WASTE TO WISDOM: UTILIZING FOREST RESIDUES FOR THE PRODUCTION OF BIOENERGY AND BIOBASED PRODUCTS

FINAL REPORT

March 2018

Citation: *Waste to Wisdom. 2018. Utilizing forest residues for the production of bioenergy and biobased products. Final Report. 78p.*

This material is based upon work supported by a grant from the U.S. Department of Energy under the Biomass Research and Development Initiative program: Award Number DE-EE0006297.

For more information please visit WasteToWisdom.com

EXECUTIVE SUMMARY

Forest residues, including unmerchantable and small-diameter trees, tops, and limbs, produced during thinning and timber harvest operations can be used to produce renewable bioenergy and bioproducts. The more efficient utilization of forest residues could also help offset the high costs of forest restoration activities, fire hazard treatments, post-harvest activities and forest management in general. Forest residues have long been underutilized and treated as waste materials because of their high collection and transportation costs as well as their low market value. While open burning is often employed to dispose of forest residues, this practice generally results in substantial negative economic and environmental impacts, including increased forest management costs and reduced local air quality.

At present, the greatest obstacle to more effectively utilizing forest residues is high transportation cost. The integration of biomass conversion technologies (BCTs) with new in-forest biomass operations could provide a cost-effective alternative to the long-distance transport of high moisture and low energy density forest residues. However, innovative new biomass feedstock technologies that produce high-quality feedstock materials from low-quality forest residues are needed to meet feedstock specifications for BCTs, including particle size and minimal contamination. BCTs can effectively convert comminuted forest residues into high-value fuels with desirable market characteristics (i.e. low moisture content and high energy density) and soil amendment products (i.e. biochar) in the woods, resulting in significantly-increased transportation efficiencies. Using a process that is either in-woods or near-the-forests would also provide substantial environmental benefits by displacing fossil fuels, improving forest health, reducing catastrophic wildfires, and reducing greenhouse gas emissions.

The primary goal of this project was to utilize waste forest residues for the production of bioenergy and biobased products as a strategy to: 1) increase energy supply from renewable sources, 2) improve the environment, and 3) promote economic development in rural, forest-dependent communities in the western U.S. Using forest residues as a feedstock for BCTs provides substantial social and economic benefits for rural, timber-dependent communities, including providing jobs for local workers and improving air quality through reduced emissions from open pile burns. In addition, converting forest residues into biochar is an effective strategy for carbon sequestration and improving the productivity of forest soils while reducing the incidence of catastrophic wildfires.

Our interdisciplinary research team, consisting of academics, business professionals and land managers, worked together for about four years (September 2013 – December 2017) to: 1) conduct field-based experiments to develop innovative tools and systems that improve the economics, accessibility, and production of quality feedstocks from forest residues (Task Area 2), 2) develop and test stand-alone in-woods or near-the-forest BCTs to evaluate the economic feasibility of commercialization of BCTs for the production of biochar, torrefied wood, and briquettes (Task Area 3), and 3) perform analyses to quantify the life cycle economic and environmental benefits of utilizing forest residues with BCTs for the production of bioenergy and bioproducts (Task Area 4). A project management team (Task Area 1) consisting of three coordinators from each Task Area (TA), a full-time project coordinator, and grant specialists from the Office of the Humboldt State University Sponsored Program facilitated the project implementation.

Production of Quality Feedstock from Forest Residues

During timber operations, treetops left from sawlog processing and small-diameter trees were delimbed and separated from the slash pile. Processed treetops (i.e. stemwood only) were converted into different feedstock sizes using three mobile, high-production, comminution machines (chipper, micro-chipper and sawdust machine). The mean geometric lengths for processed treetops chipped using a regular chipper are highly uniform: more than 95% of the chipped materials were less than 50 mm in length. Micro-chipper and sawdust machines produced small sizes of chipped materials (<5mm in length) to meet feedstock specification technologies that require small particles. All these chipping machines showed high production capacity levels (20-30 bone dry metric tons (bdmt)/hour), resulting in comminution costs ranging from $11.00 to $13.00/bdmt. The average bulk densities of chipped materials ranged between 220 - 322 kg/m^3, which is much higher than ground materials (137 kg/m^3). Further evidence of the good-quality feedstock produced from forest residues was the low moisture content (<20%) and ash content (<1%).

The Forest Concepts woody biomass baler can handle all remaining forest residuals including low-density tops, branches, and understory brush biomass and create high-density biomass bales that are amenable to truck transportation, long-term storage, and grinding at the time of use. A lightweight, modular baler was specified for mounting on forwarders, trailers, truck chassis and the like. A self-propelled, remotely-controlled baler was specified as an alternative to in-woods grinders. Finished bales had an average volume of 1.36 m^3 (48 ft^3) and a typical bulk density of approximately 350 kg/m^3 (22 lb/ft^3) at 15% to 29% moisture content.

Appropriate biomass operations logistics coupled with the production of pre-processed feedstocks such as biochar, briquettes, or torrefied wood chips within a supply chain can enhance the economic transportation capacity of a biomass recovery operation. Transportable biomass conversion facilities producing biochar, briquettes, and torrefied wood were modeled and optimized for five sub-regions within the Pacific Northwest to characterize the potential economic viability of transportable designs. The optimal transportable design included facility movement on a 1 to 2.5 year frequency depending on product and region with biochar being the most likely to be economically viable. Biochar is the most likely candidate for a transportable conversion system given its relatively low power consumption, high allowable input moisture content, and low product transportation cost.

Lessons learned:

1. Quality feedstocks that meet the specifications for different biomass conversion technologies can be produced by using different comminution machines, especially when stemwood is separated from the forest residue piles during logging or thinning operations.

2. Field trials demonstrated that the Forest Concepts woody biomass baler can handle all remaining forest residuals and create high-density biomass bales that

are amenable to truck transportation, long-term storage, and grinding at the time of use.

3. Biomass sorting and arrangement at a timber harvesting or forest thinning site is to be done in a de-coupled manner. However, biomass supply should be scaled to meet BCT capacities and planned to occur *concurrently with biomass conversion* and feedstock comminution operations that take place at the same site.

Forest Residues Conversion into Biobased Products

All three biomass conversion technologies evaluated in this study were modified to be suitable for mobile, in-field operation with forest residues. By analyzing the quality of products from each machine with different feedstocks, specifications were developed based on moisture content, ash content, and particle size distribution of comminuted forest residues. The biochar machine could accept the widest range of feedstocks up to 100 mm particles sizes, 20% ash, and 25% moisture; briquettes with the highest density and durability (DU) were produced from feedstock between 8% and 12% moisture content and a high fraction (>50%) of fine particles or sawdust; the torrefier performed best with feedstock moisture content below 10% but could accept up to 25%; feedstock particle size specifications for the torrefier were stringent, requiring the majority of the particles to be between 3 and 25 mm.

One of the main constraints across all technologies is achieving the target moisture content before conversion. This was successfully completed by integrating waste heat drying. Excess heat from torrefaction or biochar production can be recovered to dry incoming residues that can be sent to the original BCT or a separate on-site BCT.BCT plant electrical loads can be met using forest residues with a biomass gasifier generator set as an alternative to a diesel generator. A mobile biomass gasifier was able to provide electricity to unbalanced, highly variable BCT loads with low power factors.

Through the Waste to Wisdom project, the three main BCTs plus a gasifier generator and a waste heat dryer were tested individually and within integrated demonstration systems to collect operational performance data for economic and environmental analyses. Two demonstration systems resulting from this project are highlighted in **Figure 1**, below.

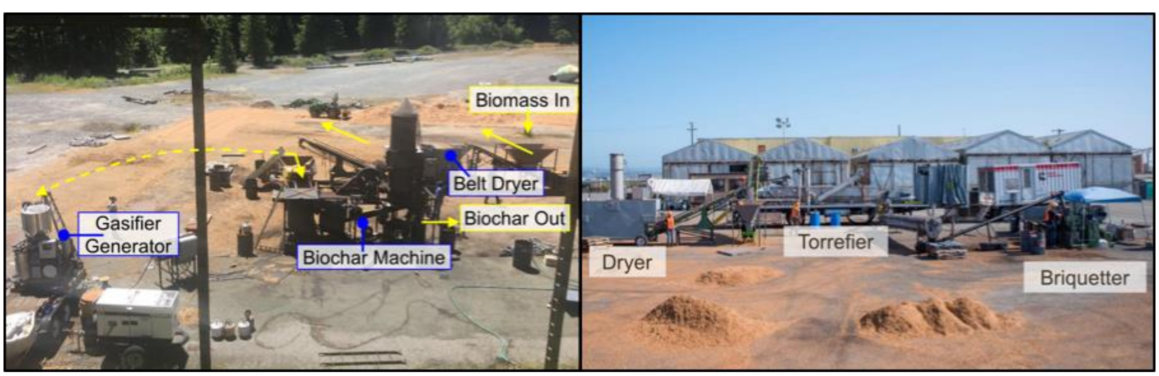

Figure 1. Integrated biochar system (left) using a waste heat dryer to dry forest residues before conversion into biochar and a biomass gasifier generator to provide electricity to the plant. The input rate was 320 kg/hr (dry basis) with 79 kg/hr of biochar production. Torrefied biomass briquettes were produced in a continuous flow torrefaction demonstration plant (right) using a dryer, torrefier, and briquetter in series. The input rate was 650 kg/hr with 550 kg/hr of torrefied briquette production.

Economics of Forest-to-Product Using Three Biomass Conversion Pathways

Forest-to-Product costs depend on feedstock costs to the biomass conversion facility, product types to be processed, facility scale, BCT facility location on the landscape, and the frequency that the facility is moved. The presence of a local pulpwood market can affect biomass availability and characteristics. State regulations and energy cost structures can also affect overall economics. Feedstock costs to the biomass conversion facility in five sub-regional studies in Washington (WA), Oregon (OR), and California (CA) varied from \$30 to \$50 per bdmt of feedstock including moving the transportable facility around the landscape. Producing the biomass products within the facility (the sum of CapEX, OpEX, Drying, Conversion and Packaging) was the most costly component **(Figure 2)** and scale dependent **(Figures 3, 4)**.

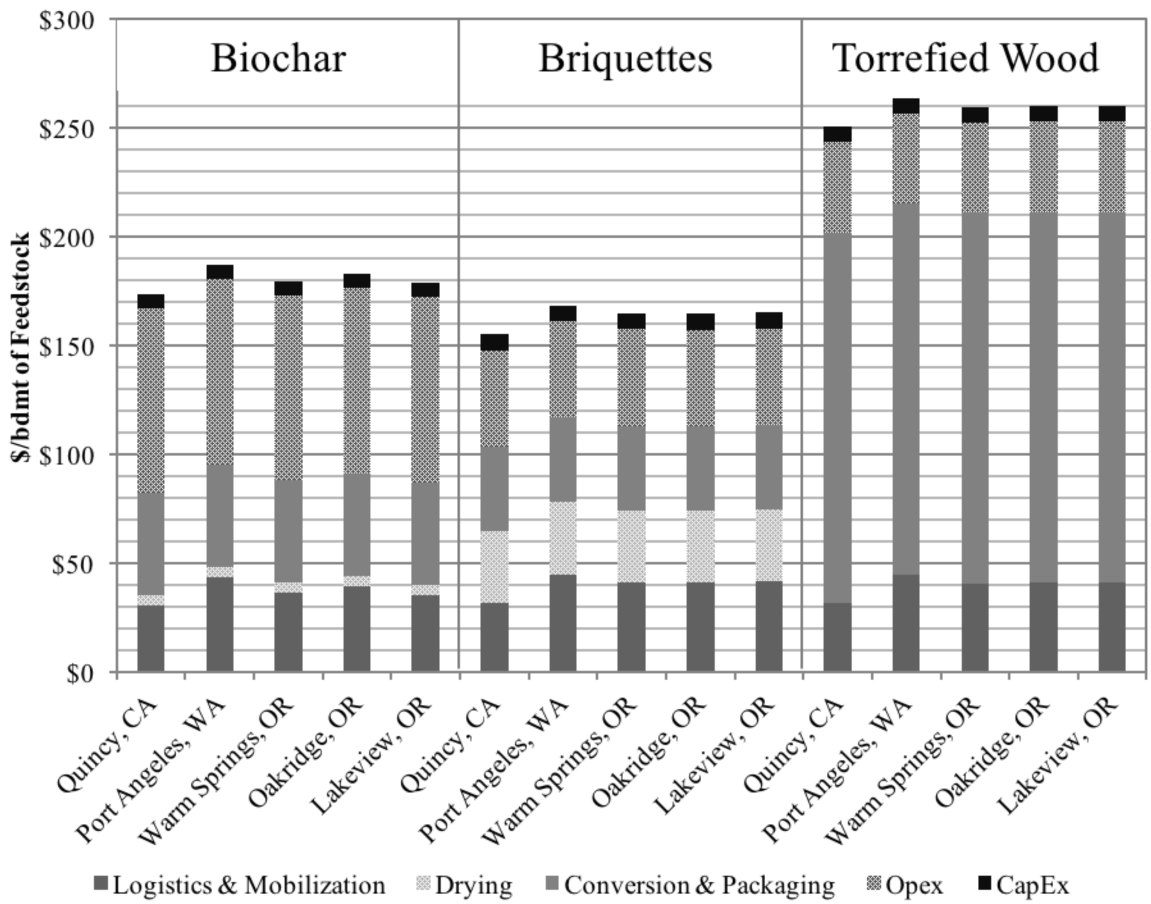

Figure 2. Production cost of product expressed as \$/bdmt of feedstock.

Cost Component	Description
Logistics & Mobilization	Includes costs associated with transport, processing, and facility mobilization
Drying	Cost incurred when reducing residue moisture content to processing specifications.
Conversion & Packaging	Conversion cost of producing biochar including cost of the core technology amortized over a ten-year period - excludes labor component [within Plant OPEX]. Packaging and loading truck costs from plant to market are also included.
Plant OpEx	Plant operational expenses of conversion facility - includes plant labor costs, power, insurance, supplies, maintenance [less conversion technology operating expenses beyond labor]
Plant CapEx	Plant capital costs related to facility - includes site prep, technology, material receiving, storage, retrieval, and mechanical installs [excludes conversion technology capital costs]

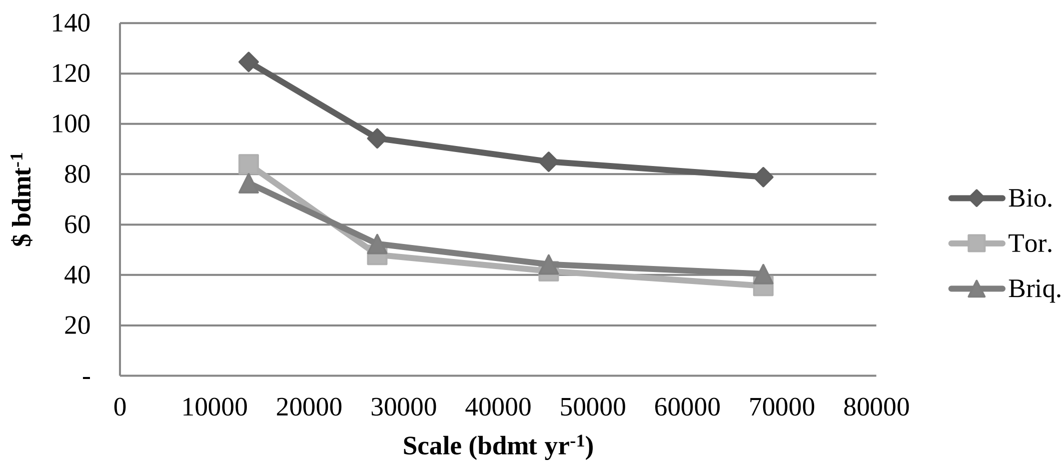

Figure 3. Core operational expenses (plant labor costs, power, insurance, supplies, maintenance, etc. [less conversion technology operating expenses beyond labor]) vs. plant scale (bdmt yr^{-1}). As plant scale increases, operational expenses (per unit input) decrease. Costs are expressed as dollars per tonne equivalent of feedstock.

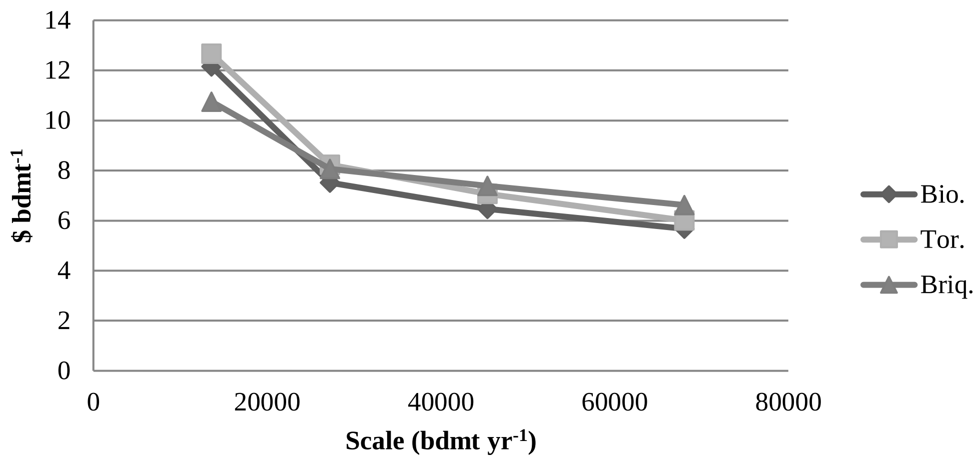

Figure 4. Core capital expenses (site prep, technology, MRS&R (Material Receiving, Storage, and Retrieval at the BCT), mechanical installs [less conversion technology capital costs]) vs. plant scale (bdmt yr^{-1}). As plant scale increases, capital expenses per unit input decrease for a ten-year facility service life. Costs are expressed as dollars per tonne equivalent of feedstock.

Lessons learned:

1. Regional feedstock composition and availability were the largest indicator of feedstock delivery costs. The absence of a regional pulp market provided low-cost small logs and logs of noncommercial species that could be handled by conventional self-loading log trucks and short trailers. Where local pulp markets exist, harvest residuals were primarily branches. Feedstock handling and transport were more expensive, requiring chipping, grinding, or baling at the landing or central landing before transport to the BCT.
2. Although transportation costs are important, they are overshadowed by the cost of biomass conversion technologies examined in this research. Biomass conversion costs are technology dependent and may be the key to lowering supply chain costs to enable market viability.
3. Feedstock moisture management was important, particularly for those biomass conversion technologies that require low moisture feedstock. Active drying based on waste heat recovery can extend the operational season for the BCT equipment, thereby improving system economics.
4. Although components of transportable plants are modular, sufficient economies of scale exist for the range of transportable plants evaluated (15,000 to 50,000 bdmt annual input) such that larger transportable plants have lower conversion costs than smaller plants.
5. Results generally indicate that system costs are largely dependent on market pricing, plant assumptions, and conversion estimates while processing and transportation costs are smaller. The latter items are, nonetheless, important contributors for small-scale biomass conversion facility design configurations.
6. Access to electrical grid-energy could be the difference between an economically-viable supply chain operation and one that is not.

Public Perceptions and Environmental Impacts

The Waste-to-Wisdom concept may not be viable and will not be sustainable if there are not positive environmental impacts from it. Environmental impacts were examined from a number of different perspectives. Life cycle analyses (LCA) were conducted on the processes and on the products to determine the impacts on the carbon cycle. The effectiveness of biochar was studied with a focus on mine site remediation because abandoned mine sites are an issue on remote forest lands and offer a potentially higher-valued use for biochar produced from nearby forest waste. In addition, the impacts of slash pile burning, the alternative to utilization, were modeled and air quality as well as human health impacts from this burning were estimated.

Biomass waste utilization can show positive environmental impacts. For example, lifecycle assessment of forest residues that were recovered and turned into feedstocks show that residues that are gasified to produce electricity at a near-woods conversion site reduce greenhouse gas emissions by 2.4 times compared with hauling those residues four hours to a larger in-town biomass generation facility. An on-site diesel generator would have a total global warming (GW) impact about 2.8 times higher than the gasifier. In another example, LCA of biomass briquettes produced from biomass waste in substituting for propane in domestic heating reduced greenhouse gas emissions by 94 percent.

The forest waste utilization conceived in Waste to Wisdom will not be possible if thinning operations and production of products from those thinnings are not also socially acceptable. Social acceptance was evaluated through a survey to determine public perceptions of forest waste utilization. While there is general public support for forest thinning and using those thinnings to produce products such as biochar and bioenergy, opposition to thinning generally increases along with increasing population density, suggesting different public education strategies and messages regarding the role of forest thinning in forest health depending on the population density.

Lessons learned:

1. Near-woods bioenergy production systems using power from on-site wood gasifier showed better environmental performance than their fossil fuel alternatives: on-site diesel and in-town grid electricity.
2. Utilization of post-harvest residues as biofuel as opposed to the typical pile and burning practice shows a notable environmental advantage.
3. Particulate matter from burning slash piles can travel great distances away from the burns and have detrimental health effects on densely-populated urban areas as well as smaller rural communities.
4. Policies and actions that would avoid in-forest pile burning would reduce adverse human health impacts and poor air quality.
5. Methodologies developed in air quality modeling work could help policymakers to identify best practices in fire management based on site-specific factors
6. Biochar made from wood waste in Montana and Idaho can be applied relatively easily to mine sites, where it aids in the site reclamation by increasing site cover and speeding revegetation. Application rates of around 22 Mg/ha (9.8 tons/acre) are the most effective for changing soil physical, chemical, and biological properties.

