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A Preliminary Assessment of the State of Harvest and Collection Technology for Forest Residues

February 2008

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Environmental Sciences Division

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EXECUTIVE SUMMARY

To meet the "Twenty in Ten Initiative" goals set in the 2007 State of the Union address, forest resources will be needed as feedstocks for lignocellulosic ethanol production. It has been estimated that 368 million dry tons can be produced annually in the U.S. from logging residues and fuel treatment thinnings. Currently, very little of this woody biomass is used for energy production due to the costs and difficulty in collecting and transporting this material. However, minimizing biomass costs (including harvest, handling, transport, storage, and processing costs) delivered to the refinery is necessary to develop a sustainable cellulosic ethanol industry. Achieving this goal requires a fresh look at conventional timber harvesting operations to identify ways of efficiently integrating energy wood collection and developing cost-effective technologies to harvest small-diameter trees.

In conventional whole-tree logging operations, entire trees are felled and skidded from the stump to the landing. The residues (also called slash), consisting of tops and limbs, accumulate at the landing when trees are delimbed. This slash can be ground at the landing with a mobile grinder or transported to another central location with a stationary grinder. The ground material is transported via chip vans, or possibly large roll on/off containers, to the user facility.

Cut-to-length harvesting systems are gaining popularity in some locations. In these operations, specialized harvesters that can fall, delimb, and cut logs to length are used. The small diameter tops and limbs accumulate along the machine's track. It can be left in the forest to dry or removed soon after harvest while logs are extracted. Removing slash during the same operation as the wood has been shown to be more efficient. However, leaving residue in the forest to dry reduces moisture content, which improves grinder performance, reduces dry matter loss during storage, and inhibits colonization of fungi that produce harmful spores.

In recent years, new machines that are specially designed for collection of small diameter wood have been developed in the U.S. and Europe. Residue bundlers and balers improve transportation and handling efficiency by densifying the material and packaging it so that it can be handled with conventional equipment. An experimental integrated harvester/grinder can fall small diameter trees and feed them into a grinder. The ground material is collected in a bin that can be dumped into a chip van. The harvester head is also capable of delimbing and bucking (cut into sections) small timber to be used for pulp and posts. Limitations of these new technologies are their large capital costs and complexity, leading to high maintenance costs and the need for highly trained operators.

To ensure that quality feedstock materials consistently enter the mouth of the refinery, the uniform format supply system concept proposes that feedstock diversity be managed at harvest, much like the current grain supply system. This allows for standardization of key infrastructure components and facilitation of a biomass commodity system. Challenges in achieving a uniform woody biomass supply include, but are not limited to, developing machines for efficient harvest of small-diameter trees in a range of topographies and conditions, developing machines and operating plans for grinding biomass as near to the stump as possible, developing cost-effective drying strategies to reduce losses and mold growth during wood chip storage, and quantifying environmental impacts of slash removal and fuel thinnings to aid landowner decisions and policy development.

1. INTRODUCTION

Forest industries are well accustomed to using woody biomass resources for energy. Secondary forest residues such as mill wastes and pulping liquors are well-utilized as feed sources for boilers of forest-product manufacturing facilities. As of 2005, these secondary forest residues contributed to nearly 50% of the nation's total biomass energy consumption (Perlack et al. 2005). In order to meet the goals stated in the "Twenty in Ten" Initiative (Bush 2007), additional forest resources will be needed as feedstocks for lignocellulosic ethanol production, and likely power production as well. Primary forest residues from logging and fuel treatment thinning operations offer the most potential for increasing biomass feedstock resources, as they are underutilized due to the cost and difficulty of their recovery (Perlack, et al., 2005).

The purpose of this technology memorandum is threefold:

1. Provide an overview of current timber harvest systems in the US and abroad that will be useful starting points for developing woody feedstock supply systems for pioneer biorefining facilities,
2. Identify unit operations that can be improved or eliminated in order to lower feedstock costs, and
3. Identify the research and development path forward in support of a uniform format woody feedstock supply system design (Hess et al. 2007) that can achieve the cost and quantity targets set forth in the biochemical and thermochemical conversion platform design documents.

2. BIOMASS PRODUCTION

The timber resources in the U.S. can annually produce 334 million dry tonnes[1] (368 million dry tons) (Perlack, et al., 2005). Of this volume, 58 million tonnes (64 million tons) are residues from logging operations and site clearing. Another 54 million tonnes (60 million) tons are from fuel treatment operations involved in reducing fire hazards. The availability estimates for these two key primary forestland resources take into account environmental concerns by assuming sufficient biomass is left on-site for nutrient recycling purposes, avoiding steep-sloped and inaccessible areas (i.e., roadless areas), and accounting for collection frequency. The forestland potential also considers the allocation of recovered resources to both energy wood and higher-valued forest products. The harvest and collection operations associated with these resources are the subject of this technical memorandum as they are currently underutilized and represent a significant fraction of the lignocellulosic materials available for conversion in biofuel facilities.

