# Modeling Biomass Collection and Woods Processing Life-Cycle Analysis*

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**Abstract**

A deterministic spreadsheet model developed in an earlier Consortium for Research on Renewable Industrial Materials (CORRIM) project that calculates cost, fuel, and chemical outputs of forest management and harvesting activities was modified to include logic for systems used to recover forest residue. Two illustrative biomass recovery systems with variations were modeled. A system to recover residues after whole-tree harvesting operations was applied to a representative forest stand in the Inland West. Whole-tree chipping in an early thinning was applied to a representative forest stand in the Southeast United States. Emission factors and life-cycle outputs were developed for the systems through the SimaPro v7.3 model using one if its environmental impact methodologies called TRACI2. Most environmental outputs, including global warming potential, had a direct relationship to fuel consumption of the recovery systems. These outputs were subsequently used as inputs to life-cycle analysis in biofuel conversion facilities. Fuel consumption for recovery of residues from the log landing was 8.10, 12.0, and 16.0 liters per bone dry metric ton (BDmT) at haul distances of 48, 97, and 145 km, respectively. Corresponding fuel consumption for whole-tree chipping and hauling at these distances was 10.5, 16.0, and 21.5 liters/BDmT. Shuttling ground residue from the landing for reload and a subsequent long haul of 145 km increased fuel consumption 32 percent over the residue recovery base case. Shuttling loose residue for centralized processing with a long haul distance of 145 km increases fuel consumption by 86 percent over recovery directly from the landing.

The location, slope conditions, and ease of access of forest biomass supplied to biofuel plants are highly variable. Additional variability derives from the size and distribution of material in the forest stand. The combination of these variables will determine the economic feasibility of biomass recovery. Generalized data on biomass recovery operations are limited because marginal economics of those systems have limited the number of field operations that fully represent the range of conditions encountered in forest biomass recovery. A modeling approach was used in this project to estimate cost, fuel consumption, and environmental output for two types of biomass recovery: recovery of forest residues after logging and recovery of biomass from the early thinning of forest stands. The environmental outputs from the modeling efforts were then forwarded to subsequent stages of biomass processing. The subsequent stages were modeled as part of a larger Consortium for Research on Renewable Industrial Materials (CORRIM) biomass life-cycle project targeting forest biomass for use as a feedstock in facilities that convert the material to a biofuel or chemical product through thermoconversion or bioconversion.

The deterministic spreadsheet model developed for the first two phases of the CORRIM life-cycle projects (Johnson et al. 2004, Oneil et al. 2010) was extended in this project to accommodate analysis of biomass recovery operations. The first two CORRIM life-cycle phases focused on various wood products, such as lumber and plywood from forest resources grown and harvested in specific regions of the country. The first phase included the Pacific Northwest and

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Southeast; the second phase added the Inland West, Northeast, and North Central regions. In each case, production rates, fuel consumption rates, and costs for harvesting equipment extracted from existing studies and expert opinion were analyzed and averaged and were then incorporated into an equipment database in the spreadsheet model. Specific equipment in the various phases of harvesting were selected from this database and were combined into harvesting systems with resulting production, cost, and fuel consumption rates per unit of volume or weight output. The spreadsheet model, called ''Harvest Factors'' integrated forest stand data for representative forest stands in the region and associated volumes and carbon calculations with energy and chemical inputs for both stand management (planting, fertilization, thinning, etc.) and forest harvesting operations to provide a base for life-cycle analysis. The forest management and harvesting components were then structured as models within the life-cycle analysis software package, SimaPro (Goedkoop and deGelder 2001, Goedkoop and Oele 2001), to provide life-cycle inventory and analysis data. SimaPro v7.3 was used to perform the life-cycle analysis of biomass recovery operations, including generation of emission factors, and as a basis for analysis of the relative contribution of the various residue recovery processes to emissions.

The Harvest Factors model was extended in this project to allow analysis of a variety of residue recovery systems. These include recovery of residue after logging from the log landing, recovery of residue through shuttle truck operations where access to the primary landing is limited, recovery of small trees through fairly traditional whole-tree recovery operations, and recovery of residues through integrated operations where primary products and residues are recovered on the same entry. Equipment data from the earlier versions of the model appropriate to biomass recovery operations were used in this project, along with information specific to equipment used in grinding and chipping biomass. The Harvest Factors model also includes the capability to calculate emission factors to the air when residue is burned rather than recovered.

Funding constraints limited the analysis in this phase of CORRIM projects to a single forest type and single recovery option within two selected regions, the Inland West and the Southeast. These regions were selected because the forest stand model descriptions from earlier phases of CORRIM projects allowed a determination of the breakdown of merchantable and residue materials and because they coincided with the assumed operational region of the thermoconversion or bioconversion facility. The biomass recovery scenarios were limited to recovery of residues from the log landing after logging and recovery of biomass from early thinning of forest stands. The specific system characteristics are illustrative of current practices and equipment used in the recovery of forest residues but should not be viewed as average results or conditions for a region. Recovery of landing residue focused on the forest stand data developed for the US Inland West. The dominant use of whole-tree harvesting of the primary product in that region often leaves logging residue at a log landing or near a road. The equipment and system assumptions for this option may also be appropriate to other regions where whole-tree harvesting is used. Recovery of material from a thinning operation with whole-tree chipping was focused on the representative forest stand data developed for the US Southeast, where more intensive forest management operations often include an early thinning of the stand. Hauling distances for the base case in each region were assumed to be slightly longer than the average hauling distance to sawmills, as determined in surveys conducted in the first two phases of CORRIM projects (Johnson et al. 2005, Oneil et al. 2010). Alternatives to the base cases were limited to consideration of changes in haul distance, the production rate of the primary processing equipment, and system options that address residue sites that are not accessible to chip vans.

Removal of biomass from the forest and the activities associated with growth, removal, and reestablishment of trees requires a broad analysis to determine the life-cycle impacts of stand establishment, stand growth, and harvesting. In most cases, investments in intensive forest management activities such as fertilization and precommercial thinning are designed to enhance the production of the primary forest product, either sawlogs for structural building products or pulpwood for paper production. The primary products, therefore, bear the environmental burdens of the stand management activities. Coproducts such as early thinnings or residuals subsequently processed for energy or chemical feedstock would not exist without the management inputs that produce the primary products, and hence the burdens of these inputs are assigned to the primary products rather than the coproducts. These factors include the fertilizer used in seedling growth, the electrical energy required to operate forest nursery pumps and to power the growing operations, and stand reestablishment activities including site preparation activities such as slash disposal and subsequent hand planting of seedlings by planting crews. The environmental burdens assigned to the recovered residue or thinned material include only those activities directly associated with the processing and removal of the material. Potential issues associated with the removal of organic material and nutrients contained in forest residues are recognized but are not specifically analyzed here beyond development of estimates of the amount of forest biomass removed and retained on the site.

Conway (1982) suggested that timber harvesting generally consists of four components: timber cutting, primary transportation, loading, and secondary transportation. Timber cutting includes felling (severing the standing tree from the stump) and processing (often called bucking, limbing, and/or topping). These steps include either removal of nonmerchantable limbs and tops and cutting of the tree into merchantable and transportable log lengths or mechanized processing such as chipping whole trees or grinding residues. Primary transportation (often called skidding on gentle slopes and yarding on steep slopes) is a material handling step that moves trees or logs from the point of felling to a loading point near a haul road. Loading involves the movement of logs or residue from decks to haul vehicles. Secondary transportation consists of the hauling of logs or field-processed chips from the woods to a process point. Variants of these basic components will also be part of most biomass recovery operations, although some components will not be required if material is already accumulated at a landing. In whole-tree chipping operations, the process normally used to recover thinned material for biomass includes felling and skidding, but the processing step is accomplished with a whole-tree chipper. Secondary transportation will involve highway truck-tractors and chip vans.

Many operations producing sawlogs as a primary product use a harvesting method called whole-tree harvesting. This is an economically preferable harvesting method that allows the limbs and tops to be removed mechanically at a landing and reduces the requirements for subsequent slash disposal across the site. When the limbs and tops are subsequently processed, the primary output product for processed residue is a bone dry metric ton (BDmT) of ground woody biomass destined for subsequent processing through thermoconversion or bioconversion. This requires some type of equipment, usually a high-horsepower grinder, to break the nonuniform residue pieces into reasonably uniform and smaller particle sizes. The process steps for recovery of residues already located at the landing include loading residue from landing piles into a grinding unit and hauling the ground material in chip vans to the final utilization point. Because the whole tree is delivered to the landing as part of the primary product harvest, there is no allocation of cost, fuel, and any corresponding environmental burdens required to deliver the tops and limbs to the landing. Those are carried by the primary product.

Hauling will normally be accomplished with chip vans, but in the mountainous parts of the western United States, the final segments of the road network may have width and curvature standards that do not allow the chip van to access the log landing directly. The difficulty of chip van access to some log landings in mountainous areas has been an ongoing issue, with experimentation on methods to shuttle loose residues (Sinclair 1985). In cases of limited access, biomass recovery and collection may require an intermediate hauling step where trucks with less volume capacity but with a shorter turning radius shuttle material from the log landing to a secondary landing located near a higher standard road. This adds material handling steps and costs to the system, but the variation was modeled in this analysis to illustrate the potential cost, fuel, and environmental impacts of this concept.