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LIST OF ABBREVIATIONS

- APL – All Power Labs, Inc.
- ASABE - American Society of Agricultural and Biological Engineers
- BSTP - Biomass Sorting and Treetops Processing
- BCT – Biomass Conversion Technology
- bdmt – bone dry metric ton
- BETO – Bioenergy Technologies Office
- BSI - Biochar Solutions Inc.
- CBRO - Centralized Biomass Recovery Operation
- CIP – Clean in Place
- CORRIM - Consortium for Research on Renewable Industrial Materials
- DCFROR - Discounted Cash Flow Rate of Return
- DOE – U.S. Department of Energy
- DU – Mechanical durability of briquettes
- EPA - US-Environmental Protection Agency
- GW - Global Warming
- gwt – green weight ton
- HHV - High Heating Value
- HSU – Humboldt State University
- LCA – Life Cycle Analysis
- LCI – Life Cycle Inventory
- MRS&R – Material Receiving, Storage, and Retrieval
- MSP - Minimum Selling Price
- NARA - Northwest Advanced Renewables Alliance
- NEI - National Emission Inventory
- NTB - Non-torrefied Briquettes
- NTT – Norris Thermal Technologies
- ORC - Organic Rankine Cycle
- PFI - Pellet Fuel Institute
- PI – Principal Investigator
- PMH – productive machine hour
- RFFI - Redwood Forest Foundation, Inc.
- RPPR - Research Performance Progress Report
- SERC – Schatz Energy Research Center
- SOPO – Statement of Project Objectives
- TA – Task Area
- TOB - Torrefied Briquettes
- TPD – Tons per Day
- USDA – U.S. Department of Agriculture
- W2W – Waste to Wisdom
- WHO – World Health Organization

TASK 1.0: PROJECT MANAGEMENT

- **Organization completing task:**

1. Han-Sup Han, P.I., Forest Operations Research Laboratory, HSU
2. Steve Karp, Executive Director, HSU Sponsored Programs Foundation

- **Description of task:**

Reports and other deliverables were provided in accordance with the Federal Assistance Reporting Checklist following the instructions included therein. Additional deliverables were submitted as required including attending Department of Energy (DOE) sponsored Peer Review meetings every other year, and occasional attendance as requested and reasonable at DOE-sponsored seminars or workshops.

- **Summary of key accomplishments:**

The Office of HSU Sponsored Programs Foundation played key roles of setting up the official contract of the Waste to Wisdom project with DOE and establishing the sub-contracts with research partners and cooperators. The Foundation also managed and supported financial implementation activities such as invoice review/approval and budget modifications in consultation with the DOE Project Manager and Monitor throughout the project performance period. Working with the project coordinators, the Office prepared and submitted SF-425 Federal Financial Reports on a quarterly basis, which summarized the status of the project budget spending and cost share certification.

For the technical side, a project management team (TA1) was formed at the beginning of the project to facilitate project management and research integration activities across the sub-tasks listed in the Statement of Project Objectives (SOPO). The team included:

1. Han-Sup Han, PI & TA1 and TA2 Coordinator, HSU
2. Arne Jacobson, Co-PI & TA3 Coordinator, Schatz Energy Research Center, HSU
3. E.M. (Ted) Bilek, Co-PI & TA4 Coordinator, Forest Products Laboratory, USDA Forest Service
4. Joel Bisson, Project Coordinator, HSU

The TA1 Coordinator was in charge of overall project coordination. The Project Coordinator was a full-time staff member based at HSU supporting all the project management activities. The task coordinators (TAs 2, 3 and 4), in addition to their own research tasks, compiled and reported the research activities within their respective task areas at the project management meetings with DOE. They also took the lead on the preparation of presenting the project progress at the DOE Peer-Review and Comprehensive Project Review meetings, as well as submission of quarterly Research Performance Progress Reports (RPPR).

The project management team and the Foundation Office performed the following activities:

1. Coordinated phone conference calls to report project progress and status to the DOE project manager and monitor on a monthly basis.
2. Submitted RPPR and SF-425 Federal Financial Reports at the end of each quarter, started on 07/01/2014 and ended on 09/30/2017.
3. Reviewed and approved budget modifications in sub-contracts. All the contract modifications were reported to DOE.
4. Made oral presentations at professional meetings and public workshops to explain the scope and the results of the Waste to Wisdom project.
5. Managed annual PI meetings to discuss an overall progress of each sub-task and plan for the next steps.
6. Reviewed and approved invoices along with their project progress reports submitted by sub-contract recipients. The HSU invoices were submitted to DOE for receiving the money.
7. Presented the project progress and status at the DOE Peer-Review and Comprehensive Project Review meetings.
8. Planned/coordinated/managed field demos for three years (2014, 2015, and 2016) showing innovative biomass operations logistics and new biomass conversion technologies that were developed and tested in the project.
9. Collaborated in presenting three public webinars summarizing the research outcomes of the W2W project.
10. Coordinated project integration research efforts of finalizing economic and environmental analysis of utilizing forest residues for production of bioenergy and bio-based products.
11. Facilitated the publication process of the W2W research papers in the Special Issue of American Society of Agricultural and Biological Engineers (ASABE) journal: 14 research papers accepted for publication.

- **Deliverables:**

  Reports and Publications

  1. Waste to Wisdom. 2018. Utilizing forest residues for the production of bioenergy and biobased products. *Applied Engineering in Agriculture*. ASABE special collection publication. 34(1): 5-10.
  2. Research Performance Progress Reports (RPPR) and SF-425 Federal Financial Reports
  3. Responses to the comments and suggestions made by the reviewers:
     a. 2015 DOE BETO Project Peer-Review meeting, Alexandria, VA. March 23, 2015
     b. 2017 DOE BETO Project Peer-Review meeting, Denver, CO. March 9, 2017

Oral presentations at professional conferences and public workshops

1. Han, H.-S. 2014. Waste to Wisdom: Utilizing forest residues for the production of bioenergy and biobased products. NARA Annual Meeting, Seattle, WA. September 15-17, 2014.

2. Han, H.-S. 2014. Waste to Wisdom: Utilizing forest residues for the production of bioenergy and biobased products. BRDI Management Conference Call Meeting, November 18, 2014

3. Han, H.-S. 2015. Waste to Wisdom: Utilizing forest residues for the production of bioenergy and biobased products. DOE Project Peer-Review meeting, Alexandria, Virginia. March 23, 2015.

4. Han, H.-S. 2015. Waste to Wisdom: Utilizing forest residues for the production of bioenergy and biobased products. Small Log Conference, Coeur d' Alene, Idaho. March 24 -26, 2015.

5. The Waste to Wisdom research team. 2015. The progress and status of the project, Waste to Wisdom: Utilizing forest residues for the production of bioenergy and biobased products. Presented at the Comprehensive Internal Review meeting, Golden, Colorado. September 18, 2015.

6. Han, H.-S., T. Bilek and A. Jacobson. 2015. Waste to Wisdom: Utilizing forest residues for the production of bioenergy and biobased products. Presented at the Comprehensive Internal Review meeting, Golden, Colorado. September 18, 2015.

7. Bilek, E.M. (Ted). 2016. Waste to Wisdom: An Update for the DOE Biomass R&D Technical Advisory Committee. Presentation during their visit to Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. August 17, 2016.

8. Han, H.-S. 2017. Utilizing forest residues for the production of bioenergy and biobased products. Presented at the 2017 DOE BETO Project Peer-Review meeting, Denver, CO. March 9, 2017.

9. Han, H.-S. 2017. Utilizing forest residues for the production of bioenergy and biobased products. Presented at a Public Workshop in Sacramento, California, May 17, 2017.

TASK 2.0: PRODUCTION OF QUALITY FEEDSTOCK FROM FOREST RESIDUES

SUBTASK 2.1. SORTING AND ARRANGING FOREST RESIDUES

- **Organization completing task:**
  1. Principal Investigator: Han-Sup Han, Humboldt State University
  2. Partners: Peterson Pacific Corporation, Steve Morris Logging LLC, and Green Diamond Resource Company

- **Description of task:**

Field-based experimental studies were applied to develop strategies and methods of sorting and arranging forest residues resulting from timber harvesting and fuel reduction thinning operations. The goal was to develop a feedstock supply that 1) minimizes contamination; 2) facilitates comminution; 3) improves moisture content control; and 4) improves handling and transportation efficiency.

- **Summary of key findings and research impacts:**

The tree tops left from sawlog processing and small-diameter trees were delimbed and separated from the slash pile. Three harvest units were selected, and each unit was divided into three sub-treatment units (no, moderate, and intensive sorting). Results showed that the cost of operations were higher for the sorted sub-units when compared to the non-sorted. The total cost of operation (felling to loading) for sawlogs was lowest at $40.81/m^3 in the no sorting treatment unit, followed by moderate ($42.25/m^3) and intensive treatment unit ($44.70/m^3). For biomass harvesting, the cost of operation (felling to delimbing and sorting) ranged from $27 to $29/bdmt. The most expensive operational phase was primary transportation; therefore, the cost of treating the forest residues had less impact on the overall cost. The cost increase ($1,150/ha) of sorting forest residues could offset cost savings from avoided site preparation expenses ($1,100/ha), provided that the forest residues were utilized.

To develop strategies to reduce moisture content in forest residues at the harvest site, we also compared four different arrangement patterns of forest residues including criss-cross, teepees, processor piled, and scattered residues in three different timber harvest units. There was an overall moisture content drop from 52% to less than 20% over the 12-month study period. Models were developed for evaluating variables affecting moisture content such as diameter, species, arrangement patterns and weather parameters. As a resulting impact of this study, a local forest company has changed its timber operation strategies to separate and process tree tops and small-diameter trees for the benefits of no slash burning and improved utilization of non-sawlog wood materials.

- **Lessons Learned:**
  1. Separating stem wood components from forest residues is operationally feasible to do, but markets for those materials are a key to successfully implement sorting and making arrangements of forest residues.
  2. Moisture content in biomass raw materials can be effectively reduced to 15% or lower by separating stem wood and piling them to facilitate air flow for 6 to 12 months on site.

- **Deliverables:**

  Peer Reviewed Papers

  1. Kizha, A.R., H.-S. Han, J Paulson, and A. Koirala. 2017. Strategies for reducing moisture content in forest residues at the harvest site. *Applied Engineering in Agriculture*. ASABE special collection publication. 34(1): 25-33.
  2. Kizha, A.R., H.-S. Han. 2017. Moisture content in forest residue piles: An insight on sampling methods and procedures. *Current Forestry Reports*. 3(1):1-11. doi 10.1007/s40725-017-0060-5.
  3. Kizha, A.R. and H.-S. Han. 2016. Processing and sorting forest residues: Cost, productivity and managerial impacts. *Biomass & Bioenergy*. Vol. 93: 97-106.

  Oral presentations at professional conferences and public workshops

  1. Kizha, A. 2015. Techniques to reduce moisture content of forest residues at the harvest site. Council on Forest Engineering Annual Conference, Lexington, Kentucky. July 19 – 22, 2015.
  2. Kizha, A. 2016. In-woods treatment of forest residues for production of quality feedstocks. Forest Products Society 70th International Convention, Portland, OR. June 29, 2016.
  3. Kizha, A. 2016. Machine activities and interaction at the landing in a cable yarding operation. Forest Products Society 70th International Convention, Portland, OR. June 28, 2016.
  4. Han, H.-S. 2017. Production of quality feedstock from forest residues: sorting, comminution, and screening. International Biomass Conference & Expo. Minneapolis, Minnesota, April 10 – 13, 2017.

SUBTASK 2.2. **DENSIFICATION OF LOOSE FOREST RESIDUES**

- **Organization completing task:**

  1. Principal Investigator: Jim Dooley, P.I., Forest Concepts Inc.
  2. Partners: Humboldt State University; Steve Morris Logging LLC; Green Diamond Resource Company; Oregon State University, Arsiero Logging Company, Rainier Wood Recyclers; Peterson Pacific Corporation; and 6k Products Company

- **Description of task:**

Upgrade the Forest Concepts prototype forest residue baler for use on forest sites. Conduct demonstration and field trial by sub-recipient Forest Concepts on forest residues generated on a Green Diamond Resource Company harvest conducted by sub-recipient Steve Morris Logging. Conduct controlled field studies on a Snoqualmie National Forest commercial thinning site in cooperation with Arsiero Logging Company. Evaluate time-study and bale transport density data and provide results to forest operations and system economics teams. Conduct a long-term bale moisture content and seasonal dry-down study to inform transportation and storage system evaluations. Prepare and publish preliminary baler specifications and estimated costs for baling logging slash.

- **Summary of key findings and research impacts:**

Sorting and separate recovery of poles from the logging slash (as studied in Subtask 2.1) results in a need to cost-effectively collect, transport, and store the remaining very low-density tops, branches, and understory brush biomass. Baling appears to be less costly than bulk hauling and/or in-woods grinding. Field trials demonstrated that the Forest Concepts woody biomass baler can handle all remaining forest residuals and create high-density biomass bales that are amenable to truck transportation, long-term storage, and grinding at the time of use.

The productivity of forest biomass collection equipment such as balers is highly dependent upon site conditions, spatial distribution of biomass, operator skill, and functional design of the equipment used. A series of empirical time studies was conducted using experienced operators to assess the specific productivity for making bales from urban, forest thinning, and forest harvest residual woody biomass. Commensurate with prior studies evaluating bundlers and forwarders, the work elements of grappling, slashing, and arranging biomass with a boom-type loader consumed approximately 63% of the total time. Biomass gathering can only be improved by better arrangement during harvest operations. Platen cycling time was directly related to chosen engine power and available hydraulic flow. Increasing platen speed will have limited benefit to total productivity, but will substantially increase fuel consumption and capital cost.

Table 1. Time study data allocation of baling time to individual work elements.

	Average of total time (for 3 reps)			Average bale minutes	
Work element	mm:ss	percent	SD		SD
Platen cycling	04:57	23.8%	5.8%	4.9	1.2
Pile working	04:49	23.1%	4.3%	4.8	0.9
Slashing	03:58	19.1%	1.1%	4.0	0.2
Pile to baler	02:18	11.1%	1.8%	2.3	0.4
Place in chamber	01:22	6.6%	0.2%	1.4	0.0
Rotating	01:19	6.3%	2.2%	1.3	0.5
Packing	01:14	6.0%	2.4%	1.2	0.5
Move baler	00:29	2.3%	0.4%	0.5	0.1
Break	00:20	1.6%	1.5%	0.3	0.3
Total	20:47			20.8	4.1
			finishing	13.0	
		min/dy	total	33.8	
		440.0	8 hr day	13.0	bales

Simulations of baler specific-production rates (time to make a bale) were informed by field study data across all sites and dates. Sensitivity analyses were used to inform the specification of functional design attributes for commercial models of woody biomass balers.

Two classes of balers are proposed for commercial development and operational field trials. A lightweight, modular baler was specified for mounting on forwarders, trailers, truck chassis and the like. A self-propelled, remotely-controlled baler was specified as an alternative to in-woods grinders.

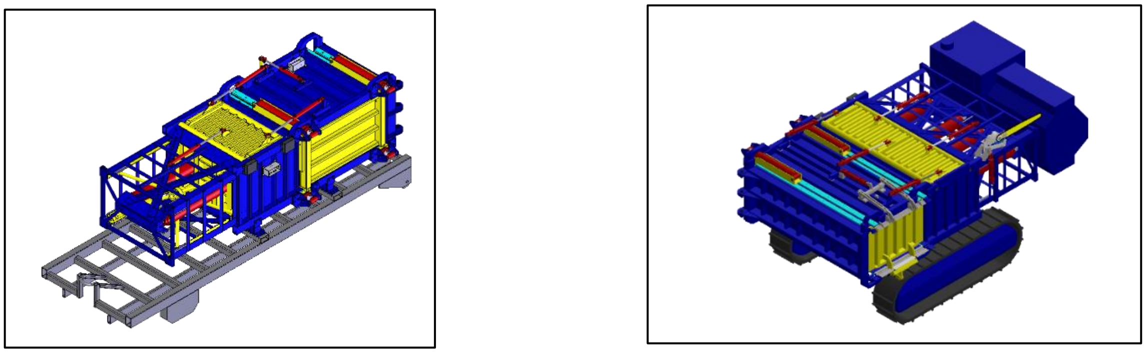


Figure 5. Concept renderings of forest utility baler (left) and large self-propelled high-production baler.

A long-term bale dry-down and moisture content study was conducted using woody biomass bales from field trials. Large rectangular bales of forest and urban biomass were produced beginning in August 2015 and periodically until June 2016. Finished bales had an average volume of 1.36 m^3 (48 ft^3) and a typical bulk density of approximately 350 kg/m^3 (22 lb/ft^3) at time of baling. Weights were measured approximately monthly until the entire lot of bales was ground into fuel in December 2016. The study found that all bales dried considerably during the spring and summer months, achieving a minimum moisture content in the early fall of 15% to 29% wet basis (wb). The ending moisture content in December 2016 ranged from 44% to 57% (wb), with a mean moisture content of 53% (wb).

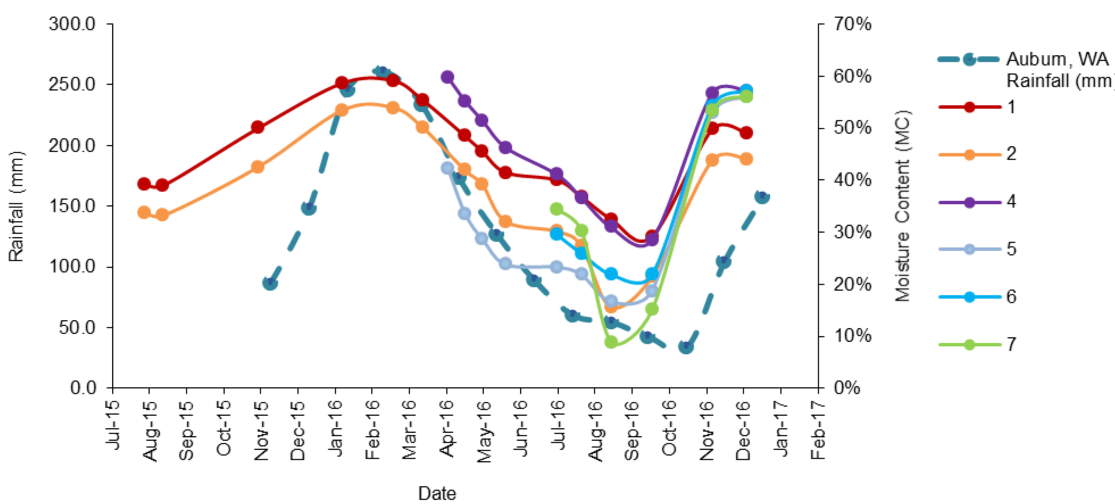


Figure 6. Forest biomass bale moisture content over time and monthly rainfall at the study site.

Biomass moisture content tracked closely with monthly rainfall and seasonal environment. Neither minimum late-summer nor peak winter moisture content was related to initial moisture content at the time of baling. Bales of forest and urban woody biomass proved to be structurally stable during long-term storage to enable handling and final transport to a centralized grinding location.

- **Lessons Learned:**

  1. Field trials demonstrated that the Forest Concepts woody biomass baler can handle all remaining forest residuals and create high-density biomass bales that are amenable to truck transportation, long-term storage, and grinding at the time of use.
  2. Biomass moisture content tracked closely with monthly rainfall and seasonal environment. Neither minimum late-summer nor peak winter moisture content was related to initial moisture content at the time of baling.
  3. Two classes of balers were proposed for commercial development and operational field trials. A lightweight, modular baler was specified for mounting on forwarders, trailers, truck chassis and the like. A self-propelled, remotely-controlled baler was specified as an alternative to in-woods grinders.

- **Deliverables:**

  Peer Reviewed Papers

  1. Dooley, J.H., M.J. Wamsley, and J.M. Perry. 2017. Moisture content of baled forest and urban woody biomass during long-term open storage. *Applied Engineering in Agriculture*. ASABE special collection publication. 34(1): 225-230.

  Conference papers with oral presentations

  1. Dooley, J.H., C.J. Lanning, and D.N. Lanning. 2015. Conceptual specification of forest residue balers using the Appreciative Design Method. ASABE Paper No. 152189213. St. Joseph, MI, American Society of Agricultural and Biological Engineers.
  2. Dooley, J.H., C.J. Lanning, and D.N. Lanning. 2016. Conceptual specification of forest residue balers for woody biomass. ASABE Paper No. 162455264. St. Joseph, MI, American Society of Agricultural and Biological Engineers.

  Reports published through Waste to Wisdom website

  1. Dooley, J.H. 2014. Baling of forest residuals (aka logging slash) for transport to centralized processing sites. Waste to Wisdom website blog. December 18, 2014.
  2. Dooley, J. H. 2015. Specification of Bale Dimensions. Design of a Forest Residue Baler - BRDI Task 2.2. Auburn, WA, Forest Concepts, LLC: 8.
  3. Dooley, J. H., C. J. Lanning, et al. 2015. Conceptual specification of large-bale forest residuals balers. Auburn, WA, Forest Concepts, LLC: 9.
  4. Dooley, J. H., C. J. Lanning, et al. 2015. Conceptual specification of forest utility balers for woody biomass. Auburn, WA, Forest Concepts, LLC: 9.
  5. Dooley, J.H., M.J. Wamsley. 2016. Woody biomass bale dry-down during storage and handling. Waste to Wisdom website blog. June 10, 2016.

Oral presentations at professional conferences and public workshops

1. Lanning, D.N. 2014. Beneficiation of woody biomass feedstocks. TAPPI IBBC International Bioenergy and Bioproducts Conference September 17, 2014.
2. Dooley, J.H. 2014. Reactor-ready feedstocks; the next generation of supply chain technologies: Improving conversion process productivity and quality through better feedstocks. TAPPI IBBC International Bioenergy and Bioproducts Conference September 17, 2014.
3. Dooley, J.H. 2015. High-density baling of biomass – Applications in urban woody biomass, switchgrass, and forest biomass. NewBio Northeast Bioenergy Webinars. Pennsylvania State University. July 14, 2015. https://www.youtube.com/watch?v=-vzd0ufev50&feature=youtu.be
4. Dooley, J.H., M.C. Perry, C.J. Lanning, D.N. Lanning. 2015. Baling woody biomass from forest residuals. Engineer's Week workshop. Auburn, Washington. February 23, 2015.
5. Perry, M.C., J.M. Perry. 2015. Forest biomass collection and utilization. SmallWood 2015 Conference. Coeur d'Alene, Idaho.
6. Dooley, J.H., C.J. Lanning, D.N. Lanning, N. Owen, J.M. Perry 2016. Overview of Waste to Wisdom project and demonstration of forest biomass bales. Washington State Biomass Working Group Workshop and Conference. Chehalis, WA. May 18, 2016.
7. Dooley, J.H., C.J. Lanning, D.N. Lanning, N. Owen, J.M. Perry 2016. Conceptual specification of large-bale forest residue balers. Society of American Foresters Annual Meeting, Portland, Oregon. June 29, 2016.
8. Dooley, J.H. 2017. Conceptual specification of forest residue balers. Waste to Wisdom Public Workshop, Sacramento, California. May 17, 2017

- **Patent Applications**

Patent Provisional Applications – Three provisional patent applications were filed with the US Patent and Trademark Office. All three were subsequently allowed to lapse.

