wood Used in District Heating and Other Alternatives. *Forest Products Journal* Vol. 63(1-2):12-23

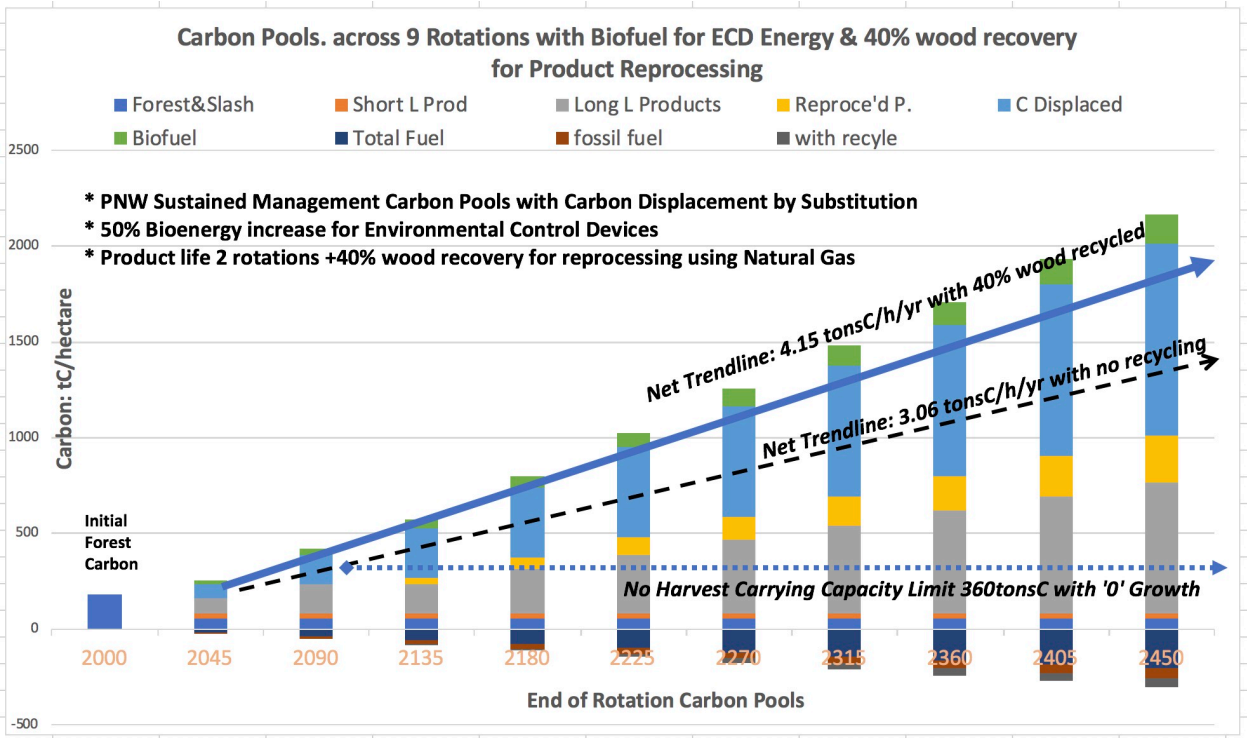

Figure 26 Growth in carbon pools with updated LCI data and 40 % recovery of clean demolition wood for reprocessing using natural gas

The best uses of wood provide an advanced carbon negative technology with high leverage to displace fossil emissions. The high-efficiency leverage to displace carbon derives from its structural strength. Replacing fossil intensive products with wood products is a high leverage carbon-negative technology for structural uses. This leverage is not matched by solar cells that neither store carbon nor displace fossil intensive building products. Undeveloped fossil-carbon recapture technology is even further out in time. There may be new and better opportunities to replace wood-based biofuel on the horizon such as algae, but that appears to be well into the future. Dovetail Partners Inc (2018)[8] in their review of 2nd and 3rd generation biofuels noted in their 'Bottom Line'; "For the near-to mid-term, at least, algae-derived biofuels are unlikely to pose competitive risks to the emerging second- generation cellulose-based biofuels industry".

Ironically Science Is Not the Limiting Factor. Understanding how to better use the science to avoid unintended consequences requires educational outreach. That outreach needs to be customized to each region's opportunities in order to gain the support of both the public, investors, and policy makers. The regional opportunities for better uses of wood resources are enormous, and a critical source of economic benefits especially for rural communities.

Final report, publications, and presentations

View or download in the Publications and Presentation sections of this report.

Lippke, B., M. Puettmann, and E. Oneil. 2019a. Effective uses of forest-derived products to reduce carbon emissions. 2019. CORRIM Technical Note 1, November 2019. 8pp.

[8] Dovetail Partners Inc. 2018. Third generation biofuels: Implications for wood derived fuels. Jim Bowyer, Jeff Howe, Richard A. Levins, Harry Groot, Katheryn Fernholz, Ed Pepke. Dovetail Partners inc. http://www.dovetailinc.org

Lippke, B., M. Puettmann, E. Oneil, and L. Mason. 2019b. The effective uses of forest-derived products to reduce carbon emissions based on updated LCI/LCA data from biofuels to innovative products and buildings. CORRIM Final Report. 41pp.

Puettmann, M. 2019. Pathway of biomass through Sawmills: Products & coproduct use for optimal carbon mitigation CORRIM Final Report. December 2019. 32pp.

Puettmann. M.E. 2019. Life cycle assessment can improve decisions to optimize wood residue use. White paper for Composite Panel Association 1pp.

Update on 22 years of CORRIM's life-cycle research: Opportunities to reduce carbon emissions. 2018. Bruce Lippke (presenter). Society of American Forests annual meeting, Portland Oregon, October 5, 2018

Update on efficiency in uses of wood products to store and displace fossil carbon emissions. 2018. Forestry Session, panel participant: "Carbon benefits of building with Wood", Bruce Lippke (presenter). Pacific Northwest Economic Region Annual Summit, Spokane WA., July 24, 2018.

Production and availability of mill residues for use in a biorefinery and associated carbon trade-offs. Maureen Puettmann (presenter), Bruce Lippke, and Steve Kelley. 2018. Forest Products Society Annual Meeting, Madison WI June 11-14, 2018

Life cycle assessment can improve decisions to optimize wood use. 2019. Maureen Puettmann (presenter). Society of Wood Science Technology, International Convention, Yosemite, California October 20-24, 2019.

Hierarchy of the most efficient products to displace fossil emissions and store carbon in products. 2019. Bruce Lippke, Maureen Puettmann (presenter), and Elaine Oneil. Society of Wood Science Technology, International Convention, Yosemite, California October 20-24, 2019.

Supply Chain Barriers (Alternate Dimensions, Elaine Oneil, Bruce Lippke)

Summary

Mitigation of climate change through reductions in atmospheric concentrations of greenhouse gases, especially carbon, will be dependent upon the deployment of forest-based strategies for uptake, substitution, displacement, and offset. Yet, the reconciliation of how carbon emissions are cycled and redistributed among atmosphere, ocean, and terrestrial pools (referred to as the 'global carbon budget') reveals significant uncertainties in the estimation of carbon exchange fluxes. When the global carbon budget is balanced, roughly one third of carbon emissions are found missing from the predictions of climate models. Generally presumed absorbed by the terrestrial biosphere (primarily forests), the 'missing sink' has become a 2.5 gigaton per year repository of unaccounted carbon emissions. From this uncertain point of departure, we begin our investigation of forest carbon including an evaluation of accounting systems from the unit process level to the global scale.

A robust literature review of over 2500 documents with a synthesis of 573 cited publications was undertaken to elucidate the challenges to implementing a woody biomass to energy strategy in the US. The literature synthesis incorporates forest carbon accounting applications including life cycle assessments, carbon debts and dividends, deferred harvests, harvested wood products, biomass-to-energy and comparative storage and displacement efficiencies. Global exercises in carbon accounting such as land use change, global trade of embodied emissions, illegal logging, forest certification, and forest carbon offsets were discussed. All are found to fail the test of effective prediction. Accounting discrepancies and leakages appear to be historically entrenched and manifold.

The cultural science section is particularly relevant to frame an understanding of the 'dueling science' inherent in decisions about the efficacy of forest management, and bioenergy development and deployment, as a climate mitigation solution. In particular, this section of the report highlights why there is such a powerful lobby towards comparing biomass recovery scenarios against counterfactuals that involve no management alternatives as an idealized construct that has no basis in history.

Baselines from which to make comparative assessments are typically assumed to occur from the decision to 'avoid harvest' after establishing a fully stocked forest stand. This baseline is not supported operationally as ROI is a driving force behind establishing a fully stocked stand. While forests sometimes regenerate naturally, unmanaged forests are typically degraded and understocked due to lack of investment and care in their management (e.g. see Figure 11 task 1). In contrast, managed forest stands have continued to show marked improvement in growth and yield over time (Figure 27).

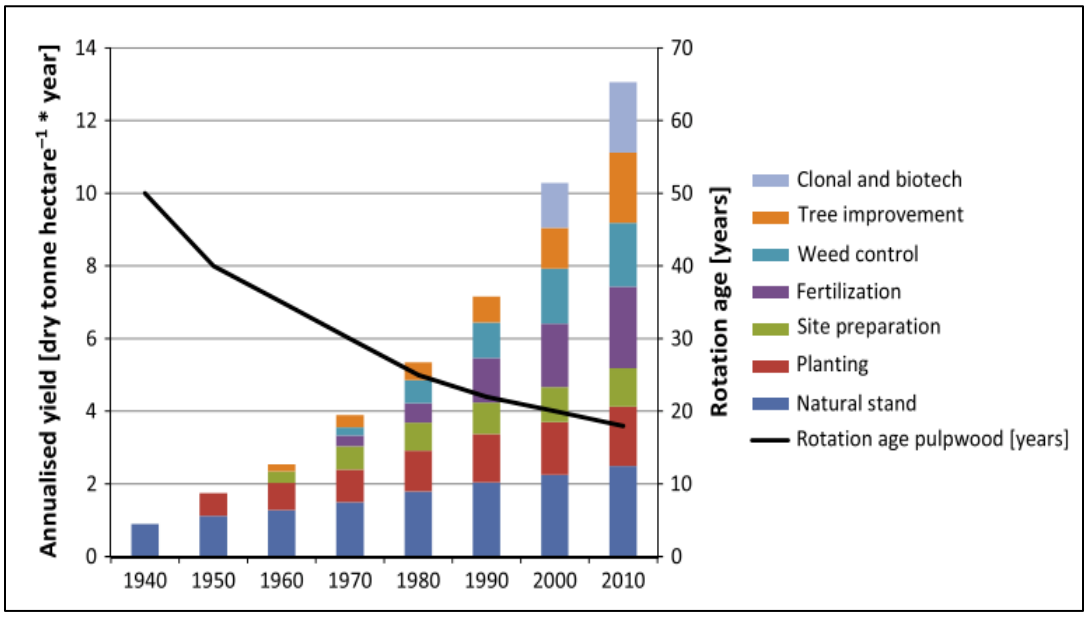

Figure 27 Silvicultural developments over 8 decades that have led to increased pine plantation productivity, heightened C uptake and storage, and shortened time to harvest in the US SE. Adapted from Fox et al. 2004[9].

Likewise, boundary conditions that examine a single stand as representative of the entire forest through time arrive at erroneous conclusions regarding carbon debt. In a sustainably managed forest that supports a vibrant forest products industry, harvest and growth are balanced over time. Such an effort ensures the continuity of the forest enterprise, as well as the continuity of the forest cover (Figure 28).

[9] Fox, T.R., E.J. Jokela, H.L. Allen. 2004. The evolution of pine plantation silviculture in the Southern United States. In: Gen. Tech. Rep. SRS–75. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. Chapter 8. p. 63-82.