1 Tonne is a metric unit approximately equivalent to 0.907 tons.

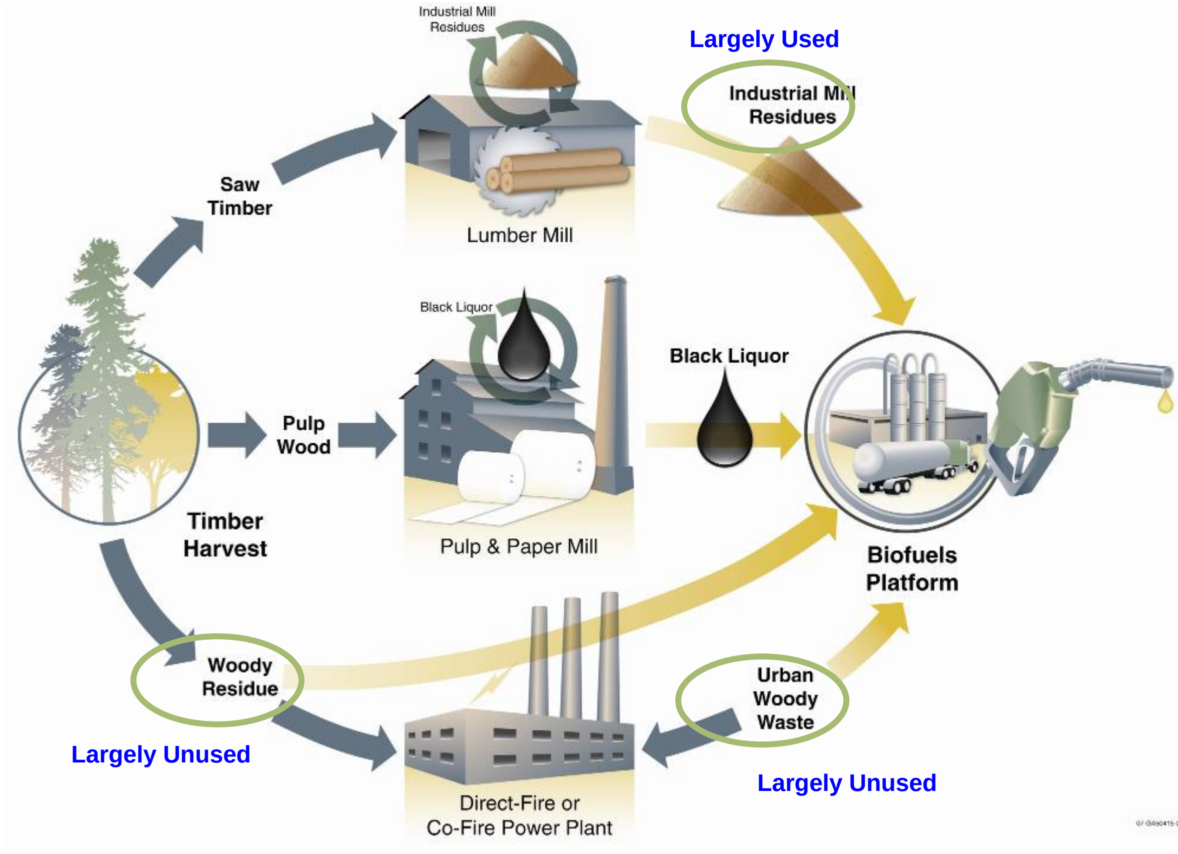

Figure 1. Potential uses of forest resources as bioenergy feedstocks. Some forest resources such as mill residues and pulping liquors are already widely utilized as energy feedstocks in forest product manufacturing facilities. Woody residues, however, are underutilized and could be a significant biomass resource for biofuels or power plants.

2.1 FOREST RESIDUES FROM COMMERCIAL LOGGING AND OTHER REMOVAL OPERATIONS

Logging residues are defined as the unused portions of growing-stock and non-growing-stock trees cut or killed by logging and left in the woods. Other removal residue is the unutilized wood cut or killed due to cultural operations such as pre-commercial thinnings or from timberland clearing. A recent analysis shows that annual removals from the forest inventory totaled nearly 18.3 billion m^3 (20.2 billion ft^3). Of this volume, 78% was for roundwood products, 16% was logging residue, and slightly more than 6% was classified as “other removals” (Smith et al. 2004). The total annual removals constitute about 2.2% of the forest inventory on timberland and are less than the net annual forest growth. The logging residue fraction is biomass removed from the forest inventory as a direct result of conventional forest harvesting operations. This biomass material is largely tree tops and small branches left on site because these materials are currently uneconomical to recover either for product or energy uses. The remaining fraction, other removals, consists of timber cut and burned in the process of land conversion or cut as a result of cultural operations such as precommercial thinnings and timberland clearing. Because the material is of low value, of low demand, and has high extraction cost, the remaining residue is left on the land. This is undesirable for aesthetic and fire-control reasons, so loggers often place the residue or “slash” into piles and burn for burning.   This can contribute to air quality issues in some areas.

Figure 2. Slash pile ready to be burned after a selective logging operation (Idaho Department of Lands).