Most of the timber harvesting activity in Southeastern US forests uses ground-based skidding to deliver material from the forest to the landing, so this method of primary transportation was used in the whole-tree chipping scenario. A whole-tree chipper processes whole trees into uniform chips, which are then hauled to the final utilization point in chip vans. The output product of biomass recovery is a bone dry metric ton of chipped woody biomass destined for subsequent processing in a biofuel processing plant.

## Objectives and Methods

The primary objectives of this project were to extend the Harvest Factor spreadsheet structure to allow modeling of a variety of biomass recovery systems and to apply the model to a limited set of biomass recovery systems typical of those available for use. The environmental outputs from those illustrative systems would be passed on for inclusion in the life-cycle analysis of energy or chemical products produced in subsequent stages of biomass processing. Life-cycle results were generated from the SimaPro life-cycle model. A secondary objective was to consider the sensitivity of results to key variables that might affect productivity and cost. The impact of variation in hauling distance and production rates of the grinder and chipper were considered for both cases. System variations that focus on accessibility of the log landing to chip vans were considered in the scenario applied to Inland West forests.

### Biomass recovery equipment

Development of the forest resources analysis for the first two phases of CORRIM projects resulted in a database of production, cost, and fuel consumption for timber harvesting equipment used in three regions of the country: the western United States, southeastern United States, and the Northeast–North Central regions (Johnson et al. 2004; Oneil et al. 2009, 2010). The database was expanded as part of this study to include equipment more focused on residue recovery, such as chippers and grinders. Production rates were developed from existing research studies and were then reviewed by operational field personnel for reasonableness and accuracy. The method used to model hauling times was also expanded to allow a breakdown of the hauling route into road classifications consistent with those used in the US Forest Service forest residue transportation model (Thompson 2005) and to allow use of either highway trucks or shorter wheel–based shuttle trucks over the road segments.

The productivity data included estimates of the utilization percentage of the equipment, and this was used to convert potential production rates in units of output per productive machine hour (PMH) to effective production rates in units of production per scheduled machine hour (SMH). Production rates for most equipment were expressed in cubic meters per scheduled machine hour. These rates were converted to a weight basis (dry kilograms or dry metric tons) using an average dry density for softwood species.

Fuel consumption rates per SMH were calculated from the rated engine power of the equipment, fuel consumption rates per horsepower per hour (Plummer and Stokes 1983, Food and Agriculture Organization of the United Nations 1992), and percent utilization of the equipment. Dividing fuel consumption per hour by a production rate resulted in a fuel consumption rate per cubic meter or dry metric ton. The database also includes hourly costs for the equipment. These fixed, variable, and labor rates are calculated using standard machine rate procedures for harvesting equipment (Miyata 1980). Hourly costs divided by hourly production rates yield a cost per cubic meter or per dry ton. System costs per unit of output are of most use when applied to specific site conditions. Because the costs developed here are based on a limited set of production rates across a region, they can be useful in comparing the relative cost differences between the system variations developed in this project but should be used with caution when applied to other specific site conditions.

Production and cost information was less available for the grinding and chipping equipment used to process the residue and whole trees. Grinding results from Harrill and Han (2010) and the related thesis by Harrill (2010) were used to model the cost and production of the grinder used to process landing residue. Productivity of the whole-tree chipper was developed from a number of studies of midsize chippers averaging 336 kW (450 hp; Mitchell and Gallager 2007, Aman et al. 2010, Harrill and Han 2012). Production rates for both the grinder and chipper assumed an adequate supply of hauling vehicles that would minimize delays waiting for chip vans.

In most chipping and grinding operations, material is transported over highways in chip vans. A common size of vans used in woods operations is 91.8 $m^3$ (120 $yd^3$) capacity. There are other sizes available, usually designed with additional axles and expanded van capacity to maximize loads within the legal weight limits of a state, but these chip van variations are often less maneuverable on winding forest roads. The turning radius and height of most chip vans can be too wide and high for winding mountainous roads, especially in the western United States. Variations to the base case for the western residue recovery scenario used a smaller truck with shorter wheel base to shuttle residue or processed biomass to a reload point.

Potential load weight of a van or truck load was based on the cubic capacity of the van or truck box, a solid volume factor representing the volume of solid biomass relative to the volume of the container, and a volume to weight conversion based on density and moisture content (wet basis) of the biomass. The actual load size was determined as the minimum of calculated load size and maximum legal load weight. Hauling productivity was determined from load weight and travel time to and from the final utilization point. Travel times were based on assumed travel speeds over five general road classifications consistent with those used in the US Forest Service developed forest residue transportation model (Thompson 2005). The breakdown in hauling distance by road type has been shown to be an important factor in overall travel time of the chip van (Pan et al. 2008, Harrill 2010) and was added to the spreadsheet model in the revisions done to accommodate residue recovery. Hauling distances for the base case for both recovery of landing residue (145 km) and whole-tree chipping (97 km) were assumed to be slightly longer than the surveyed haul distances to sawmills in the Inland West and Southeast from Phase I and II of the CORRIM projects (Johnson et al. 2005, Oneil et al. 2010). The percentage of haul distance in each road classification was assumed to be the same for both regions.

The ratios of solid wood volume to the volume capacity of the vehicle used factors developed from field observations in an early residue recovery study (Johnson 1989) and verified by more theoretical calculations of Briggs (1994). One influence on the cost and fuel consumption rates for hauling relates to the assumed moisture content of the material. Because material in whole-tree chipping is generally skidded directly to the chipper and blown into chip vans immediately, the material was assumed to have a moisture content of 50 percent (wet basis). If the material were stockpiled for chipping or grinding, moisture content might be reduced to something similar to that assumed for piled residue, 30 percent (wet basis). Reduced moisture content will generally make the long-distance transportation more efficient. The truck capacities, solid volume factors, and assumed travel speeds for the hauling options are shown in Table 1.

## Biomass yields

The biomass yields and forest management assumptions for the two scenarios were developed from forest stand modeling conducted in the first two phases of CORRIM projects. The selected stands are representative of those in the region but should not be considered as regional averages. Scenarios for timber production in the Inland West were aligned with a combination of land ownership, moisture regime (dry, moist, cold), management intensity, and elevation of the forest. Estimated yields of biomass attributed to the primary product (sawlog or pulpwood) and the associated residual material were determined for each land ownership and then aggregated by forest group (dry, moist, cold) and management intensity into three general categories: state and private dry forests, state and private moist-cold forests, and US Forest Service dry, moist, and cold forests (Oneil et al. 2009). Vegetation growth for the scenarios was simulated using the forest vegetation simulator (FVS) developed by the US Forest Service (Wykoff et al. 1982, Wykoff 1986). The Landscape Management System (McCarter et al. 1998) linked FVS to a carbon module that estimates biomass by tree component: stem, roots, branches, and foliage. Estimates of tree biomass by component were used to estimate the standing and removed carbon pools over time, along with the logging residual that would either be left in the woods for disposal or moved to the landing as part of the whole-tree harvest. The largest single land classification in the Inland region by harvested volume was moist-cold forests on state and private lands. These are also the lands with the greatest amount of current harvest activity, so the analysis of biomass recovery operations focused only on processing of landing residues from timber harvesting in this land classification.

Residue disposal in the Inland West generally includes burning of the residual slash to reduce fire hazard and to prepare the site for planting. This can involve broadcast burning of material on the ground of a harvested area or burning of mechanically created piles at either the landing or across the site. The predominant method for most private

*Table 1.—Assumptions on load capacities, solid volume factors, and travel speeds for hauling options.*[a]

| Travel distances and speeds | Spur road | 1½ lanes | 2-lane gravel | 2-lane highway | Interstate | Total/avg. |
|---|---|---|---|---|---|---|
| Avg. one-way distance (km) | 4.0 | 8.0 | 16.1 | 32.2 | 84.5 | 144.8 |
| Avg. truck speed (km/h) | 9.7 | 32.2 | 46.7 | 88.5 | 99.8 | 87.3 |
| Hauling load capacity | Cubic capacity ($yd^3$) | Solid vol factor[b] | Load wt at cubic capacity (GMT) | Legal highway load wt (GMT) | % moisture content (wet basis) | Load wt (BDmT)[c] |
| Chip van (stockpiled material) | 92 | 0.44 | 32.3 | 22.7 | 30 | 15.9 |
| Chip van (whole-tree chipping) | 92 | 0.44 | 32.3 | 22.7 | 50 | 11.3 |
| Shuttle truck with ground residue | 23 | 0.44 | 8.1 | 9.1 | 30 | 5.7 |
| Shuttle truck with loose residue | 23 | 0.18 | 3.3 | 9.1 | 30 | 2.3 |

[a] GMT = green metric tons; BDmT = bone dry metric tons.
[b] Johnson (1989) and Briggs (1994).
[c] Based on minimum of load weight or legal weight.

and state land managers is to pile the material and to then burn the piles. This allows more flexibility in meeting state limitations on open burning. Because of the whole-tree operation, large quantities of limbs and crowns accumulate at the landing, but there are still portions of the tree and unmerchantable trees that remain in the woods. Field studies conducted by Oneil and Lippke (2009) indicated that even with whole-tree harvesting, as little as 40 to 50 percent of the total residual biomass ends up at the log landing. This rate of recovery from whole-tree harvesting operations suggests that a significant amount of the biomass and, therefore, nutrients is left in the woods. Nutrient retention can be an important factor to site productivity in some soils.