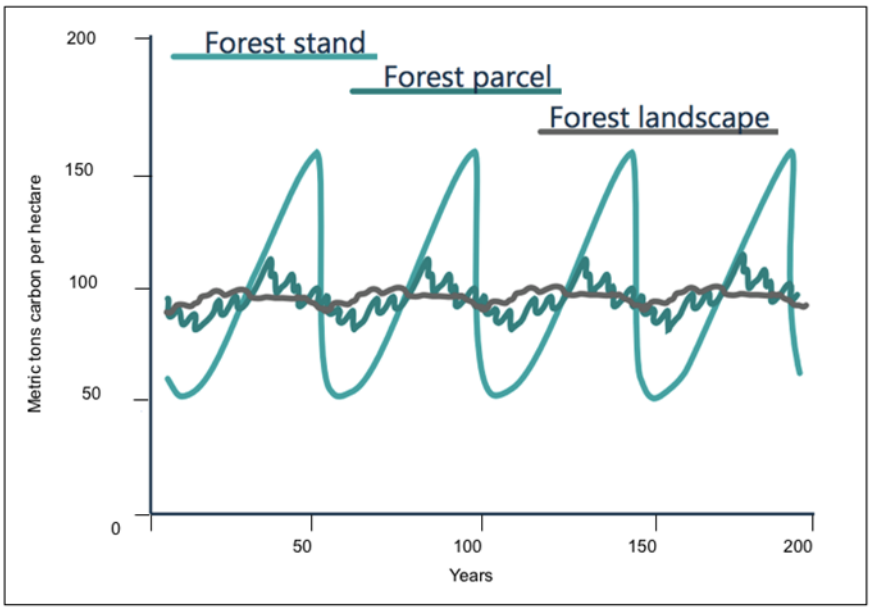

Figure 28 Graphic representation of the spatial and temporal dynamics of C storage for a typical PNW forest managed on 45-year rotations presented as: the growth and harvest cycles of one forest stand (in turquoise), an average per ha for 10 forest stands harvested in sequential intervals (in teal), and an average for 100 stands harvested sustainably as part of a "normal" forest (in brown). Adapted from McKinley et al. 2011[10] and Janowiak et al. 2017[11].

In lieu of objective conception, disparate accounting baselines, boundaries, and methodologies have generated incorrect assumptions, calculus leakages, and political controversies. These controversies have slowed the adoption of wood as a climate negative technology and reduced its effective incorporation into the suite of climate change mitigation strategies. The results indicate that a critical review of how we account for carbon in forestry is needed. Amidst large uncertainties, under-exploited opportunities to which most everyone should agree are identified as "low hanging fruit" and recommended for implementation.

Under current protocols, when the *Global Carbon Budget* is reconciled, its boundary extends to encompass all the Earth and its atmosphere, and its leakage of unaccounted CO_2 is of a magnitude better likened to a torrent than a trickle. Greater than 30% of annual CO_2 emissions disappear into the terrestrial biosphere; a 'missing sink' accompanied by shallow explanations and deep uncertainty. Adding to the inaccuracies of C accounting schemes have been attempts to limit forest use within the face of growing demand. Yet, it is a fundamental of economics that as demand remains strong so then will supply be found. As with the mass balance equation of the *Global Carbon Budget*, supply and demand must be reconciled. Decisions that reduce access to land, food, fiber, fuel, and timber resources (restrained supply)

[10] McKinley, D.C., M.G. Ryan, R.A. Birdsey, C.P. Giardina, M.E. Harmon, L.S. Heath, R.A. Houghton, R.B. Jackson, J.F. Morrison, B.C. Murray, D.E. Pataki, K.E. Skog. 2011. A synthesis of current knowledge on forest and carbon storage in the United States. Ecological Applications. 21(6):1902-1924.

[11] Janowiak, M., W.J. Connelly, K. Dante-Wood, G.M. Domke, C. Giardina, Z. Kayler, K. Marcinkowski, T. Ontl, C. Rodriguez-Franco, C. Swanston, C.W. Woodall, M. Buford. 2017. Considering Forest and Grassland Carbon in Land Management. GTR WO-95. USDA Forest Service. WA. D.C. 68 p

without offering alternatives have been shown to result in commensurate carbon leakage (unaffected demand).

Our review shows that unrealistic baselines and ill-defined boundaries have discounted or ignored such global forest system fundamentals as:

- the dynamics of environmental disturbances and recoveries,
- the fluxes and pools that make up the fast and slow domains of the C cycle,
- the inherent imbalances of producer and consumer economies,
- the global requirements for delivery of goods, services, and energy, and
- an uninterrupted history of anthropogenic influence.

Recommendations that flow from the literature synthesis include broad policy position recommendations as well as specific land use and manufacturing efficiency recommendations that appropriately reflect the role of woody biomass as a central component of the circular carbon economy. Broad policy position recommendations include:

- Deforestation is considered responsible for almost 90% of global estimated C emissions due to land-use change since 1850 (Houghton 1999)[12] yet sustainable harvest activities have been incorrectly labeled as 'degradation' by IPCC guidance. This is simply incorrect. Changes to these definitions and the paradigm behind them to more accurately characterize the role of forestry in supplying bio-based goods and services from the fast domain of the carbon cycle are required.
- Biases that have evolved from the man/nature dichotomy and which discount the benefits of the sustainable use of forests can and should be openly discussed. Historical forest management by indigenous cultures worldwide has demonstrably impacted the "natural" condition of forests, rendering the comparison of bioenergy and forest management alternatives to 'untouched' or 'no management' alternatives as a false dichotomy.
- To accurately characterize the benefit and hierarchy of using forests to mitigate climate change, carbon accounting systems must include the whole life cycle at a temporal and spatial scale that is relevant to the questions being asked. Attributional LCA (ACLA) has a significant role to play at specific scales but using ACLA to inform land use and broad policy questions provides contrary solutions that inevitably lead to unintended consequences. Different tools are required to characterize needs at broad scales.
- Forests have been and will be best cared for by local peoples with enduring commitments to specific landscapes. The uncertainties associated with public forest lands discourage long-term investment. For forestry mitigation projects to become viable on a broad scale, certainty over future commitments is needed since forestry requires a much longer planning horizon than other land use investments. In the US and throughout the World, it is private forests that attract legitimate business interest, are the most productive, and can best be protected from theft, deforestation, and degradation. Illegal logging and deforestation predominantly occur in developing countries with extensive public forest ownership, low per capita income, and land tenure claims of indigenous peoples and frontier settlers that remain unresolved. In the US, where 56% of forest lands are privately owned there is the greatest potential for mitigating climate change.

[12] Houghton, R.A. 1999. The annual net flux of carbon to the atmosphere from changes in land use 1850-1990. Tellus. 51(2):298-313.

- Maintain and grow wood markets of all kinds. They sustain viable tracts of forest land. Effective use of forests and forest products to reduce C emissions requires viable markets for the full spectrum of the value recovery hierarchy including low grade logs and process residuals.
- Technical land use, manufacturing, and use recommendations that follow the principles of the circular carbon economy include:
- To maximize carbon uptake, grow trees efficiently, and harvest timber to be manufactured according to a product hierarchy that prioritizes long-lived products. Following harvest, trees must be re-planted.
- Implement cascading use policies that follow a hierarchy of optimal uses favoring long lived products over short term products.
- Whenever possible the combustion of waste streams to provide onsite factory energy (for example, heat and electricity) will maximize conversion efficiencies.

Final report, publications, and presentations

View or download in the Publications and Presentation sections of this report.

Mason, L., B. Lippke, and E. Oneil. 2019. Baselines, Boundaries, and Forest Carbon Conundrums. CORRIM Final Report 122 pp.

Managed forest carbon sustainability: myths and metrics. 2019. Elaine Oneil (presenter). Society of Wood Science Technology, International Convention, Yosemite, California October 20-24, 2019.

Task 6 of SOPO Management (CORRIM)

This task includes costs for overall project management under the CORRIM administrative contract originally held at the University of Washington, as well as CORRIM direct expenses for publications, LCA critical review, and travel and presentations. In May of 2017, CORRIM moved its management function from the University of Washington into a stand-alone entity that is managed by Maureen Puettmann as the newly appointed CORRIM Director of Operations.

We anticipate significant interaction with National Labs and the DOE technical team as part of this project and have budgeted travel accordingly. These costs are programmatic in nature and will be invoiced separately from travel for administrative purposes such as for DOE peer review which are included within the G&A total. All of the work produced has been included in our publication and presentation list in this.

Listed below are the three BETO Program reviews presentations. Click on titles to view or download pdf.

BETO Review 2015

BETO Review 2017

BETO Review 2019

Publications

2016

1. Aizpurua, Carlos Ernesto, Process Simulation and Techno-Economic Evaluation of Alternative Biorefinery Scenarios. NCSU PhD Dissertation, 2016
2. Hall, Kevin. 2016 MS Thesis, Assessing and modeling the growth of *Eucalyptus benthamii*in the Southern United States, North Carolina State University

2017

3. Ren, X., Meng, J., Chang, J., Kelley, S.S., Jameel, H., Park, S., (2017) Effect of blending ratio of pine wood and bark on the properties of pyrolysis bio-oils, Fuel Processing Technology, 167, pg. 43
4. Yang, S. 2017. Understanding land use and land cover change: national forest dynamics and regional willow crop environmental impacts based on spatial modeling and spatial life cycle assessment. A dissertation submitted in partial fulfillment of the requirements for the Doctor of Philosophy Degree State University of New York College of Environmental Science and Forestry Syracuse, New York, June 2017. 172pp.

2018

5. Edmunds, C.W., André, N., Hamilton, C., Reyes Molina, E., Park, S., Kelley, S.S., Fasina, O., Adhikari, S., Shankar Tumuluru, J., Rials, T.G., Labbé, N., (2018) Blended Feedstocks for Thermochemical Conversion: Biomass Characterization and Bio-Oil Production from Switchgrass-Pine Residue Blends, Frontiers in Energy Research, vol 6, UNSP 79
6. Frank, J., Brown, T. Volk, T.A. Heavey, P., Malmsheimer, R. 2018. A stochastic techno-economic analysis of shrub willow production using EcoWillow 3.0S. Biofpr. DOI: 10.1002/bbb.1897
7. Han, Jeongwoo, Christina E. Canter, Hao Cai, Michael Wang, Zhangcai Qin, Jennifer B. Dunn, Richard Gustafson, Stephen S. Kelley, Rodrigo Morales, Elaine E. Oneil, Longwen Ou, Sunkyu Park, Maureen Puettmann, Neethi Rajagopalan, Timothy Volk, and Aaron Weiskittel. 2018. Carbon Dynamics for biofuels produced from woody feedstocks, Technical Report #: ANL/ESD-18/10, Argonne National Laboratory, Chicago. IL. 72 pp
8. Shaler, S., A. Weiskittel, J. Puhlick, and P. Heisl. 2018. Forest carbon stocks and emissions from harvesting operations in spruce-fir forests of Maine, USA. CORRIM Final Report. 20pp.
9. Ou, L., H. Kim, S.S. Kelley, and S. Park. 2018. Impacts of feedstock properties on the process economics of fast pyrolysis biorefineries, BioFPR, 12(3), 442-452

2019

10. Lan, K., L. Ou, S. Park, S.S. Kelley, and Y. Yao 2019. Life cycle analysis of decentralized preprocessing systems for fast pyrolysis biorefineries with blended feedstock in the southeastern United States. Energy and Technology, early access, doi.org/10.1002/ente.201900850
11. Lippke, B., M. Puettmann, and E. Oneil. 2019a. Effective uses of forest-derived products to reduce carbon emissions. 2019. CORRIM Technical Note 1, November 2019. 8pp.
12. Lippke, B., M. Puettmann, E. Oneil, and L. Mason. 2019b. The effective uses of forest-derived products to reduce carbon emissions based on updated LCI/LCA data from biofuels to innovative products and buildings. CORRIM Final Report. 41pp.
13. Mason, L., B. Lippke, and E. Oneil. 2019. Baselines, boundaries, and forest carbon conundrums. CORRIM Final Report 122 pp.
14. Oneil, E.E., J. Puhlick, A. Weiskittel, 2019. Regional variations in the lifecycle assessment of softwood residue recovery for biofuel production for the Pacific Northwest and northeast regions of the USA, CORRIM report, 52 pp.
15. Ou, L., H. Kim, S.S. Kelley, and S. Park. 2018. Impacts of feedstock properties on the process economics of fast pyrolysis biorefineries, BioFPR, 12(3), 442-452

16. Puettmann, M. 2019. Pathway of biomass through Sawmills: Products & coproduct use for optimal carbon mitigation CORRIM Final Report. December 2019. 32pp.
17. Puettmann. M.E. 2019. Life cycle assessment can improve decisions to optimize wood residue use. White paper for Composite Panel Association 1pp.
18. Scouse, A., K. Lan, P. Nepal, Y. Yao, S. Kelley. 2019. The influence of forestry practices, manufacturing variables, and end-of-life decisions on softwood lumber CO2 emissions (submitted to Forest Policy and Economics).