The amount of logging and other removal residue was estimated using the U.S. Department of Agriculture Forestry Inventory and Analysis program's Timber Product Output Database Retrieval System. For the U.S., total logging residue and other removals currently amount to nearly 61 million tonnes (67 million) dry tons annually: 44.4 million dry tonnes (49 million dry tons) of logging residue and 16.3 million dry tonnes (18 million dry tons) of other removal residue.

Not all of this resource is potentially available for bioenergy and biobased products. Generally, these residues tend to be relatively small pieces consisting of tops, limbs, small branches, and leaves. Stokes reported a wide range of recovery percentages, with an average of about 60% potential recovery behind conventional forest harvesting systems (Stokes 1992). With newer technology, it is estimated that current recovery is about 65%. Other removals, especially from land-clearing operations, usually produce different forms of residues and are not generally as feasible or as economical to recover. It is expected that only half of the residues from other removals can be recovered. The amount of biomass that can be sustainably harvested varies by soil and vegetation type and is the subject of some debate among soil scientists and foresters. Some portion of this material, especially the leaves and parts of tree crown mass, may be needed on site to replenish nutrients and maintain soil productivity.

Because many forest operations involve the construction of roads that provide only temporary access to the forest, it is assumed that these residues are removed at the same time as the harvest or land clearing operations that generate the residues. Limiting the recoverability of logging and other removal residue reduces the size of this forest resource from about 61 million to 37.2 million dry tonnes (67 million to 41 million dry tons). About three-fourths of this material would come from the logging residue. Further, because of ownership patterns, most of the logging residue and nearly all residues from other sources (e.g., land clearing operations) would come from privately owned land. The spatial distribution of these resources is shown in Figures 3 and 4.

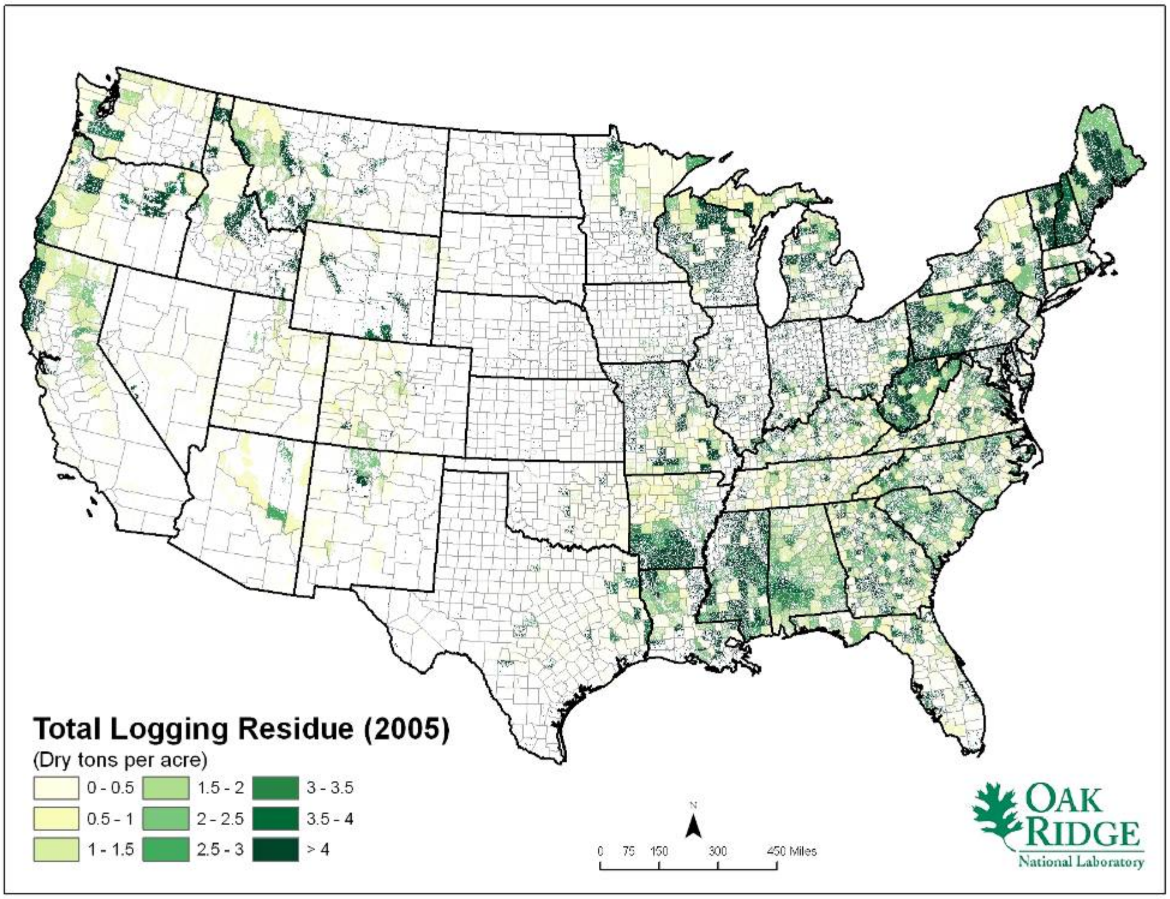

Figure 3. Spatial distribution of logging residues.