Scenarios developed for the Southeast forest management analysis in the Phase I forest resource project of CORRIM represented a composite of stands from the extensive database managed by the Forest Productivity Cooperative at North Carolina State University and Virginia Tech University (Hafley et al. 1982, Buford 1991). The corresponding carbon analysis was done with the related NUTREM2 model (North Carolina State Forest Nutrition Cooperative [NCSFNC] 2000). The three forest management scenarios represented combinations of site index and a corresponding level of management intensity. The first reflected nonindustrial private forests (NIPF) with low-intensity management that might be implemented by the small landowner. The second reflected high-intensity management on NIPF lands and/or low-intensity management on industrial lands. The third scenario reflected high-intensity management on industry lands. The midintensity management category represented the largest percentage of managed forest lands and was selected as the forest type in this analysis.

The midintensity management category included a first commercial thinning at stand age 17 years and a final harvest at stand age 25 years. In the original analysis material from the first thinning was allocated to pulpwood with no merchantable sawlogs. The assumption for this scenario was that this material was diverted from pulpwood to a biomass market. Because biomass can include bark, limbs, and tree crown material, the mass of biomass was higher than it would have been if the material had been allocated to a pulpwood market. Results of field studies of whole-tree chipping by Stokes and Watson (1991) indicated that of the total available biomass, 84 percent was actually recovered. A technical feasibility study on recovering biomass (Perlack et al. 2005) used a recovery factor of 85 percent. We assumed an overall recovery percentage of 84 percent. This was based on an assumption that all of the merchantable-sized stem and bark and 60 percent of the residual stem and branch material would be recovered. The rest of the residual material remains on site. Recovered and residual material for the two recovery scenarios are shown in Table 2.

### Residue disposal by burning

Forest residues in the western United States that are not recovered will require disposal, generally through some type of burning activity. Emission factors to the air generated through burning activities are based on emission factors developed in studies that document and model emission rates from prescribed burns, both broadcast and in piles. An original report to the Environmental Protection Agency by Battye and Battye (2002) that has been subsequently used by other reports on emissions from burning (Prichard et al. 2006, Wiedinmyer et al. 2006) was used to develop emissions to the air from burning. Emission factors for burning piles at the landing are included to allow a comparison of the emissions generated from residue recovery with emissions that might be generated from the burning.

## Results: Biomass Recovery

### Scenario 1: Recovery of residue at the log landing

Recovery of residues after logging generally involves a grinding unit that reduces the residue to a transportable size. The grinder is fed from existing landing piles with a separate hydraulic loader; ground biomass moves with a conveyor from the grinder into a haul vehicle. Production of the loader is tied directly to the production capacity of the grinder. However, recovery of residue from sites in the mountainous west faces physical restrictions, especially in the road network required to haul field-processed material. The base case for this scenario assumes direct access to the landing by chip vans. In addition to variation in the grinder production rate and hauling distance, other variations consider two options for shuttling material to a central landing. Grinding and hauling from the original log landing (grind at landing) is the most economical of the three variations. The other two variations are more experimental at this point, but their analysis allowed development of a spreadsheet model structure to handle these options and allows cost and environmental impact comparisons to the base case. The variations include (1) grinding of residue at the log landing with use of smaller haul vehicles to shuttle the field-processed residue to a secondary landing located near a highway for reloading into highway vans (grind and shuttle) and (2) locating the grinding unit at a secondary landing near a highway and shuttling loose residue from the primary to the secondary landing in smaller haul vehicles (shuttle loose).

Primary equipment includes a horizontal grinder to convert nonuniform slash residue to consistent, ground material and a hydraulic loader to feed the grinder. If material needs to be shuttled to a secondary landing, a short wheel-based haul vehicle is required, assumed in this case to be a modified dump truck with 22.9 $m^3$ (30 $yd^3$) of volume capacity. When loose residue is hauled to the secondary landing, an additional loader is needed at the primary log landing to load the truck. When ground residue is hauled to the secondary landing, a front-end loader is needed at that landing to move ground residue to the haul trucks. In this

*Table 2.—Harvest volumes and recovered biomass from Inland moist-cold forests in state and private ownership and from thinning in the Southeast United States.*

| | Harvested and recovered material | |
|---|---|---|
| | Inland moist-cold forests | Southeast thinning |
| Harvest vol ($m^3$/ha) | 261 | 111 |
| Biomass available (BDmT/ha)[a] | 72.1 | 50.0 |
| Recovered biomass (BDmT/ha) | 32.5 | 42.2 |

[a] BDmT = bone dry metric tons.

case the distance traveled from the primary landing to the secondary landing was assumed to be 4.0 km (2.5 mi). The overall hauling distance for the base case was arbitrarily set at 145 km (90 mi), slightly longer than the surveyed distance to sawmills of 129 km (80 mi) found in a survey conducted in the CORRIM Phase II forest resource project. The Harvest Factor/SimaPro models were also run at hauling distances of 48 km (30 mi) and 97 km (60 mi). Sensitivity of results to the production rate of the grinder was also considered through model calculations with the production rate per PMH increased and decreased by 20 percent from the base case. The production rates, production costs, and fuel consumption rates for the base system, variations in grinder production, and for the two shuttle system options are shown in Table 3. The impact of hauling distance changes on cost and fuel consumption will be shown with results for whole-tree chipping.

A 20 percent decrease in the grinder production rate results in an 11 percent increase in total costs and a 6.5 percent increase in fuel consumption (Table 3, B). A 20 percent increase in grinder production results in a 7 percent decrease in total cost and a 4.4 percent decrease in fuel consumption (Table 3, C). The cost and fuel consumption changes include a small change in the results for hauling because loading time for the trucks is based on grinder production. Costs on board the highway truck are significantly less when the highway truck can negotiate all roads to the primary landing ($17.60/BDmT) compared with an 89 percent increase in costs when grinding at the primary landing and shuttling the ground residue to a secondary landing ($33.20/BDmT; Table 3, D) and a 152 percent increase when shuttling the loose residue for grinding at the secondary landing ($44.30/BDmT; Table 3, E). The added cost to shuttle loose residue in the third option is partially offset by an increase in grinder productivity when located at

*Table 3.—Production rates, costs, and fuel consumption of components of the options for grinding residues at log landings in the Inland West at one-way hauling distance from the log landing of 145 km and shuttle hauling distance of 4.0 km with biomass at 30 percent moisture content (wet basis).*[a]

| | | % use | Production rate (BDmT/SMH) | Production cost ($/BDmT) | Diesel use (liters/BDmT) | Lubricant use (liters/BDmT ) |
|---|---|---|---|---|---|---|
| A. Biomass from landing slash direct to mill (grind at landing): base; grinder production = 36 BDmT/PMH | | | | | | |
| Loading | Hydraulic loader with on-site grinder | 65 | 23.6 | 4.70 | 0.82 | 0.01 |
| Processing | On-site horizontal grinder | 65 | 23.6 | 12.90 | 3.01 | 0.05 |
| Subtotal | To truck | | | 17.60 | 3.83 | 0.06 |
| Hauling | Chip van, 120 $yd^3$, direct from landing grinder | 90 | 2.8 | 31.80 | 12.13 | 0.22 |
| System total | To mill | | | 49.40 | 15.96 | 0.28 |
| B. Biomass from landing slash direct to mill (grind at landing): −20% production; grinder production = 29 BDmT/PMH | | | | | | |
| Loading | Hydraulic loader with on-site grinder | 65 | 18.9 | 5.80 | 1.02 | 0.02 |
| Processing | On-site horizontal grinder | 65 | 18.9 | 16.20 | 3.76 | 0.07 |
| Subtotal | To truck | | | 22.00 | 4.78 | 0.09 |
| Hauling | Chip van, 120 $yd^3$, direct from landing grinder | 90 | 2.7 | 32.80 | 12.21 | 0.22 |
| System total | To mill | | | 54.80 | 16.99 | 0.31 |
| C. Biomass from landing slash direct to mill (grind at landing): +20% production; grinder production = 44 BDmT/PMH | | | | | | |
| Loading | Hydraulic loader with on-site grinder | 65 | 28.3 | 3.90 | 0.68 | 0.01 |
| Processing | On-site horizontal grinder | 65 | 28.3 | 10.80 | 2.51 | 0.05 |
| Subtotal | To truck | | | 14.70 | 3.19 | 0.06 |
| Hauling | Chip van, 120 $yd^3$, direct from landing grinder | 90 | 2.9 | 31.20 | 12.07 | 0.22 |
| System total | To mill | | | 45.90 | 15.26 | 0.28 |
| D. Biomass from landing through intermediate load site (grind and shuttle ) | | | | | | |
| Loading | Hydraulic loader with on-site grinder | 65 | 23.6 | 4.70 | 0.82 | 0.01 |
| Processing | On-site horizontal grinder | 65 | 23.6 | 12.90 | 3.01 | 0.05 |
| Hauling | Dump truck, modified, ground biomass | 65 | 4.0 | 10.00 | 6.22 | 0.11 |
| Subtotal | Landing to intermediate load site | | | 27.60 | 10.05 | 0.17 |
| Loading | Front-end loader | 85 | 19.6 | 5.60 | 1.02 | 0.02 |
| Subtotal | To truck | | | 33.20 | 11.07 | 0.19 |
| Hauling | Chip van, 120 $yd^3$, loaded from stockpile | 90 | 3.3 | 27.00 | 9.96 | 0.18 |
| System total | To mill | | | 60.20 | 21.03 | 0.37 |
| E. Process postharvest residue at central site (shuttle loose) | | | | | | |
| Loading | Hydraulic loader with loose residue | 65 | 23.6 | 4.70 | 0.82 | 0.01 |
| Hauling | Dump truck, modified, loose residue | 90 | 1.5 | 26.10 | 15.52 | 0.28 |
| Subtotal | Landing to intermediate load site | | | 30.80 | 16.34 | 0.29 |
| Loading | Hydraulic loader with centralized grinder | 85 | 30.8 | 3.60 | 0.76 | 0.01 |
| Processing | Centralized horizontal grinder | 85 | 30.8 | 9.90 | 2.80 | 0.05 |
| Subtotal | To truck | | | 44.30 | 19.90 | 0.35 |
| Hauling | Chip van, 120 $yd^3$, from central grinder | 90 | 3.5 | 25.70 | 9.84 | 0.18 |
| System total | To mill | | | 70.00 | 29.74 | 0.53 |