In Progress

19. Morales-Vera, R., M. Puettmann, T. Volk, S. Kelley, and R. Gustafson. Life cycle assessment of short rotation woody crops for production of bioethanol. The case of Eucalyptus, Willow, and Poplar grown in USA. *Environmental Science and Technology* (in preparation).

Presentations

2012

1. Biomass Feedstock Supply: Cost and Life Cycle Analysis. 2012. Han-Sup Han. 66th Forest Products Society International Convention. June 3, 2012 Washington D.C.
2. Pellets Production Alternatives and their Impacts. 2012. Adam Taylor. 66th Forest Products Society International Convention. June 3, 2012 Washington D.C.
3. Comparison of Bio-oil Produced from Southern Pine Slash to that from Clear Pine Wood. 2012. Maureen Puettmann. 66th Forest Products Society International Convention. June 3, 2012 Washington D.C.
4. Bioethanol from Lignocellulosic Feedstocks: A Life Cycle Assessment of Thermochemical Conversion Pathways. 2012. Jesse Daystar. 66th Forest Products Society International Convention. June 3, 2012 Washington D.C.
5. Impact of Feedstock on Lifecycle Carbon and Water Usage in Producing Ethanol from Wood Feedstocks using Bioconversion Processes. 2012. Rick Gustafson. 66th Forest Products Society International Convention. June 3, 2012 Washington D.C.
6. Summary of LCI/LCA Impacts for a Wide Range of Available Collection and Processing Alternatives Including Unintended Consequences 2012. Bruce Lippke. 66th Forest Products Society International Convention. June 3, 2012 Washington D.C.

2015

7. BETO Program Review
8. Carbon Cycling, Environmental & Rural Economic Impacts of Collecting & Processing Specific Woody Feedstocks into Biofuels – SOPO. 2015. Agronne National Lab. November 16, 2015
9. Carbon Cycling, Environmental & Rural Economic Impacts of Collecting & Processing Specific Woody Feedstocks into Biofuels – Harvest Systems. 2015. Agronne National Lab. November 16, 2015
10. Process simulation of fast pyrolysis into transportation fuels: Model sensitive to variations in biomass chemical composition. 2016. Aizpurua, C., Kim, H., Jameel, H., Park, S., Kelley, S.S., ACS annual meeting, 249, Denver, CO, March 22, 2015

2016

11. Spatially explicit life cycle assessment of willow biomass production in northern New York. 2016. Yang, S. T. Volk, M-O. Fortier. 2016. Short Rotation Woody Crops Operations Working Group meeting, St. Petersburg, FL, Oct. 11 – 13, 2016.

12. Introduction of Bioenergy Systems in the US. 2016. Ou, L., Kim, H., Park, S., Kelley, S.S., – Tampere Applied Sciences University (TAMK), Tampere Finland, Sept 20, 2016
13. Life Cycle Analysis of Forest Carbon Sinks. 2016. Ou, L., Kim, H., Park, S., Kelley, S.S., – T3 Consortium meeting, Tampere, Finland, Oct. 13, 2016
14. Introduction of Bioenergy Systems in the US. 2016. Ou, L., Kim, H., Park, S., Kelley, S.S., – JAMK, Jyvaskyla, Finland, Nov. 12, 2016
15. Optimization of financial, environmental and social attributes in a biorefinery. Aizpurua, C., J. Daystar, T. Hays, H. Kim, R. Radics, N. Rajagopalan, C. Reeb, E. Reyes, L. Xiao, R. Gonzalez, S. Park, R. Venditti, and S. Kelley. November 17, 2016. IFM^{2}E.
16. Carbon Cycling, Environmental & Rural Economic Impacts of Collecting & Processing Specific Woody Feedstocks into Biofuels. 2016. Oneil, E., R. Morales-Vera, and N. Rajagopalan. Agronne National Lab. December 5, 2016

2017

17. BETO Program Review
18. Poplar biomass using short rotation coppice silviculture for acetic acid production: techno-economics assessment and environmental impacts. 2017. Morales et al. Brazil, Biofuels, Bioenergy, & Bioeconomy, 2017.
19. Carbon cycles in US wood-based bioenergy systems. 2017. Seminar at Tampere University of Applied Sciences, Kelley, S.S. (presenter), Tampere, Finland, Nov. 1, 2017
20. Woody biomass in energy cycles. 2017. Kelley, S.S. S. Park, N. Rajagopalan, L. Ou. Presentation to USDA NIFA staff, and SE Foresters, Auburn University, Nov 14-15, 2017
21. Southern pine and short rotation woody biomass for production of bioenergy. 2017. Kelley, S.S., S. Park, N. Rajagopalan, L. Ou, and M. Herrera. Seminar at the University of Concepcion Technology Center, Concepcion, Chile, Dec 18, 2017

2018

22. Update on 22 years of CORRIM's life-cycle research: Opportunities to reduce carbon emissions. Bruce Lippke (presenter). Society of American Forests annual meeting, Portland Oregon. October 5, 2018
23. Update on efficiency in uses of wood products to store and displace fossil carbon emissions. Forestry Session, panel participant: "Carbon benefits of building with Wood", Bruce Lippke (presenter). Pacific Northwest Economic Region Annual Summit, Spokane WA., July 24, 2018
24. LCA for environmental assessment: The case of poplar to ethanol. Morales, Vera, R. (presenter), Gustafson, R., Shuren, R. 3° Coloquio de Investigación UCM Curicó-Los Niches. 2018. Sustentabilidad desde la transdisciplinariedad: Propiciando diálogos colaborativos para el desarrollo sustentable. Curicó Region del Maule, Chile, Sept 2018.
25. Poplar to ethanol production using short rotation coppice silviculture: Life cycle assessment. 2018. Morales Vera, R. (presenter), Gustafson, R., Shuren, R. II Conferencia Chilena de Análisis de Ciclo de Vida. Santiago, Chile, August 2018.
26. Greenhouse gas and energy balance of willow biomass crops are impacted by prior land use and distance from end users. 2018. Volk, T.A., Yang, S., Fortier, M-O, and O. Therasme. Woody Crops International Conference, Rhinelander, WI. July 23-25, 2018.
27. Effects of biomass composition on the economics and life cycle impacts of bio-oil biorefinery. Longwen Ou, Hoyong Kim, Maria Herrera, Yuan Yao, Sunkyu Park and Stephen S. Kelley (presenter). 2018. Forest Products Society Annual Meeting, Madison WI June 11-14, 2018
28. Production and availability of mill residues for use in a biorefinery and associated carbon trade-offs. Maureen Puettmann (presenter), Bruce Lippke, and Steve Kelley. 2018. Forest Products Society Annual Meeting, Madison WI June 11-14, 2018

29. LCA of poplar to ethanol production using short rotation coppice silviculture. 2018. Rodrigo Morales (presenter) and Rick Gustafson. Forest Products Society Annual Meeting, Madison WI June 11-14, 2018
30. Regional variations in the lifecycle assessment of softwood residue recovery for biofuel production for the Pacific Northwest and northeast regions of the USA. Elaine Oneil (presenter), et al. 2018. Forest Products Society Annual Meeting, Madison WI June 11-14, 2018

2019

31. BETO Program Review
32. Hierarchy of the most efficient products to displace fossil emissions and store carbon in products. 2019. Bruce Lippke, Maureen Puettmann (presenter), and Elaine Oneil. Society of Wood Science Technology, International Convention, Yosemite, California October 20-24, 2019.
33. Life cycle assessment can improve decisions to optimize wood use. 2019. Maureen Puettmann (presenter). Society of Wood Science Technology, International Convention, Yosemite, California October 20-24, 2019.
34. Managed forest carbon sustainability: myths and metrics. 2019. Elaine Oneil (presenter). Society of Wood Science Technology, International Convention, Yosemite, California October 20-24, 2019.
35. Modeling silvicultural and process variation and its influence of life-cycle carbon emissions for durable wood products. 2019. Scouse, A. (presenter), K. Lan, P. Nepal, Y. Yao, S. Kelley. Society of Wood Science Technology, International Convention, Yosemite, California October 20-24, 2019.

Website

All publications and presentation will be uploaded to the CORRIM website after this report is approved by DOE. We will continue to add publications as they are completed by the subcontractors

www.corrim.org

Appendix A Phase I August 2010 - June2012

A.1 Phase I Award Announcement

The public announcement of this award was November 12, 2009 in a news release from USDA NIFA and the Department of Energy. Click here for the announcement.

A.2 Phase I Project Management Plan

Phase I had 14 technical deliverables plus a management function. These were aggregated into 4 main task types for DOE reporting. Those task types were A: feedstock collection; B: Processing Models for Conversion; C: Economics, life cycle assessments, comparative analyses; and D: outreach and education. These tasks were directed towards addressing three barriers identified by DOE in their 2010 strategic plan. In Table 22 we show the distribution of tasks, and the impact of the funding withdrawal with most Tasks listed as incomplete (I), and several listed as not-started (NS) as they were in the process of beginning when the funding withdrawal occurred. Only one deliverable was complete within that time frame.

Table 22: Task, Subtask, and Status of Phase 1 deliverables by recipient at project suspension in June 2012.

Barrier	DOE Task and subtask number	Status (I, C, NS)	CORRIM task and subtask description
St-E	A	I	Task 1. Biofuel feedstock collection by region
St-E	A.1	I	Task 1a. Biofuel feedstock collection of fire risk reduction thinnings for the Inland West ($30,000 +$5,000 consulting to incorporate California): PI Elaine Oneil, U. of Washington:
St-E	A.2.1	I	Task 1b. PNW and Inland West forest residuals ($20,000); PI Elaine Oneil, U. of Washington:
St-E	A.2.2	I	Task 1c. SE forest residuals $(20,000); PI Bob Abt, NCSU:
St-E	A.2.3	I	Task 1d. NE/NC forest residuals ($20,000); PI, Tim Volk, ESF:
St-E	A.3	I	Task 2. Management and Collection of Short Rotation Woody Crops (SRWC) for Biofuel ($60,000), PI Tim Volk, ESF
St-E	A.4	I	Task 3a. Feedstock Collection Equipment Technology Alternatives ($50,000 allocated to 3 consultants and travel); PI, Leonard Johnson, Professor Emeritus, U of Idaho.
St-D	B.3.1	C	Task 3b. Feedstock Preprocessing of Pellets ($20,000) PI, John Katers, University of Wisconsin-GreenBay
St-F	C.1.5	I	Task 4. Impact of incentives on feedstock collection ($10,000); PI, Bruce Lippke, Professor Emeritus, U of Washington.
St-F	C.1.1	I	Task 5a. Forest Sustainability (Char, Soil carbon) and Disturbance impacts on soil carbon, forest productivity, and nutrient sustainability ($15,000); PI, Elaine Oneil, U. of Washington.
St-F	C.1.2	I	Task 5b. Emission tradeoffs between non-point source decomposition, wildfire, and biofuel feedstock fed boilers ($20,000); PI, Elaine Oneil, U. of Washington.
St-F	C.1.3	I	Task 6a. Infrastructure, and scale barriers ($15,000) PI Larry Mason, U. of Washington.
St-F	C.1.4	I	Task 6b. Rural Economic Impacts ($40,000); Larry Mason, U. of Washington.