1. U.S. Provisional Patent Application No: 62/216,750
   Filing Date: September 10, 2015
   Title: Biomass densification through baling
2. U.S. Provisional Patent Application No: 62/232,861
   Filing Date: September 25, 2015
   Title: Conceptual specifications of forest utility balers for woody biomass
3. U.S. Provisional Patent Application No: 62/232,892
   Filing Date: September 25, 2015
   Title: Conceptual specifications of large-scale forest residuals baler

SUBTASK 2.3. **PRODUCTION OF HIGH QUALITY FEEDSTOCKS THROUGH COMMINUTION.**

- **Organization completing task:**
    1. Forest Operations Research Laboratory, HSU.
    2. Collaborators: Peterson Pacific Corporation, Steve Morris Logging LLC, and Green Diamond Resource Company.
- **Description of task:**

Processing equipment and equipment configurations that produce high quality feedstock material, with low contamination, and suitable for use with BCTs were identified.

Additionally, the effects of different chipping knives and grinding bits on the size distribution of feedstock material, as well as fuel consumption and productivity of the different comminution (i.e. chipping and grinding) technologies were examined.

- **Summary of key findings and research impacts:**

Forest residues generated from timber harvest or thinning operations are a potential source of woody biomass for various bioenergy and bioproducts. New emerging in-woods biomass conversion technologies, such as torrefaction or briquetting, require specific feedstock characteristics to improve operational efficiencies. To meet these feedstock specification requirements, we evaluated three mobile, high production, comminution machines that produce different sizes of feedstock.

The first trial was to use a disc-chipper or a grinder that is commonly used to produce wood chips. The knife setting for the chipper was set to produce wood chip target sizes of 19 mm or smaller while the screen setting for a grinder was to produce hog fuel less than 50 mm. In an effort to increase feedstock quality, our study separated sub-merchantable trees and tops from slash piles during the timber harvest. A portion of the separated material was further processed to remove limbs to create five material types: processed and unprocessed, conifer and hardwood stem wood, and slash (stems, limbs and chunks). The quality of the feedstock produced was characterized by moisture content, particle-size distribution, bulk density, and ash content. Moisture content of sample collected ranged from 19 to 29%. The mean geometric lengths for unprocessed hardwood, unprocessed conifer, processed hardwood, processed conifer, and slash were 20.60, 18.27, 18.16, 17.41, and 47.47 mm, respectively. The bulk density of the five material types ranged from 137.20 – 322 kg/m^3. The least amount of ash were observed in processed conifer samples (0.27%) and greatest in ground slash (1.5%). The results showed that a high quality feedstock can be produced by separating stem wood from other residues during a harvest.

The second trial was to use a 12-knife, 570-kW drum micro-chipper to produce wood chips small than 63 mm in size. This study evaluated the size distribution, moisture content, bulk density, and ash content of particles generated from micro-chipping stem wood that was separated from forest residues. Four material types: processed and unprocessed, softwood and hardwood stems were produced, air-dried, and chipped in-woods. The average moisture content for the four material types ranged between 18% and 23%. Unprocessed hardwood and softwood produced micro-chips with the longest (6.45 mm) and shortest (4.28 mm) geometric mean particle length, respectively. The bulk density of the four material types ranged from 226.82 – 299.53 kg/m^3. Ash content ranged from 0.25% and 1.18%. The chipper produced 34.0 bone-dry metric tonne (bdmt) of micro-chips per productive machine hour (PMH) at a cost of $10.38/bdmt while consuming 2.66 liters of diesel per bdmt. The productivity, fuel consumption, and operating costs were similar to other high production chipping and grinding machines reported in the literature. The primary difference and advantage of using a micro-chipper was the size of chips produced, which can meet certain feedstock specifications and improve transportation by having a greater bulk density.

The last comminution machine we tested was a sawdust machine that process small-diameter logs into sawdust-sized feedstocks. We evaluated the effect of small-diameter processed hardwood (SH) and small and large-diameter processed softwood (SS and LS) stems had on the productivity and cost of a track mounted sawdust machine that produced sawdust. In addition, moisture content, particle size distribution, bulk density, and the effect of knife wear were evaluated. The sawdust machine's 298-kW engine was capable of comminuting all material types except the LH stems. The machine's productivity ranged between 18.3 and 26.7 bdmt/ PMH at a cost of US $5.30 and US $3.60/bdmt, respectively. The moisture content of material used in the study ranged between 26% and 36%. The geometric mean particle lengths for SH, SS, and LS were 4.7, 5.3, and 4.4 mm, respectively. The machine could not process LH materials due to limited power. The bulk density of feedstock produced ranged between 234 and 281 kg/m^3. Analysis indicated that knife wear did not have a significant effect on comminution productivity and feedstock quality while comminuting 60 green metric tons (gmt) of forest residues. The results from this study suggested that this sawdust machine can be useful in producing feedstock for new biomass conversion technologies that require small, uniform particles.

- **Lessons learned:**

    1. Quality feedstocks (i.e. uniform in size and low ash content) that meet different biomass conversion technologies can be produced by using different comminution machines, especially when stem wood is separated from the forest residue piles during logging or thinning operations.

    2. Productivity, fuel consumption, and operating costs were similar to similar sized chipping and grinding machines with the advantage of producing various sized wood chips from forest residues.

- **Deliverables:**

    <u>*Publications:*</u>

    1. Bisson, J. A., & Han, H.-S. 2016. Quality of feedstock produced from sorted forest residues. *American Journal of Biomass and Bioenergy*, *5*(2), 81-97.

    2. Lee, E., J. Bisson and H.-S. Han. 2017. Evaluating the production cost and quality of feedstock produced by a sawdust machine. *Biomass & Bioenergy*. doi: 10.1016/j.biombioe.2017.06.010.

    3. Bisson, J. and H.-S. Han. Micro-chipping forest residues: an evaluation of feedstock quality, productivity and cost. Submitted to *Biomass and Bioenergy*.

    4. Bisson, J. 2016. Production of quality of feedstocks using different comminution machines. MS Thesis. Humboldt State University, Arcata, CA. 125p.

Oral presentations at professional conferences and public workshops:

1. Bisson, J. 2016. Quality of feedstock produced from sorted forest residues. Thesis defense presented to committee and public at Humboldt State University, Arcata, CA. April 29, 2016.

2. Bisson, J. 2016. Quality of feedstock produced from sorted forest residues. Forest Products Society 70th International Convention, Portland, OR. June 29, 2016.

Field demonstrations:

1. *In-woods feedstock production operations & biomass conversion systems:*
   A live demo directly linking between in-woods feedstock production operations and biomass conversion systems running near the forest. The audience observed forestry machines producing quality feedstock from forest residues and biomass conversion systems producing biochar, torrefied wood, and briquettes, all in one site. Big Lagoon, California. June 17, 2015.

2. *Sawdust machine operations producing biomass feedstock:*
   This demo was to show and explain how stem-wood can be processed into sawdust-size feedstock materials in the woods, which can then be used to produce a wide range of bioenergy and bio-based products. Green Diamond Resource Co. forestlands near Blue Lake, California. July 20, 2016.

SUBTASK 2.4. **CONTROLLING FEEDSTOCK SIZE WITH NEW SCREENING TECHNOLOGIES.**

- **Organization completing task:**

  1. Forest Operations Research Laboratory, HSU

  2. Collaborators: Peterson Pacific Corp., Green Diamond Resource Co., Lane Forest Products Co., and Beaver Korea Corp.

- **Description of task:**

This task evaluated up-to-date feedstock screening technologies (deck and star) for two different types of materials (wood chips and hog fuel) for their screening productivity and accuracy. This task focused on the effects of incorporating these innovations into biomass operations with the intention of improving feedstock quality and meeting BCT particle size requirements.

- **Summary of key findings and research impacts:**

Biomass feedstock particle size is one of the biggest issues in fuel handling efficiency but also, matching the specific feedstock size to current conversion technologies is required to improve consumer confidence in fuel quality assurance. To meet the specification biomass feed stock size requirements for mobile biomass conversion technologies, we analyzed the productivity and size distribution of the two different screen machines, star and deck screening machines for two different material types (hog fuel and wood chips).

Both machines were set up to separate feedstock into three different size categories: unders (<10 mm), accepts (10 – 51 mm), and overs (> 51 mm). Results from the study indicated that the star screener (62.61 and 50.95 gmt/hour) was more productive than the deck screener (26.80 and 15.63 GmTs/hour) when separating wood chips and hog fuel. Also, there was additional cost to apply screening systems to distribute the size of the materials; $3.53/gmt and $6.05/gmt for deck screen with wood chips and hog fuel and $1.61/gmt and $1.98/gmt for star screen with wood chips and hog fuel. For size distribution of screened materials, the13-mm size materials had the highest portion of the accept size class, and the 25-mm size materials were primarily found in the oversize class, and pan size materials (e.g., sawdust) had the highest portion of the under size class. The feedstock materials screened using star and deck screening machines still had size variations exceeding over or under sizes in the under, accept, and over size classes. To improve the quality of screened materials, definitions of the size (under, accept and over) should to be further refined.

There were still size and shape variations in screened biomass materials. Especially, hog fuel or grounded materials appeared to have spear shape (long length ratio compared to width and thickness) much more than chipped materials, causing a problem of diving into screen holes and resulting in heterogeneous size and shape and shape. For the goal of producing of quality feedstock, we used the ASABE definitions for chips, chunks, cubes, shavings, sticks, and strings to characterize biomass feedstock materials. Wood chips and hog fuel shapes are defined based on. Length, width, and thickness of the particles were measured using digital caliper to classify the shapes of the biomass materials. As a result of shape classification, hog fuel materials had more variations in shape than did wood chips. Controlling the length of hog fuel materials was the most important factor determining size and shape distributions of the grounded materials.

Inclined deck screens DS6162 are very common, economical and productive. However, the material such that longer slender particles can “spear” through the screen openings. To reduce diving problems, this study tested two different screen combinations using Deck screen. First screen setting was consisted with four sets of two-inch deck screens on the top screen and second screen setting with one 19-mm and three 51-mm deck screens on the top. There was significant reduction of oversized material in the accept size class also, compared to the screening results using a deck screen machine with four 51-mm deck screens. Furthermore, there was no difference in screening productivity for both wood chips and hog fuel when two screen set-ups in a deck screening machine were used.

- **Lessons learned:**

  1. Star screen performed better than deck screen machine in screening productivity and fuel consumption and had higher productivity with chipped materials than hog fuel (i.e. ground materials).
  2. Size variations in screened materials showed within each of under, accept, and over size class, but little concerns for biomass conversion operations.
  3. Combination screen setting in a deck screen machine significantly improved screening results by reducing diving problems without impacting screening productivity.

- **Deliverables:**

  Publications:

  1. Woo, H. and H.-S. Han. 2018. Performance of screening biomass feedstocks using star and deck screen machines. *Applied Engineering in Agriculture*. ASABE special collection publication. 34(1): 35-42.
  2. Woo, H, and H.-S. Han. Shape classification of comminuted woody biomass materials. Submitted to *Biomass and Bioenergy*.

  Oral presentations at professional conferences and public workshops:

  1. Woo, H. and H.-S. Han. 2017. Performance of screening comminuted woody biomass feedstocks using star and deck screen machines. The 125 International Union of Forest Research Organizations (IUFRO) Congress, September 18-22, 2017. Freiburg, Germany.
  2. Han, H.-S. 2017. Production of quality feedstock from forest residues: sorting, comminution, and screening. Public Workshop on the Waste to Wisdom Project, Sacramento, May 17, 2017.

  Field demonstrations:

  1. *Deck screening operations to control feedstock sizes:*
     A deck machine was operated to show how wood chips and hog fuel were screened to produce uniform feedstock in size. Different screen settings that were designed to improve screening performance were also presented. Big Lagoon, California. June 17, 2015.

SUBTASK 2.5. **CENTRALIZED BIOMASS FEEDSTOCK OPERATIONS SUPPORTING BCTS**

- **Organization completing task:**

  1. Forest Operations Research Laboratory, HSU
  2. Collaborators: Peterson Pacific Corp., Steve Morris Logging LLC, and Green Diamond Resource Co.

- **Description of task:**

Various opportunities and issues associated with biomass feedstock operations logistics were explored with an emphasis to attain a balanced system configuration that can be integrated with BCTs that are set up and run near the forests. The objectives of this study were to examine the logistic effects of integrating a BCT into a Centralized Biomass Recovery Operation (CBRO) based on the availability and storage facilities required for the operations. Concurrently, this study examined two different CBRO workflows/supply chains in order to facilitate integration into a variety of supply chains. Based on the volume of forest residues (biomass) to be processed as well as if the operations within the supply chain were coupled or de-coupled, the scenario selected for the modelling had spatial requirements that varied quite significantly. Two models were developed to evaluate the logistics of the supply chain based on physical location of the comminution and BCT process.

- **Summary of key findings and research impacts:**

Appropriate biomass operations logistics coupled with the production of pre-processed feedstocks such as biochar, briquettes or torrefied wood chips within a supply chain can enhance the economic transportation capacity of a biomass recovery operation. Potential benefits include local energy independence from fossil fuels as well as newly accessible international markets for advanced feedstocks. The space for centralized pre-treatment and conversion sites range from 0.09 ha to 1.45 ha. This study used the Location-Allocation tool within the Network Analyst extension in Arc GIS to generate total and average one-way travel times for analysis of each model. The models used the Maximize Market Share problem type. A sensitivity analysis was conducted in order to explore the effect that having multiple BCT sites has on the total and average one-way travel time of either model. System balance was determined for all iterations of both logistics models which all scenarios within a given Logistics model exhibited shorter travel times than the other. Logistically, arranging comminution and BCT operations to occur at the same in-woods site returned shorter total and average travel times than arranging the two activities to occur at separate in-woods sites.

- **Lessons Learned:**

1. BCT and comminution operations should take place at the ***same site*** to most effectively minimize transportation time within a BCT integrated CBRO supply chain.
2. To avoid storage constraints at the BCT site, biomass collection and supply should be scaled to meet BCT capacities and planned to occur *concurrently with conversion.*
3. Coupled BCT and CBRO operation was not feasible for many situations due to the large biomass storage space.
4. Fewer processing sites within the supply chain will reduce total travel time, which can be attributed to the additional transportation time required to forward comminuted biomass to CBRO sites.

- **Deliverables*:***

Publications:

1. Paulson, J., Kizha, A.R., Han, H-S. Integrating biomass conversion technology and centralized biomass recovery operation: Evaluating the logistics and supply chain. *Logistics* (under review).
2. Paulson, J. 2016. Logistics of integrating a biomass conversion technology into a centralized biomass recovery operation supply chain. MS Thesis. Humboldt State University, Arcata, CA. 78p.

Oral presentations at professional conferences and public workshops:

1. Han, H.-S. 2017. Production of quality feedstock from forest residues: sorting, comminution, and screening. Public Workshop on the Waste to Wisdom Project, Sacramento, May 17, 2017.

SUBTASK 2.6. **INTEGRATION OF BCTS WITH LANDSCAPE LEVEL PLANNING AND TRANSPORTATION LOGISTICS**

- **Organization completing task:**
  1. Principal Investigator: John Sessions, Oregon State University
  2. Michael Berry, Oregon State University
- **Description of task:**

Develop a landscape scale feedstock development scheduling model to optimize the selection of production pathways including collection, comminution, product upgrading (moisture control, densification, and in-woods biomass conversion), and transportation in order to identify pathway streams using BCTs that maximize net revenues while reducing adverse environmental impacts.

- **Summary of key findings and research impacts:**

Transportable biomass conversion facilities producing biochar, briquettes and torrefied wood were modeled and optimized for five sub-regions within the Pacific Northwest: Quincy, CA; Lakeview, OR; Oakridge, OR; Port Angeles, WA, and Warm Springs, OR to characterize the potential economic viability of transportable designs. A mixed integer linear program was developed to characterize the supply chain from residue extraction to market optimizing transportation, production and plant mobility in order to minimize the supply chain costs.

Regional variations including log markets, energy rates, truck regulations and road networks were evaluated to differentiate regional costs and market viabilities. The optimal transportable design included facility movement on a 1-2.5 year frequency depending on product and region with biochar being the most likely to be economically viable. Larger scale plants were more cost effective than smaller scale plants. The presence or absence of a pulp market affected supply chain pathways and costs. Regional feedstock composition and availability was the largest indicator of feedstock delivery costs. Regional supply chain costs varied 5-10% depending on product and region being produced. Transportation, including plant mobilization, accounted for 15%-30% of the overall supply chain cost. The difference between having the full suite of supply chain pathways available and optimized as compared to restricting pathways to use either landings, or central landings, or direct delivery to BCT amounted to a difference of up to 10% of total supply chain costs. Conversion costs typically exceed feedstock and logistics costs and are highly technology dependent. Torrefied wood was the most sensitive to diesel fuel price sensitivity as its conversion process was most energy intensive (±12%-13%) and biochar least sensitive (±3%-5%). Transportation accounted for 5%-30% of the variations due to diesel prices depending on product and region. When including grid-connectivity, cost reductions were approximately 6%-7% for biochar, 27%-29% for briquettes and 33-38% for torrefied wood. Biochar is the most likely candidate for a transportable conversion system given its relatively low power consumption, high allowable input moisture content, and low product transportation cost. A rise in diesel price, while incentivizing transportable conversion facilities due to more cost effective transportation, would be more than offset by the higher cost energy consumption during the conversion process when compared with grid-power with the potential exception of biochar. Additionally, a transportable operation with grid-power could be the difference between an economically viable supply chain operation and one that is not.

- **Lessons Learned:**

  1. Regional feedstock composition and availability were the largest indicator of feedstock delivery costs. The absence of a regional pulp market provided low cost small logs and logs of noncommercial species that could be handled by conventional self-loading log trucks and short trailers. Where local pulp markets exist, harvest residuals were primarily branches. Feedstock handling and transport were more expensive requiring chipping, grinding, or baling at the landing or central landing before transport to the BCT.

  2. Although transportation costs are important, they are overshadowed by the cost of biomass conversion technologies examined in this research. Biomass conversion costs are technology dependent and may be the key to lowering supply chain costs to enable market viability.

  3. Feedstock moisture management was important, particularly for those biomass conversion technologies that require low moisture feedstock.

  4. Although components of transportable plants are modular, sufficient economics of scale exist such that for the range of transportable plants evaluated (15,000 to 50,000 bdmt annual input), larger transportable plants have lower conversion costs than smaller plants.

  5. Results generally indicate that system costs are largely dependent on market pricing, plant assumptions and conversion estimates while processing and transportation costs are smaller, but important contributors for small scale biomass conversion facility design configurations.

  6. Access to electrical grid-energy could be the difference between an economically viable supply chain operation and one that is not.

- **Deliverables*:***

  Publications:

  1. Berry, M., and J. Sessions. 2018. The economics of biomass logistics and conversion facility mobility: An Oregon case study. Applied Engineering in Agriculture. *Applied Engineering in Agriculture*. ASABE special collection publication. 34(1): 57-72.

  2. Berry, M., and J. Sessions. 2018. A forest-to-product biomass supply chain in the Pacific Northwest, USA: A multi-product approach. Applied Engineering in Agriculture. *Applied Engineering in Agriculture*. ASABE special collection publication. 34(1): 109-124.

  3. Berry, M., J. Sessions, and R. Zamora-Cristales. 2018. Subregional comparison for the forest-to-product supply chains on the Pacific West Coast, USA. Applied Engineering in Agriculture. *Applied Engineering in Agriculture*. ASABE special collection publication. 34(1): 157-174.

4. Zamora, R. and J. Sessions. 2015. Economics and logistics of double trailers in transporting forest biomass on steep terrain. California Agriculture Journal 69(3):76-81.

Oral presentations at professional conferences and public workshops:

1. Berry, M. and J. Sessions. 2017. Landscape modeling: Integration of feedstock production, BCTs, and marketing. Public Workshop, Sacramento, California, May 17, 2017.
2. Berry, M. 2017. The economics of biomass logistics and conversion facility mobility: Regional concepts. Western Forestry Graduate Research Symposium, Corvallis, Oregon. April 21, 2017.
3. Berry, M. 2016. Landscape Modeling: Concepts, Updates, Baselines and Integration. DOE BRDI Comprehensive Project Review, Golden, Colorado. November 30, 2016.
4. Berry, M. and J. Sessions. 2016. Development and optimization of a northern California biomass supply chain model. Forest Products Society 70th International Convention, Portland, OR. June 28, 2016.
5. Berry, M. 2016. Development and optimization of a northern California biomass supply chain model. Poster Presentation. NARA Annual Meeting, Seattle, WA. May 3, 2016.
6. Berry, M. 2016. Development and optimization of a northern California biomass supply chain model. Poster Presentation. Western Forestry Graduate Research Symposium, Corvallis, Oregon. April 22, 2016.
7. Sessions, J., H-S. Han, J. Petitmermet, and M. Berry. 2015. Integration of BCTs with landscape level planning and transportation logistics. Presented at the Comprehensive Internal Review meeting, Golden, Colorado. September 18, 2015.

TASK 3.0: BIOFUELS AND BIOBASED PRODUCT DEVELOPMENT

SUBTASK 3.1. **SCALE UP AND DEVELOPMENT OF FIELD READY UNIT**

- **Organization completing task:**
  1. Principal Investigator: Arne Jacobson, Schatz Energy Research Center (SERC), HSU
  2. Biochar Solutions, Inc. (BSI)
- **Description of task:**

This task involvde the adaptation and scaling up of BSI's biochar production unit to be a field-ready, high production system. Activities included: 1) develop field applicable tooling and parts box; 2) add a level sensor based reactor loading control to reduce operator effort; 3) develop and add stack fire protection to improve fire safety in field operations; 4) increase the throughput capacity of the unit.

- **Summary of key findings and research impacts:**

The process of adapting the BSI biochar unit for field operations involved work to reduce operator effort, improve safety, and reduce fire risk. A standard field tool kit was assembled that included an operations manual, hand tools for disassembling and reassembling the machine, electrical test equipment, a shovel, a fire extinguisher, face shield and welding gloves.

The unit was designed and fabricated to be field ready to allow set-up and take-down to take six hours or less. Two 26,000 lb gross vehicle weight flatbed trucks are required to move the operation from one landing to the next.

The initial build had the feed hopper set up to be tipped by a forklift to cause feedstock to fall onto the feeder conveyor. This was not practical and one person's full attention was needed to meter feedstock from the hopper onto the conveyor. BSI built a screw conveyor into the bottom of the feedstock hopper and experimented with various level sensors in the reactor to control the screw conveyor motor for automated feedstock delivery to the reactor. Infrared and ultrasonic level sensors did not function in the harsh environment above the reactor due to high temperatures, incoming feedstock, interference from dust, and mechanical vibrations. The best configuration was determined to be a paddle wheel type level sensor with a long shaft separating the paddle from the sensor electronics so that the high temperatures in the reactor did not impact the measuring system.