[a] BDmT = bone dry metric tons; SMH = scheduled machine hour; PMH = productive machine hour.

a central landing rather than at log landings that will require frequent moves. If hauling distances decreased or increased but maintained the current percent allocation by road classification, the corresponding changes in cost and fuel consumption would be \$0.193/BDmT and 0.081 liters/BDmT/km, respectively. Reduction in hauling distance in just the highest standard road, however, would have less effect on overall cost and fuel consumption changes. Total costs including hauling could be expected to change by \$0.126/BDmT with each kilometer change in interstate transport miles, and fuel consumption could be expected to change by 0.053 liters/BDmT/km.

### Scenario 2: Recovery of forest thinnings

Whole trees harvested in the thinning of Southeast forest stands were cut with a mechanized feller buncher, moved to a landing with ground-based skidders, and chipped in the woods with a whole-tree chipper. Processed chips were hauled with chip vans to the final utilization point. In whole-tree chipping, the entire tree including the crown is fed into the chipper, but breakage and mishandling will leave some of the trees and limbs in the woods.

Analysis was run for whole-tree chipping at three arbitrary hauling distances: 48, 97, and 145 km one way (30, 60, and 90 mi) and with a 20 percent increase and decrease in chipper productivity. Hauling distance for the base case was set at 97 km, slightly longer than the average haul distance to sawmills of 92 km determined in mill surveys conducted in the CORRIM Phase I forest resource project (Johnson et al. 2005). The percent distances in each road category were assumed to be the same as for the 145-km haul distance shown in Table 1 for the recovery of landing residue.

Summaries of cost, production, and fuel consumption for the equipment used in the whole-tree chipping operation and the variations in chipper productivity are shown in Table 4 for a 97-km haul.

A 20 percent decrease in the chipper production rate results in a 4.7 percent increase in total cost and a 2.4 percent increase in overall fuel consumption (Table 4, B). A 20 percent increase in the rate results in a 3.0 percent decrease in cost and 1.6 percent decrease in fuel consumption (Table 4, C). The percent changes are not as large as for the grinder since the chipping system also includes significant cost and fuel consumption in the felling and skidding steps.

Costs and fuel consumption of whole-tree operations in thinnings are compared with costs of grinding and hauling residue directly from the landing at three hauling distances in Figures 1 and 2. Costs and fuel consumption rates of felling, skidding, and whole-tree chipping thinnings are slightly higher than the corresponding values when grinding logging residues at the landing. Because truck speeds were assumed to be constant within each road classification, both total cost and fuel consumption are linearly related to haul distance. The difference in the slope of linear changes by distance between the two cases is related to the difference in assumed moisture content of the processed material, 30 percent moisture with ground residue and 50 percent with whole-tree chips.

## Carbon and Life-Cycle Analysis

### Carbon production and removal

Carbon estimates were calculated using procedures developed in earlier CORRIM studies. Western carbon estimates used assumptions of Gholz et al. (1979) and Jenkins et al. (2003). In the Southeast carbon estimates were developed through the NUTREM2 model (NCSFNC 2000) developed and used in that region.

*Table 4.—Production rates, costs, and fuel consumption of components for whole-tree chipping thinned material in the Southeast United States at one-way hauling distance from the log landing of 97 km with biomass at 50 percent moisture content (wet basis).*[a]

| | | % use | Production rate (BDmT/SMH) | Production cost (\$/BDmT) | Diesel use (liters/BDmT) | Lubricant use (liters/BDmT ) |
|---|---|---|---|---|---|---|
| A. Biomass from thinning with whole-tree chipping: base; chipper production = 47 BDmT/PMH | | | | | | |
| Felling | Large biomass feller buncher | 85 | 28.0 | 3.50 | 0.81 | 0.01 |
| Skidding | Large biomass skidder | 80 | 6.6 | 10.60 | 2.64 | 0.05 |
| Processing | Medium whole tree chipper | 75 | 31.7 | 6.30 | 1.30 | 0.02 |
| Subtotal | Stump to truck | | | 20.40 | 4.75 | 0.08 |
| Hauling | Chip van, 120 $yd^3$, with medium chipper | 90 | 3.1 | 29.00 | 11.25 | 0.20 |
| System total | Stump to mill | | | 49.40 | 16.00 | 0.28 |
| B. Biomass from thinning with whole-tree chipping: −20% production; chipper production = 34 BDmT/PMH | | | | | | |
| Felling | Large biomass feller buncher | 85 | 28.0 | 3.50 | 0.81 | 0.01 |
| Skidding | Large biomass skidder | 80 | 6.6 | 10.60 | 2.64 | 0.05 |
| Processing | Medium whole tree chipper | 75 | 25.4 | 7.90 | 1.62 | 0.03 |
| Subtotal | Stump to truck | | | 22.00 | 5.07 | 0.09 |
| Hauling | Chip van, 120 $yd^3$, with medium chipper | 90 | 3.0 | 29.70 | 11.32 | 0.20 |
| System total | Stump to mill | | | 51.70 | 16.39 | 0.29 |
| C. Biomass from thinning with whole-tree chipping: +20% production; chipper production = 51 BDmT/PMH | | | | | | |
| Felling | Large biomass feller buncher | 85 | 28.0 | 3.50 | 0.81 | 0.01 |
| Skidding | Large biomass skidder | 80 | 6.6 | 10.60 | 2.64 | 0.05 |
| Processing | Medium whole tree chipper | 75 | 38.1 | 5.30 | 1.08 | 0.02 |
| Subtotal | Stump to truck | | | 19.40 | 4.53 | 0.08 |
| Hauling | Chip van, 120 $yd^3$, with medium chipper | 90 | 3.2 | 28.50 | 11.21 | 0.20 |
| System total | Stump to mill | | | 47.90 | 15.74 | 0.28 |

[a] BDmT = bone dry metric tons; SMH = scheduled machine hour; PMH = productive machine hour.

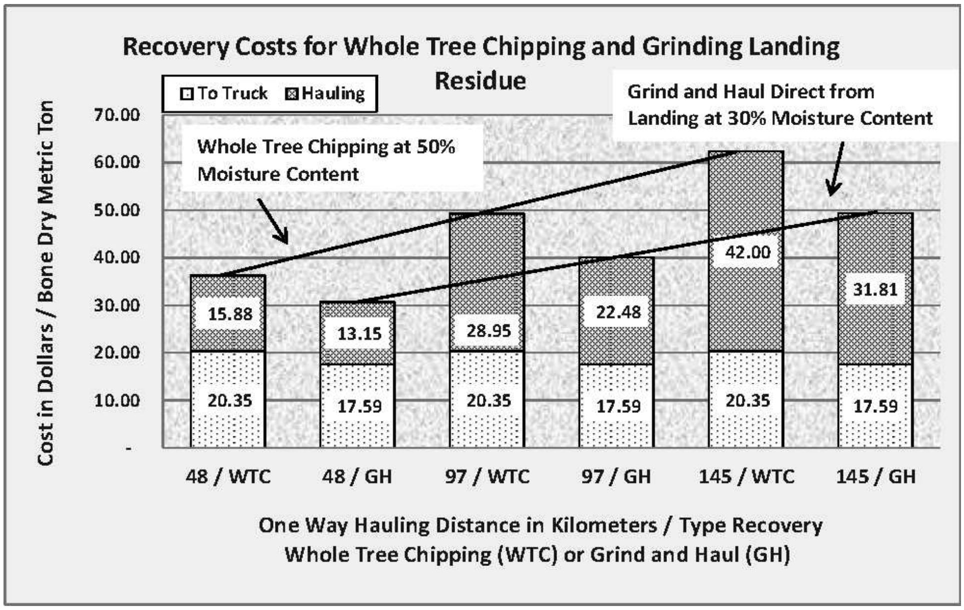


*Figure 1.—Cost of chipping and hauling thinned material for biomass compared with costs of processing residues directly from the landing at three haul distances.*

Calculated carbon pools included material removed in the harvest of the primary forest products of sawlogs in the Inland West, material removed as whole-tree chips or residual biomass, and residual material from the harvesting operations left on the site. The carbon expected to be removed and retained on site in the final sawlog/pulpwood harvest in the Southeast United States is not shown; the residual retained on site is just the residue from the thinning operation. Carbon quantities were segmented into the merchantable stem and bark, crown material that includes both the crown stemwood and foliage, and roots. There is a base assumption in this study that fine roots grow and decompose at about the same rate. This means they do not add net carbon to the system.