Barrier	DOE Task and subtask number	Status (I, C, NS)	CORRIM task and subtask description
St-D	B	I	Task 7A. Processing models - Bioconversion of woody biomass ($140,000); PI, Richard Gustafson, U. of Washington.
St-D	B.1.1.1	I	Raw feedstocks using the data provided by the feedstock collection tasks will be simulated, including the following: dedicated Short Rotation Woody Crops chipped with bark, fire reduction thinnings, and both softwood and hardwood forest residuals from commercial harvest.
St-D	B.1.1.2	I	Capital cost and operating cost of the optimized process model for each feedstock will be determined. Capital and operating costs will be determined as a function of biorefinery scale. Economic data will be supplied to the team working on Task 8c for detailed economic analysis. Raw material costs will be provided by the teams working on Tasks 1-4. Emission controls needed to bring emissions in compliance with federal regulations will be incorporated into the economic models.
St-D	B.1.1.3	I	Comparison of the economic and environmental impact of bioconversion processes will be made with gasification processes developed under Task 7B. The primary basis of comparison will be one liter of ethanol fuel product – or its energy equivalent if an alternative fuel is produced in the simulation.
St-D	B	I	Task 7B. Processing models - Gasification of woody biomass to produce mixed alcohols ($140,000); PI Richard Venditti, N.C. State University.
St-D	B.1.2.1	I	Raw feedstocks to be simulated include the following: dedicated Short Rotation Woody Crops chipped with bark, fire reduction thinnings, and both softwood and hardwood forest residuals from commercial harvest.
St-D	B.1.2.2	I	Capital cost and operating cost of the optimized process model for each feedstock will be determined. Capital and operating costs will be determined as a function of biorefinery scale. Economic data will be supplied to team working on Task 8c for detailed economic analysis. Raw material costs will be provided by teams working on Tasks 1-4. Emission controls needed to bring emissions in compliance with federal regulations will be incorporated into the economic models.
St-D	B.1.2.3	I	Comparison of the economic and environmental impact of gasification processes will be made with bioconversion processes developed under Task 7A. The primary basis of comparison will be one liter of ethanol fuel product – or its energy equivalent if an alternative fuel is produced in the simulation.
St-D	B	I	Task 7C. Processing models - Pyrolysis of woody biomass to produce stabilized pyrolysis oil ($139,822); PI, Phillip Steele, Mississippi State University.
St-D	B.1.3.1	I	Process simulations will be used to estimate life cycle inventory data for biorefineries that produce stabilized pyrolysis oil by pyrolization of wood biomass followed by esterification to stabilize the product and allow it to be burned as an alternative to petroleum fuel oil. These models will determine the raw material and energy demands (or credits) for the processes. In addition, the process atmospheric and aqueous emissions will be determined.
St-D	B.1.3.2	I	The process models will be optimized for each feedstock. The primary optimization criteria and basis for comparisons to other fuels will be minimization of carbon emissions per liter of fuel product or equivalent energy produced. Emission controls will be incorporated into the process models to bring the emissions in compliance with current Federal regulations.
St-D	B.1.3.3	I	Capital cost and operating cost of the optimized process model for each feedstock will be determined. Capital and operating costs will be determined as a function of biorefinery scale. Economic data will be supplied to the team working on Task 8c for detailed economic analysis. Raw material costs will be provided by teams working on Tasks 1-4. Emission controls needed to bring

Barrier	DOE Task and subtask number	Status (I, C, NS)	CORRIM task and subtask description
			emissions in compliance with federal regulations will be incorporated into the economic models.
St-F	C.2.1	NS	Task 7 D. Best biofuel processing/collection alternatives and integration with pulp mill ($40,000); PI Rick Gustafson, U. of Washington.
St-D	B.2.1.1	NS	Task 8A. LCI development for collection alternatives ($50,000 PIs Johnson and Puettmann)
St-D	B.2.1.2	NS	Task 8B. Cradle to gate LCI development and LCI/LCA database access ($30,000), PI, Maureen Puettmann, WoodLife.
St-F	C.3.1	NS	Task 8C. Bioprocessing economic feasibility and investment analysis ($40,0000. PI Ken Skog, Forest Products Laboratory.
St-F	C.2.2	NS	Task 8D. LCI/LCA integration and best fiber allocation alternatives ($40,000); PI, Richard Gustafson U. Of Washington & consultants.
St-F	C.1.6	NS	Task 9. Scenario based national/regional estimates of biofuel production and carbon mitigation potential constrained to optimal scale facilities ($80,000) co-PIs Elaine Oneil and Larry Mason, U. of Washington.
St-F	C.4.1	NS	Task 10. Other (non-carbon) environmental impacts of concern ($25,000); PI Joyce Smith Cooper U. of Washington,
St-B	D.1	NS	Task 11. Peer Reviews of developed LCIs for each processing stage and integrated LCA comparisons (Reviews $14,000, Publication costs $18,000). CORRIM
St-B	D.2	I	Task 12. Learning modules ($40,000); PI Adam Taylor, U. of Tennessee
St-B	D.3	NS	Task 13b. Interactive video modules ($20,000). Video Producer Matthew McLaughlin, U. of Washington under co-PI Rick Gustafson.
St-B	D.4	NS	Task 13c. Web delivery & evaluation ($30,000 over 3 years). Matthew McLaughlin, U. of Washington under co-PI Rick Gustafson.
St-B	D.5	NS	Task 14. Web training, curriculum use and evaluation ($20,000). CORRIM

A.3 Proposed CORRIM deliverables to DOE for the 75% of planned year one funding that we received

1. Pyrolysis – Mississippi State: The 75% of the first-year allocation was used to sample bundles of totally green whole trees (thinnings, or restoration sites?). One person was removed from funding limiting research activity but a PhD candidate that had worked on the basic modeling under a prior grant will be able to enter the data for an LCI analysis and compare the results to loblolly pine trees without branches and needles. The minerals in the needles are about $1/10^{th}$ that in switchgrass but in conjunction with dirt we expect the bio-oil yields to drop. We will be getting an average across needles, clear wood from small stems, bark and dirt with the yield reduction largely a function of the metals. Alternative handling has included burning the slash or hauling it back to the forest and spreading it like mulch to decompose. Methods of drying by stacking wood for a period of time in the forest to remove needles (and metals) are possible but will not be evaluated nor will any of the other alternatives planned under the original grant. A completed paper is planned for the March time frame for this pyrolysis feedstock option. Under-funding to complete this project will essentially come from sharing information and researchers.

See topic 3 in presentation list for the FPS annual convention and record the presentation as interactive video for tutorial usage based on the 1st year support from DOE.

2. Gasification - NCSU: Researchers were moved to a different project where they will still be working on biofuels. Will complete an evaluation of the economics of thermo-conversion as an extension to the LCI modeling completed under the prior grant. We will also complete a paper comparing agricultural feedstocks with forest biomass partially funded under prior grants.

While there are two types of feedstock analyses that were planned in the original grant there is insufficient funding to make such comparisons. Papers will be completed on the economic analysis of the first thermo-chemical processing analysis and the comparative LCI analysis of agricultural feedstock alternatives.

See topic 4 in presentation list for the economic analysis for thermo-chemical ethanol at the FPS annual convention and record the presentation as interactive video for tutorial usage based on the 1st year support from DOE.

3. Fermentation - U Washington: A change of feedstock from willow as a short rotation woody crop which is high in moisture will be made to forest residuals from a dry forest area to demonstrate the range of impacts from fermentation. The findings from the prior research project will be extended to include these findings in an additional paper.

See topic 5 in presentation list for the FPS annual convention and record the presentation as interactive video for tutorial usage based on the 1st year support from DOE.

4. Pellets – U Wisconsin Green Bay: The project was completed comparing the LCI impacts of pellet production and alternative uses and will be published in a special issue featuring a range of biofuel processing alternatives.

See topic 2 in presentation list for the FPS annual convention.

These data were integrated with a quite different analysis of pellets that was completed by U of Tennessee with different funding. NEED ref to Adam's pellet study in special issue in 2012

5. Short Rotation Woody Crop feedstock – ESF: The potential for higher yielding willow will be added to the prior analysis. Land use change impacts on carbon in the soil carbon and root system will be included. The analysis of the impact of N2O litter fall on Nitrogen loading is being analyzed. Results will include samples from the NY region but cannot be extended to the NE forest region on constrained funding.

This topic did not make the presentation list for the FPS annual convention as planned due to shortage of time at the special session.

6. Advances in biomass collection for biofuel processing – Humboldt State and Consultants: The potential of alternative collection equipment and timing of treatments will be analyzed in a paper demonstrating that cost improvements are likely of greater importance than the emissions from collection activities.

See topic 1 in presentation list for the FPS annual convention and record the presentation as interactive video for tutorial usage based on the 1st year support from DOE.

7. Comparisons of carbon displacement efficiency for feedstock and processing alternatives- U of Washington and Consultants:

An updated comparison across available feedstock and processing alternatives will focus on best combinations for either carbon displacement efficiency (emissions reduced per carbon in the wood used) and EPA's emission reduction efficiency (net emissions from using biofuels/emissions from currently used fossil fuels). Tradeoffs between contributing to energy independence and carbon mitigation will be discussed.

See topic 6 in presentation list for the FPS annual convention and record the presentation as interactive video for tutorial usage based on the 1st year support from DOE.

8. Job creation from the economic impact of biofuel collection and processing - U of Washington and Consultants:

Have not determined how this can be supported under constrained budgets.

9. Avoiding unintended consequences caused by incentive policies - U of Washington and Consultants

Have not determined how this can be supported under constrained budgets.

A.4 Phase 1 Topics presented at a Special Session at Forest Products Society International Convention

Biofuel environmental performance

Sunday, June 3, 2012: 3:00pm - 4:50pm

Washington, DC

Moderator Maureen Puettmann, LCI/LCA consultant:

The session provides a synopsis of the DOE funded research on the LCA of biofuels produced using 3 distinct processes and 3 distinct kinds of feedstock. After the detailed presentations we provide a final integrated summary that compares and contrasts the LCA, quantifies linkages to carbon mitigation and energy independence objectives, and identifies policy related impacts of the range of choices that are currently under consideration.

Agenda:

Brief Session Introduction

Brief introduction by moderator on prior research findings by CORRIM leading up to these comprehensive LCI/LCA comparisons. Click here to view Introduction Presentation

Listed below are the titles of the reports, papers and presentations by Task. Click on titles to view or download pdf.

1 Advances in biomass collection for biofuel processing

Han Sup Han, Humboldt State; Leonard Johnson, professor emeritus U of Idaho; Tim Volk, ESF

The impacts of feedstock collection (thinnings, forest residuals, and short rotation woody crops) under current technology will be summarized and contrasted with potential alternative collection equipment and timing of treatments. Advances in yield improvements for short rotation woody crops such as willow will also be covered. Cost improvements are shown to be of greater importance than the emissions from collection activities under current policy.