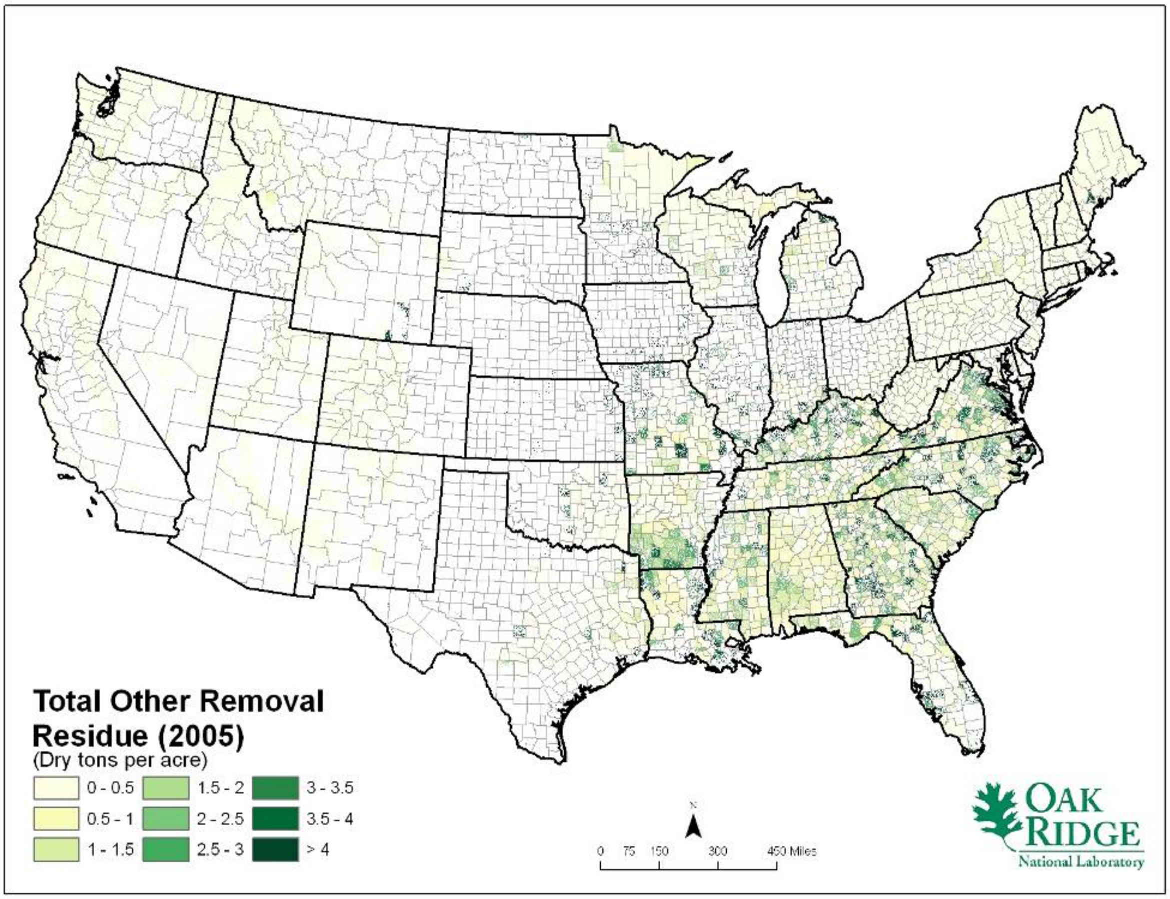

Figure 4. Spatial distribution of other removal residues.

2.2 FOREST FUEL TREATMENT THINNINGS

Currently, there are vast areas of U.S. forestland that are overstocked with relatively large amounts of woody materials. This excess material has built up over years as a result of forest growth and alterations in natural fire cycles. Over the last ten years, federal agencies have spent more than $8.2 billion fighting forest fires, which have consumed over 20 million hectares (49 million acres). The cost of fighting fires does not include the costs of personal property losses, ecological damage, loss of valuable forest products, or loss of human life. The Forest Service and other land management agencies are currently addressing the issue of hazardous fuels buildup and looking at ways to restore ecosystems to more fire-adaptive conditions. The removal of excess woody material would also improve forest health and productivity (Graham et al. 2004).

In August 2000, the National Fire Plan was developed to help respond to severe wildland fires and their impacts on local communities while ensuring sufficient firefighting capacity for future fires. The National Fire Plan specifically addresses firefighting capabilities, forest rehabilitation, hazardous fuels reduction, community assistance, and accountability. Recently, the Healthy Forest Restoration Act (HFRA) of 2003 was enacted to encourage the removal of hazardous fuels, encourage utilization of the material, and protect, restore, and enhance forest ecosystem components. HFRA is also intended to support R&D to overcome both technical and market barriers to greater utilization of this resource for bioenergy and other commercial uses from both public and private lands. Removing excess woody material has the potential to make relatively large volumes of forest residues and small-diameter trees available for bioenergy and biobased product uses.

Figure 5. Large amounts of dead trees in a dense stand make a forest susceptible to fire (D. Brad Blackwelder, INL).