Soil carbon estimates are not quantified in this study, but other research has shown that the direct impacts of forest management activities on soil conditions can result in positive or negative consequences on soil carbon stores depending on soil type, temperature, moisture conditions, and level of disturbance. Harrison et al. (2011) notes that short-term fluctuations in soil carbon at various depths can be expected with any kind of disturbance or management, but most studies have failed to capture the impacts for the entire depth of the soil profile. This has often led to

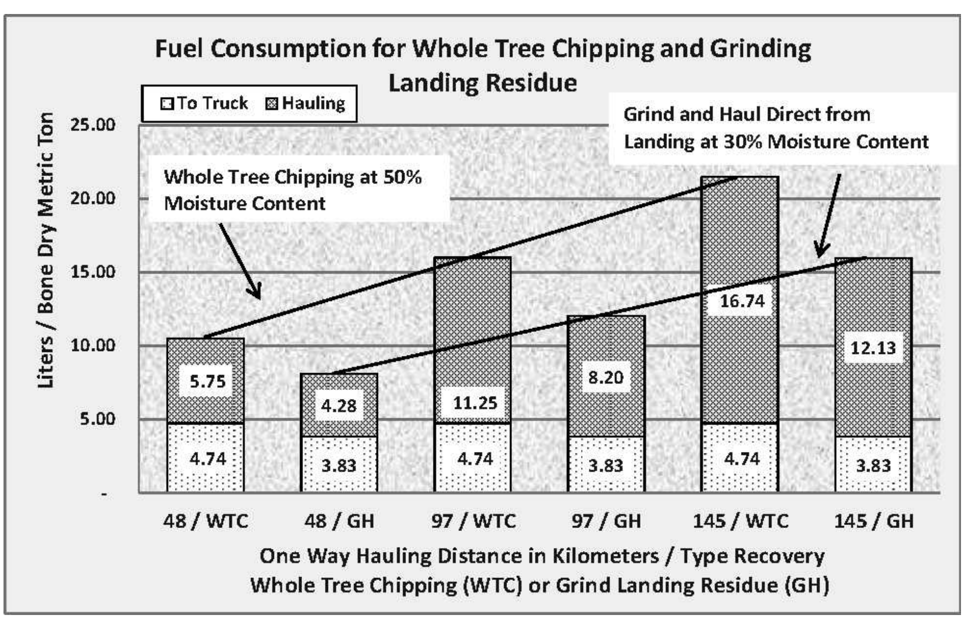


*Figure 2.—Fuel consumption to chip and haul thinned material for biomass compared with costs of processing residues directly from the landing at three haul distances.*

*Table 5.—Carbon pools by tree component removed from the woods and left in the woods following residue recovery activities in the Inland West and Southeast United States.*

| | Inland West moist-cold forest (kg/ha) | | | Southeast thinning (kg/ha) | |
|---|---|---|---|---|---|
| | Removed through sawlog harvest | Removed through residue recovery | Residual of harvested material remaining on site | Removed through thinning | Residual of harvested material remaining on site |
| Stem + bark | 23,800 | 3,900 | 4,700 | 17,300 | 1,400 |
| Crown | | 11,200 | 13,700 | 3,800 | 2,500 |
| Roots | | | 20,300 | | 10,600 |
| Total | 23,800 | 15,100 | 38,700 | 21,100 | 14,500 |

erroneous conclusions of impacts where these may be very small. A synopsis of long-term soil productivity studies (Powers et al. 2005) across multiple US study sites shows no overall change in soil carbon storage over a 10-year study period but large fluctuations in some parts of the profile during the same time frame. Contrary to what one might expect, they also found no difference in soil carbon storage with and without biomass retention, except that there was more carbon stored where biomass had been removed. The large uncertainties identified by these researchers suggest that assumptions of relatively small changes in long-term soil carbon with biomass removal at the levels considered for this study are reasonable.

Carbon pools removed from and left in the woods following primary product harvesting and residue recovery are shown in Table 5.

## SimaPro life-cycle analysis

SimaPro v7.3 is a software package designed for analyzing the environmental impact of products over their life cycle and was used to perform the life-cycle analysis, to generate emission factors, and to analyze the relative contribution of the various residue recovery processes to emissions. It was developed in The Netherlands by PRé Consultants B.V. (Goedkoop and deGelder 2001, Goedkoop and Oele 2001) and includes the US Life-Cycle Inventory (USLCI) database for many chemicals and materials. The relative contribution of residue recovery processes to overall environmental impact used the Tool for the Reduction and Assessment of Chemical and other Environmental Impacts (TRACI) 3.03 method (TRACI2) developed by the US Environmental Protection Agency and incorporated within SimaPro.

SimaPro process models were developed for each piece of equipment used in the thinning and residue recovery operations. These models used the same primary SimaPro database sources for resources such as diesel fuel as the biomass conversion stages modeled in other aspects of the project. The fuel and lubricant consumption rates in the SimaPro models match those shown for the systems in Tables 3 and 4. Diesel fuel was the primary power source for all residue recovery operations. Lubricant consumption in the residue recovery equipment generally consists of hydraulic oils and general lubricants required for the hydraulic systems and moving parts of the equipment. Lubricants are not consumed through combustion but are replaced through regular maintenance activities. Used lubricating fluids were assumed to be recycled.

Emission factors were developed for the material on board the long-distance haul vehicle and also for material delivered to a final utilization point. Emissions to the air and life-cycle assessment factors associated with removal of the residue material in the Inland West of the United States are also compared with those associated with disposal of the residue in the woods through burning. Burning of residue piles in the woods generally requires travel and personnel to prepare the material and surrounding areas for burning and to monitor the burn as it progresses. The life-cycle models of the piling and burning processes include the resources required by the crew and equipment to prepare the site and material for burning, along with the emission factors associated with the actual combustion of slash in the forest.

Emissions to the air were calculated by SimaPro based on the fuel consumption and production rates developed for systems discussed earlier. Selected emissions to the air are shown both as processed and loaded on the long-distance truck and after long-distance hauling in Table 6 for the base case and the two shuttle alternatives considered in recovery of landing residue. Emission factors for whole-tree chipping and hauling in thinned stands and for grinding and hauling residues directly from the log landing hauling are shown for three hauling distances in Table 7. A 20 percent decrease in grinder productivity would result in a 6.6 percent increase in each factor; a 20 percent increase in grinder productivity would result in a 4.4 percent decrease in each factor. The corresponding percentages for changes in chipper productivity are a 2.5 increase in each factor with a 20 percent decrease in the production rate and a 1.6 percent decrease in each factor with a 20 percent productivity increase.

The life-cycle assessment as calculated by the TRACI2 method includes measurements of global warming potential (GWP), acidification, carcinogenics, noncarcinogenics, respiratory effects, eutrophication, ozone depletion, ecotoxicity, and smog. Each is measured in unit equivalents specific to that impact category. GWP, for example, is measured as a $CO_2$ equivalent but includes factors in addition to $CO_2$ in its calculation. The GWP of processes associated with each of the residue processing and chipping options are shown in Figure 3. GWP totals for each option include both processing and hauling at a 145-km distance. The GWP for burning the piled slash at the landing is shown for comparison.