2 Pellets production alternatives and their impacts

Adam Taylor, U of Tennessee; John Katers, U of Wisconsin GreenBay; Maureen Puettmann, consultant

A range of pellet plants in the upper Midwest have been surveyed developing LCI/LCA impacts for different feedstocks. The benefits of lower cost transportation of feedstock and feedstocks costs are contrasted with increased energy inputs for processing. Feedstocks from hardwood floor residuals with high energy burdens are compared with waste feedstocks with low burdens. The LCI/LCA impacts for residential wood pellets were also compared to fossil fuels.

3 Comparison of Bio-oil Produced from Southern Pine Slash to that from Clear Pine Wood

Phillip Steele and Kanthi Penmetsa, U of Mississippi; Maureen Puettmann, consultant

This study compares the quality and yields of bio-oil between results for past studies of utilization of clear southern pine wood to that produced from pine slash. Slash and tops developed during a first thinning comprised the biomass for this study. Over an 8-hour workday 5 skidder bundles were randomly selected from among those delivered to a whole-tree delimber. All slash and tops were collected and weighed. A random sample of this material was immediately weighed. The biomass was chipped to paper chip size followed by drying to 5% MC; the material was then ground to a pyrolysis particle size of 1 – 3 mm in dimension. We found that the yield of bio-oil from pine slash averaged about 40% compared to 65% we

generally obtain from pine clear wood. Char yield for slash was about 27% compared to 23% for pine clear wood. Water content of the slash bio-oil was 37.4% compared to the 24% we usually obtain for clear pine. Ash contained in the slash feedstock contained 1.83% compared to about 0.4% for clear pine. The high ash content indicates that the stem bark and needles on the pine limbs contain a relatively high level of minerals. High mineral content is known to reduce pyrolysis yield and produces higher water content and is likely the most influential variable in determining the difference in results between slash and clear wood. This data will be utilized to develop an LCI analysis that compares the results of processing harvest slash.

4 Bioethanol from Lignocellulosic Feedstocks: A Life Cycle Assessment of Thermochemical Conversion Pathways

Jesse Daystar, PhD Student, Richard Venditti, Professor, Ronalds Gonzalez, Research Professor, Hassan Jameel, Professor, Mike Jett, PhD Student, College of Natural Resources, North Carolina State Univ.

Due to the Energy Independence and Security Act (EISA) mandated biofuels production, many 2nd generation biofuel production pathways are being examined on a technical and economic basis. However, to be considered a 2nd generation biofuel, certain greenhouse gas (GHG) reductions are required under the Renewable Fuel Standard (RFS). Biomass gasification is widely known as a promising 2nd generation biofuels production pathway due to high alcohol yields and more flexible feedstock requirements relative to bioconversion. The purpose of this work was to examine the alcohol yields and GHG emissions from the thermoconversion process for six feedstocks on a gate-to-gate basis. These feedstocks included: (1) natural hardwood, (2) loblolly pine, (3) Eucalyptus, (4) Miscanthus, (5) corn stover, and (6) switchgrass. Using the NREL thermochemical model (Aden et al. 2007) and SimaPro, a GHG analysis and life cycle assessment were performed. An NREL simulation model (Phillips et al. 2007) was used for the baseline material of hybrid poplar, resulting in a yield and GHG emission of 105,441 L metric ton-1 and 2.8 kg CO2 eq. per liter, respectively. Compared to the NREL base model using hybrid poplar as feedstock, loblolly pine produced the highest alcohol yields, an 8.5%increase, and the lowest GHG emissions per liter of ethanol, a 9.1% decrease. Corn stover, due to the high ash content, had the lowest yields and the highest GHG emissions per liter of ethanol. The results were highly sensitive to ash and water content of the biomass, indicating that biomass properties can significantly affect the environmental impacts of the process.

5 Impact of feedstock on lifecycle carbon and water usage in producing ethanol from woody feedstocks using bioconversion processes

Richard Gustafson, Jordon Crawford and Eric Budsberg, College of the Environment, U of Washington

Two likely sources of woody feedstocks for biofuel production are planation grown hardwoods and softwood forest residuals. In some regions, a biorefinery may have to use both of these feedstocks to have sufficient volumes of reasonably price raw material for their process. In this study, the impact of feedstock on the life cycle global warming potential and freshwater consumption are investigated. Rigorous CORRIM developed LCA/LCI models are coupled with ASPEN process simulations to assess the life cycle impacts. The contrasting composition, recalcitrance, and feedstock acquisition requirements of these two raw materials provide an informative contrast in the potential life cycle impacts of biofuels

6 Summary of LCI/LCA impacts for a wide range of available collection and processing alternatives including unintended consequences

Bruce Lippke, President Emeritus CORRIM and professor emeritus U of Washington;

Maureen Puettmann, Consultant; Elaine Oneil, U of Washington and Executive Director CORRIM

A Comparison across alternative feedstock and processing alternatives for producing products reveals different impacts on carbon mitigation and energy independence. Comparison metrics focus on best combinations for either carbon displacement efficiency (emissions reduced per carbon in the wood used) or

EPA's measurement standard for emission reductions (net emissions from using biofuels as a percentage of emissions from currently used fossil fuels). Non-trivial tradeoffs between contributing to energy independence and carbon mitigation will be discussed. Options for using forest residuals to reduce emissions in current plants and co-gen facilities will also be evaluated. Current policies to reduce carbon emissions and increase energy independence are at best not efficient and likely to have unintended consequences. The complications of carbon accounting across many interacting carbon pools will be evaluated demonstrating where unintended consequences are likely and what is required to avoid them.

Appendix B – Phase II August 2015 – September 2019

B.1 Phase II Statement of Project Objective

The Consortium for Research on Renewable Industrial Materials (CORRIM), a 20-research institution non-profit consortium, has developed a comprehensive suite of peer-reviewed life cycle analyses (LCA) of wood building materials. Much of this work is accessible as journal articles, the website (www.corrim.org) and the US LCI database (www.nrel.gov/lci/). While historically the majority of CORRIM's work has focused on durable wood products, which can sequester biomass carbon for 50 years or more, much of the underlying information on the planting, growth, and harvesting of wood is useful for any conversion process using wood. The CORRIM databases have recently been extended to provide comparisons for woody-biofuels for two regional analyses using basic wood production system parameters for softwoods (Johnson et al 2012). Feedstock sources include commercial thinnings in the SE and forest residuals for a subset of plots in the Inland West. Preliminary data on short rotation woody crop (SRWC) production parameters have also been collected and analyzed. All of these feedstocks can be used for production of biofuels using either biochemical or thermochemical manufacturing processes.

GREET is a comprehensive, robust platform that can be used for the LCA evaluation of many different biofuels produced using either biochemical or thermochemical processes. This web-based platform allows the user to evaluate the environmental implications of different combinations of biomass feedstocks, biofuels conversion processes, and modes of vehicles transportation. The GREET model is sensitive to input parameters and the variability in woody biomass characteristics, both regionally and by feedstock type, make it particularly challenging to incorporate woody feedstocks into the GREET model. Since many of these woody biomass materials can have multiple uses the LCA allocation issues require careful definition and tracking. The CORRIM expertise in woody feedstock analysis, and durable wood products, will be used to develop a series of data sets and alternative cases that can be easily incorporated into the GREET model for robust assessment of the relative impacts in expected outcomes on a regional basis. This work will also include consideration of the impacts of natural variation in the composition and reactivity of the different woody biomass feedstocks.

The overall goal of this work is to provide DOE with high-quality information that allows for a detailed, comprehensive analysis of the benefits and liabilities of using woody feedstocks for the production of biofuels on a regionally specific basis. Specifically, this work will provide:

1. data that allows for comprehensive LCA evaluation of the implications of using forest and manufacturing residues from current, regionally specific commercial systems for the production of biofuels. These systems include softwoods in the Pacific Northwest (PNW) and Southeast (SE) US, and Northeastern (NE) US.
2. data on the potential for using regionally specific dedicated SRWC for production biofuels, e.g., Poplar in the PNW, Eucalyptus in the SE and Willow in the NE.
3. an LCA of the impacts of using woody biomass as a feedstock for different biochemical and thermochemical biofuels production processes
4. an analysis of the impacts of natural variations in wood composition and pretreatments production scenarios on the LCA of wood-based biofuels
5. an analysis of the GHG implications of using woody feedstocks for the production of both biofuels and the current commercial suite of short-lived and durable wood products.

Taken as a whole this research will provide a definitive assessment of the technical, and environmental, impacts of broad use of woody biomass for the production of transportation fuels. This assessment is necessary if forest biomass is to be widely used for biofuels that require, in advance, an understanding of the consequences of such a course of action. In addition, Life Cycle Inventory data and Assessments (LCI/LCA) on greenhouse gas emissions will be necessary to understand qualification of biofuels made

from forest-based biomass under the Energy Independence and Security Act (EISA) of 2007. The impacts of different policies and other alternatives management strategies will be characterized as sensitivity scenarios to better inform the adoption of appropriate policies, marketing, and investment strategies to reach energy independence goals with reduced greenhouse gas (GHG) emissions while effectively managing cellulosic resources.

B. PROJECT SCOPE

Technical Areas: (C) Biofuels Development Analysis for (i) strategic guidance, (ii) energy and environmental impacts

To meet this objective, we will combine biomass growth/yield models, data on recovery options, biomass quality and characteristics, and use them in GREET as the preferred biofuels process model to characterize the mass and energy implications for specific woody biomass feedstocks and biofuel processing alternatives. Specifically, the chemical composition, and LCA burdens of the different woody feedstocks will be used as inputs for the DOE developed integrated engineering process models, and will be used to develop LCAs for greenhouse gases (GHG) and other environmental risk indices using TRACI for a comparison of 2nd generation wood based biofuels and fossil fuels. This work will then identify the combinations of woody biomass-conversion technology that have the biggest impacts on the LCA. These cases will then be used to inform potential changes in the GREET models, which will be conducted by ANL staff.

The initial woody feedstocks of interest include 3 regional variations on forest residuals and thinnings and 3 regionally specific short rotation woody crops (SRWC). We will develop life cycle inventory data such as total GHG emissions representative of biofuels conversion processes and compare the impacts with alternative fuel sources and product uses in order to identify the implications of differing allocations of wood-based carbon. We will use the research protocols and LCI/LCA information from the traditional production and uses of woody biomass already developed by CORRIM for wood products and biofuel produced from mill residuals as a framework for the modeling. Using that framework, we will develop parallel information for the collection of feedstocks and the production of biofuels using DOE design case biochemical and thermochemical process models. Alternative technologies, with their impacts on the value chain, will be compared for different forest treatments, harvesting, and collection equipment. This will drive regional differences and determine the best biofuel processing alternatives including fermentation, gasification and pyrolysis. The effects of feedstock variation, e.g., sugar and lignin content, moisture content, ultimate and proximate analysis and ash content, will be matched with processing alternatives. The effects of the size of the processes plant will be matched with alternative infrastructure. Alternative configurations and policy assumptions covering a range of scenarios will be used to project potential regional and national reductions in GHG emissions and energy dependence as well as rural economic impacts.

C. TASKS TO BE PERFORMED

Introduction

For each region, species mix, and forestry system, an LCI and LCA will be generated based on the most common practices for the region, as well as for a suite of future alternatives. Outputs for this task will be based on the current allocations between short-life products (paper and process heat) and durable products (wood products in building systems). These data will include the specifics of forest growth and yield, allocation between current products and future biofuels products, and be based on volume estimates by forest type, forest management and harvesting systems within the region. The outputs of the analysis will include biomass quantity, quality (sugars and lignin content, moisture content, ultimate and proximate analysis and ash content), and production system inputs for the most common practices, and a select range of alternative practices.

Data will be developed in a form suitable for input into SimaPro LCA software models which will be compiled to a uniform and consistent standard with outputs generated for inclusion in the DOE engineering process models. This data will serve DOE mission in three functions, 1) raw data will be delivered to DOE, the NREL hosted LCA database, and the ORNL hosted KDF, 2) the data will also serve to support the DOE funded GREET model with a wider array of commercially viable feedstock information on both SRWC and forest residues from commercial harvesting systems, and 3) the data will also serve other researchers who would need data on the composition and LCA burdens of woody biomass as they work to develop their own novel biofuels conversion processes.