Several iterations of spark arrestor designs were tested for the biochar machine. As initially tested the machine emitted a significant number of embers from the exhaust stack because there was no spark arrestor system. This caused regular, small spot fires at the industrial test site in Pueblo, Colorado and burns on operator's clothing and skin. To address this, BSI fabricated a spark arrestor and placed it on top of the flare. The first spark arrestor design was based on a steam locomotive spark arrestor that relies on changes in gas velocity and centrifugal force to drop embers out of the exhaust. Pilot testing on the first iteration of spark arrestor was encouraging and third-party gas and particulate emissions sampling was conducted. Unfortunately, the feedstock used during the air testing had a high moisture content, which led to inconsistent operation inside the reactor and variable results. In most cases, the results indicated that particulate matter emissions were relatively low, which was consistent with empirical observations by operators, who observed a significant reduction in embers during normal operations.

The spark arrestor was shipped to Branscomb, California and installed on the biochar machine located at a forest operations site operated by the Redwood Forest Foundation, Inc. (RFFI). The spark arrestor created too much back pressure because the RFFI biochar machine had an installed heat exchanger inside the stack that was not fully incorporated into the spark arrestor design. The spark arrestor inlet pipe was located directly above the heat exchanger tubes that transect the exhaust stack. This piping arrangement caused a pressure drop that reduced the exhaust flow significantly and impacted operation of the reactor. As a result, SERC worked with RFFI staff to implement a conical stainless steel screen spark arrestor that proved to be very effective. About halfway through the second operating season this screen began to deteriorate, which led to the recommendation that the spark arrester screen be replaced once per year on BSI machines that have the heat exchanger option.

BSI decided to scale up their biochar machine by adding a second process train to the reactor without changing the reactor size. This design was fabricated and tested. Aside from the addition of the second process train, a major modification of the flare was implemented to increase combustion air, reduce the gas velocity, and increase the residence time of the exhaust gas. A refractory lining was added to the flare to reduce the external surface temperature of the stack. The improvements to the flare slightly increase capital cost, but improved the longevity of the machine by reducing the thermal stresses applied to the metal structure and improved the safety of the machine for the operator. By adding the second process train to the reactor the biochar production capacity was increased by a factor of approximately 1.4.

Additional improvements to the scaled-up machine included enhancing the char cooling system by adding a larger radiator with a fan, increasing the size of the outlet airlock to reduce clogging, increasing combustion air to reduce carbon monoxide and unburned hydrocarbon emissions, and identifying next-step design improvements such as increased reactor size, automated controls for combustion air blowers using feedback from an oxygen sensor in the flare and for the main blowers using feedback from pressure sensors in the anoxic zone.

- **Lessons Learned:**

1. Fire safety is paramount to becoming field ready for forest deployment.
2. Spark arrestor design depends on HEX installation in flare due to back pressure considerations. Screen type spark arresters should use stainless steel with 0.024 inch openings. The cumulative area of the screen openings should exceed the smallest area in the exhaust flow path by a factor of 1.25 and the screen material should be replaced annually.
3. Sensor technology for level based control must be selected for a harsh environment (dust, heat, temperature, gases, etc.). A paddle wheel level sensor was the best option to control reactor bed depth.
4. Increasing throughput requires increasing the reactor volume instead of adding second blower.
5. To prevent auto ignition of biochar after production, the biochar should be quenched and the quenching water should be allowed to drain for reuse. Our

research shows that even a well-designed cooling auger is not likely to eliminate all embers from the biochar produced, and it only takes one ember to cause a fire in the product.

6. A minimum of 100 feet of defensible clear space around the machine is required for safe operation at a forest operation site.

- **Deliverables:**

Publications:

1. Severy, M., D. Carter, K. Palmer, A. Eggink, C. Chamberlin, and A. Jacobson. 2018. Performance and emissions control of commercial-scale biochar production unit. *Applied Engineering in Agriculture.* ASABE special collection publication. 34(1): 73-84
2. [BSI] Biochar Solutions, Inc. 2014. Biochar Machine Field Ready Tool Kit Documentation.

SUBTASK 3.2. **TESTING AND FIELD DEPLOYMENT**

- **Organization completing task:**

- Principal Investigator: Arne Jacobson, Schatz Energy Research Center, HSU
- Biochar Solutions, Inc.

- **Description of task:**

BSI worked with SERC to collect operational performance data that was used to evaluate opportunities for stand-alone energy operation. BSI set up the biochar unit for operation and evaluation at a site in northern California. The unit was tested with multiple feedstocks. BSI provided input to Task 4 team members to support the economic analysis, market analysis and life cycle assessment tasks.

- **Summary of key findings and research impacts:**

Two commercial biochar production machines – a single-auger unit and a larger dual-auger version – were operated to evaluate feedstock specifications, biochar quality, throughput rates, and emissions profiles. Biochar was produced from woody biomass feedstocks of various species, contamination levels, comminution methods, and moisture contents. Feedstocks with ash content exceeding 15% dry basis or moisture content exceeding 25% wet basis were observed to decrease fixed carbon content of biochar and to increase the labor effort required to operate the machine. The dual-auger version of the machine was able to process 380 kg/hr of biomass feedstock (dry basis) to produce 63 kg/hr of biochar with a mean electricity demand of 4.5 kW. Average CO, propane, NO_x, and SO_2 emission rates from the flare of this machine were measured to be 160, 120, 51, and 43 g/hr, respectively, with total particulate matter (PM), PM_{10}, and $PM_{2.5}$ emission rates of 380, 40, and 4.5 g/hr, respectively. Results from these experiments indicate that high-quality biochar can be produced from a variety of feedstocks, including forest residuals, as long as the ash and moisture content are within the specifications. Future research and development should focus on increasing the throughput of the machine, implementing an automated control system to reduce the operational effort, and improving safety and product consistency.

Performance data were collected at the point of manufacture in Pueblo, Colorado during a two-week testing period. An extensive suite of instrumentation was added to the machine and then a series of tests were conducted with multiple feedstocks. Data collected were used to inform design development for improvements to the base machine and for developing the scaled-up machine. The data were analyzed and processed before they were provided to Task 2 and Task 4 team members for used in their research.

The biochar machine was then shipped to Branscomb, California to an abandoned mill site, where it was operated by RFFI as part of their biochar production operation. RFFI operated the machine in Branscomb for two seasons using feedstock from the Usal forest, which they own and are working to restore. During the first season of operation it became clear that not having a way to manage feedstock moisture content of wet forest residuals was significantly impacting operational success.

SERC transported a biomass dryer (Beltomatic Model 123B) to Branscomb along with a 20-kilowatt biomass gasifier generator set (All Power Labs PP20). SERC configured an integrated system consisting of the biochar machine, the dryer, and the gasifier generator set. The biochar machine produced biochar and waste heat for the dryer. The dryer became the point of input for the feedstock into the system and only used process heat from the biochar machine (no propane) to dry the feedstock. Using the biochar waste heat, the dryer was observed to reduce incoming feedstock moisture content to less than 25% wet basis so it could be used for biochar production. The biomass gasifier was configured to power the biochar machine and the dryer using the same feedstock that was being used to make the biochar. SERC instrumented this system and collected operational data to be used in Task 4 research efforts and by RFFI for operations planning.

Transportation costs to bring feedstock to Branscomb were high due to a four-hour round trip from the forest landing to the machine. SERC worked in partnership with RFFI to evaluate the suitability for the machine to be moved closer to the feedstock point of origin, such as a forest landing, so that the economics of the biochar operation could be improved through reduced transportation costs. For the 2017 operating season, RFFI transported the biochar machine closer to the source of the feedstock in Piercy, California where the feedstock transportation time was less than 30 minutes. SERC again provided the dryer and configured it to use process heat from the biochar machine to expand the moisture specification of the biochar machine from 25% to 45% (wet basis) and extend the duration of the annual operating season by two months.

Transportation, fire hazard, feedstock moisture management, and various operator effort and safety concerns were adequately addressed at RFFI's new site for biochar production. Uncertainty of market prices and difficulty in securing a reliable off-take agreement with a biochar re-seller has emerged as a significant challenge that must be faced for RFFI to continue its biochar operation.

- **Lessons Learned:**

  1. Feedstock specifications are 25% maximum moisture content (wet basis) and 15% maximum ash content (dry basis). Chipped and ground particles up to 100 mm and occasionally larger can be accepted to this machine.

2. Reducing moisture content improves machine throughput and biochar quality while reducing labor requirements.
3. Machine can accept forest residuals as long as they meet the feedstock specifications.
4. High ash content feedstocks increase operations and maintenance and reduces biochar fixed carbon content.
5. Many opportunities for technology improvement exist to further reduce operator effort and improve safety, product quality, and consistency.

- **Deliverables:**

<u>*Publications:*</u>

1. Severy, M., D. Carter, C. Chamberlin, and A. Jacobson. 2016. *Biochar Testing Results Report*. Retrieved from http://wastetowisdom.com/wp-content/uploads/2016/07/Biochar-Testing-Results.pdf
2. Eggink, A., K. Palmer, M. Severy, D. Carter, and A. Jacobson. 2018. Utilization of wet forest biomass as both the feedstock and electricity source for an integrated biochar production system. *Applied Engineering in Agriculture.* ASABE special collection publication. 34(1): 125-134.

<u>*Oral presentations at professional conferences and public workshops:*</u>

1. Carter, D. 2016. Biochar Production from Forest Residuals. Forest Products Society 70th International Convention, June 29, 2016, Portland, OR.
2. Carter, D. 2016. Integrated Biochar Production System Using Forest Residues. U.S. Biochar Initiative 2016 Conference, August 23, 2016, Corvallis, OR.
3. Jacobson, A., D. Carter, and M. Severy. 2015. *Biochar Production Using Forest Residues.* Presented on November 16, 2015. The webinar can be accessed at http://wastetowisdom.com/webinars/webinar-biochar-production-using-forest-residuals/
4. Carter, D. 2015. Biochar Conversion Unit Technology Review. Presented at *RFFI Biochar Demonstration Project Regional Technical Transfer Workshop*, April 9, 2015, Eureka, CA.

SUBTASK 3.3. **ADAPT UNIT FOR FIELD READINESS AND OPERATION**

- **Organization completing task:**

1. Principal Investigator: Arne Jacobson, Schatz Energy Research Center, HSU
2. Norris Thermal Technologies

- **Description of task:**

Norris Thermal Technologies (NTT) upgraded their pilot-scale torrefaction unit to be suitable for field operation. This included modifications to maintain operability and durability during unit transport and to provide protection from the elements during outdoor operation. NTT worked closely with SERC to collect operating data that was used to evaluate opportunities for field operation.

- **Summary of key findings and research impacts:**

This subtask focused on testing and modification of a pilot-scale torrefier to inform the design of the larger demonstration unit built for subtask 3.4. The pilot-scale unit was modified to be mobile and protected during outdoor operation by mounting the entire system on a flatbed trailer with a rolling softcover canopy. The pilot-scale unit was transported and set up at an outdoor, remote, near-forest operations site in Big Lagoon, California for performance testing.

The torrefier was operated with a variety of biomass feedstocks including tops and forest residues to determine the boundaries of feedstock specifications. During testing and data analysis, operational challenges were identified to be improved on the scaled up version of this machine. These challenges are described in the list below.

1. Throughput rate - The input rate was 5 kg/hr. This would be scaled up by two orders of magnitude for the demonstration unit. The main limiter for the throughput rate was the length of the reactor followed by the capacity of the air locks.
2. Feedstock particle size - The maximum particle size was limited to 25 mm due to bridging in the narrow feed hopper. The hopper was placed directly over a vaned, rotary air lock that would become jammed when each vane was fully loaded and particles would become lodged between the stator and the rotor.
3. Oxygen infiltration - The pyrolysis reaction needs to be isolated from air and oxygen or else combustion will be initiated and the product becomes inconsistent with some highly-charred particles. Rotary air locks were used at the inlet and outlet of the reactor to isolate the reaction, but combustion was still identified based on observing the temperature profile in the reactor and inconsistency of product quality. The vanes of the inlet air lock could not be completely filled due to a particle size issue described above. Oxygen also infiltrated through seams of the reactor enclosure or was present inside the reactor during start up. To mitigate oxygen leaks on the scaled-up unit, three measures were implemented:
    a. Controlling the blower speed of the reactor gas outlet automatically to maintain neutral or slightly positive pressure in the reactor to avoid inward air leaks.
    b. A nitrogen purging system was installed on the reactor that could be operated to flush out any residual air upon startup or used to subside combustion in the event of an air leak.
    c. Procure air locks more appropriate for woody biomass chips that allow a greater portion of solid material into the reactor and less air.
4. Clean in place (CIP) system - the pump O-rings failed and caused a leak because they were not rated for the corrosive cleaning agents. It was determined that a CIP system was unnecessary for this system and removed for the scaled-up unit.
5. Auger surface temperature measurement - The thermocouple inserted in the reactor auger to measure the surface temperature had an electrical short that delivered unreliable measurements. The thermocouple was electrical isolated on the larger unit.

6. Fire safety - Small embers from combustion in the reactor can exit through the cooling auger and result in smoldering fires in the production collection hopper.

A statistical analysis of operational results from production tests showed that the higher heating value of torrefied biomass is influenced by residence time, reactor temperature, and species. The specific electrical demand was approximately 1 kWh/kg of feedstock, which is primarily used for electrically heating the pyrolytic auger reactor. An experimental study performed on this pyrolytic screw conveyer to determine the residence time in the reactor as a function of auger speed showed that the observed residence time was significantly longer than the ideal residence time due to internal mixing.

Torrefied biomass produced from the pilot-scale torrefier was densified into briquettes without the use of a binder. The throughput rate of this machine made it difficult to generate enough torrefied material for production-length densification testing at each torrefaction operating condition, but the screening tests displayed strong potential for producing torrefied briquettes from the larger unit.

- **Lessons Learned:**

1. The particle size specification is the most critical requirement for the feedstock due to limitations of the inlet rotary airlock and dosing system.

2. Removing oxygen from the reactor is essential for producing a homogeneous product with the desired properties of torrefied biomass. The torrefier must be improved to eliminate air intrusion.

3. Hot torrefied biomass can pose a fire hazard after exiting the reactor if the cooling auger does not sufficiently cool the biomass.

4. Specific electric power demand (approximately 1 kWh/kg) on the pilot unit was very high due to an electrically heated auger and slow feeding system.

5. Due to internal mixing in the reactor, the measured residence time deviated from the anticipated residence time by -8% for a positive step change, +60% for a negative step change, and +7% for a pulse addition of a tracer.

- **Deliverables:**

Publications:

1. Partridge, A. 2016. *Product characteristics in a pilot scale biomass torrefier with heated screw conveyance* (Senior Honors Thesis). Retrieved from http://scholarworks.smith.edu/theses/1653/

2. Charles, C., D. Carter, and A. Jacobson. (forthcoming). *Measuring residence time distributions of wood chips in a screw conveyor reactor*. Manuscript in preparation.

3. Casini, I. 2017. *Estimating Product Composition and Thermal Dynamics in a Continuous Feed Biomass Torrefier* (Senior Honors Thesis). Retrieved from http://scholarworks.smith.edu/theses/1813/

Oral presentations at professional conferences and public workshops:

1. Severy, M. 2016. Testing of Norris Thermal Technologies Pilot-Scale Torrefier at Big Lagoon, CA. Forest Products Society 70th International Convention, June 29, 2016, Portland, OR.

SUBTASK 3.4. **SCALE UP UNIT, AND FIELD DEPLOYMENT AND TESTING**

- **Organization completing task:**
    1. Principal Investigator: Arne Jacobson, Schatz Energy Research Center, HSU
    2. Norris Thermal Technologies
- **Description of task:**

NTT set up their pilot-scale torrefaction unit at a field site in northern California and tested it using multiple feedstocks. NTT worked to scale up their pilot-scale unit to approximately 15 tons per day of torrefied product. NTT tested the larger unit at a forest operations site. NTT provided input to Task 4 team members to support the economic analysis, market analysis, and life cycle assessment tasks.

- **Summary of key findings and research impacts:**

The scaled up torrefier reactor and auxiliary components were mounted onto two flatbed trailers and transported from manufacturing in Indiana to a field site in Northern California for three weeks of testing. The plant is considered semi-mobile because it can be setup and disassembled in six hours each with two people and two forklifts. The torrefier is permanently mounted on a trailer, while auxiliary components, such as the cooling auger, chiller, and flare, are loaded onto and off a second trailer for transportation.

The main improvements to the design of the torrefaction system were to:

1. Increase throughput by over 100 times to process 15.6 tons of bone dry feedstock per day (650 kg/hr) by increasing the length and diameter of the reactor.
2. Eliminate oxygen infiltration into the reactor to retain consistent product quality. This is primarily achieved by installing a nitrogen purge for system start up and controlling blower speed to maintain neutral pressure inside the reactor.
3. Fire safety improved and no embers were observed in the torrefied product due to a larger cooling auger and eliminating combustion in the reactor.

Torrefaction experiments were conducted at various conditions with input biomass feedstock ranging from 4% to 25% moisture content (wet basis), 10 and 20-minute reactor residence times, and final product temperatures between 214°C and 324°C. The torrefier was connected to a briquetter to demonstrate a continuous flow plant design and understand the torrefaction conditions that contribute towards producing a high-quality briquette.

Optimal operating conditions, evaluated based on throughput rate, specific electricity demand, torrefied briquette grindability, briquette volumetric energy density, water absorption, and briquette durability (DU), were identified to occur with a short residence time (10 minutes), low feedstock moisture content (<11% wet basis), and high final product temperature between 267°C and 275°C. Under these conditions, the system was able to process 510 – 680 kg hr^{-1} (wet basis) feedstock with a dry mass yield of 79% to 84% to produce torrefied biomass with a higher heating value 21.2 - 23.0 MJ/kg (dry basis) compared to 19.6 MJ kg^{-1} for the original biomass. Torrefied briquettes produced at these conditions had a neatly stacked packing density of 990 kg/m^3 and a volumetric energy density of 21,800 MJ/m^3. Their specific grinding energy was an average 37% of the energy required to grind a raw biomass briquette. These torrefied briquettes were more durable (94% DU) than raw briquettes (85% DU) directly following production, but were less durable after undergoing temperature and humidity fluctuations associated with long distance transportation simulation (74% DU for torrefied and 84% DU for non-torrefied briquettes). The electrical demand of the torrefier ranged from 112 to 160 kW for a 10-minute residence time (specific electricity demand ranged from 0.2 to 0.5 kWh/kg), but 90% of that load was consumed by the electrically-heated reactor. Designing a torrefier to use process heat from syngas generated during the reaction has the potential to reduce electricity demand by an order of magnitude.

The impacts from this demonstration plant are promising for commercial scale production of high quality torrefied biomass and briquettes. Scaling up equipment to this size provided many challenges in process control, but the efforts resulted in the largest torrefaction plant reported in the literature that we are aware of. The scale, however, needs to be further developed to meet the high demands of power plants and the vast supply of forest residues.

- **Lessons Learned:**

1. The scale of this technology was increased by two orders of magnitude. The current throughput rate will match the consumption rate of a 1 MW_e power plant. Torrefiers should still increase in scale to meet the demand for larger industrial use.
2. Low moisture content feedstock below 10% enables the reactor to achieve the product temperatures required to produce torrefied biomass with significant improvements to energy density. Feedstocks with higher moisture content require slower throughput rates and more energy to achieve the same degree of torrefaction. Integrating a dryer upstream of a torrefier will improve the product quality and economics of the system.
3. Shorter residence times with higher temperatures have lower specific energy consumption than longer residence times.
4. The final product temperature, rather than the reactor temperature setpoint, is the best indicator for degree of torrefaction.
5. Torrefied biomass can be densified into durable briquettes without the addition of a binder. Using the same primary feedstock, torrefied biomass was able to produce denser and more durable briquettes than the original feedstock.
6. Torrefaction significantly reduces the grinding energy for both chips and briquettes to less than 30% of the energy required to grind the original biomass.
7. Alternative heating sources, such as utilizing energy from the syngas produced during the reaction, should be investigated to reduce the electrical demand of the reactor heating element.
8. Tar or condensable gas generation can be an expensive waste disposal issue due to acetic acid concentration which lowers the pH to between 2.7 and 3.1. Tar generation should be minimized or sent to a thermal oxidizer for combustion alongside the syngas.

- **Deliverables:**

  Publications:

  1. Severy, M., C. Chamberlin, A. Eggink, and A. Jacobson. 2018. Demonstration of pilot-scale plant for torrefaction and briquetting. *Applied Engineering in Agriculture.* ASABE special collection publication. 34(1): 85-98.

  Oral presentations at professional conferences and public workshops:

  1. Severy, M. 2016. Design and Test Plan of Scaled-Up Torrefaction Unit. Forest Products Society 70th International Convention, June 29, 2016, Portland, OR.
  2. Severy, M., S. Alanya-Rosenbaum, R. Bergman, and E.M. Bilek. 2017. Lifecycle assessment and economics of torrefied biomass. August 8, 2017. The webinar can be accessed at http://wastetowisdom.com/webinars/lifecycle-assessment-and-economics-of-torrefied-biomass/

SUBTASK 3.5. **ASSESS SUITABILITY OF COMMERCIAL BRIQUETTING UNIT FOR FIELD OPERATION.**

- **Organization completing task:**
  1. Principal Investigator: Arne Jacobson, Schatz Energy Research Center, HSU
  2. Pellet Fuels Institute

- **Description of task:**

Pellet Fuel Institute (PFI) assessed the adaptability of existing commercial biomass briquetting equipment for use in or near woods to process a variety of forest residue types. Forest residues that have been comminuted in the woods were processed into densified briquettes and torrefied wood was tested as a feedstock for briquetting. Modifications needed for field operation were evaluated and/ implemented. PFI addressed issues inherent in creating a field deployable system, including the necessary support and material handling equipment.

- **Summary of key findings and research impacts:**

PFI and SERC evaluated commercially ready densification technologies to determine feedstock and site suitability. The most suitable technology determined was high pressure briquetting, which provides increased adhesion through mechanical interlocking of particles and requires less pre-processing of feedstock compared to pellet mills or screw-extruder type technologies by accepting a wider range of particle sizes. Pellet mills require dried feedstock with very small particle sizes, i.e. sawdust, and would require significant pre-processing of forest residue type materials. High pressure piston briquetting is more energy efficient, because it does not use heat for processing as the screw-extruder system does, requiring less energy with a lower capital costs. The lower energy requirements, wider range of acceptable particle sizes and moisture contents make the high-pressure piston briquetter the most suitable technology for this project.