Consistent with GWP calculations for burning that would take place in wood-fired boilers, emissions of biogenic $CO_2$ present in the wood are not counted in the GWP calculation. Other emissions that contribute to GWP that arise from burning are counted. The highest GWP occurs when loose residue is shuttled from the primary log landing to a secondary central landing for processing, because it was the option with the highest fuel consump-

*Table 6.—Selected emissions to the air from residue recovery operations on board the long haul truck and including a 145-km haul to the process point; emissions from piling and burning the same residue quantities are shown for comparison.*[a]

| | On board the long haul truck (kg/BDmT processed residue) | | | Including hauling at 145-km distance (kg/BDmT processed residue) | | | |
|---|---|---|---|---|---|---|---|
| Emissions to the air | Grind at landing | Grind and shuttle | Shuttle loose residue | Grind at landing | Grind and shuttle | Shuttle loose residue | Piling and burning (kg/BDmT) |
| Aldehydes, unspecified | 1.47E−04 | 4.24E−04 | 7.62E−04 | 6.11E−04 | 8.06E−04 | 1.14E−03 | 7.38E−05 |
| Ammonia | 7.37E−05 | 2.13E−04 | 3.83E−04 | 3.07E−04 | 4.05E−04 | 5.72E−04 | 2.43E−01 |
| $CO_2$, biogenic | 8.53E−03 | 2.47E−02 | 4.43E−02 | 3.56E−02 | 4.69E−02 | 6.63E−02 | 1.57E+03 |
| $CO_2$, fossil | 1.17E+01 | 3.38E+01 | 6.06E+01 | 4.86E+01 | 6.41E+01 | 9.06E+01 | 5.68E+00 |
| CO, biogenic | | | | | | | 3.32E+01 |
| CO, fossil | 1.02E−01 | 2.94E−01 | 5.28E−01 | 4.23E−01 | 5.58E−01 | 7.89E−01 | 1.24E−01 |
| Formaldehyde | 7.57E−05 | 2.19E−04 | 3.93E−04 | 3.16E−04 | 4.16E−04 | 5.88E−04 | 5.29E−01 |
| Hydrogen chloride | 1.09E−04 | 3.15E−04 | 5.66E−04 | 4.54E−04 | 5.98E−04 | 8.45E−04 | 5.48E−05 |
| Isoprene | 2.14E−04 | 6.20E−04 | 1.11E−03 | 8.93E−04 | 1.18E−03 | 1.66E−03 | 1.08E−04 |
| Methane | 1.51E−02 | 4.37E−02 | 7.84E−02 | 6.29E−02 | 8.29E−02 | 1.17E−01 | 7.60E−03 |
| Methane, fossil | 1.08E−03 | 3.12E−03 | 5.61E−03 | 4.50E−03 | 5.93E−03 | 8.38E−03 | 2.33E+00 |
| Methanol | | | | | | | 3.28E−01 |
| Nitrogen oxides | 2.13E−01 | 6.16E−01 | 1.11E+00 | 8.87E−01 | 1.17E+00 | 1.65E+00 | 2.60E+00 |
| VOC, nonmethane | 7.10E−03 | 2.05E−02 | 3.69E−02 | 2.96E−02 | 3.90E−02 | 5.51E−02 | 2.07E+00 |
| Particulates, $<2.5\ \mu m$ | | | | | | | 3.96E+00 |
| Particulates, 2.5–10 μm | 6.56E−03 | 1.90E−02 | 3.41E−02 | 2.73E−02 | 3.60E−02 | 5.09E−02 | 4.46E+00 |
| Particulates, unspecified | 1.12E−03 | 3.23E−03 | 5.81E−03 | 4.66E−03 | 6.14E−03 | 8.68E−03 | 6.87E+00 |
| Propene | 1.64E−04 | 4.75E−04 | 8.53E−04 | 6.84E−04 | 9.02E−04 | 1.28E−03 | 8.29E−05 |
| Sulfur dioxide | 5.94E−03 | 1.72E−02 | 3.09E−02 | 2.48E−02 | 3.26E−02 | 4.61E−02 | 8.33E−01 |
| Sulfur oxides | 1.18E−02 | 3.41E−02 | 6.12E−02 | 4.91E−02 | 6.48E−02 | 9.15E−02 | 5.92E−03 |
| VOC | 5.58E−03 | 1.62E−02 | 2.90E−02 | 2.33E−02 | 3.07E−02 | 4.34E−02 | 2.83E+00 |

[a] BDmT = bone dry metric tons; VOC = volatile organic compounds.

tion per unit of output. Most of the fuel consumption occurred during the transport of the loose residue by shuttle truck from the log landing to the central grinding landing. GWP for piling and burning is slightly higher than for the two recovery options as a result of the methane and CO emissions from burning that contribute toward the GWP impact factor score.

Figure 4 shows GWP as a function of changes in the production rate of the processors at a haul distance of 145 km. Contributions of each component of the residue

*Table 7.—Emissions to the air from whole-tree chipping operations in thinned stands and grinding and hauling residue directly from the log landing at three hauling distances.*[a]

| | Whole-tree chipping without haul, 32 BDmT/SMH (kg/BDmT) | Whole-tree chipping and hauling (kg/BDmT) | | | Grinding landing residue and hauling (kg/BDmT) | | |
|---|---|---|---|---|---|---|---|
| Emissions to the air | | 48 km | 97 km | 145 km | 48 km | 97 km | 145 km |
| Aldehydes, unspecified | 1.81E−04 | 4.02E−04 | 6.12E−04 | 8.23E−04 | 3.10E−04 | 4.61E−04 | 6.11E−04 |
| Ammonia | 9.12E−05 | 2.02E−04 | 3.08E−04 | 4.13E−04 | 1.56E−04 | 2.32E−04 | 3.07E−04 |
| $CO_2$, biogenic | 1.06E−02 | 2.34E−02 | 3.56E−02 | 4.79E−02 | 1.81E−02 | 2.68E−02 | 3.56E−02 |
| $CO_2$, fossil | 1.44E+01 | 3.20E+01 | 4.87E+01 | 6.55E+01 | 2.47E+01 | 3.67E+01 | 4.86E+01 |
| CO, biogenic | | | | | | | |
| CO, fossil | 1.26E−01 | 2.78E−01 | 4.24E−01 | 5.70E−01 | 2.15E−01 | 3.19E−01 | 4.23E−01 |
| Formaldehyde | 9.37E−05 | 2.08E−04 | 3.16E−04 | 4.25E−04 | 1.60E−04 | 2.38E−04 | 3.16E−04 |
| Hydrogen chloride | 1.35E−04 | 2.98E−04 | 4.55E−04 | 6.11E−04 | 2.30E−04 | 3.42E−04 | 4.54E−04 |
| Isoprene | 2.65E−04 | 5.88E−04 | 8.95E−04 | 1.20E−03 | 4.54E−04 | 6.74E−04 | 8.93E−04 |
| Methane | 1.87E−02 | 4.14E−02 | 6.31E−02 | 8.47E−02 | 3.20E−02 | 4.74E−02 | 6.29E−02 |
| Methane, fossil | 1.34E−03 | 2.96E−03 | 4.51E−03 | 6.06E−03 | 2.28E−03 | 3.39E−03 | 4.50E−03 |
| Methanol | | | | | | | |
| Nitrogen oxides | 2.64E−01 | 5.84E−01 | 8.89E−01 | 1.19E+00 | 4.51E−01 | 6.69E−01 | 8.87E−01 |
| VOC, nonmethane | 8.79E−03 | 1.95E−02 | 2.97E−02 | 3.98E−02 | 1.50E−02 | 2.23E−02 | 2.96E−02 |
| Particulates, $<2.5\ \mu m$ | | | | | | | |
| Particulates, 2.5–10 μm | 8.12E−03 | 1.80E−02 | 2.74E−02 | 3.68E−02 | 1.39E−02 | 2.06E−02 | 2.73E−02 |
| Particulates, unspecified | 1.38E−03 | 3.06E−03 | 4.67E−03 | 6.27E−03 | 2.37E−03 | 3.51E−03 | 4.66E−03 |
| Propene | 2.03E−04 | 4.50E−04 | 6.86E−04 | 9.22E−04 | 3.48E−04 | 5.16E−04 | 6.84E−04 |
| Sulfur dioxide | 7.35E−03 | 1.63E−02 | 2.48E−02 | 3.33E−02 | 1.26E−02 | 1.87E−02 | 2.48E−02 |
| Sulfur oxides | 1.46E−02 | 3.23E−02 | 4.92E−02 | 6.62E−02 | 2.50E−02 | 3.70E−02 | 4.91E−02 |
| VOC | 6.91E−03 | 1.53E−02 | 2.33E−02 | 3.13E−02 | 1.18E−02 | 1.75E−02 | 2.33E−02 |

[a] BDmT = bone dry metric tons; SMH = scheduled machine hour; VOC = volatile organic compounds.