Yield (Han et al 2014) and recovery limitations (Johnson, et al 2012) have been identified as critical drivers of LCA results for biomass production systems, generating LCA impact differences of up to 20%. With current technologies and market prices, biomass recovery is limited to those materials that are most easily accessible (Perez-Garcia et al 2012), which varies between regions. Our study will compile data on regionally specific opportunities to increase recovery using different harvest systems and use the revised yields and energy consumption to assess the LCI impacts of improved processes. Yield is very sensitive to assumptions used in biomass modeling. For example, Melson et al. (2011) found a range of uncertainty of 36% relative to the mid-point of all models when comparing multiple biomass equations for five major PNW species and even higher uncertainty levels when estimating biomass for trees outside the diameter range for model development. Others have reported similar differences depending on the equations used.

The delivered moisture and ash content are also significant drivers for thermochemical processes (Daystar, et al, 2013). This work was based on the DOE gasification design case and it shows, as expected, that the higher moisture biomass requires more process energy for the drier, and thus provides a lower yield of biofuel, and an associated higher GHG burden for the biofuel product. Ash contained in the biomass is a “dead load” on the process and has the same impact of decreasing yield, albeit to a lesser extent, and generating a higher GHG burden for the biofuel.

Biofuel yield is also very sensitive to assumptions used in biomass process modeling. In the case of the biochemical process modeling, the yield of biofuel is a function of the amount of sugar and the heat integration is sensitive to the amount of lignin and still bottoms. In both the gasification and pyrolysis process models the moisture content and the ash content both impact biofuel yield. And DOE is working to enhance the sensitivity of these process models to make them more responsive to quality and composition of the biomass.

In order to illuminate the impacts of these sensitivities, in this work we will retain regional experts in growth and yield, biomass allocation, and recovery potential to refine estimates of biomass quantity and characteristics derived from sampled and modeled data for each region, forest type, and production system under examination. For commercial softwood harvest systems, the range of woody biomass yield, based on both land productivity and regionally specific harvesting practices, will be used to scale sample data to the regional level in Task 5. Scaling uses simulation model inputs and parameters built into the CORRIM forest carbon assessment tool. This tool utilizes the most current inventory data in the Federal Forest Inventory and Analysis (FIA) databases, projects yield forward, and summarizes regional yield based on a range of input parameters. Recent data provided by the DOE funded “High Tonnage” studies will also be included in these analyses.

Task 1 – LCI of the current, regionally specific commercial systems.

In this task three commercially relevant, regional woody biomass production systems that are dominant in their respective regions will be studied. These include softwood Douglas-fir/hemlock systems common in the PNW, plantation loblolly pine systems common in the SE, and softwood fir/spruce forestry systems common in the NE US. For each system an LCI data set will be developed. This LCI data set will be based on current commercial practice, and therefore focus on forest residue collection and forest thinnings. Because the current commercial wood production systems have long production cycles that vary from 25-65 years, average yearly input values will be derived using forest inventory simulation data

for each region in order to detail both the quantity of the inputs and the timing of the inputs. Regional differences in the growth rates and commercial thinning practices will also be considered.

The LCI will also detail the timing and mass of biomass available for biofuels production, in conjunction with the continued production of paper and durable wood products. The disruptive nature of wood pellets being exported for the European markets will also be considered. This task will include a consideration of the impacts of improving forest silviculture, biofuel markets, and harvesting technology.

Process steps will include the collection of all input data for each forest management and biomass collection activity (machine capacity utilization, fuel use, labor, lubricants etc.) to support the development of the life cycle inventories (LCI) by region. Sensitivity analysis will focus on those management and collection alternatives that may affect energy use and GHG emissions or the cost of collection.

Task 2 – LCI of regionally-specific, dedicated SRWC for production biofuels

In this task three regionally specific, dedicated SRWC will be studied. Specifically, poplar for the PNW, Eucalyptus plantations in the SE, and willow in the NE. For SRWC the base assumptions are that 100% of the biomass, and the associated LCI burdens are attributed to the biofuels production process. Also, in the case of SRWC the time period between planting and harvest is much shorter, so the implications of the timing between the inputs and output are less significant. With SWRC there is also significant potential for increasing the productivity with new planting stock. This will include the analysis of growth, and yield alternatives, collection of all input data for each forest management, and biomass collection activity (machine capacity utilization, seedling production, fertilization and herbicide use at establishment, fuel use, labor, etc.) that will support the development of a life cycle inventory (LCI) and the identification of land use change limitations and alternatives.

Task 3 – LCA of the impacts of using woody biomass as a feedstock for different biochemical and thermochemical biofuels production processes

DOE has invested heavily in the development of detailed engineering process models that serve as base cases for different biofuels production processes tracked by the DOE program. Specifically, there are detailed ASPEN Plus process models for a) the biochemical conversion of biomass to ethanol, b) the thermochemical conversion of biomass to mixed alcohols via gasification, and c) thermochemical conversion of biomass to hydrocarbon fuels via pyrolysis and upgrading. The GREET LCA models also use these DOE engineering process models for the overall calculation of the LCA impacts of alternative biofuels production and consumption pathways.

This task will use the best available DOE ASPEN based engineering process models , namely a) the biochemical conversion of biomass to ethanol or hydrocarbons, and b) thermochemical conversion of biomass to hydrocarbon fuels via pyrolysis and upgrading, and combine them with the chemical composition and reactivity data for the six woody feedstock production scenarios detailed in Tasks 1 and 2 to estimate the performance of the woody feedstocks in these conversion processes.

The chemical composition data will be provided by the CORRIM team based on their ongoing synergistic USDA funded projects. For the biochemical process the effects of the chemical composition and changes in the yield of monomeric sugars of the woody feedstocks on the yield of biofuel. In the case of the thermochemical model the effects of moisture content and ash will be evaluated. The SRWC hardwoods will be evaluated for biochemical conversion processes consistent with the findings of Budsberg et al (2012), and the softwoods will be evaluated as a feedstock for thermochemical processes. In both cases the best available DOE engineering process models will be used.

Task 4 – an analysis of the impacts of natural variations in wood composition and production scenarios on the LCA of wood-based biofuels

Sensitivity analysis will be conducted for a suite of production alternatives for each region with the two feedstock and appropriate biofuels production alternatives. This sensitivity analysis will account for natural variation in wood composition, e.g., sugar and lignin content, moisture content, ultimate and proximate analysis and ash content, and associated biofuels production potential. For example, it is clear that for biochemical conversion processes the yield of ethanol increases with increasing biomass sugar content, but the lignin-rich residue is also needed for production of heat and power to run the biofuels production plant. In the case of thermochemical conversion, it is also clear that the moisture content, and to a lesser extent the ash content, of the incoming biomass play a key role in the heat balance for the plant and the overall biofuel yield. These effects will be evaluated for the specific feedstocks and conversion technologies. In addition, allocation of environmental burdens among products, biofuels, and short-term and durable wood products, has proven critical in the wood to energy life cycle assessments conducted to date. For this project we will test a range of allocations, including current practice, and scenarios with increasing amounts of woody residues that could be recovered for biofuels production, without limiting the production of durable wood products. Increasing amounts of woody biomass recovery are likely to alter the incoming feedstock quality. Data will be developed on the potential range of variation in wood characteristics under different scenarios. That data will be available for incorporation into the processing models.

Sensitivity analysis across the range of alternatives for feedstock and production alternatives will be provided for the different regional feedstock outlined tasks 1 through 3. These data outputs will be inputs to the LCA models that will ultimately be used to establish a matrix of the range of potential outcomes for the suite of regional analyses conducted as part of this project. Quality control, synthesis of feedstock and production processes for comparative analysis, and development of uncertainty estimates for all feedstock x region x production process alternatives that are developed in Tasks 1, 2 and 3 will be managed by experienced CORRIM LCA experts.

Task 5 – an analysis of the carbon storage implications of using woody feedstocks for the production of both biofuels and the current commercial suite of short-lived and durable wood products.

In task 5 we integrate across the supply chain to generate a range of alternative hierarchies of GHG benefit from using woody biomass for energy. An initial hierarchy of GHG benefits for a range of wood uses has been developed (Lippke et al 2012) based on LCA results for a small suite of feedstocks, production assumptions, and processing alternatives. The results of this project will substantially expand on this hierarchy and begin to quantify the expected uncertainties across a range of processing and production alternatives, wood characteristics, and wood qualities.

Task 5 takes outputs from Tasks 1 through 4 and integrates them across the supply chain to generate a range of alternative hierarchies of GHG benefit from using woody biomass for energy. This integration of scale, hierarchy, and supply chain data will be used to develop a framework of carbon storage benefits, provide for the scaling of sample data to the regional level, develop an expanded hierarchy of wood use by region, and report on supply chain scale barriers that are expected to vary on a regional basis.

Across all the work the data and analysis will be subjected to review by the DOE technical teams to make sure they are consistent with the needs of GREET, and that the engineering process models are used to their full advantage in testing the effects of natural variation on biofuels yield.

Appendix C - Financial Report

NOTE: A full financial report is not available by the time this technical report was due.

C.1 Award Chronology

The following is a chronology of this award. It includes the significant dates affecting the award, the "stoppage" which occurred after invoice 8 and the reallocation of funds that occurred after June 2017, and again in the summer of 2019.

In March of 2010 CORRIM was awarded DE-EE0002992 in the amount of $1,430,656 with a cost share of 369,633 for a total award of $1,800,168. The submission of all paperwork and revisions to the grant application were finalized and the award was signed between CORRIM and DOE on August 30, 2010. At that time the subrecipients were: University of Washington (UW), North Carolina State University (NCSU), State University of New York (SUNY), University of Tennessee, Johnson and Associates, Humboldt University, WoodLife Consulting, University of Wisconsin – Green Bay, USDA Forest Service – Forest Product Lab, and CORRIM Management.

On June 30, 2011, DOE notified CORRIM via a phone meeting that they would not allocate the remaining funds due to budget shortfalls, but they did not want to cancel the contract, only suspend it until the start of FY12 (Oct 2011). At the end of this phase of work, CORRIM had invoiced $399,802 in federal funds and $126,039 cost share (incorrectly reported at $123,003). In late 2014, CORRIM and DOE began conversations about reinstating the award. The refining of the scope of work was directed towards a subset of the original sub-recipients, including UW, NCSU, SUNY, and some new sub-recipients that could best provide the needed information including University of Maine, WoodLife, Alternate Dimensions, Lippke Associates, and CORRIM Management. The updated scope of work was accepted on August 4, 2015. The maximum 5-year term for DOE grants led to an expiry on August 30, 2015, so a special extension was requested. hat extension took effect on December 3, 2015. At that time, CORRIM maintained a management contract at the University of Washington and all management functions were paid to that account.

In May 2017, CORRIM moved its management function from the University of Washington into a stand-alone entity that was managed by Maureen Puettmann as the newly appointed CORRIM Director of Operations. At this time, CORRIM began working with DOE to update our PMC (EERE335) to reflect this change and also to reallocate an additional $85,000 in funds consistent with the project development. These new allocations were approved by DOE by May 2018. The new allocations are in the four "EERE 335" files for UW, NCSU, Management and ALL and can be found in folder "Indirect Rate Justification". As the fund reallocation was well within the 10% threshold for requiring DOE to re-issue a new assistance agreement form, no updates occurred to that form at that time. In the summer of 2019, CORRIM again reallocated funds to ensure that the close-out and integration of all results were completed as needed. The total re-allocation in 2017 and 2019 did not exceed the 10% threshold.