Fuel treatment thinnings are classified as standing and downed trees in overstocked stands that, if removed, would leave the stand healthier, more productive, and less susceptible to fire hazard. The overstocking of many forest stands has resulted from years of forest growth without harvesting and from alteration of natural fire cycles. The amount and location of potential fuel treatment wood in timberlands was generated in 2004 by the U.S. Forest Service using a model called the Fuel Treatment Evaluator. This assessment tool identifies, evaluates, and prioritizes fuel treatment opportunities. Timberland fuel treatment data, retrieved by state and county and in collaboration with U.S. Forest Staff, were modified based on several assumptions. Thinnings were assumed to be 60% accessible on public lands and 80% accessible on private lands. Only 80% of the accessible material was assumed to be collectable in a given stand. Of the collected material, 70% was assumed to be larger pieces usable for high-value products; thus, only 30% was assumed to be available for energy. Next, a 30-year harvest cycle was assumed. Estimation of potential fuel treatment thinnings from “other forestland” (forested areas not categorized as “timberland”) was based on the Forest Inventory Analysis database using similar assumptions (Miles 2004).

In total, there are about 7.6 billion dry tonnes (8.4 billion dry tons) of treatable biomass in inventory that are potentially available for bioenergy and biobased products. However, only a fraction is removable in any year given the combination of recoverability, accessibility, and harvest cycle factors noted previously. These factors reduced the amount of fuel treatment biomass that can be sustainably removed on an annual basis to about 44.4 million dry tonnes (49 million dry tons) from timberlands and about 10 million dry tonnes (11 million dry tons) from other forestlands. Most of the fuel treatment biomass from timberlands would come from privately owned lands; slightly less than 20% of the material would come from national forests. In contrast, proportionately more of the fuel treatment biomass allocated to bioenergy and biobased products on other forestland land would come from publicly held lands. Most of these lands are located in the western regions of the country. The 54.4 million dry tonnes (60 million dry tons) of fuel treatment biomass assumes that a relatively large percentage (70%) goes to higher-valued products. If feedstock prices for small diameter wood were to increase relative to conventional forest products, the amount of biomass available for bioenergy and biobased products could increase substantially. The spatial distribution of these resources is shown in Figures 6 and 7.

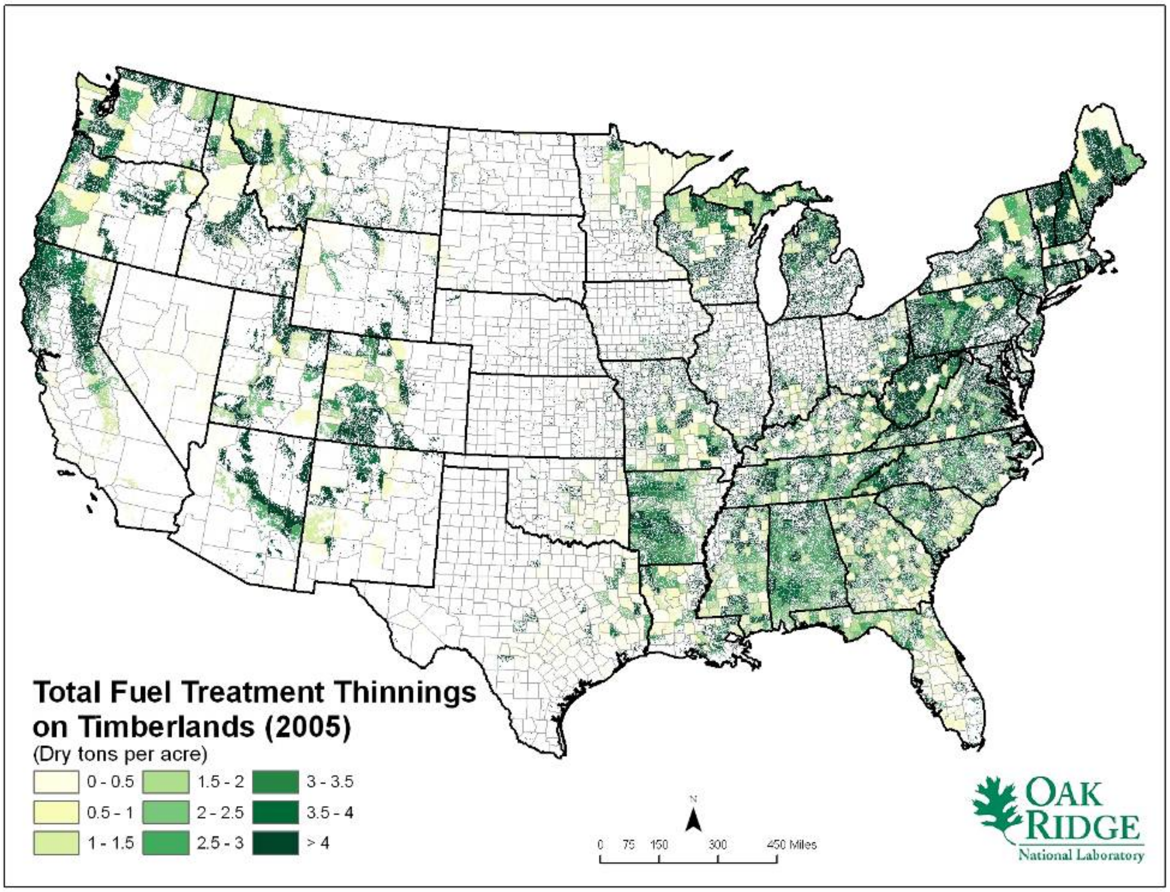

Figure 6. Spatial distribution of fuel treatment thinnings from timberlands.