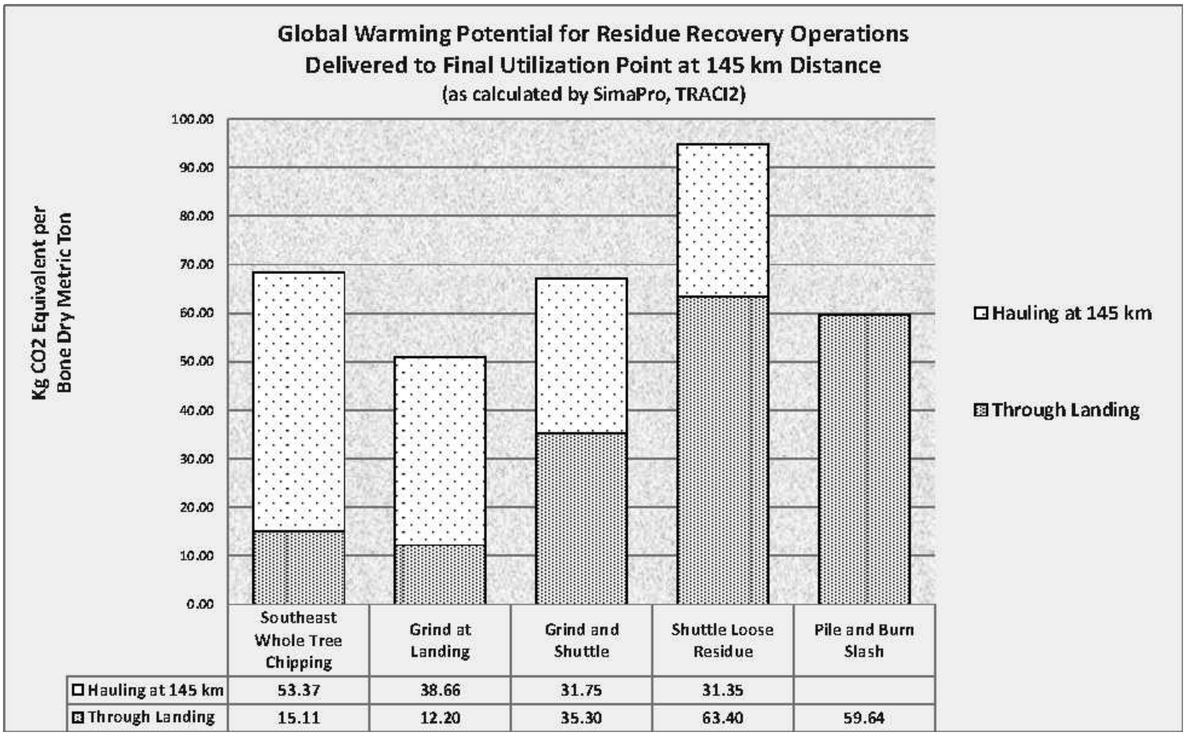


*Figure 3.—Global warming potential for residue recovery operations delivered to final use point at 145-km distance as calculated by the SimaPro TRACI2 method.*

recovery or whole-tree chipping system are directly related to the fuel consumption of that component as shown in Tables 3 and 4. Figure 5 shows the contrast of the net GWP $CO_2$ equivalent for each of the options when the $CO_2$ captured by the residue and thinned material over its growth cycle is included. The GWP of these feedstock collection processes is very small when integrated with the conversion stages needed to produce a final bioproduct.

A selected set of environmental indicators as calculated by TRACI2 is shown for burning, whole-tree chipping with a 145-km haul, and the three grinding options in Figure 6. The indicators do not include the carbon uptake captured by the residue and thinned material that was shown in Figure 5. The emissions related to acidification are much higher for the burning option than for any of the recovery options because of the large amounts of ammonia, $NO_x$, and $SO_x$

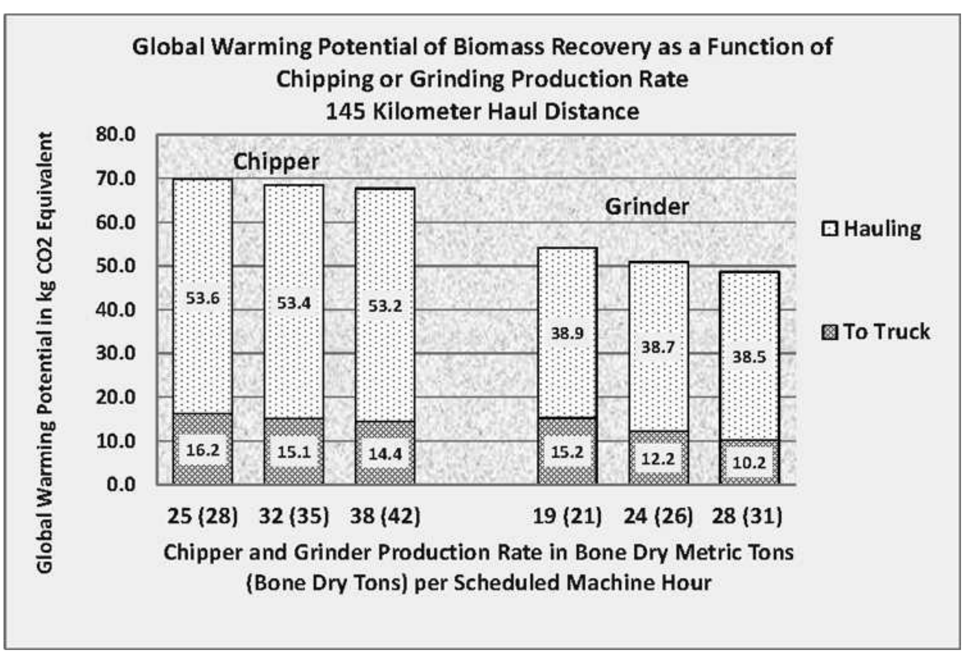


*Figure 4.—Impact of 20 percent increase or decrease in the production rate per scheduled hour of the chipper and grinder on global warming potential.*

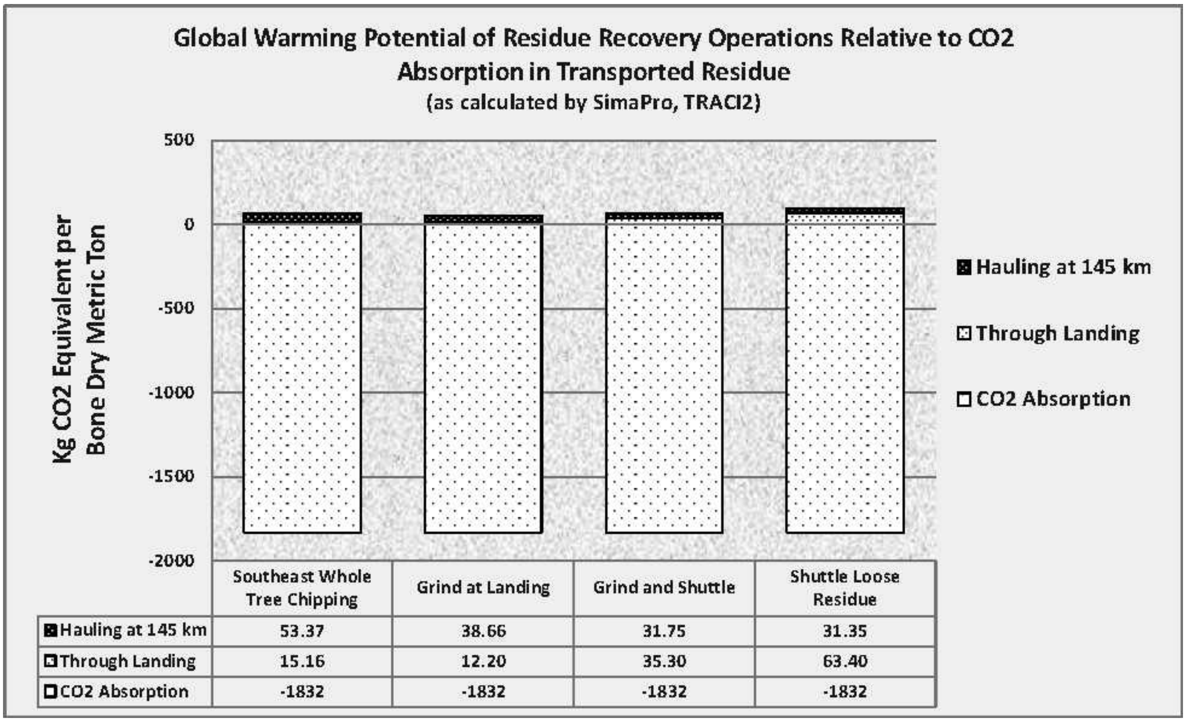


*Figure 5.—Net global warming potential of residue recovery operations relative to $CO_2$ adsorption in the transported material.*