C.2 Spending Summary

Table 23 shows the spending summary for federal amounts only for each invoice beginning FY10Q4 – FY19Q4. Invoice 24 was submitted on Febuary 5, 2020.

Table 23 Spending summary for federal share presented by CORRIM fiscal years for Invoice 1-24. Note: Invoice 24 is not paid.

CORRIM FY	TOTAL	CORRIM Indirect	Management	UW Technical	U Tenn	SUNY	NCSU	MSU	WoodLife	Green Bay	Humboldt	University of Maine	Alternative Dimensions	Lippke	Supplies	Software	Travel	Publications
2010/2011	$ 25,921.18	$ -	$ 18,898.94													$ 7,022.24		
	$ 25,921.18	**$ -**	**$ 18,898.94**	**$ -**	**$ -**	**$ -**	**$ -**	**$ -**	**$ -**	**$ -**	**$ -**	**$ -**	**$ -**	**$ -**	**$ -**	**$ 7,022.24**	**$ -**	**$ -**
2011	$ 61,796.33	$ -	$ 8,542.29	$ 30,377.51				$ 20,716.41	$ 372.06	$ 1,788.06								
2011	$ 78,214.43	$ -	$ 9,461.09	$ 30,548.08	$ 1,322.25	$ 4,565.20		$ 20,174.22	$ 845.94	$ 5,121.09	$ 4,365.80					$ 1,810.76		
2011	$ 71,932.05	$ -	$ 8,348.84	$ 6,098.09	$ 2,307.56	$ 13,262.58	$ 17,131.27	$ 20,960.51	$ 250.00		$ 3,573.20							
	$ 211,942.81	**$ -**	**$ 26,352.22**	**$ 67,023.68**	**$ 3,629.81**	**$ 17,827.78**	**$ 17,131.27**	**$ 61,851.14**	**$ 1,468.00**	**$ 6,909.15**	**$ 7,939.00**	**$ -**	**$ -**	**$ -**	**$ -**	**$ 1,810.76**	**$ -**	**$ -**
2012	$ 125,614.87	$ -	8,348.84	77,944.36	3,501.55	6,807.56	15,921.71	-		13,090.85	-							
2012	$ 16,117.86	$ -	$ 1,200.00						$ 937.50		$ 13,980.36							
2012	$ 7,301.91	$ -	$ 1,200.00			$ 6,101.91												
2012	$ 12,904.02	$ -	$ 5,047.85						$ 788.00								$ 7,068.17	
	$ 161,938.66	**$ -**	**$ 15,796.69**	**$ 77,944.36**	**$ 3,501.55**	**$ 12,909.47**	**$ 15,921.71**	**$ -**	**$ 1,725.50**	**$ 13,090.85**	**$ 13,980.36**	**$ -**	**$ -**	**$ -**	**$ -**	**$ -**	**$ 7,068.17**	**$ -**
	$ 41,007.33	$ -	$ 21,274.54						$ 1,837.50				$ 2,000.00			$ 8,336.00	$ 7,559.29	
2016	$ 70,919.76	$ -	$ 4,854.35	$ 15,999.20			$ 33,710.79		$ 9,325.75				$ 6,625.00				$ 404.67	
2016	$ 50,434.55	$ -	$ 1,380.86	$ 23,998.80		$ 3,421.93	$ 21,632.96											
	$ 162,361.64	**$ -**	**$ 27,509.75**	**$ 39,998.00**	**$ -**	**$ 3,421.93**	**$ 55,343.75**	**$ -**	**$ 11,163.25**	**$ -**	**$ -**	**$ -**	**$ 8,625.00**	**$ -**	**$ -**	**$ 8,336.00**	**$ 7,963.96**	**$ -**
2017	$ 55,311.69	$ -	$ 5,591.79	$ 30,836.86		$ 2,620.08	$ 2,026.23					$ 14,236.73						
2017	$ 81,839.12	$ -	$ 2,490.00	$ 20,747.70		$ 3,765.07	$ 246.30		$ 5,687.50			$ 13,652.55	$ 26,750.00			$ 8,500.00		
2017	$ 63,019.30	$ -	$ -	$ 28,295.61		$ 5,564.54			$ 8,006.60			$ 13,652.55	$ 7,500.00					
2017	$ 82,835.85	$ -	$ -	$ 23,001.45		$ 5,147.19	$ 15,558.39		$ 7,525.00			$ 20,478.82	$ 7,125.00	$ 4,000.00				
	$ 283,005.96	**$ -**	**$ 8,081.79**	**$ 102,881.62**	**$ -**	**$ 17,096.88**	**$ 17,830.92**	**$ -**	**$ 21,219.10**	**$ -**	**$ -**	**$ 62,020.65**	**$ 41,375.00**	**$ 4,000.00**	**$ -**	**$ 8,500.00**	**$ -**	**$ -**
2018	$ 63,181.42	$ -	$ -	$ 58,116.74		$ 3,664.68								$ 1,400.00				
2018	$ 72,995.60	$ -	$ -	$ 30,189.47			$ 25,871.03		$ 4,812.50			$ 8,166.27		$ 1,200.00		$ 2,400.00	$ 356.33	
2018	$ 103,027.86	$ 15,598.67	$ 40,497.04	$ 23,952.48			$ 10,995.84		$ 1,925.00			$ 3,551.11	$ 1,875.00	$ 857.00	$ 5.63		$ 3,770.09	
2018	$ 40,235.71	$ 4,047.27	$ 13,516.27				$ 8,289.67		$ 10,062.50					$ 4,320.00				
	$ 279,440.59	**$ 19,645.94**	**$ 54,013.31**	**$ 112,258.69**	**$ -**	**$ 3,664.68**	**$ 45,156.54**	**$ -**	**$ 16,800.00**	**$ -**	**$ -**	**$ 11,717.38**	**$ 1,875.00**	**$ 7,777.00**	**$ 5.63**	**$ 2,400.00**	**$ 4,126.42**	**$ -**
2019	$ 47,349.49	$ 4,904.82	$ 8,033.00	$ 17,332.16		$ 1,769.42			$ 2,800.00			$ 1,261.97		$ 8,223.00			$ 3,025.12	
2019	$ 69,776.38	$ -		$ 321.48		$ 7,611.68	$ 47,418.22		$ 6,300.00				$ 8,125.00					
2019	$ 36,059.14		$ -			$ 1,429.22	$ 26,449.67		$ 1,706.25						$ 936.00	$ 5,300.00	$ 238.00	
2019	$ 17,288.33	$ 3,555.58	$ 6,120.25						$ 7,612.50									
2019	$ 123,096.62	$ 3,500.00	$ 19,277.67				$ 60,418.55		$ 39,900.40									
	$ 293,569.96	**$ 11,960.40**	**$ 33,430.92**	**$ 17,653.64**	**$ -**	**$ 10,810.32**	**$ 134,286.44**	**$ -**	**$ 58,319.15**	**$ -**	**$ -**	**$ 1,261.97**	**$ 8,125.00**	**$ 8,223.00**	**$ 936.00**	**$ 5,300.00**	**$ 3,263.12**	**$ -**

Table 24 shows the spending summary for cost amounts only for each invoice beginning FY10Q4 – FY19Q4. Invoice 24 was submitted on Febuary 5, 2020.

Table 24 Spending summary for cost share presented by CORRIM fiscal years for Invoice 1-24. Note: Invoice 24 is not paid.

Invoice #	DOE Qrt	CORRIM FY	TOTAL	UW Technical	U Tenn	SUNY	NCSU	MSU	WoodLife	Green Bay	Humboldt	University of Maine	Alternative Dimensions	Lippke
1	FY10Q4	2010/2011	$ -											
			$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
2	FY11Q1	2011	$ 4,869	$ 4,408						$ 461				
3	FY11Q2	2011	$ 29,265	$ 5,854	$ 1,728	$ 1,876		$ 16,103	$ -	$ 1,385	$ 2,319			
4	FY11Q3	2011	$ 47,036	$ 32,488	$ 1,795	$ 5,705	$ 5,773	$ 1,276						
			$ 81,170	**$ 42,750**	**$ 3,523**	**$ 7,581**	**$ 5,773**	**$ 17,379**	**$ -**	**$ 1,846**	**$ 2,319**	**$ -**	**$ -**	**$ -**
5	FY11Q4	2012	$ 34,719	$ 24,031	$ 1,791	$ 2,271	$ 3,370	$ -		$ 3,257	$ -			
6	FY12Q1	2012	$ -											
7	FY12Q2	2012	$ 10,130			$ 10,130								
8	FY12Q3	2012	$ -											
			$ 44,849	**$ 24,031**	**$ 1,791**	**$ 12,401**	**$ 3,370**	**$ -**	**$ -**	**$ 3,257**	**$ -**	**$ -**	**$ -**	**$ -**
9			$ 735						$ 735					
10	FY16Q2	2016	$ 17,870				$ 11,490		$ 3,730				$ 2,650	
11	FY16Q3	2016	$ 56,377	$ 36,247		$ 5,828	$ 14,301							
			$ 74,981	**$ 36,247**	**$ -**	**$ 5,828**	**$ 25,791**	**$ -**	**$ 4,465**	**$ -**	**$ -**	**$ -**	**$ 2,650**	**$ -**
12	FY16Q4	2017	$ 8,404			$ 1,687	$ 2,963					$ 3,754		
13	FY17Q1	2017	$ 21,669			$ 2,775	$ 2,319		$ 2,275			$ 3,600	$ 10,700	
14	FY17Q2	2017	$ 13,283			$ 3,480			$ 3,202			$ 3,600	$ 3,000	
15	FY17Q3	2017	$ 33,013	$ 7,794		$ 3,106	$ 10,853		$ 3,010			$ 5,401	$ 2,850	
			$ 76,369	**$ 7,794**	**$ -**	**$ 11,048**	**$ 16,134**	**$ -**	**$ 8,487**	**$ -**	**$ -**	**$ 16,356**	**$ 16,550**	**$ -**
16	FY17Q4	2018	$ -											
17	FY18Q1	2018	$ 15,178				$ 9,017		$ 1,925			$ 2,154		$ 2,083
18	FY18Q2	2018	$ 9,920				$ 5,920		$ 770			$ 936	$ 750	$ 1,543
19	FY18Q3	2018	$ 12,613				$ 5,708		$ 4,025					$ 2,880
			$ 37,711	**$ -**	**$ -**	**$ -**	**$ 20,645**	**$ -**	**$ 6,720**	**$ -**	**$ -**	**$ 3,090**	**$ 750**	**$ 6,506**
20	FY18Q4	2019	$ 42,056	$ 34,054			$ 5,054		$ 1,120			$ 335		$ 1,494
21	FY19Q1	2019	$ 22,020				$ 15,450		$ 2,520				$ 4,050	
22a	FY19Q2	2019	$ 11,912				$ 11,230		$ 683					
23b	FY19Q3	2019	$ 3,045						$ 3,045					
24	FY19Q4	2020	$ 4,886						$ 4,886					
			$ 79,033	**$ 34,054**	**$ -**	**$ -**	**$ 31,733**	**$ -**	**$ 12,253**	**$ -**	**$ -**	**$ 335**	**$ 4,050**	**$ 1,494**

Table 25 shows the total federal share for each CORRIM fiscal year. As explained earlier, a reallocation of funds was done during FY19Q3. Due to the length of the award and additional complications with invoicing with DOE, CORRIM management and subsequent indirect rate required additional funds to support the efforts of the Director of Operations related to the DOE grant management. WoodLife took on a major role in editing and contributing to Task 5 which required additional funds as well as major role in aiding all Tasks in there LCA methodologies.