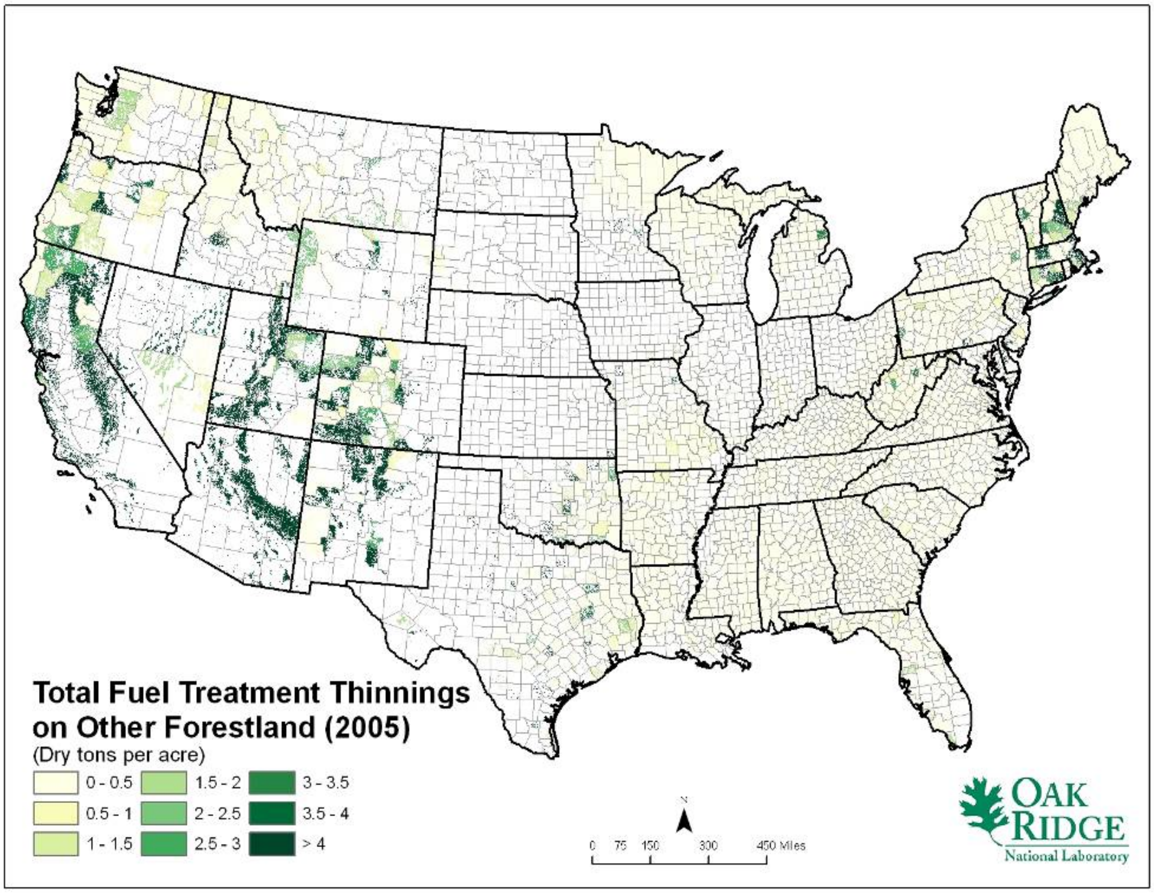

Figure 7. Spatial distribution of fuel treatment thinnings from other forestlands.

3. WOODY HARVEST, COLLECTION, AND HANDLING SYSTEMS

Current logging technologies are designed for felling, extracting, and transporting high-quality saw logs or pulpwood from forests. If convenient, logging residues (limbs and small diameter tree tops) and small, non-merchantable trees are occasionally recovered for use as energy wood by paper mills or power plants. More often than not, logging residues are left in the woods, as the costs of removal have traditionally exceeded market value of the material. However, as the demand for biomass feedstocks to produce cellulosic ethanol increases, a new market for logging residues will develop. Because biomass for ethanol production is, and will likely remain, a low-value product relative to roundwood, harvest and handling costs must be minimized in order for collection to be economically feasible. Adding residue collection to a logging operation requires a fresh examination of the operation’s equipment and supply chain logistics. This paper addresses existing logging technologies that have been adapted for collection and transport of forest residues and new technologies currently under development. Technologies for collecting woody biomass were also previously discussed in detail by Leinonen (2004) in a report comparing logging residue collection in the US and Finland. Figure 8 shows the major components of bioenergy feedstock supply chains. Assembling a biomass supply chain to meet the 2012 Department of Energy (DOE) feedstock cost target of $44 per dry tonne ($40 per dry ton) (2007 dollars) requires consideration of the benefits and drawbacks of technologies available for each component of the chain.