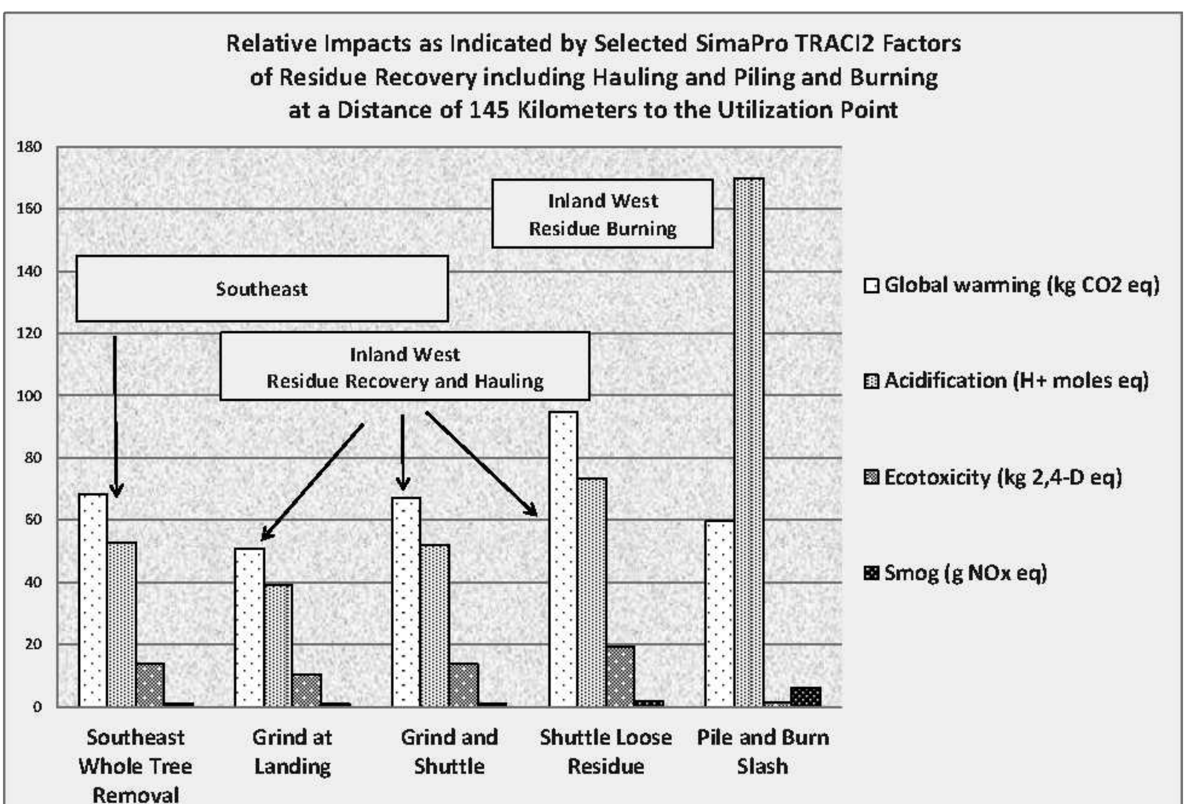


*Figure 6.—Relative impacts as indicated by selected SimaPro TRACI2 factors of residue recovery and piling and burning at 145-km distance from final use point.*

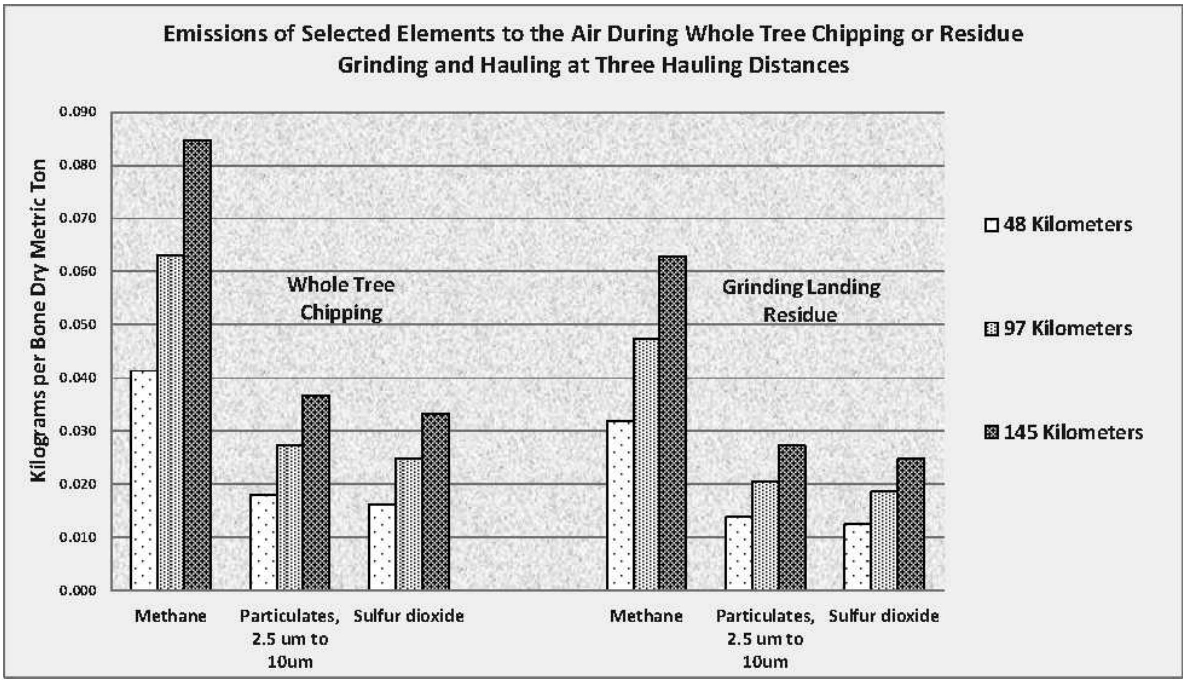


*Figure 7.—Emissions of selected elements to the air during whole-tree chipping and grinding operations at three hauling distances.*

that are released under open burning conditions. Ecotoxicity indicators as measured by 2-4,D equivalents, though low, are slightly higher for the recovery options than for burning and are likely related to the manufacturing steps required to produce fuel. Figure 7 shows selected emissions to the air for whole-tree chipping and grinding directly from the landing at three hauling distances.

The dry ton weight of a load in hauling can have a significant effect on fuel consumption per bone dry metric ton and the corresponding GWP. The dry ton load weight will be affected by the moisture content of the fuel and legal weight that can be hauled on state and federal highways. Legal weights vary by state. Payloads for this study were assumed to be limited to 22.7 metric tons, and this represented the limiting factor on load sizes for highway trucks. At 50 percent moisture content (wet basis) in the whole-tree chipping scenario, load size was calculated to be 11.3 BDmT. If load size had been based on the capacity of the chip van, the load would have been 16.2 BDmT. This load could also have been achieved with a moisture content of the residue of 28.6 percent (wet basis). If chip van volume had limited load capacity and residue had been at 28.6 percent moisture content, GWP for the system would have been reduced by 30 percent.

## Conclusions and Future Work

Fuel consumption rates per hour of operation for equipment used in processing and transporting residues and thinned material are fairly predictable. Production rates, however, depend on many site and operator factors. The production rates used in this study were developed from existing studies and expert opinion and are illustrative of those that may be encountered with these systems. Hauling distances were arbitrarily selected to bracket distances that would likely be encountered in the field. Hourly cost rates also represent averages and may not reflect current prices of commodities such as diesel fuel. Results for site-specific studies could vary significantly from these results and will require site-specific analysis, especially with respect to recovery costs.

The Harvest Factors spreadsheet model developed in earlier phases of CORRIM projects that links forest stand volumes, forest management activities, and timber harvest systems was modified to allow analysis of a variety of residue recovery operations. The model modifications will allow enhancement of the equipment database, development of additional biomass recovery systems, and future analysis biomass recovery under a broader range of conditions.

One area where research continues to be needed is in long-distance transportation equipment that is cost-effective and can access log landings without the requirement for additional road realignment or widening. This includes steerable chip vans and mounting the chip container on western log truck trailers. If direct access to the log landing is not possible, then additional focus will be needed on equipment that can efficiently compact loose biomass for short distance transportation to a centralized landing. Loose residue is less efficient because there is a great deal of air space between the solid wood pieces. Handling residues in mountainous terrain has been a focus of research projects since the 1980s (Sinclair 1984, 1985). Compacting loose residue in some fashion could make that option more efficient. Various devices to compact full trees and residues through baling were investigated in early residue studies (Fridley and Burkhardt 1984). The development in Scandinavia of a biomass bundler led to commercialization of bundling both in North America and Scandinavia that creates cylindrical bundles of slash. It was the subject of substantial testing in the United States and Canada (Rummer et al. 2004) but is generally too costly to use under current market values for residues. There continue to be efforts to develop simple, cost-effective bundling techniques through baling devices (Dooley et al. 2008, Klepac and Rummer 2010). Other experiments involve compaction of the residues in the hauling unit. Some proposed methods of compaction on board the truck are fairly sophisticated (Johansson et al. 2006, Lindroos et al. 2010), while others simply involve packing the residue with the loading machine.

Achieving gains in the density of the transported loose residue would allow simple operations at the log landing and greater centralization and efficiency in the processing step on sites where chip van access to the log landings in limited. Centralized processing will allow more efficient use of the grinder because fewer moves of the processing unit will be required. Highway trucks will also benefit because transportation over the lowest standards of roads with the slowest travel speeds will be eliminated. The tradeoff will be in the extra material handling steps created by the shuttle and compaction operations and the lower load capacities of the shuttle vehicles.

Lower residue collection costs would open additional biomass to economic recovery and increase the amount of the economically collectable feedstock and the use of biofuels, resulting in lower overall fossil fuel emissions. The innovations and field tests being conducted of new equipment and system configurations could result in increased cost and production efficiencies. In some regions there is also a relationship between biomass retained on a forest site and future forest productivity. The increased focus on biomass removal and processing will need inputs that dictate how much biomass is removed, how much is retained on site, and from what components of the tree.

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