Table 25 Spending summary for federal share presented in total amounts by CORRIM fiscal years

CORRIM FY	TOTAL	CORRIM Indirect	Management	UW Technical	U Tenn	SUNY	NCSU	MSU	WoodLife	Green Bay	Humboldt	University of Maine	Alternative Dimensions	Lippke	Supplies	Software	Travel	Publications
2010/2011	$ 25,921.18	$ -	$ 18,898.94													$ 7,022.24		
2011	$ 211,942.81	$ -	$ 26,352.22	$ 67,023.68	$ 3,629.81	$ 17,827.78	$ 17,131.27	$ 61,851.14	$ 1,468.00	$ 6,909.15	$ 7,939.00	$ -	$ -	$ -	$ -	$ 1,810.76	$ -	$ -
2013	$ 161,938.66	$ -	$ 15,796.69	$ 77,944.36	$ 3,501.55	$ 12,909.47	$ 15,921.71	$ -	$ 1,725.50	$ 13,090.85	$ 13,980.36	$ -	$ -	$ -	$ -	$ -	$ 7,068.17	$ -
	$ 399,802.65	$ -	$ 61,047.85	$ 144,968.04	$ 7,131.36	$ 30,737.25	$ 33,052.98	$ 61,851.14	$ 3,193.50	$ 20,000.00	$ 21,919.36	$ -	$ -	$ -	$ -	$ 8,833.00	$ 7,068.17	$ -
2016	$ 162,361.64	$ -	$ 27,509.75	$ 39,998.00	$ -	$ 3,421.93	$ 55,343.75	$ -	$ 11,163.25	$ -	$ -	$ -	$ 8,625.00	$ -	$ -	$ 8,336.00	$ 7,963.96	$ -
2017	$ 283,005.96	$ -	$ 8,081.79	$ 102,881.62	$ -	$ 17,096.88	$ 17,830.92	$ -	$ 21,219.10	$ -	$ -	$ 62,020.65	$ 41,375.00	$ 4,000.00	$ -	$ 8,500.00	$ -	$ -
2018	$ 279,440.59	$ 19,645.94	$ 54,013.31	$ 112,258.69	$ -	$ 3,664.68	$ 45,156.54	$ -	$ 16,800.00	$ -	$ -	$ 11,717.38	$ 1,875.00	$ 7,777.00	$ 5.63	$ 2,400.00	$ 4,126.42	$ -
2019	$ 293,569.96	$ 11,960.40	$ 33,430.92	$ 17,653.64	$ 17,653.64	$ 10,810.32	$ 134,286.44	$ -	$ 58,319.15	$ -	$ -	$ 1,261.97	$ 8,125.00	$ 8,223.00	$ 936.00	$ 5,300.00	$ 3,263.12	$ -

Table 26 shows the total cost share contribution for each institution/subcontract by CORRIM fiscal year. As of invoice 24, $399,019 cost share has been contributed (as reported in last spending summary submitted to DOE (Table 27)). Total cost share for the award to $399,019, or $24,866 over the committed amount on the award. The discrepancy comes from the original award. All the cost share was not reported during invoicing for that period. This was reported during the audit.

Table 26 Cost share contribution presented in total amounts by CORRIM fiscal years

CORRIM FY	TOTAL	UW Technical	U Tenn	SUNY	NCSU	MSU	WoodLife	Green Bay	Humboldt	University of Maine	Alternative Dimensions	Lippke
FY11Q1	**$ 81,170**	$ 42,750	$ 3,523	$ 7,581	$ 5,773	$ 17,379	$ -	$ 1,846	$ 2,319	$ -	$ -	$ -
FY11Q4	**$ 44,849**	$ 24,031	$ 1,791	$ 12,401	$ 3,370	$ -	$ -	$ 3,257	$ -	$ -	$ -	$ -
	$ 126,019	$ 66,781	$ 5,313	$ 19,982	$ 9,142	$ 17,379	$ -	$ 5,103	$ 2,319	$ -	$ -	$ -
FY16Q2	**$ 74,981**	$ 36,247	$ -	$ 5,828	$ 25,791	$ -	$ 4,465	$ -	$ -	$ -	$ 2,650	$ -
FY17Q4	**$ 76,369**	$ 7,794	$ -	$ 11,048	$ 16,134	$ -	$ 8,487	$ -	$ -	$ 16,356	$ 16,550	$ -
FY18Q4	**$ 37,711**	$ -	$ -	$ -	$ 20,645	$ -	$ 6,720	$ -	$ -	$ 3,090	$ 750	$ 6,506
FY19Q4	**$ 79,033**	$ 34,054			$ 31,733		$ 7,368			$ 335	$ 4,050	$ 1,494
FY20Q1	**$ 4,886**						$ 4,886					
	$ 398,999	**$ 144,876**	**$ 5,313**	**$ 36,858**	**$ 103,445**	**$ 17,379**	**$ 31,926**	**$ 5,103**	**$ 2,319**	**$ 19,781**	**$ 24,000**	**$ 8,000**

Table 27. Invoice 24b "Review Spending Summary for DOE FY19Q4 and CORRIM FY20Q1. Under review as Febuary 13, 2020.

Recipient:	CORRIM			☐ Yes **Have any potential conflicts of interest been identified?**	
DOE Award #:	DE-EE0002992				
Invoice Number	Invoice 24b			☐ Yes **Were competitive bidding procedures used to ensure reasonable costs?**	
Dates (To/From)	July 1, 2019 - September 30, 2019				
Invoice Submission Date	2/4/2020				
Project Title	Consortium for Research on Renewable Industrial Materials				
Spending Summary for Invoice Review					
Cost Categories	**Approved Budget**	**Prior Cumulative Total**	**This Invoice**	**Cumulative TOTAL SPENT**	
>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>	**7/27/2015**	**6/30/2019**	**9/30/2019**		
a. Personnel	$ -		0.00	0.00	
b. Fringe Benefits	$ -		0.00	0.00	
c. Travel	$ 27,068	22,886.30	0.00	22,886.30	
d. Equipment / software					
e. Supplies	$ 38,833.00	$ 33,915.40	0.00	33,915	
f. Contractual	$ 1,706,787.00	$ 1,238,282.48	123,096.62	1,361,379.10	Invoices for woodlife; corrim management; corrim indirect
f. cost share	*$ 374,153.00*	*$ 394,133.21*	*4,885.83*	*399,019.04*	Cost share only associated with "Contractual": This invoice only Woodlife
g. Construction	$ -	0.00	0.00	0.00	
h. Other publications	$ 32,000	0.00	0.00	0.00	
i. Total Direct Charges (sum of a to h) + cost share	$ 2,178,841.00	$ 1,689,217.39	$ 127,982.45	1,817,199.84	
j. Indirect Charges	$ -	$ -	$ -	0.00	
k. Totals (sum of i and j) with cost share	**$ 2,178,841.00**	**$ 1,689,217.39**	**$ 127,982.45**	**1,817,199.84**	
DOE Share	1,430,535.00	1,295,084.18	123,096.62	1,418,180.80	budget $1,430,535; Actual $1,418,181
Cost Share	374,153.00	394,133.21	4,885.83	399,019.04	Committed $374,153; Actual $399,019
Calculated Cost Share Percentage	10.4%	13.2%	1.9%	22.0%	
Preparer Signature:	Maura Puerto	2/4/2020			
Authorized Official Signature:					

Table 28 shows the invoice payments and status for invoices 1-23. Note invoice 24 was submitted on Febuary 5, 2020. and has not been paid.

Table 28 Vipers invoice status report, exported 12/28/2019.

Invoice Status Report
Run Date: 2/13/2020

Funding	Purchase Order	Invoice Number	Amount	Paid Amount	Recd. Date	Due Date	Paid Date	Status	Site
	EE0002992	24B	$123,096.62	$0.00	02/05/2020	02/06/2020		Under Review	NETL
	EE0002992	23B	$17,288.33	$17,288.33	01/06/2020	01/07/2020	01/24/2020	Paid	NETL
	EE0002992	24A	$4,489.19	$0.00	10/04/2019	10/05/2019		Cancelled By: maureen@	NETL
	EE0002992	24	$4,489.19	$0.00	09/26/2019	09/27/2019		Cancelled By: maureen@	NETL
	EE0002992	23A	$17,288.25	$0.00	09/12/2019	09/13/2019		Cancelled	NETL
	EE0002992	23	$17,288.25	$0.00	08/12/2019	08/13/2019		Cancelled By: maureen@	NETL
	EE0002992	22A	$36,059.63	$36,059.63	07/18/2019	07/19/2019	09/05/2019	Paid	NETL
	EE0002992	22	$36,059.63	$0.00	05/23/2019	05/24/2019		Cancelled	NETL
	EE0002992	20C	$47,349.49	$47,349.49	03/13/2019	03/14/2019	04/10/2019	Paid	NETL
	EE0002992	21A	$69,776.38	$69,776.38	02/02/2019	02/04/2019	03/18/2019	Paid	NETL
	EE0002992	21	$69,776.28	$0.00	01/23/2019	01/24/2019		Cancelled By: maureen@	NETL
	EE0002992	20A	$47,674.62	$0.00	01/09/2019	01/10/2019		Cancelled	NETL
	EE0002992	20	$47,674.62	$0.00	11/27/2018	11/28/2018		Cancelled	NETL
	EE0002992	19	$40,235.71	$40,235.71	08/10/2018	08/13/2018	08/29/2018	Paid	NETL
	EE0002992	18	$103,027.85	$103,027.85	05/15/2018	05/16/2018	06/28/2018	Paid	NETL
	EE0002992	16B	$63,181.42	$63,181.42	02/01/2018	02/02/2018	02/07/2018	Paid	NETL
	EE0002992	17	$72,995.60	$72,995.60	01/30/2018	01/31/2018	02/22/2018	Paid	NETL
	EE0002992	16	$63,182.42	$0.00	12/04/2017	12/05/2017		Cancelled	NETL
	EE0002992	15	$82,837.85	$82,837.85	09/08/2017	09/11/2017	11/30/2017	Paid	NETL
	EE0002992	14	$63,019.30	$63,019.30	04/25/2017	04/26/2017	05/15/2017	Paid	NETL
	EE0002992	13	$81,839.72	$81,839.72	02/17/2017	02/21/2017	02/22/2017	Paid	NETL
	EE0002992	12	$55,311.69	$55,311.69	11/17/2016	11/18/2016	12/07/2016	Paid	NETL
	EE0002992	11	$50,434.55	$50,434.55	08/25/2016	08/26/2016	09/09/2016	Paid	NETL
	EE0002992	10	$70,919.76	$70,919.76	06/02/2016	06/03/2016	07/05/2016	Paid	NETL
	EE0002992	9	$41,007.33	$41,007.33	01/20/2016	01/21/2016	01/27/2016	Paid	NETL
	EE0002992	8	$12,904.02	$12,904.02	07/10/2012	07/11/2012	07/13/2012	Paid	NETL
	EE0002992	7	$7,301.91	$7,301.91	04/27/2012	04/30/2012	05/03/2012	Paid	NETL
	EE0002992	6	$16,117.86	$16,117.86	02/10/2012	02/13/2012	02/28/2012	Paid	NETL
	EE0002992	5	$125,613.84	$125,613.84	12/16/2011	12/19/2011	01/13/2012	Paid	NETL
	EE0002992	4	$71,932.05	$71,932.05	08/04/2011	08/05/2011	08/09/2011	Paid	NETL
	EE0002992	3REVISED	$78,214.43	$78,214.43	05/26/2011	05/27/2011	06/01/2011	Paid	NETL
	EE0002992	3	$0.00	$0.00	05/05/2011	05/06/2011		Cancelled	NETL
	EE0002992	2A	$59,636.21	$59,636.21	03/07/2011	03/08/2011	03/10/2011	Paid	NETL
	EE0002992	2B	$2,160.12	$2,160.12	03/07/2011	03/08/2011	03/10/2011	Paid	NETL
	EE0002992	1	$25,921.18	$25,921.18	11/10/2010	11/12/2010	11/18/2010	Paid	NETL
			$1,726,105.30	$1,295,086.23					