A hydraulically actuated piston press manufactured by RUF Briquetting Systems was used for this testing. The RUF 200, RUF RB 440, and RUF 1100 were tested. The

RUF 200 was used in a near-woods field testing environment at Big Lagoon, California. The RUF 200 has a small footprint at just over 100 ft^2 and has a consistent energy demand. The briquetter was modified for in-woods or near-woods outside use by adding a rain cover. Produced briquettes were ejected via chute into super sacks for industrial use. A pre-processing feedstock screener was used as testing showed that feedstock particle size should be nominally 50 mm or less, with no particles larger than 100 mm. A belt dryer was used to dry incoming feedstock to the acceptable range for the briquetter (less than 15%). Feedstocks tested with moisture content above 15% made poor quality briquettes. Torrefied biomass was found to make high quality briquettes (see Section 3.6).

- **Lessons Learned:**

  1. Briquetting technology is well developed and can be modified to be suitable for field operation as it has a small footprint and consistent electricity demand.
  2. Smaller feedstock particle sizes make higher quality briquettes, with a maximum nominal particle size of 50 mm and a maximum particle size of 100 mm to prevent jamming the machine.
  3. Maximum feedstock moisture content is 15%.
  4. Extrusion type presses do not appear to be suitable for densifying forest residuals.
  5. Electrical load was consistent with minimal variability. Electricity cost to produce was relatively low at ~$6 per ton for the RUF 200.
  6. The large particles float to the top of feedstock hopper when the hopper is nearly depleted, producing lower quality briquettes.
  7. Torrefied biomass can make high quality briquettes without the use of binders

- **Deliverables:**

  Reports:

  1. [PFI] Pellet Fuels Institute. 2015. Existing Performance and Operational Data for Briquetting Machinery.
  2. Crouch, J. 2016. Address modifications to briquetter for field deployable system.

SUBTASK 3.6. **OPERATE A BRIQUETTING UNIT**

- **Organization completing task:**

  1. Principal Investigator: Arne Jacobson, Schatz Energy Research Center, HSU
  2. Pellet Fuels Institute

- **Description of task:**

PFI operated a briquetting unit at a site in Oregon during Year 1 to create sample outputs. During this period, PFI worked closely with SERC to characterize the electricity and heat/fuel drying requirements of a briquetting unit. During Year 2, PFI set up a briquetting unit for operation at a field site. PFI provided input to Task 4 team members to support the economic analysis, market analysis and life cycle assessment tasks.

- **Summary of key findings and research impacts:**

In Year 1, two high pressure, hydraulic briquetters manufactured by RUF Briquetting Systems, Inc. were tested at Bear Mountain Forest Products Inc. in Cascade Locks, Oregon. Significant findings include: 1) low operator effort required, 2) steady electrical demand, 3) feedstock moisture content must be in a specified range, and 4) smaller particles produce denser and more durable briquettes.

The RUF RB 440 had a mass throughput of 325 kg/hr at an average electrical demand of 19 kW across tested feedstocks, resulting in an electricity cost of $10.53 per ton at $0.18/kWh. The RUF 1100 had a mass throughput of 491 kg/hr at an average electrical demand of 42 kW across tested feedstocks, accounting for an electricity cost of $15.40 per ton at $0.18/kWh. A variety of feedstocks were tested including different species and comminution methods. Mixtures of feedstocks were also tested for a total of 12 specific test runs for briquette characterization and four test runs to characterize machine production. These tests generated initial samples and results that show a wide variety of feedstocks can be densified into biomass briquettes. Briquettes were analyzed for the following quality characteristics: mass, packing density, moisture content, proximate analysis, gross calorific value, durability, grindability, water absportion, and transportation simulation.

Briquetting increased feedstock density by factors ranging from 2.3 to 5.6 with final packing densities between 550 and 850 kg/m^3 where feedstocks with smaller particles, i.e. sawdust and shavings, had higher densities likely because of less interstitial spaces between particles. Moisture content for feedstocks ranging from 9% to 13% had no significant impact on briquette quality. Comminution method appears to have the greatest impact on briquette durability where chipped biomass produced briquettes with 46% durability, and briquettes produced from sawdust, shavings or mulch had an average durability greater than 89%. Mixing chips with sawdust at 50% increased durability to 89%. Briquettes were exposed to the temperatures and relative humidity experienced in an enclosed container during transit from the Pacific Northwest United States to East Asia using an environmental chamber. Briquettes with initial moisture content between 8% and 11% showed an increase in water content in the range of 5% to 20%, resulting in final a final briquette moisture content between 10% and 13%. One test had an initial moisture content of 14.3% and a final moisture content of 14.1%. These results indicate that moisture content shifts toward an equilibrium. Post-transportation simulation briquette durability was within ±5% of original durability indicating that a typical trans-oceanic shipping journey is not likely to result in significant briquette degradation. Grindability testing of briquettes showed that briquettes made from smaller particles had lower grinding energies.

In Year 2, a high pressure, hydraulic briquetter was used in a near-woods field testing environment at Big Lagoon California. Significant findings include: 1) the briquetter can be used in a near woods location without connection to the electric grid, 2) briquette durability is a function of particle size distribution and moisture content, 3) torrefied biomass can be densified into a high-quality briquette, 4) the maximum moisture content for making a high-quality briquette is ~15%, and 5) feedstock particle size must be less than four inches.

The RUF 200 had a mass throughput of 218 kg/hr at an average electrical demand of 6.8 kW across tested feedstocks, accounting for an electricity cost of $5.57 per ton at $0.18/kWh. A variety of feedstocks were tested including chipped and ground Douglas fir, chipped Redwood, chipped and ground Tanoak, chipped forest slash, and chipped torrefied biomass for a total of 57 test runs. Average packing density ranged between 769 and 905 kg/m^3 for raw briquettes where feedstocks with smaller particles had higher densities, and averaged 764 kg/m^3 for torreified briquettes. Feedstock moisture contents ranged from 2% to 14% and torrefied biomass moisture content was 1%. Raw feedstocks with lower moisture content produced higher quality, more durable briquettes. Briquettes made from feedstocks with moisture content 6% or less showed the highest tested durabilities over 90% durable. The lowest durability was noted in the feedstock moisture content range of 10% to 15% where the average durability was 70%. Torrefied briquettes had an average durability of 86%. Post transportation durability tests showed that the raw briquettes in the feedstock moisture content range of 10% to 15% had no change in durability, while the remaining raw briquettes had reduced durability where briquettes averaged 75% durable. The largest durability change in the post-transportation results was the torrefied briquettes where the durability was reduced from 86% to 51% indicating that a trans-oceanic shipping journey could have significant effect on torrefied briquette quality. Grindability testing of briquettes showed that briquettes made from torrefied biomass had the lowest grinding energies, making torrefied briquettes a candidate for use with existing equipment at a pulverizing coal power plant.

- **Lessons Learned:**

1. Feedstock particle size distribution and moisture contents are the most significant factors for briquette quality and durability.
2. The RUF briquetter is a robust technology and easily adaptable to field operations.
3. The RUF briquetter requires minimal operator effort, primarily to load the feed hopper.
4. Densified torrefied wood and raw slash feedstocks can be made into high quality durable briquettes without the use of binders.
5. Briquette moisture content reaches an equilibrium in simulated trans-oceanic transportation.
6. Briquettes have a relatively small electricity cost to produce.

- **Deliverables:**

Publications:

1. Severy, M., Carter, D., C. Chamberlin, and A. Jacobson. 2016. Briquetter testing and results: Testing in a commercial setting.

Oral presentations at professional conferences and public workshops:

1. Eggink, A. and J. Crouch. 2016. Briquette quality and durability across multiple feedstocks. *Forest Products Society 70th International Convention*, June 29, 2016, Portland, OR.
2. Nelson, D. 2016. Producing densified biomass from forest residuals. *Pellet Fuels Institute Annual Conference*, July 26, 2016, Asheville, NC.

SUBTASK 3.7. **ASSESS POTENTIAL TO UTILIZE WASTE HEAT FOR ENERGY INPUT NEEDS**

- **Organization completing task:**
  1. Principal Investigator: Arne Jacobson, Schatz Energy Research Center, HSU
- **Description of task:**

SERC evaluated the potential to recover waste heat in a usable format to provide energy input needs for BCTs. This included generation of electrical power from available waste heat. Energy sources that wered considered included waste heat from the BCTs and other onsite sources such as waste heat from diesel powered grinders used for biomass comminution. Once potential heat sources were measured, the team assessed several heat-to-electricity generation technologies, including organic Rankine cycle generators (ORC). SERC also assessed the ability of respective biomass conversion devices to utilize power generated from the heat-to-power devices, in particular load-following performance and the need for thermal or electrical energy storage. As part of this assessment, SERC identified, procured, and tested under laboratory conditions a suitable electricity generation technology. The objective of this testing was to assess the potential for using this technology to produce electrical energy for the BCTs at an in-woods BCT plant. SERC will also perform detailed measurements or estimations of electricity requirements for the three biomass conversion technologies.

- **Summary of key findings and research impacts:**

The waste heat resource and energy input needs of each BCT were measured and characterized to assess the potential for waste heat recovery and the energy requirements for electricity and auxiliary fuel. Results from the technical and economic analysis showed that converting waste heat into electricity for use at the BCT site is not technically practical because 1) auxiliary fuel or a battery bank is required for startup, shutdown, and peak demand and 2) it is not economically competitive with other remote power alternatives. Rather than converting waste heat into electricity at a low efficiency, waste heat is better used to remove moisture from incoming biomass feedstock to meet the BCT specifications and increase throughput capacity. Based on technical and economic criteria, the best alternative to a diesel generator at an in-woods BCT plant was found to be a small biomass gasifier generator. Following this initial assessment, the performance of both a waste heat recovery dryer and a biomass gasifier generator set were tested under this subtask, as described below.

A commercial belt dryer was modified to use waste heat as the energy source instead of propane. Preliminary tests were performed using waste heat from a torrefier and verification tests were performed using waste heat from the stack of the biochar machine. The dryer performed similarly with waste heat or with propane. Using waste heat, the dryer was able to reduce biomass moisture content from 45% to 25% (wet basis) with a throughput of 350 dry kg/hr. The water evaporation rate was proportional to the belt speed, indicating that drying was limited by biomass throughput and heat transfer. The input air flow rate did not significantly impact the water removal rate. Drying feedstock before conversion with waste heat improves the performance and reduces the energy consumption of BCTs. During torrefaction, drier biomass reduces the volume of tar generation and decreases the energy requirements in the reactor by reducing the latent heat demand. By applying waste heat drying to a biochar machine, the feedstock specifications can be increased to 45% moisture instead of 25% moisture and lengthen the duration of the field operating season into the early spring and late fall.

A 20 kW_e gasifier generator produced by All Power Labs (APL) was tested using woody biomass feedstocks in a controlled environment with a programmable load and in the field connected to a BCT. Lab testing showed that feedstock species and moisture content between 15% and 25% (wet basis) all produced electricity with a thermal efficiency of approximately 10% from biomass to electricity on a high heating value (HHV) basis. At all tested load conditions, including ramping rates up to 4 kW/s, the engine generator was able to maintain frequency regulation within 0.7 Hz and voltage regulation within 5%, which meets criteria to operate a remote BCT.

The research impacts from this subtask were verified and validated by partnering with Redwood Forest Foundation, Inc., a commercial biochar producer, to provide waste heat drying and remote power from a gasifier at their field operation in northern California. The dryer is able to extend their operating season by two months by capturing waste heat and allow them to immediately process wet forest residuals without passive air or solar drying. The biomass gasifier generator was able to replace a diesel generator and provide power to the dryer and biochar machine without the use of fossil fuels. Their machine was able to process 320 dry kg/hr of biomass at 36% moisture content (wet basis) into 75 kg/hr of biochar with a single operator. Labor hours were divided among the biochar machine, dryer, and gasifier as 0.49, 0.16, 0.28 labor hours per productive machine hour, respectively, for a total of 0.92 labor hours per operating hour.

- **Lessons Learned:**

  1. Waste heat generated from the biochar machine and torrefier is useful for drying incoming biomass feedstock. The first biochar machine tested, for example, produces up to 750 kW of waste heat. It is not feasible to recover waste heat from other on-site components, such as a chipper or grinder, because the heat resource is smaller and the logistical considerations associated with highly mobile equipment.
  2. Drying feedstock with waste heat provides additional benefits to the BCTs processes. For the torrefier, dryer feedstocks reduce the energy requirements and increase the throughput of the torrefier; for the biochar machine, dryer feedstocks reduce operating and maintenance labor requirements and extend the operating season into wetter months; and for the briquetter, dry feedstocks are required to produce a dense and durable briquette.
  3. A biomass gasifier generator set is the best alternative to a diesel engine for powering BCTs at off-grid locations. A gasifier can meet the peak power demand required for the BCT electrical loads including startup and shutdown without being reliant on waste heat generated from on-site.
  4. The biomass gasifier has acceptable load following performance up to 4 kW/s change in load with unbalance loads and low power factors. Under these conditions, the frequency and voltage deviations were within acceptable ranges.

5. Based on the lifecycle assessment conducted under Task 4, the emissions from the biomass gasifier tested in Task 3.7 are much more favorable than a diesel generator. The levelized cost of energy is comparable.

6. Using the biomass gasifier and waste heat dryer, an integrated BCT operation was demonstrated without the use of fossil fuels for typical applications, such as propane for drying and diesel for electric power generation.

- **Deliverables:**

<u>*Publications:*</u>

1. Severy, M., D. Carter, C. Chamberlin, and A. Jacobson. 2016. *Remote power selection memo, part 1: Technology selection*. Retrieved from http://wastetowisdom.com/wp-content/uploads/2016/07/Remote-Power-Generation-Part1.pdf

2. Palmer, K., M. Severy, C. Chamberlin, A. Eggink, and A. Jacobson. 2018. Performance analysis of biomass gasifier genset at varying operating conditions. *ASABE Applied Engineering in Agriculture.* ASABE special collection publication. 34(1): 135-143.

<u>*Oral presentations at professional conferences and public workshops:*</u>

1. Palmer, K. 2016. Suitability Analysis of Gasifier Genset for Powering Remote Biomass Conversion Technologies. *Forest Products Society 70th International Convention,* June 29, 2016, Portland, OR.

SUBTASK 3.8. **TEST BCTS USING A VARIETY OF RESIDUE TYPES AND TREE SPECIES UNDER FIELD CONDITIONS**

- **Organization completing task:**

1. Principal Investigator: Arne Jacobson, Schatz Energy Research Center, HSU

- **Description of task:**

Working in close collaboration with the Task 3 technology partners, SERC coordinated and led activities associated with comparative testing of the BCTs at forest operations sites using target feedstocks. SERC's role included instrumentation, in-field monitoring, and analysis of system performance. The measurements included input fuel and output product characteristics, fuel and product mass flow rates, emissions, and auxiliary energy use. Economic and operational parameters such as labor utilization, operation and maintenance needs, and startup and shutdown requirements were also recorded.

- **Summary of key findings and research impacts:**

By working closely with industry partners, SERC was able to recommend design improvements to the BCT equipment which were implemented between phases of testing. The impact of this research has improved the design and manufacture of BCTs with developments in scale, safety, automation, and product consistency.

BCTs were tested under a variety of conditions in the field with numerous feedstocks included forest residues. Testing activities are listed in Table 2. These testing activities included instrumenting the machine with sensors to measure mass throughput, energy flows, and emission rates. Feedstock and product samples were evaluated in the lab for quality characteristics. Labor measurements and operations and maintenance were recorded where applicable.

The culmination of testing activities resulted in demonstration of transportable biomass conversion facilities. The key demonstrations systems were:

1. Torrefied Briquette Pilot Plant – producing 600 kg/hr of torrefied briquettes using a dryer, torrefier and briquetter. Transportability is 6 hours to load or unload the equipment onto trailers. This was a research demonstration plant in Samoa, California.

2. Integrated Biochar Production System – producing 75 kg/hr biochar from 40% moisture content (wet basis) forest residues using a waste heat dryer, biochar machine, and gasifier generator set for electricity production. Biomass was the sole feedstock for heat, electricity, and biochar. Transportability is 12 hours to load or unload the equipment. This was a commercial operation for a local land manager in Branscomb, California.

3. Near Forest Conversion Facility – on site use of biomass screener and conversion equipment including a briquetter, gasifier generator, and torrefier, which provided waste heat to a dryer. Comminuted biomass was screened, dried and sent to the BCTs for conversion. This was a research demonstration facility in Big Lagoon, California.

Table 2. Testing activities conducted during this project.

Task	BCT	Partners	Test Location	Instrumentation	Feedstocks	Connected to:	Scale	Test Dates
3.2	Biochar	BSI	Pueblo, CO	Mass balance Energy balance Emissions	Mill residues Forest residues		300 kg/hr input	Aug 2014
3.2	Biochar	BSI	Pueblo, CO	Mass balance Emissions	Conifer chip		400 kg/hr input	Nov 2016
3.2	Biochar	BSI RFFI	Branscomb, CA	Operator hours	Tanoak residues	Waste heat dryer Gasifier generator	300 kg/hr input	Jun 2016
3.2	Biochar	BSI RFFI	Piercy, CA	Operator hours	Tanoak residues	Waste heat dryer	300 kg/hr input	May 2017
3.3	Torrefaction	NTT	Lindon, UT	Commissioning	Tanoak residues		10 kg/hr output	Feb 2015
3.3	Torrefaction	NTT	Big Lagoon, CA	Mass balance Energy balance	Variety of species Including tops	Waste heat dryer	10 kg/hr output	Jul 2015

Task	BCT	Partners	Test Location	Instrumentation	Feedstocks	Connected to:	Scale	Test Dates
3.4	Torrefaction	NTT	Tippecanoe, IN	Commissioning	Tanoak residues		600 kg/hr output	May 2016
3.4	Torrefaction	NTT	Samoa, CA	Mass balance Energy balance Emissions	Tanoak residues	Dryer Briquetter	600 kg/hr output	Aug 2016
3.6	Briquetter	BMFP PFI RUF	Cascade Locks, OR	Mass balance Energy balance	Mill residues Forest residues		440 kg/hr & 1,100 kg/hr	Apr 2015
3.6	Briquetter	PFI RUF	Big Lagoon, CA	Mass balance Energy balance	Forest residues Torrefied biomass		200 kg/hr	Jul 2015
3.5	Briquetter	PFI RUF	Samoa, CA	Mass balance Energy balance	Torrefied biomass	Torrefier Dryer	400 kg/hr	Aug 2016
3.7	Gasification	APL	Arcata, CA	Mass balance Energy balance Emissions Operator hours	Redwood Tanoak Douglas fir	Programmable load	20 kW	Apr 2016
3.7	Gasification	APL	Big Lagoon, CA	Demonstration	Forest residues		20 kW	Jul 2015
3.7	Gasification	APL RFFI	Branscomb, CA	Mass balance Operator hours	Tanoak residues	Biochar machine Dryer	20 kW	Jun 2016

The key findings from field tests are enumerated in the relevant tasks above. Data from these testing activities were analyzed during Subtask 3.9 and shared with researchers in Task Area 4 for lifecycle assessment and economic analyses.

- **Lessons Learned:**

  1. Lessons learned from testing the BCTs are described in Subtasks 3.1 through 3.7.

- **Deliverables:**

  Oral presentations at professional conferences and public workshops:

  1. Public Demo. 2015. *Demonstration of Torrefier, Gasifier Generator Set, Briquetter, and Biomass Dryer*. June 24, 2015, Big Lagoon, CA.
  2. Public Demo. 2016. *Torrefaction and Briquetting Demonstration Plant*. July 28, 2016, Arcata, CA.

SUBTASK 3.9. **PERFORM DATA ANALYSIS AND REPORT ON OUTCOMES**

- **Organization completing task:**

  1. Principal Investigator: Arne Jacobson, Schatz Energy Research Center, HSU

- **Description of task:**

SERC assembled, organized, and archived data collected from operation of the BCTs. SERC analyzed the data and prepared internal reports comparing measured parameters for the different forest residue types and species studied. Analysis of the data, including modeling of hypothetical operating scenarios, was used to draw conclusions about the ability to operate commercial-scale BCTs independent of outside energy sources, feasibility of product scale-up, and potential for operating equipment jointly to make the best use of energy and material outputs. SERC took primary responsibility for contributing material on Task 3 outcomes for the final project report.

- **Summary of key findings and research impacts:**

Performance and cost data collected through testing activities were summarized into datasets that were shared with the project team along with internal reports. These datasets provided key input data to Task Areas 2 and 4 to perform economic analysis and lifecycle assessment. Under Subtask 3.9, SERC developed a spreadsheet tool that used the measured performance of BCTs to model hypothetical operating arrangements and integrated systems with annual throughput up to 50,000 BDT. This spreadsheet tool calculated the required site area, number of machines, drying requirements, size of the electric generator, and auxiliary fuel. As an example, a scenario with an annual throughput of 50,000 BDT and 250 production days using a biochar machine as the primary BCT requires a total footprint of 5.2 acres, where 2.8 acres is used for feedstock storage. The list below enumerates the datasets and products developed by Task 3 and shared among the project partners.

1. Datasets

    a. Biochar Machine Testing Dataset - steady state and time series operational data with different feedstocks including emissions; feedstock and product quality measurements

    b. Biochar Integrated System Dataset - steady state mass/energy flow for biochar plant with integrated waste heat dryer and gasifier generator; time and motion studies for each system component

    c. Gasifier Lab Testing Data - steady state and time series operational data with different feedstocks including emissions

    d. Gasifier Time and Motion Study - labor tasks and time requirements to operate gasifier

    e. Torrefier Pilot System Dataset - torrefier reactor conditions; steady state operational data; feedstock and product quality measurements

    f. Torrefier Demonstration System Dataset - torrefier reactor conditions; steady state mass/energy flow including emissions data; feedstock and product quality measurements

    g. Torrefied Briquette Densification Data - mass flow; feedstock and product quality measurements to densify torrefied biomass

    h. Briquetter Commercial Operation Data - time series electrical demand; feedstock and product quality measurements

i. Briquetter Field Testing Data - feedstock and product quality measurements

j. Briquette Emissions from Woodstove Combustion - emissions data of cordwood, briquettes, and torrefied briquettes

k. Waste Heat Dryer Performance Data - drying characteristics and speed using waste heat belt dryer

2. Spreadsheet Models

   a. Mobile BCT Plant Sizing Spreadsheet - calculates required area, drying capacity, number of machines, size of electrical generator, and production rates for an integrated biomass conversion facility.