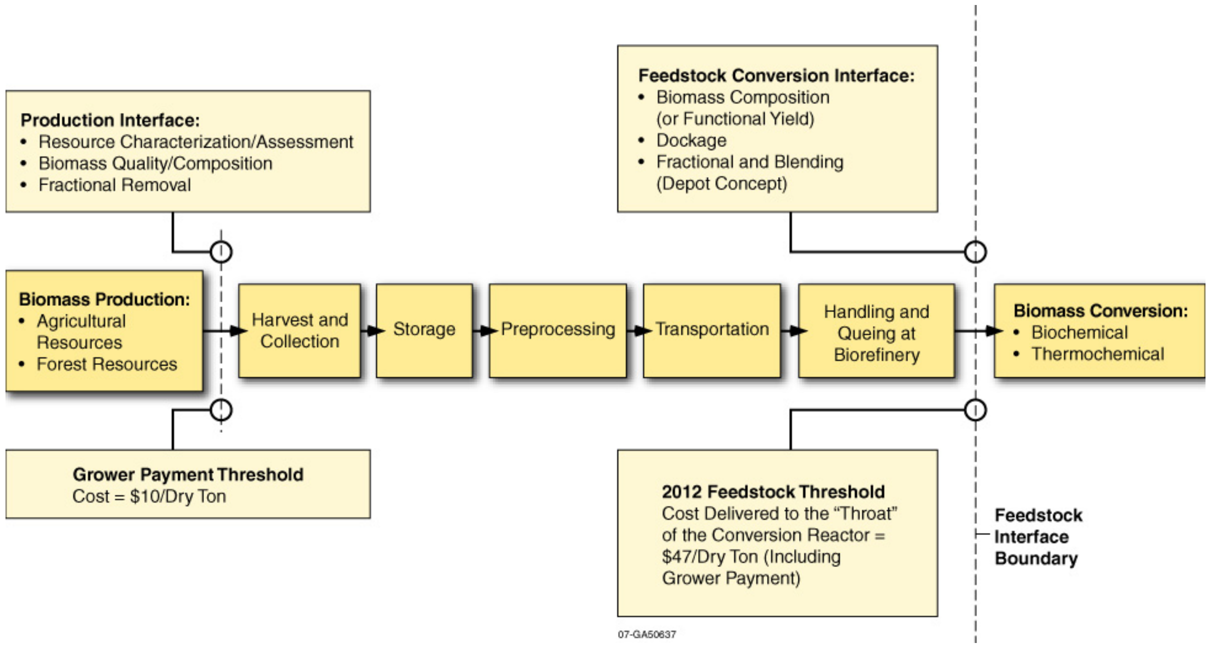

Figure 8. Bioenergy feedstock supply chain. The efficiency and feasibility of each step in the biomass supply chain must be carefully evaluated to meet the 2012 cost target of $47 per dry ton.

Biomass Production is the beginning of the feedstock supply chain. It involves producing biomass feedstocks to the point of harvest. Production addresses important factors such as selection of feedstock type (e.g., hardwood, softwood), land use issues, policy issues, and silvicultural practices that drive biomass yield rates and directly affect harvest and collection operations.

Harvest and Collection encompasses all operations associated with getting biomass from its source to the storage or queuing location. In addition to logging and hauling, this often includes some form of densification, such as bundling or chipping, to facilitate handling and storage.

Preprocessing must occur prior to conversion to physically transform the feedstock into the format required by the biorefinery. Preprocessing can be as simple as grinding and formatting the biomass for increased bulk density or improved conversion efficiency, or it can be as complex as improving feedstock quality through fractionation, tissue separation, and blending.

Transportation consists of moving biomass from one point to another and occurs throughout the supply system. Transportation options are generally fixed and well-defined for respective locations throughout the country and can include truck, rail, or barge. The system used will directly effect how the feedstock is handled and fed into the conversion process. Transporting and handling methods are highly dependent on the format and bulk density of the material, which makes them tightly coupled to each other and all other operations in the feedstock supply chain.

Storage and Queuing are essential operations in the feedstock supply system. They are used to deal with seasonal harvest times, variable yields, and delivery schedules. The objective of a storage system is to provide the lowest-cost method (including cost incurred from losses) of holding the biomass material in a stable, unaltered form (i.e., neither quality improvements nor reductions) until it is called for by the biorefinery. *Handling* includes unloading the biomass from the trucks (or other transport medium) at the plant-receiving yard, transporting it into short-term storage (queuing), and transferring it from storage into the plant for the pretreatment process. Feed handling systems are also integral parts of harvesting, collection, and preprocessing.