3. Input Data to Project Team

   a. Feedstock Specifications for BCTs - particle size, moisture content, ash content specifications for each BCT

   b. Capital, Operation, and Labor Expenses for BCTs - economic input data used by Task 4 to calculate production costs

   c. Commercial Price Data for Bioproducts - collected pricing data for biochar and briquettes through industry partners and contacts; provided data to Task 4

Results from this work have demonstrated the beneficial combination of multiple BCTs into a single plant. Integrating multiple pieces of equipment along with a screener at a single site can more effectively use the wide range of particle sizes produced from chippers and grinders while eliminating underutilized fine and large particles that would arise from a plant with a single BCT. The feedstock limitations discovered through Task 3 and listed in **Table 3** uncover synergies between multiple BCTs. For example, if fine particles can be used in a briquetter and larger particles in a biochar machine, then both machines will produce a higher quality product than if the combined feedstock stream was used in a single machine. In addition, waste heat from the biochar machine can be used to dry feedstock for the briquetter, which has a lower tolerance for moisture content.

Table 3. Feedstock specifications generated from testing under Task Area 3.

BCT	Manufacture	Moisture Content	Ash Content	Longest Particle Dimension	Fine Particles	Chip	Hog-fuel	Rock and Soil
Briquetting	RUF Briquetting	4% - 15%	No limit	50 mm	Fines work very well	Yes, w/ fines	Yes	A few
Torrefaction	Norris Thermal Technologies	<20%	No limit	25 mm	Limited fines <3.14 mm	Yes	No	Yes
Biochar	Biochar Solution, Inc.	<25%	<20%	100 mm	Limited fines, if possible	Yes	Yes	Yes
Gasification	All Power Labs	10% - 30%	<15%	38 mm	<10% particles <12 mm	Yes	No	No

- **Lessons Learned:**

1. Integration of multiple BCTs at a single site allows for complete use of the wide range of particle sizes available after harvest and comminution of forest residuals. Briquetters work best with fine particles, the torrefier requires small particles with limited dust, and the biochar machine can accept large particles.
2. Combining multiple BCTs at a single site allows for effective use of waste heat from one machine to dry feedstock for other BCTs with tighter moisture content specifications.
3. Comminuted feedstocks produced from forest residues can be used in BCTs as long as they meet the moisture, ash, and particle size specifications listed above.

- **Deliverables:**

<u>Oral presentations at professional conferences and public workshops:</u>

1. Jacobson, A., D. Carter, and M. Severy. 2017. Biomass conversion technologies: System performance, case studies, and implications for California's forest management. *Waste to Wisdom Public Workshop*, May 17, 2017, Sacramento, CA.
2. Palmer, K. and A. Eggink. 2017. Biomass for economic revitalization. Oral presentation at *Western Klamath Restoration Partnership Workshop*, June 6, 2017, Happy Camp, CA.

TASK 4.0: BIOFUELS AND BIOBASED PRODUCT DEVELOPMENT ANALYSIS

SUBTASK 4.1. CONSTRUCT A SUITE OF ECONOMIC MODELS TO EVALUATE THE EQUIPMENT BEING STUDIED IN TASKS 2 AND 3

- **Organization completing task:**

  1. Principal Investigator: E.M. (Ted) Bilek, USDA Forest Service, Forest Products Laboratory. Madison, Wisconsin.

  2. Kamalakanta Sahoo, Post-doctoral Research Associate, USDA Forest Service, Forest Products Laboratory. Madison, Wisconsin.

- **Description of task:**

A suite of fully integrated economic models was needed that could be used to evaluate the equipment and biomass utilization pathways. The models were used to calculate break-even costs including not only capital and operating costs, but also taxes, loans, and inflation. Where market prices did not exist, the break-even costs were used as transfer prices for raw materials produced by the equipment in TASK 2 going to TASK 3.

- **Summary of key findings and research impacts:**

The economic and financial feasibility of processing and converting woody biomass waste into higher-valued feedstocks were evaluated. The biomass came from logging operations and forest health treatments in northern California, Oregon, and Washington. The machine rate models were used to evaluate the different pathways of supplying quality feedstocks to portable plant locations in near the forest to produce either solid biofuels or biochar. Three products were evaluated: biomass briquettes, torrefied wood, and biochar. We used a discounted cash flow rate of return (DCFROR) model to estimate the minimum selling price (MSP) of these products produced from forest residues. In addition, the costs of producing and shipping bales of condensed biomass to energy plants for grinding were compared with the costs of grinding and shipping directly for power production.

The cost of biomass sorting and treetops processing (BSTP) was varied between \$56/bdmt to \$155/bdmt based on the intensity of sorting biomass. However, the cost of BSTP can be supplemented by costs saved during land preparation and re-planting in the forest lands. The cost of chipping and microchipping were about \$7 and \$9 per bdmt respectively. The cost of baling forest residues (i.e., slash piles) was much higher than grinding due to the high cost of the forest biomass baler and its lower overall productivity compared with a grinder. About 30% to 40% of the total cost was contributed by equipment feeding to a grinder/chipper/screener. Assuming a 32 km distance between landing and plant, the most economical way to deliver quality forest residues was transporting processed stem wood to plant and comminuted to chips there (~\$20.00/bdmt, assuming zero cost of BSTP). Grinding slash at the landing and transporting ground biomass (i.e., hog-fuel) to a plant (< 220 km away) was more economical than transporting bales from the landing and grinding at the plant. Economic feasibility of baling and BSTP requires a significant improvement in their productivity or recognition of benefits including reduced wildfire risk and improved forest health.

MSPs of biomass briquettes, torrefied briquettes, and biochar produced from forest residues considering a plant of annual biomass input capacity of about 2500 bdmt was estimated to be \$161.5/bdmt, \$274.3/bdmt, and \$1044.2/bdmt, respectively, assuming a 16.5% nominal before tax and finance discount rate and 2% inflation per year. Incorporating five-year loan financing at 40% of initial capital investment at 6.00% interest compounded monthly and 40% income taxes, the MSPs for biomass briquettes, torrefied briquettes, and biochar drop to \$156.4/bdmt, \$257.0/bdmt, and \$962.8/bdmt respectively.

At these MSPs, biochar and briquettes are the most attractive product options and although there are not yet well-developed markets for these products, appear to offer the most potential for utilizing forest waste. Torrefied briquettes presently have an even more-limited market, and at the MSPs that we calculated, may not offer an economic proposition. However, there are possibilities to decrease torrefied briquette production costs and also to gain higher prices through niche markets, which may make this product more attractive in the future.

- **Lessons learned:**

1. Size matters.
    a. Labor is one of the largest costs in small-scale systems and one that is highly amenable to scale-up factors. Larger systems that use the same amount of labor are far more cost-effective than very small-scale systems.
    b. Uniformity in feedstock leads to a more uniform product. While it may seem obvious in hindsight, unless the feedstock going into a torrefier or biochar machine is relatively uniform to begin with, the product coming out of the machine will not be uniformly torrefied or charred, and may not be acceptable to customers.
2. Productivity matters.
    a. Due to different machine sizes, it can be difficult to match machine productivities in order to come up with a production system that can manufacture processed feedstock at a low unit cost. This means that having alternative markets (e.g. for woodchips) would be important for a biomass processing operation in order to avoid inventory buildups.
    b. With start-up and shut-down times on the machines possibly taking an hour, overall system daily productivity can be increased by extending the operating day, which increases productive hours on a one-to-one basis.
3. Feedstock cost may be unacceptable unless the landowner bears at least a portion of the extractions cost recognizing that the reduction in biomass means reduced land preparation and reforestation costs, reduced wildfire risks, and possibly improved site productivity due to the elimination of scorched earth under burn piles.
4. Of the products examined for conversion of low-valued biomass into quality feedstocks and bioproducts in near-forest production systems, biochar offers the most economic potential. The biochar machine that was used in the W2W project was more tolerant to feedstock variability than the torrefier and in addition biochar production reduces the biomass by about three quarters, increasing final product shipping efficiencies.

- **Deliverables:**

  Publications:

  1. Sahoo, K. and E.M. Bilek. 2018. Economic analysis of forest residues logistics options to produce quality feedstocks. Waste to Wisdom (BRDI) Subtask 4.1 Final Report. March. 33 p.

  2. Sahoo, K. and E.M. Bilek. 2018. Economic analysis of solid biofuels and biochar production from forest residues using portable production systems. Waste to Wisdom (BRDI) Subtask 4.1 Final Report. March. 36 p.

  Oral presentations at professional conferences and public workshops:

  1. Bilek, E.M., R. Bergman, D. Sasatani, and D. Page-Dumroese. 2015. Waste to Wisdom, Task Area 4: Biofuels and Biobased Product Development Analysis. A webinar presented as part of the Waste to Wisdom series. December 7.

  2. Bilek, E.M. 2017. The economics of Waste to Wisdom. Public Workshop, Sacramento, California, May 17, 2017.

  3. Bilek, E.M., S. Alanya-Rosenbaum, M. Severy, and R. Bergman. 2017. Near-forest woody biomass torrefaction. A webinar presented as part of the Waste to Wisdom series. August 4.

  4. Bilek, E.M., E. Oneil, and D. Page-Dumroese. 2017. Waste to Wisdom, Task Area 4: Biochar. A webinar presented as part of the Waste to Wisdom series. August 23.

SUBTASK 4.2. **DEVELOP A TOOL TO EVALUATE THE VALUE OF BIOCHAR AS A SOIL AMENDMENT FOR CARBON SEQUESTRATION**

- **Organization completing task:**

  1. Principal Investigator: Deborah S. Page-Dumroese, P.I., USDAFS Rocky Mountain Research Station

  2. Principal Investigator: Ivan Eastin, University of Washington (UW)

  3. Principal Investigator: Elaine Oneil, University of Washington Forest Resources LCA

  4. In collaboration with Indroneil Ganguly and a graduate student, UW and Kolby Hirth, Forest Products Laboratory, Madison, WI

- **Description of task:**

The objective of this task was to evaluate if and where biochar applications would be appropriate on forest soils. We determined that biochar could be used to remediate mine soils. Field trials were established on plots and pre- and post-biochar application soil and vegetation samples were collected. In addition, lab and field trials on select mine land sites were used to determine the feasibility of biochar being used to absorb heavy metals. Carbon sequestration outcomes of using forest residues to produce biochar relative to the business as usual case of piling and burning residues for fire risk reduction were assessed using a life-cycle inventory and assessment technique.

- **Summary of key findings and research impacts:**

In general, biochar can be applied to any forest, range, or mine site. Although results from site-to-site vary, carbon can be sequestered effectively on any of these sites. Mine soils contaminated by iron (with over 200,000 ppm) could be remediated with biochar. In small-scale laboratory studies, biochar was able to effectively reduce lead contamination by about 80%. Heavy metal contamination of soils is a global challenge on many forested minelands. Usually, these types of sites resist attempts at regeneration and biochar may offer one solution to effectively restore soils, particularly when they are adjacent to fish-bearing streams. Biochar contains greater amounts of oxygen-containing surface functional groups that enhance sorption of metals in controlled laboratory studies. However, testing of biochar in a field setting should be conducted. Of course, in the presence of soil, the importance of the oxygen-containing groups on biochar depends on soil and biochar properties. This offers an opportunity to design biochars that are specific to the contaminated site and soil properties. For example, high pyrolysis temperatures or steam activation of biochar could improve heavy metal retention capacity.

The carbon consequences of using forest residue as a biochar feedstock relative to disposing of it through open burning was determined using life-cycle analysis. Upstream data for five scenario locations weighted by material type and harvest type show that the production of biochar provides an improved carbon sequestration profile over piling and burning. This benefit is in addition to its impact on improved forest growth and accounts for all inputs to recover feedstocks and generate the biochar. The pile and burn options are nearly carbon neutral with a net global warming potential (GWP) emission of -0.04 t CO_2 eq per ton of biomass burned. Net GWP emission for 1 metric of feedstock are -0.29 and -0.63 t CO_2 eq for biochar produced with ground tops and pulpwood and biochar produced with medium chips using a diesel generator respectively. Negative numbers indicate that more carbon is stored than is released from combustion of material from all sources. When a diesel generator is used, there is a 66 percent decrease in net carbon storage for the tops/pulpwood biochar system and 14 percent decrease in biochar system that used chipped pulpwood. The use of the biomass gasifier (power pallet) to supply the energy for the biochar machine stored an additional 7 percent CO_2 during forest growth and lower CO_2 eq emissions by 3 percent over the diesel generator for biochar produced with tops and pulpwood.

- **Lessons learned:**

1. It was extremely difficult to analyze biochar for heavy metal content and care is needed to ensure a uniform product for analysis.
2. We needed to group elements in the multi-element standards, as well as having a good idea as to which samples need to be diluted by how much in order to stay within a good working range.
3. Equipment purchased for this project – using a digestion method – was highly accurate and could become a standard method for biochar or contaminated soil analyses.
4. The analysis shows that despite the many challenges of producing biochar in remote locations, there are complementary benefits in providing long term storage

of recalcitrant carbon. Those benefits can be measured as improvements of the emission profile over that released from open burning.

- **Deliverables:**

Publications:

1. Ott, M. 2016. Using organic amendments to restore degraded mineland soils. MSc Thesis. University of Idaho. 128 p.
2. Page-Dumroese D.S., M.R. Ott, D.G. Strawn, and J.M. Tirocke. 2018. Using organic amendments to restore soil physical and chemical properties of a mine site in northeastern Oregon, USA. Association of Scientists in Agricultural and Biological Engineering. *Applied Engineering in Agriculture*. ASABE special collection publication. 34(1): 43-55.
3. Oneil, E.E. and M.E. Puettmann. 2017. To burn or not to burn: where, when and how to burn to minimize environmental impacts. Chapter 3, pp. 41-50 in: Oneil, E.E., Comnick, J.M., Rogers, L.W., and M.E. Puettmann. 2017. Waste to Wisdom: integrating feedstock supply, fire risk and life cycle assessment into a wood to energy framework. Final report on Waste to Wisdom: Subtask 4.2, 4.7 and 4.8. HSU BRDI grant DE-EE0006297. December. 50 p.

Oral presentations at professional conferences and public workshops:

1. Page-Dumroese D.S. 2015. Biochar use on forest, range, and mine land soils. Invited webinar on the Evaluation of the Economics and Environmental Benefits from Using Forest Residues.
2. Page-Dumroese D.S. 2016. Using forestry feedstocks to create biochar and improve soil productivity and carbon sequestration. Panel on Frontiers in Biochar at the Western States Wood Energy Team Forum 2016. Missoula, MT.

SUBTASK 4.3. **IDENTIFY AN INPUT/OUTPUT MODELING PROTOCOL TO ASSESS ECONOMIC IMPACTS OF BCTS**

- **Organization completing task:**

1. Principal Investigator: Ivan Eastin, University of Washington
2. Daisuke Sasatani, Research Associate, University of Washington

- **Description of task:**

It is important to understand the economic and marketing potential of products manufactured from biomass conversion technologies (BCT). To evaluate the community economic impacts, economic input/output (I/O) models were used to estimate the economic impacts of establishing a bioenergy product sector based on the utilization of forest residuals. The team developed an I/O methodology and identified the protocol required to assess the economic impacts on local communities.

- **Summary of key findings and research impacts:**

This project assessed the economic impacts of establishing transportable biomass conversion (BCT) facilities producing biochar, torrefied briquettes/chips and wood briquettes for five sub-regions within the Pacific Northwest region: Quincy, CA; Lakeview, OR; Oakridge, OR; Port Angeles, WA and Warm Springs, OR. Since the regional markets for products made from forest residue were dispersed through each sub-region, we estimated the demand curve for each product in each sub-region in order to understand the economic feasibility of locating a BCT operation within each sub-region. Economic models were developed to consider the market price of the bioenergy products, the potential market size, and transportation costs in each region.

Since wood briquettes can substitute for firewood within the residential heating market, the pricing can be very competitive between the two products based on total heat value. Wood briquettes are a densified product and can be more efficiently delivered to retail stores. The distance from the biomass conversion facility to retail stores is proportional to the transportation cost, with the transportation costs of wood briquettes offsetting the profitability of conversion facilities. Thus, the biomass conversion facilities that are located near heavily populated areas, such as Port Angeles and Warm Springs, have a transportation advantage and the potential to generate higher profits.

Although there might be some lucrative niche markets in the future, the main market for torrefied briquettes is very specific at this moment – coal power plants. Conversion facilities producing torrefied briquettes would likely need to target domestic or offshore coal plants. If they cannot receive energy subsidies or price premiums, it will be very difficult for them to be profitable under the current market environment due to their higher production and transportation costs.

Producing biochar for use as a soil amendment is still an immature market and demand is currently small. However, market research suggests that some people (e.g., organic farmers) have a high willingness-to-pay for high quality biochar. The retail price of biochar fluctuates between $250 and $4,950 per short ton based on a wide variety of factors. Thus, biochar producers should consider implementing a marketing strategy that employs a price skimming strategy. Distance from market is still a critical factor to be considered in locating a biochar production facility. In the case of biochar, where smaller volumes of higher margin products can be sold, using an innovative transportation system may help to overcome market access problems. This study attempts to show a bench mark demand curve, but the market penetration rate and consumers' willingness-to-pay for biochar products substantially affect the shape of the demand curve. In other words, the quality of the products and marketing effectiveness (e.g., availability in certain retail stores, advertisement, packaging, and labeling) will hugely influence the profitability of a biochar conversion facility.

This study also assessed the community impacts of a BCT operation in each sub-region. We used an input-output analysis (I/O) to measure the economic impacts of the introduction of the conversion facility in the five different sub-regions. In the I/O analytical framework, the direct economic impacts include the economic activities directly attributed to the sale of BCT products (wood briquettes, torrefied briquettes and biochar). The direct effects caused by the initial spending of the conversion facility also generate additional economic activity within each region. These indirect effects generated by the conversion facility are the business-to-business transactions that occur as firms engage in economic transactions with the conversion facility. As the direct and indirect effects of the conversion facility create new jobs, local households increase their spending on local goods and services. This type of increased economic activity is referred to as the induced effect. The total economic impacts of the new conversion facility are the sum of the direct, indirect and induced impacts within each location. For example, assume that the conversion facility were located in the Quincy CA location and that it produced 49,000 BDT of wood briquettes. The results of the I/O analysis suggest that this type of facility could generate $7.6 million in revenue, including $5.1 million from biomass product sales and $2.5 million from transportation to markets. We estimate that this $7.7 million of direct economic effect would generate $2.2 million in indirect economic effects and $0.8 million in induced economic effects within Plumas County, CA. Based on our analysis, this new wood briquettes facility could increase the county's economic output by 0.8% and contribute to the creation of 61 new jobs within the region. Similar analyses were completed for the other products and markets.

- **Lessons Learned:**

  1. Distance from market is a critical factor to be considered in locating a BCT production facility. The main customers for bioenergy products are residential households and as delivery costs rise, they substantially impact the profitability of the BCT facility.
  2. Increasing the market penetration rate and improving the quality of the products will increase revenue. Adopting appropriate marketing strategies (e.g., advertising, price skimming, convenience and product quality) can encourage consumers to switch from competing products (e.g., firewood, wood pellets, soil composts) to W2W products (e.g., wood briquettes and biochar).
  3. High retail prices for biochar, wood briquettes and torrefied briquettes do not necessarily guarantee profitability, especially in those locations where market access and market size are low. In addition, the volume of production in areas where market size is low needs to be taken into consideration as large volumes of production will likely result in market saturation and reduced profitability and growth potential. W2W producers in rural locations need to be sensitive to this oversupply issue.
  4. Manufacturing W2W products can contribute to the economic development of rural timber-dependent communities within the Pacific Northwest (PNW) region. Since biomass collection is labor intensive, this activity can create substantial jobs in the forestry sector while expanding employment opportunities in other sectors within the local community (e.g., transportation).
  5. The level of economic growth that local communities experience in the long-run depends on how economically sustainable the BCT facility will be. Many internal and external factors influence the operation of a BCT facility, which brings substantial business risk. In the future, it is important to discuss ways that the public sector might help to mitigate the business risk since BCT's bring both environmental and social benefits to the local community.

- **Deliverables**

  <u>*Publications*</u>

  1. Sasatani, D., and I. Eastin. 2018. Demand Curve Estimation of Locally Produced Woody Biomass Products. *Applied Engineering in Agriculture*. ASABE special collection publication. 34(1): 145-155.

Oral presentations at professional conferences and public workshops:

1. Sasatani D., and I. Eastin. 2017. Demand Side Perspective of W2W Products and Economic Impact Analysis of W2W Operations. Public Workshop, Sacramento, California, May 17, 2017.
2. Sasatani D. 2016. An Input-Output Analysis of the Potential Regional Economic Impacts of Biomass Usage in Western States. International Convention. Forest Products Society 70th International Convention. June, 2016, Portland, OR.
3. Waste to Wisdom Task Area 4 Webinar "Economic and Environmental Benefits of Utilizing Forest Residues" presented December 7, 2015.

SUBTASK 4.4. **DEVELOP AIR QUALITY INDICATORS**

- **Description of task and project objective:**

The overall goal of the project was to develop an objective, data driven, and geo-spatially nuanced assessment of the beneficial regional environmental and health impacts associated with avoiding prescribed woody biomass burns in the Pacific Northwest. This study focused on air pollution related health impacts. Specifically, this study evaluated the impact on human health by considering the pollutants' fate and human exposure.

- **Organization completing task:** University of Washington (UW) and Forest Products Laboratory (FPL)

1. Dr. Indroneil Ganguly, Assistant Professor, UW
2. Dr. Rick Bergman, Project Leader and Research Wood Scientist, FPL
3. Dr. Ivan Eastin, Professor, UW
4. Dr. Francesca Pierobon, Research Associate, UW
5. Cody Sifford, Graduate Student, UW

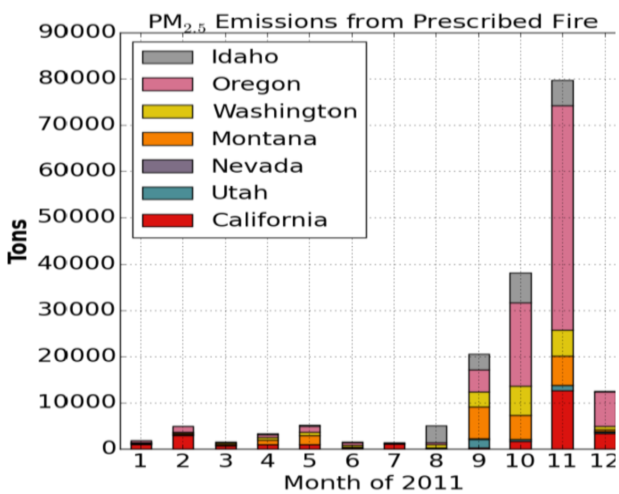
- **Summary of key findings and research impacts:**

The burning of woody biomass in forests (prescribed burns and wildfires) is a major source of greenhouse gas emissions in the western US. Biomass burning also adversely affects local and regional air quality, with acute negative impacts on human health at the local and global levels. Forest operations in the Pacific Northwest (PNW) produce a large amount of harvest residues that are commonly collected, piled and burned in prescribed fires. Alternate bio-based solutions are being proposed in this project to recover woody biomass residues for the production of bioenergy and bio-products. Biomass burns emit a large amount of chemicals, including particulate matter, organic, and inorganic compounds, with potential adverse environmental and health impacts. While most environmental assessments of wood products are focused on the impact on global warming, very few studies have considered the impact of burning slash pile burns on human health. The aim of this study was to calculate the impact on human health that result from prescribed fires in the PNW. In this study, the impact on human health was calculated while considering the pollutants' fate and human exposure as a result of open slash burn.

This study was divided in two sections. The first section evaluated the overall air-quality-related environmental impact of prescribed burns in the Pacific Northwest region. In the second section a case study was developed evaluating the beneficial air quality impacts associated with economically removing slash from forest harvest locations and avoiding the corresponding prescribed burns and air emissions.

Section 1: Overall air quality related health impacts in PNW as a result of prescribed burns

Methodology: The study used the National Emission Inventory (NEI) prescribed fires data compiled by the US-Environmental Protection Agency (EPA). The EPA estimates of the prescribed burn emissions are modelled from a variety of sources and are included in the BlueSky modeling framework. The data sources include: (i) SMARTFIRE satellite reporting; (ii) ground based Incident Command System (ICS-209) reports; and (iii) prescribed-burn reporting systems.



Emissions of PM2.5 from wildfire and prescribed burns for 2011 based on NEI-2011 (Source: Ravi, V., 2016)

Figure 7. All prescribed burns related emissions were factored-in and carcinogenic and non-carcinogenic impacts were estimated.

For this study we established 2011 as a typical year for prescribed burns. Accordingly, NEI 2011 emissions data was extracted and analyzed using the AIRPACT modeling system. Once the fire information was available, fuel loading maps and fuel consumption models were used to estimate the total fuel consumed. Emissions of 54 different pollutants including $PM_{2.5}$, CO, CH4, NOx, SO2, NH3 and VOCs were then calculated. These emissions were distributed spatially and temporally using the SMOKE modeling system, which also calculates the plume rise for the fires (Herron-Thorpe et al., 2014). The emissions associated with the 37 days of Oct/Nov period were considered.

- **Results:**

For calculating the health impacts it is assumed that the population was exposed to 30% of the ambient pollution (as a result of staying indoors, air purification systems, etc.). Given similar prescribed burns are a regular annual phenomenon, it was also assumed that that the population was exposed to similar levels of pollution for 37 days of every year for 70 years (lifetime). The results indicate that the number of cancer cases that can be attributed to prescribed burns over a **70-year** period is as follows:

1. Washington:............................**40 cases**
2. Oregon:...................................**55 cases**
3. N. California (north of SFO): ......**2 cases**

<u>Section 2: CASE STUDY: Simulation exercise of the potential beneficial role of W2W</u>

Methodology: A realistic simulation study (based on real air quality data over a 29-day burn period) was conducted to investigate the $PM_{2.5}$ level escalation as a result of prescribed fires around the county of Grays Harbor in Washington State. The area of study included 214 Watershed Administrative Units (WAU) comprising 11 counties and 3 timbersheds in Southwest Washington. Regional biomass availability for this study was calculated using the Washington State Biomass calculator. Using the USFS BlueSky smoke modeling system, the study estimated the emissions associated with burning approximately 800,000 bdmt of residual biomass, or about 30% of total residual biomass available in this three-county region of Washington State.

The results of this study revealed a significant increase in poor air quality zones in the direct vicinity of the pile burns, primarily caused by an escalated $PM_{2.5}$ (small particulate matter) level. The results revealed that, depending on the amount of slash burned and the weather conditions, on some of the days in the study period, particulate matter traveled great distances from the pile burn locations. For example, in seven of the 29 days, the air pollution reached densely-populated areas such as Seattle and Tacoma, in addition to affecting smaller communities. The results further showed that the ambient particulate matter ($PM_{2.5}$) concentrations, because of the simulated pile burns, exceeded EPA's air quality standards on multiple days and in multiple locations across the western part of the state. On 13 of the 29 simulated burn days, the daily average ambient $PM_{2.5}$ concentration, in at least one of the 16 km^2 pixels exceeded the EPA's "unhealthy" air quality levels (> 55.5 $\mu g/m^3$), and reached "very unhealthy" levels (>150 $\mu g/m^3$) on 3 of those days. It should be noted that these levels are more than double the EPA's prescribed limits for daily exposure (< 25 $\mu g/m^3$) and the World Health Organization (WHO) has an even lower threshold for daily $PM_{2.5}$ level exposures. The study also revealed that over the 29-day burn period approximately **430 thousand human-days** were affected by higher than the EPA recommended ambient $PM_{2.5}$ levels.

- **Lessons learned:**

1. Depending on the amount of slash burned and the weather conditions, particulate matter traveled great distances away from the pile burns, reaching densely populated areas such as Seattle and Tacoma, in addition to affecting smaller communities.

2. Particulate matter concentrations with the added pile burns exceeded several poor air quality thresholds over the burn period. On some of the days, $PM_{2.5}$ concentrations exceeded EPA's "very unhealthy" air quality threshold.

3. Our results also showed that 3 of the 29-day pile burning scenario account for 80% of the daily total impacted population affected by pile burn $PM_{2.5}$ concentrations that exceeded the WHO guideline of 25$\mu g/m^3$.

4. Policies aimed at promoting alternative uses of biomass that would avoid in-forest pile burning would dramatically reduce the adverse impacts on human health and poor air quality.
5. In areas where slash pile burning cannot be avoided, the methodology developed in this study can help policy makers identify best practices in fire management based on site-specific factors, such as meteorological conditions, air chemistry, biomass supply, number of slash piles (including their size and shape), population density, and site morphology.
6. Since the above factors are site specific, the application of this methodology to other regions of the country would be beneficial in learning how slash pile burning affects populations in other parts of the country.

- **Deliverables**

Publications:

1. Sifford, C. 2016. Developing an Impact Assessment of Local Air Quality as a Result of Biomass Burns, MS Thesis, University of Washington, Seattle
2. Sifford, C. and I. Ganguly (2017 in-press), Developing an Impact Assessment of Local Air Quality as a Result of Biomass Burns, CINTRAFOR working paper, University of Washington, Seattle
3. Alanya-Rosenbaum, S., R. Bergman, I. Ganguly, and F. Pierobon. 2018. A comparative life-cycle assessment of briquetting logging residues and lumber manufacturing coproducts in Western United States. *Applied Engineering in Agriculture*. ASABE special collection publication. 34(1):11-24.
4. Ganguly, I., F. Pierobon, F., C. Sifford, et al. (2017 – in review). Air quality related health impacts of prescribed burns in the Pacific Northwest.

Oral presentations at professional conferences and public workshops:

1. Pierobon F., I. Ganguly, C. Sifford, V. Ravi, E. Alvorado, I. Eastin, and B. Lamb, 2016. Environmental impact assessment of prescribed fires incorporating air chemistry and pollutants dispersion in the Pacific Northwest. Oral Presentation presented at WFE, 2016
2. Ganguly I, F. Pierobon, C. Sifford, V. Ravi, E. Alvorado, I. Eastin, and B. Lamb. 2016. Avoided impacts of slash pile burning in the Pacific Northwest. Oral Presentation presented at FPS, 2016.
3. Ganguly I. (presenter), C. Sifford, F. Pierobon, V. Ravi, E. Alvorado, I. Eastin, and B. Lamb. 2017. Evaluation of avoided impacts of slash pile burning: a tool to improve fire management in the Pacific Northwest. Oral Presentation presented at SEFS environmental seminar, University of Washington, Seattle.
4. Ganguly, I., F. Pierobon, C. Sifford, et al. 2017. Air quality related health impacts of prescribed burns in the Pacific Northwest, Poster presented at IUFRO 2017 in Vancouver, BC, Canada.

SUBTASK 4.5. **CONDUCT A WORKSHOP TO EXPLORE STAKEHOLDER PERCEPTIONS**

- **Organization completing task:**
  1. Principal Investigator: Ivan Eastin, Professor, University of Washington
  2. Daisuke Sasatani, Research Associate, University of Washington
  3. Indroneil Ganguly, Assistant Professor, University of Washington
  4. Tait Bowers, Doctoral Candidate, University of Washington

- **Description of task:**

One challenge of conducting forest harvesting and thinning activities is the efficient disposal of unused forest residues (e.g., branches and tops). Typically, unmerchantable forest residues are collected into slash piles where they are later burned. While there are many potential markets for forest residuals, high collection and transportation costs mean that most forest residuals are left in the forest where they are burned in slash piles. In addition, ongoing consolidation within the forest products industry has altered the traditional utilization of forest resources. The closure of many pulp mills, which were historically the main buyers of low grade logs, has forced nearby forestland owners to find alternative markets for low-quality pulpwood. Developing markets for currently unmerchantable forest residues would encourage forest owners to conduct pre-commercial thinning operations, which would help to improve the health and fire resilience of western forests. In many rural forest-dependent communities, economic conditions including the unemployment rate, employment growth, and household incomes, pale in comparison to major urban areas. There are significant differences between these urban and rural areas in terms of economic diversity, economic growth, industrial structure, social well-being, and political viewpoints. People living in rural and urban areas often hold very different views about forest management practices and woody biomass-based energy ("bioenergy") utilization. Using forest residuals to produce bioenergy products must take into account the varied perceptions of both rural and urban communities since they often influence those who make important forest policy decisions. Consequently, understanding the public perceptions of converting woody biomass into bioenergy products is critically important to gaining public support for this type of project. In this research, a web-based survey was used to target urban and rural residents in the western PNW region to explore their attitudes and perceptions regarding forest management and forest thinning and the use of forest residuals in the production of woody bioenergy products and biochar.

- **Summary of key findings and research impacts:**

In this research, we explored public support for thinning activities in western forests and the use of the resultant forest residuals in the production of bioenergy products and biochar. This represents one of only a few studies where survey respondents were given the option to indicate that they "have no opinion" about a subject. This is important because past studies suggest that people who do not have a strong understanding of an issue (e.g., biochar) are more likely to indicate their support for the issue, which can skew the survey results. Overall, the results of this research indicate that the majority of respondents support thinning of forests and using the forest residuals generated during those thinning activities to produce bioenergy products and biochar. We applied multinomial regression and a simulation-based approach to explore and help visualize how demographic and social factors influence public acceptance of forest thinning activities and the use of forest residuals to produce bioenergy products and biochar. Public acceptance of forest thinning, bioenergy products and biochar show different results based on a variety of variables, including level of education, household income, gender, location, and frequency of visits to National Forests. These results suggest that different communication strategies and messages are needed in order to educate the public about the role of forest thinning in improving the health and fire resilience of western forests and the economic benefits that can be derived from using the resultant forest residuals in the production of bioenergy products and biochar.

Although the majority of the respondents in this survey supported forest thinning (56.0%), it is important to note that almost a third (27.4%) opposed thinning activities. The survey results clearly show that opposition to forest thinning increases as urban density increases (from rural areas to small cities to large urban areas). Rural residents living in the coastal Pacific Northwest region are surrounded by forests and they are more aware of the direct positive relationship between sustainable forest management (including forest thinning) and forest health, fire resilience and rural economic development. In contrast, many urban residents only visit forests occasionally and they generally do not have a strong understanding of how unmanaged, overcrowded forest conditions can adversely impact forest health and increase the chances of insect infestations and catastrophic wildfires. Previous research has found that many urban residents tend to overemphasize the amenity values of forests while being more likely to view forest management activities as being destructive to forests and wildlife. However, given the asymmetrical influence of people living in urban areas on natural resource policies (relative to people living in rural areas), these results suggest that it is important to ensure that urban people better understand that sustainable forest management, including thinning overly-dense forests, is critical to maintaining healthy forests that are resilient to both insect infestations and catastrophic wildfires.

In contrast to the thinning results, survey respondents indicated strong support for producing bioenergy products (79.5%) and biochar (73.0%) from forest residuals derived from forest thinning operations. More importantly, very few people actually opposed the production of bioenergy products (9.1%) or biochar (9.0%) from forest residuals and opposition to bioenergy products does not appear to be related to population density. The results also show that a sizable proportion of respondents had no opinion about using forest residuals for bioenergy/biochar (11.4% and 18.1%, respectively). These results taken together suggest that education could be an important strategy for demonstrating the positive impacts that well-designed thinning activities can have on forest health and fire resilience within western forests. Utilizing the woody residuals derived from forest thinning can help improve the sustainability of these operations (both environmentally and ecologically), while producing bioenergy products and biochar can help support rural economic development.

The survey results clearly show that a slight majority of people living within the coastal Pacific Northwest region support forest thinning, while a significant majority support the use of forest residuals for the production of bioenergy products and biochar. The results show that support increased significantly as household income increased and as the level of education of the respondent increased. While support for bioenergy products and biochar was robust across the different types of locations (rural areas, small towns and large urban areas), support for forest thinning was substantially less (but still over 50%) within large urban areas. These findings suggests that there is a strong need to educate people living in large cities about the positive impacts that sustainable forest management (including forest thinning activities) can have on improving forest health and increasing forest resilience to insect infestations and catastrophic wildfires.

- **Lessons Learned:**

  1. The results of this research indicates that the majority of respondents support thinning of forests and using the forest residuals generated during those thinning activities to produce bioenergy products and biochar.
  2. The survey results clearly show that opposition to forest thinning increases as urban density increases (from rural areas to small cities to large urban areas).
  3. These results suggest that different communication strategies and messages are needed in order to educate the public in rural and urban areas about the role of forest thinning in improving the health and fire resilience of western forests and the economic benefits that can be derived from using the resultant forest residuals in the production of bioenergy products and biochar.

- **Deliverables**

  Publications:

  1. Sasatani, D., I. Eastin, C.T. Bowers, and I. Ganguly. 2018. Public Acceptance of Pre-Commercial Thinning and Energy and Soil Amendment Products from Post-Harvest Residues in Western Forests of the U.S. *Applied Engineering in Agriculture*. ASABE special collection publication. 34(1): 99-108.

  Oral presentations at professional conferences and public workshops:

  1. Bowers, T., D. Sasatani, and I. Eastin. 2017. Public Perceptions of Forest Management Activities for Bio Energy Products. Public Workshop, Sacramento, California, May 17, 2017.
  2. Bowers, T. 2016. Public Perceptions in the PNW Region of Using Forest Residuals for BioEnergy. International Convention. Forest Products Society 70th International Convention. June, 2016, Portland, OR.
  3. Bowers, T. 2015. Waste to Wisdom Task Area 4 Webinar “Public Perceptions of Utilizing Forest Residues” presented December 7, 2015.

SUBTASK 4.6. **EVALUATE IMPACTS ON FOREST SOILS**

- **Organization completing task:**

  1. Principal Investigator: Deborah S. Page-Dumroese USDA Forest Service, Rocky Mountain Research Station

- **Description of task:**

This task considered the ecological sustainability of using biochar as a soil amendment, focusing on its impact on forest soils (including carbon storage and nutrient cycling), forest productivity, water quality and air quality. An investigation into the avoided costs and environmental benefits needed in the social and environmental analysis was also undertaken. Biochar application field studies supported estimation of carbon sequestration potential.

- **Summary of key findings and research impacts:**

Many North American forests face management challenges related to wildfire, insect and disease outbreaks, and invasive species, resulting, in part, from overstocked or stressed stands. Forest restoration or rehabilitation treatments often involve thinning and regeneration harvests that can produce 40-60 million dry metric tons of woody biomass per year. To reduce wildfire hazard from the resulting residual biomass, slash pile burning is often used. However, in-woods processing to create chips, slash forwarding to recover previously discarded material, or mobile pyrolysis may all be used to decrease costs and add value to unmerchantable wood. The use of in-woods pyrolysis or other methods of creating biochar (e.g., sawmills, wood product facilities, bioenergy plants, kilns, etc.) are other methods for creating biochar while processing merchantable wood.

Biochar can be made in many different ways using a wide variety of feedstocks. All production methods and feedstocks result in differences in biochar physical and chemical properties. The key is selecting the appropriate biochar for each soil type. All studies described in this section have used biochar from waste wood from thinning operations in Montana or Idaho. One caution from our study sites is that biochar applications on forest sites should not disturb the surface organic horizons. Several study sites on forest, range, and mine lands were installed and used to determine ecosystem responses to biochar applications. On every site evaluated, increased soil moisture was noted after biochar was added; particularly at the 22 Mg/ha application rate. Moisture content increased from 2%-19%, depending on soil type, ecosystem, and pre-application soil organic matter content.

There are few forestry field trials from which to we could infer methods, biochar application rates, or anticipated responses. However, we installed five new forestry trials. Of particular importance to forestry operations are the beneficial effects related to bulk density reduction on skid trails or log landings when biochar is used. Unlike chips, masticated wood, wood straw, agricultural straw or other surface amendments, biochar adds carbon to forest soils and is likely the reason for the increased water holding capacity.

One key finding on forest range, and mine sites is that soil cover was increased by the use of biochar. Soil cover less than 20% can result in erosion and increased runoff. On our sites soil cover increases ranged from 42%-67%.

- **Lessons learned:**

1. Forest feedstocks offer the most uniform biochar, but pH and other physical properties of biochar can alter the effectiveness of applications.
2. Application rates around 22 Mg/ha are the most effective for changing soil physical, chemical, and biological properties.
3. Application of biochar on range and mine sites can be relatively easy with existing equipment (*i.e.,* range rake, tractor), but on forest sites the biochar spreader is much more efficient.

- **Deliverables:**

  Publications

1. Jang, W., C.R. Keyes, D.S. Page-Dumroese. 2015. Long-term effects on distribution of forest biomass following different harvesting levels in the northern Rocky Mountains. *Forest Ecology and Management.* 385: 281-290.
2. Scott, D.A., D.S. Page-Dumroese. 2016. Wood bioenergy and soil productivity research*. Bioenergy Research*. doi: 10.1007/s12155-016-9730-6.
3. Jang, W., D.S. Page-Dumroese, and C.R. Keyes. 2016. Long-term changes from forest harvesting and residue management in the northern Rocky Mountains. *Soil Science Society of America Journal*. doi:10.2136/sssaj2015.11.0413.
4. Anderson, N., R. Bergman, and D.S. Page-Dumroese. 2017. A supply chain approach to biochar systems. In: *Biochar: a regional supply chain approach in view of climate change mitigation*. Chapter 2. Cambridge University Press.
5. Bergman, R., H. Gu, D.S. Page-Dumroese, and N. Anderson. 2017. Life cycle analysis of biochar. In: *Biochar: a regional supply chain approach in view of climate change mitigation*. Chapter 3. Cambridge University Press.
6. Page-Dumroese, D.S., M. Coleman, S.C. Thomas. 2017. Opportunities and uses of biochar on forest sites in North America. In: *Biochar: a regional supply chain approach in view of climate change mitigation*. Chapter 15. Cambridge University Press.
7. Page-Dumroese, D.S., M.D. Busse, J.G. Archuleta, D. McAvoy, and E. Roussel. 2017. Methods to reduce forest residue volume after timber harvesting and produce black carbon. *Scientifica*. https://doi.org/10.1155/2017/2745764
8. Jang, W., D.S. Page-Dumroese, and H.-S. Han. 2017. Comparison of heat transfer and soil impacts of air curtain burner burning and slash pile burning. *Forests*, 8: 297-312.

Oral presentations at professional conferences and public workshops:

1. Anderson, H., C. Keyes, and D. Page-Dumroese. 2015. Ponderosa Pine Responses to Biochar Treatments on the Bitterroot National Forest: Impacts on Tree Growth and Soil Properties. SAF National Convention, Baton Rouge, LA.
2. Page-Dumroese, D.S., M. Coleman, S. Cook, M. Jurgensen, D. Lindner, J. Tirocke, K. Draeger, J. Sarauer, and L. Sherman. 2015. Impacts of forest biomass removal on soil quality and biodiversity. AFRI grant PI meeting. Denver CO.
3. Page-Dumroese, D.S., M.F. Jurgensen, J.M. Tirocke, J. Rogers, and C. Miller. 2016. Decomposition under biochar-amended soils. European Society for Ecological Restoration. Munich, Germany.
4. Anderson, H., C. Keyes, D. Page-Dumroese, and M. Coleman. 2016. Ponderosa pine ecosystem response to thinning, biochar, fertilization or mastication in the Bitterroot National Forest: Impacts on tree growth and soil properties. European Society for Ecological Restoration. Munich, Germany.

5. Page-Dumroese, D.S. 2016. Maintaining and improving soil and site productivity during bioenergy harvest operations. IUFRO Forestry and Research Meeting. Beijing, China.
6. Page-Dumroese, D.S., M.F. Jurgensen, J.M. Tirocke, J. Rogers, and C. Miller. 2016. Decomposition under biochar-amended soils. 3rd Annual Asian-Pacific Biochar Meeting. Chuncheon City, S. Korea.
7. Page-Dumroese, D.S. 2016. Wildfire, biochar, and soil disturbance. Korea University, Seoul, S. Korea.
8. Page-Dumroese, D.S. 2016. Using biochar to reduce fuels and enhance soil productivity. Kookmin University, Seoul, S. Korea.
9. Page-Dumroese, D.S., M.F. Jurgensen, J.M. Tirocke, J. Rogers, and C. Miller 2016. Decomposition under biochar-amended soils: Restoring soil function. European Society for Ecological Restoration, Freising, Germany.
10. Page-Dumroese, D.S. 2016. Using biochar for soil restoration. Region 3 Water-Soil-Wildlife-Timber Annual Meeting. Pinetop, AZ
11. Page-Dumroese, D.S., M.F. Jurgensen, J.M. Tirocke, J. Rogers, and C. Miller. 2016. Decomposition under biochar-amended soils. Northwest Society for Ecological Restoration. Portland, OR.
12. Page-Dumroese, D.S. 2016. Slash piles to biochar: Sustainable harvesting to increase forest productivity. University of Montana.

SUBTASK 4.7. **CONDUCT LIFE CYCLE ANALYSES**

- **Organization completing task:**

1. Principal Investigator: Rick Bergman, P.I., USDAFS Forest Products Laboratory
2. Principal Investigator: Elaine Oneil, P.I., University of Washington.
3. Sevda Alanya Rosenbaum, Postdoctoral fellow, USDAFS Forest Products Laboratory.
4. Maureen Puettmann, WoodLife Environmental Consultants, LLC

- **Description of task:**

Forest Resources LCA:

1. Developed a cradle to gate life cycle inventory (LCI) for the forest collection processes and conduct a life cycle assessment (LCA) using the TRACI method (Bare 2011) to determine comparable environmental footprints from harvest to utilization.
2. Provided relative comparisons of fuels (torrefied wood and pellets) to fossil fuel sources and biochar to the alternative of prescribed burning and/or wildfire impacts as federal land management tools.

Biochar Processing, Torrefied Wood, and Densified Briquettes LCAs:

1. Developed a cradle to gate life cycle inventory (LCI) for biochar processing, torrefied wood, and densified briquettes and then conducted life cycle assessments (LCAs) using the TRACI method (Bare 2011) to determine comparable environmental footprints from harvest to utilization.

- **Summary of key findings and research impacts:**

In this study, a comprehensive, cradle-to-gate LCA was developed for the near-woods demonstration-scale production of wood briquettes, torrefied wood and biochar from post-harvest logging residues and forest collection and processing of the biomass feedstock.

Life cycle assessment of forest residue recovery. Feedstocks can be recovered from existing logging residue piles at the roadside or landing, or extra effort can be expended to recover them from the harvest setting. On average, recovery of under-utilized pulp logs from landing piles accounts for 32% of the total impact of feedstock recovery relative to recovery from the harvest setting. Recovery of logging residues from slash (tops and branches) is 76% of the total burden of recovering them from the harvest setting. Pulp recovery is 47% more efficient than slash recovery at the landing, but only 41% more efficient when delivered to the BCT site if truck and trailer combinations are used for hauling ground slash. Otherwise, hauling pulp logs is 48% more efficient than hauling ground residue. Regardless of hauling options, supply is constrained by distance to a processing center. When one-way haul distances for 4 hours and 2 hours were compared, the available feedstock residues were reduced by 85%-90% depending on accessibility constraints across the 5 regional scenarios evaluated.

Life cycle assessment of biochar production. Setting a biochar quality standard (based on percentage fixed carbon) will determine the type of feedstock that can acceptable in the BSI machine. Of the feedstocks used in the LCA model (n=5), 3 of the produced biochar qualities were above 65%. When biochar contains above 65% fixed carbon, carbon emission were lowest with the exception of medium chips with the highest fixed carbon of 83%. When carbon impacts are scaled to a tonne of fixed carbon in the biochar, there is direct relationship between global warming potential (GWP) and percentage fixed carbon (Puettmann et al. 2017).

Life cycle assessment of briquette production. Life cycle assessment (LCA) of cradle-to-gate near-woods production of non-torrefied (NTB) and torrefied briquettes (TOB) was performed based on the functional unit of 1 MJ of energy contained in the briquettes produced. Total Global Warming (GW) impact of producing TOB was about 12 g CO_2 eq./MJ of TOB. The LCA analysis revealed that bioconversion of forest residues close to biomass source using a gasifier genset instead of transporting feedstock (maximum 4-hour drive) to an in-town facility with access to grid electricity results in 2.4 times lower GHG emissions. Also, using a diesel generator instead of a wood gasifier for remote power generation for near-woods operations was about 3 times higher (Alanya-Rosenbaum et al. 2017b). The dryer process account for 73% and 26% of the GW impact in NTB and TOB production, respectively. In addition, pile and burn credits result in substantial benefits for all ten impact categories. Use of briquettes to substitute for propane for domestic heating reduced greenhouse gas emissions by 94% (Alanya-Rosenbaum et al. 2018).

- **Lessons Learned:**

1. Near-woods bioenergy production systems using power from on-site wood gasifier showed better environmental performance than their fossil fuel alternatives; on-site diesel and in-town grid electricity (Alanya-Rosenbaum et al. 2018).
2. Results indicate that the GW impact was highly dependent on drying process in NTB production and torgas management at TOB production, therefore use of high-efficiency dryer systems, using field-dried feedstock with lower MC and efficient recovery of torgas is crucial (Alanya-Rosenbaum et al 2017b).
3. Utilization of post-harvest residues as biofuel as opposed to the typical pile and burning practice shows a notable environmental advantage (Alanya-Rosenbaum et al. 2018).
4. Carbon impacts are lowered by 63%-70% depending on the feedstock when a biomass gasifier is substituted for the diesel generator (Puettmann et al. 2017).
5. If moisture content could be lowered for the chips, chipping feedstocks would be the best feedstock choice with low ash and high biochar quality resulting in lower carbon impacts (Puettmann et al. 2017).
6. Transporting the biochar conversion machine to a place in town, would add about 20% to the carbon impacts over a remote site when using portable energy sources (Puettmann et al. 2017).
7. In-town conversion of feedstock into biochar could benefit from using grid electricity where impacts could be lowered by as much as 42% over the diesel generator (Puettmann et al. 2017).
8. Forest residue recovery is constrained by haul distance with 85%-90% fewer acres and tons available if haul distances are increased from 2 hours one-way travel time to 4 hours one-way travel time access in-town processing facilities (Oneil et al. 2017).
9. Residues recovered as waste, without upstream burdens allocated from the harvest unit, is more efficient to handle in log form until it reaches the BCT site. Trucking configurations that can haul ground slash are constrained by road conditions from remote harvest operations (Oneil et al. 2017).

- **Deliverables**

Publications:

1. Alanya-Rosenbaum S, and R. Bergman. 2016a. Gate-to-gate life cycle inventory analysis of briquetting post-harvest logging residues. In: Proceedings, Forest Products Society 70th International Convention. June 26-28, 2016. Portland, OR. 8 p.
2. Alanya-Rosenbaum S, and R. Bergman. 2016b. Gate-to-gate life cycle inventory analysis of torrefying post-harvest logging residues. In: Proceedings, Forest Products Society 70th International Convention. June 26-28, 2016. Portland, OR. 8 p.
3. Alanya-Rosenbaum, S., R. Bergman, and E. Oneil. 2017. Cradle-to-gate life-cycle inventory of torrefied briquettes from post-harvest forest residues. White Paper.

Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory.

4. Puettmann, M., K. Wilson, and E. Oneil. 2017, Life cycle assessment of biochar from post-harvest forest residues, Final Report. December 13, 2017. Pp. 50

5. Oneil, E.E. and M.E. Puettmann. 2017. Life cycle assessment of forest residue recovery for small scale bioenergy systems. Chapter 2, pp. 27-37 in: Oneil, E.E., J.M. Comnick, L.W. Rogers, and M.E. Puettmann. 2017. Waste to Wisdom: Integrating Feedstock Supply, Fire Risk and Life Cycle Assessment into a Wood to Energy Framework. Final report on Waste to Wisdom: Subtask 4.2, 4.7 and 4.8. HSU BRDI grant DE-EE0006297. December. 50 p.

6. Alanya-Rosenbaum, S., R. Bergman, I. Ganguly, and F. Pierobon. 2018. A comparative life-cycle assessment of briquetting logging residues and lumber manufacturing coproducts in Western United States. *Applied Engineering in Agriculture*. ASABE special collection publication. 34(1): 11-24.

Oral presentations at professional conferences and public workshops:

1. Bergman R, N. Anderson, and W. Chung. 2015. Keynote Session Speaker. Life cycle impacts of wood supply chain. CASTLE Conference: Towards a Sustainable Bioeconomy: Innovative Methods and Solutions for the Agriculture and Forest Sectors. Sant Pau Art Nouveau Site in Barcelona, Spain. October 21–23, 2015.

2. Bergman R, Alanya-Rosenbaum, S., M. Puettmann, and E. Oneil. 2015. Life cycle analysis of distributed-scale biomass conversion technologies (BCTs). Slides 21-30. Waste to Wisdom webinar series. Madison, WI. December 7, 2015. (http://wastetowisdom.com/webinars/).

3. Bergman R, N. Anderson, K. Paustian, H.-S. Han, H. Gu, J. Field, and S. Alanya-Rosenbaum. 2016. Life cycle analysis of biomass utilization for biofuels and bioproducts. Northeast Woody/Warm-season Biomass Consortium (NEWBio) Coordinated Agriculture Project Annual Meeting. State College, PA. July 26-28, 2016.

4. Bergman R. 2016a. FPL's "Lightening Session" on Climate Change. Climate Change Science Advisor "Lightening Session". (webinar). Madison, WI. January 13, 2016

5. Bergman R. 2016b. Life cycle analysis and FPL's role. Forest Service Research Executive Team and Southern Group of State Foresters Meeting. Madison, WI. November 1, 2016.

6. Alanya-Rosenbaum S. and R. Bergman. 2017a. Life-cycle analysis of briquetting post-harvest wood residues. Public Workshop. Sacramento, CA. May 17, 2017. (http://wastetowisdom.com/reports/).

7. Alanya-Rosenbaum S. and R. Bergman. 2017b. Life cycle analysis of torrefying post-harvest wood residues. Waste to Wisdom webinar series. Madison, WI. August 9, 2017. (http://wastetowisdom.com/webinars/).

8. Bergman R., and S. Alanya-Rosenbaum. 2017. Environmental assessment of briquetting forest residues and sawmill residues in Pacific Northwest through life cycle assessment. International Union of Forest Research Organizations (IUFRO) Division 5 Meeting. Vancouver, British Columbia. June 12-16, 2017.

9. Alanya-Rosenbaum S, and R. Bergman. 2017c. Life-cycle impact assessment on torrefied briquette production from post-harvest forest residues. LCA XVII Conference. Portsmouth, NH. October 3-5, 2017.

SUBTASK 4.8. **EVALUATE IMPACTS ON FIRE REDUCTION AND FOREST PRODUCTIVITY GAINS**

- **Organization completing task:**

1. Principal Investigator: Elaine Oneil, P.I., University of Washington.

- **Description of task:**

Use GIS spatial analysis linked to inventory data to evaluate the potential feedstock volumes available from selected forest types in the western region under a range of sustainable management scenarios and relative to transportation distance, natural disturbance impacts, and economic variables.

- **Summary of key findings and research impacts:**

Regardless of hauling options, supply is constrained by distance to a processing center. When one-way haul distances for 4 hours and 2 hours were compared, the available feedstock residues were reduced by 85%-90% depending on accessibility constraints across the five regional scenarios evaluated. Ownership pattern, pulp markets, accessibility (road networks), and tree diameter distribution were major factors in determining available biomass supply. In particular, regional differences in pulp markets coupled with piece size could increase available pulp quality material from 30% (Port Angeles) to 47% (Lakeview), which greatly influences available supply.

- **Lessons Learned:**

1. Forest residue recovery is constrained by access with 85%-90% fewer acres and tons available if haul distances are reduced to reflect a 4 hours one way travel time to 2 hours one way travel time to in-town processing facilities. The addition of in-woods recovery to roadside recovery does not substantially impact these reductions. This result shows the critical need for remote BCT sites in order to take advantage of forest residuals in an economic manner.

2. Initial results provided estimates of residual biomass that was lower than expected for some locations, particularly in southeast Oregon. It was determined the problem was the assumption of a pulp market for small-diameter logs, which does not exist in all areas. Stem biomass was therefore broken out for logs with a small-end diameter greater than 6 inches and logs with a small-end diameter between 4 inches. This breakout was done on both trees with a DBH between 4 and 6 inches and top logs of larger trees. The results allowed the small-diameter logs to be

analyzed as pulp or residual harvest biomass, depending on the assumption of whether or not an active pulp market exists at a particular location.

3. Netdown factors impact availability of residual biomass in a non-uniform manner with large variability in available/total residues across the five scenario locations. The spatially explicit methodology results in more granularity in assessing where available biomass is likely to exist on the landscape and is therefore able to generate refined predictions for haul distance, harvest intensity and timing, amount of material at roadside, and recovery potential.

- **Deliverables**

Publications

1. Oneil, E.E. J.M. Comnick, and L.W. Rogers. 2017. A high-resolution spatially explicit database for quantifying forest products, fire, carbon, air quality and economics in the Pacific Coastal states. Chapter 1, pp. 12-26 in: Oneil, E.E., J.M. Comnick, L.W. Rogers, and M.E. Puettmann. 2017. Waste to Wisdom: Integrating Feedstock Supply, Fire Risk and Life Cycle Assessment into a Wood to Energy Framework. Final report on Waste to Wisdom: Subtask 4.2, 4.7 and 4.8. HSU BRDI grant DE-EE0006297. December. 50 p.

SUBTASK 4.9. **CONDUCT OUTREACH**

- **Organization completing task:**

1. Co-Principal Investigator: Craig Rawlings, Forest Business Network (FBN)
2. Tom Waddell, Forest Business Network

- **Description of task:**

Conduct outreach and public relations efforts over the duration of the project through the creation of 1) online platforms (website, social media, press releases); 2) advertising inventory (banner ads, classified advertising, email marketing, event sponsorship); 3) stakeholder engagement opportunities (webinars, conference speaking engagements); and 4) annual team meetings in order to promote the free flow of information between team members. The goal is to increase awareness about bioproducts and the project's objectives, and to help influence positive perception of environmental products.

- **Summary of key findings and research impacts:**

The Waste to Wisdom website (www.wastetowisdom.com) realized the following traffic and stats: 19,754 sessions (a session is the period of time a user is actively engaged with the website); 13,496 users; 45,316 pageviews (total number of pages viewed and repeated views of a single page are counted); and the following top 10 states by viewership (CA 2,649; OR 1,656; WA 988; Null 724; MT 710; WI 579; CO 507; TX 491; ID 347; AZ 330). Advertisements in the weekly Forest Business Network email newsletter amounted for 12,348 clicks. A banner ad and mentions/links on the Forest Business Network site referred 955 users to the Waste to Wisdom website. The press releases garnered 640,117 headline impressions; 9,470 full release reads; and 10,329 total media deliveries. The five webinars attracted 270 registered participants while the webpages for each webinar received a total of 2,535 page views. The webinars have garnered 805 views on the Waste to Wisdom YouTube channel so far. FBN helped secure 13 speaking engagements for W2W team members. The various annual team meeting and public demos/workshops produced the following results: May 13, 2014, Team Field Trip (team attendance, 32); May 14, 2014, Launch and Annual Meeting (team attendance, 32); June 24, 2015, Public Field Day (public attendance, 45; team attendance, 30); June 25-26, 2015, Annual Meeting (team attendance, 32); June 29, 2016, W2W Panels at FPS Convention (team attendance, 29); June 30, 2016, Annual Meeting (team attendance, 30); July 28, 2017, Conversion Technologies Public Demo (public attendance, 28; team attendance, 10); May 17, 2017, Public Workshop (public attendance, 80; team attendance, 23); May 18, 2017, Annual Meeting (team attendance, 22).

- **Deliverables**

    1. Webinar: Biochar Production Using Forest Residuals. (2015, November 17). Retrieved from http://wastetowisdom.com/webinars/webinar-biochar-production-using-forest-residuals/.

    2. Webinar: Production of Quality Feedstock from Forest Residues for Emerging Biomass Conversion Technologies (2015, October 21). Retrieved from http://wastetowisdom.com/webinars/webinar-production-of-quality-feedstock-from-forest-residues-for-emerging-biomass-conversion-technologies/.

    3. Webinar: Evaluation of Economic and Environmental Benefits from Utilizing Forest Residues. (2015, November 19). Retrieved from http://wastetowisdom.com/webinars/evaluation-of-economic-and-environmental-benefits-from-utilizing-forest-residues/.

    4. Webinar: Life Cycle Assessment and Economics of Torrefied Biomass. (2017, August 10). Retrieved from http://wastetowisdom.com/webinars/lifecycle-assessment-and-economics-of-torrefied-biomass/.

    5. Webinar: Life Cycle Assessment and Economics of Biochar from Forest Residues. (2017, August 23). Retrieved from http://wastetowisdom.com/webinars/lifecycle-assessment-and-economics-of-biochar-from-forest-residues/.

    6. Webinar: Economics of Transportable Biomass Conversion Facilities for Producing Biochar, Briquettes and Torrefied Wood Utilizing Forest Harvest Residues. (2017, October 18). Retrieved from http://wastetowisdom.com/webinars/economics-of-transportable-biomass-conversion-facilities-for-producing-biochar-briquettes-and-torrefied-wood-utilizing-forest-harvest-residues/.

    7. Subtask 1.1 Photo Essay Sorting and Arranging Forest Residues. (2015, May). Retrieved from http://wastetowisdom.com/subtask-1-1-photo-essay/.

    8. Subtask 1.2 Photo Essay Densification of Loose Forest Residuals. (2015, May). Retrieved from http://wastetowisdom.com/feedstock-development/subtask-1-2/subtask-1-2-photo-essay/.

    9. Subtask 1.3 Photo Essay Production of High Quality Feedstocks through Comminution. (2015, May). Retrieved from http://wastetowisdom.com/feedstock-

development/subtask-1-3/subtask-1-3-photo-essay/.

10. Subtask 3.2 Photo Essay Develop a Tool to Evaluate the Value of Biochar. (2015, May). Retrieved from http://wastetowisdom.com/sustainability-analysis/subtask-3-2/subtask-3-2-photo-essay/.
11. Waste to Wisdom. (2015). Waste to Wisdom Project Launches New Website Focusing on Its Innovative Forest Biomass Research [Press release]. Retrieved from http://www.prweb.com/releases/2015/05/prweb12703557.htm.
12. Waste to Wisdom. (2015). Webinar to Highlight the Waste to Wisdom Project and its Production of Quality Feedstocks from Forest Residues [Press release]. Retrieved from http://www.prweb.com/releases/2015/10/prweb13010744.htm.
13. Waste to Wisdom. (2015). Waste to Wisdom Webinar to Highlight the Evaluation of Economic and Environmental Benefits of Utilizing Forest Residues [Press release]. Retrieved from http://www.prweb.com/releases/2015/12/prweb13104706.htm
14. Waste to Wisdom. (2017). Life Cycle Assessment and Economics of Torrefied Biomass to be Focus of August 9 Webinar [Press release]. Retrieved from http://www.prweb.com/releases/2017/07/prweb14516804.htm.

ACKNOWLEDGEMENTS

The entire Waste to Wisdom project team gratefully acknowledges the funding support for this project from the U.S. Department of Energy under the Biomass Research and Development Initiative (BRDI): Award Number DE-EE0006297.

Task Area 1: Project Management

The project management team (Han-Sup Han, Arne Jacobson, Ted Bilek, and Joel Bisson) would like to thank all the W2W research team members and project partners for their strong support and helpful collaboration. We particularly appreciate the guidance, support, and advice from our project managers, Art Wiselogel, Elliot Levine, and Steven Thomas. The effort from Humboldt State University Sponsored Programs Foundation and, in particular, our grant analyst Anthony Johnson to manage this funding was greatly appreciated.

Task Area 2: Feedstock Production and Supply Logistics

Our W2W research work in feedstock productions and supply logistics was not possible without generous support and cooperation from our research partners and collaborators in planning & implementing all the field-based experiments and active demonstrations in the woods, including Mike Alcorn for hosting all the field experiment and demonstrations in the Green Diamond Resource Company forestlands, Steve Morris for helping biomass operations experiments using his machines, Larry Cumming for his technical advice and allowing us to use Peterson Pacific Corp. manufacturing machines, Oren Posner for hosting the feedstock screening testing in his Lane Forest Products Company site, and Moon-hyun Cho for letting us use his sawdust machine (Beaver Korea Corp.). Baling data and field trials were supported by Mike Malgarini of Arsiero Logging, technician Matt Wamsley and lead operator Jason Perry. The key research tasks and objectives were managed and accomplished by the enthusiastic Task Area 2 research team members, and their names and research topics are highlighted in the deliverables (i.e. oral presentations, papers published in the journal, graduate thesis, reports, patent information, and demonstrations) that are presented in this report. Our special thanks go to Joel Bisson and Anil Kizha for taking on a lot of the load in day-to-day project management activities and for helping the TA2 research team members with implementation of the research projects. The final acknowledgement goes to the group’s Principal Investigators (PIs), who made the work happen: Jim Dooley, John Sessions, and Han-Sup Han.

Task Area 3: Development of Biomass Conversion Technologies

The Schatz Energy Research Center acknowledges the work of the many partners that contributed to Task Area 3. We greatly appreciate the work and dedication of all organizations and individuals who helped make this project come together. We give thanks to our project partners, including Biochar Solutions, Inc. and Jonah Levine; Green Diamond Resource Company with special thanks to Mike Alcorn; Pellet Fuels

Institute, including especially John Crouch, Jennifer Hedrick, and Derek Nelson; Redwood Forest Foundation, Inc., with special thanks to Judith Harwood and Mark Welther; Norris Thermal Technologies with special thanks to Daron (Chuck) Norris and Aaron Norris; Denise McKahn, Associate Professor at Smith College and her student, Anna Partridge; and Steve Morris Logging Company. We also must acknowledge the support of many other collaborators on this project, including All Power Labs, Inc.; Bear Mountain Forest Products; Colorado Biochar Resources and Pueblo Wood Products with special thanks to Brad Dunmire; California Redwood Company; North Coast Air Quality Management District; RUF Briquetting Systems and Greg Tucholski; and OMNI Test Labs. The team from the Schatz Center included Director Arne Jacobson and Co-Director Charles Chamberlin; professional staff David Carter, Mark Severy, Anthony Eggink, Richard Engel, Allison Hansberry, Marc Marshall, Kyle Palmer, Greg Pfotenhauer, and Jim Zoellick; and students Steven Harrison, Emily Klee, Yaad Rana, and Richard Williams.

Task Area 4: Biofuels and Biobased Products Development Analysis

Task Area 4’s work would not have been possible first without the generous sharing of data and time by the researchers in Task Area 2 and Task Area 3. The economics work would not have been possible without the dedicated work of Kalamankanta Sahoo. Maureen Puettmann, Kelpie Wilson, Sevda Alanya-Rosenbaum, assisted with the life cycle analysis/air quality impacts. Luke Rogers, Jeffrey Comnick, and Andrew Cooke created the spatial analysis and timber volume estimates that made possible detailed biomass feedstock supply and network analysis used for the lifecycle analysis, air quality impacts, and optimization modeling. The biochar impact work was made possible the help of the Umatilla National Forest (for the mine restoration), Humboldt-Toiyabe National Forest (range land restoration), Dr. Kas Dumroese (seedlings for mine restoration), the Bitterroot National Forest (forest thinning and biochar), Kolby Hirth for soil sample analysis, and Tom Miles from the International Biochar Initiative. Indroneil Ganguly, Daisuke Sasatani, and Tait Bowers worked with economic impact modeling and public perceptions of forest waste utilization. And Tom Waddell helped to develop the W2W website, keep it working, helped organize field days and webinars, and helped to promote W2W’s accomplishments. The final TA-4 acknowledgement goes to the group’s PIs, who made the work happen: Rick Bergman, Ted Bilek, Ivan Eastin, Elaine Oneil, Deborah Page-Dumroese, and Craig Rawlings.