3.1 HARVEST AND COLLECTION

Small diameter wood for energy can be harvested with timber in a two-pass system or a one-pass, integrated system. In the two-pass system, energy wood is cut and piled in the forest to dry while timber is extracted. Residues (non-merchantable tops and limbs) are then collected and removed in a later operation. The one-pass system is an integrated approach in which all products are harvested in a single operation. One-pass systems include whole-tree harvesting and in-forest delimbing in which residues are collected at the same time as timber. Increasing the degree of integration in logging operations with one-pass systems has been shown to be cost-effective. However, other factors, such as the value of drying biomass in the forest, may make a two-pass system more desirable.

3.1.1 Conventional Timber Harvest Methodology

In U.S. mechanized logging operations (see Figure 9), timber is typically harvested as whole trees or, less frequently, as cut-to-length logs. In whole-tree logging operations felled trees are extracted to the landing where limbs and tops are removed before logs are transported onto the mill yard or pulp plant. Cut-to-length systems in which limbs and tops are removed and logs are cut to the desired length while still in the woods are also available. Harvesting logging residues is possible in either system, but feasibility varies with how it is executed. Choice of technologies should account for scale of the logging operation, nature of the forest site, infrastructure, and integration (if necessary) into the existing logging operation.

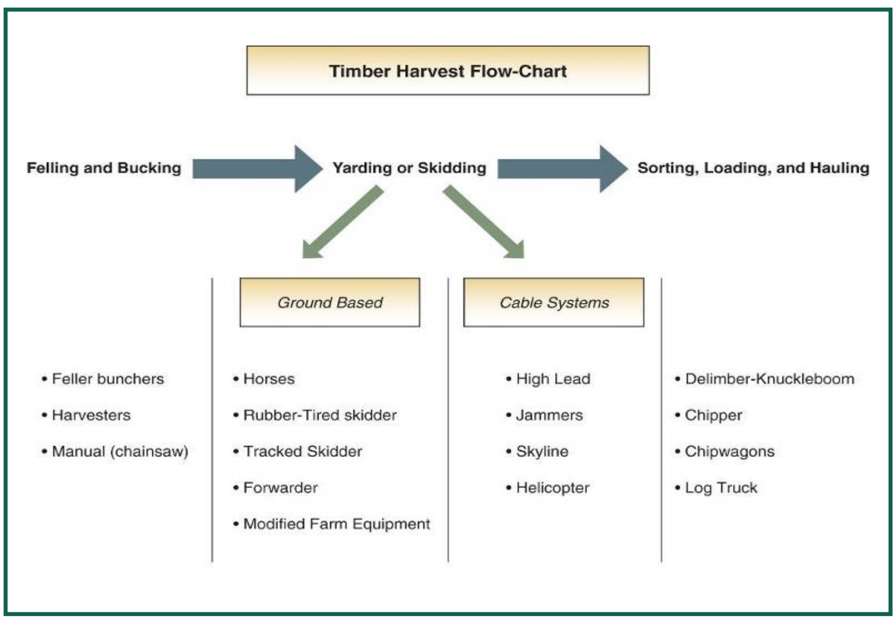

Figure 9. Logging unit operations. There is considerable variability in technologies utilized in modern timber harvesting operations. In this paper, only methods that are amenable to cost effective residue collection or collection of thinning materials are discussed.

In whole-tree harvesting systems, a feller buncher (see Figure 10) can be used to fall and stack trees. The feller buncher head grips the tree, saws it through at the base, and gathers it into the accumulator pocket. The feller buncher then carries the bunch of trees to the roadside and stacks them up. In a conventional, two-pass system trees are then delimbed on site and cut into sections (bucked) or dragged whole with a tractor (skidded, see Figure 11) to the yard or landing. The logging residues (also called slash) are left in piles in the forest to dry. Logs are loaded onto log trucks and transported to a saw mill to be turned into lumber or to a mill for products such as paper and oriented strand board (OSB).

Figure 10. Feller buncher harvesting saw timber. Feller bunchers are used in conventional whole-tree logging operations to cut and accumulate trees for extraction from the forest (D. Brad Blackwelder, INL).

Figure 11. Grapple skidder used to drag whole trees from forest to landing. Skidders grasp tree bunches and drag them from the forest to the landing (Vannatta Forestry Museum).

Both rubber wheel and track feller-bunchers are available. Rubber wheel machines are generally faster and must drive to the tree that is to be felled. A track machine, on the other hand, has a felling head on the end of a knuckle boom with a longer reach, reducing their travel through the forest compared to wheeled machines. Production rates of feller-bunchers depend on tree size, forest density, and terrain conditions, such as slope. On steeper slopes a cable system may be set up to improve safety and erosion control. The logs are attached to a cable and pulley that transports the log to the landing for processing. The logs are then delimbed, bucked, and sorted or they are delimbed, topped, and stacked as tree-length logs.

3.1.2 Integrated Residue Collection with Whole-Tree Logging

If slash is being collected on a logging site, efficiency of the operation will likely improve as the degree of integration between timber and residue harvest increases. In integrated (also called one-pass) whole-tree logging operations (see Figure 12); trees are felled and transported to the yard with top and limbs intact. They are then delimbed, topped, and bucked at the landing (see Figure 13). This method results in slash accumulation at the landing. In areas with access to cogeneration facilities, the slash can be chipped and used for the production of electricity and/or heat.

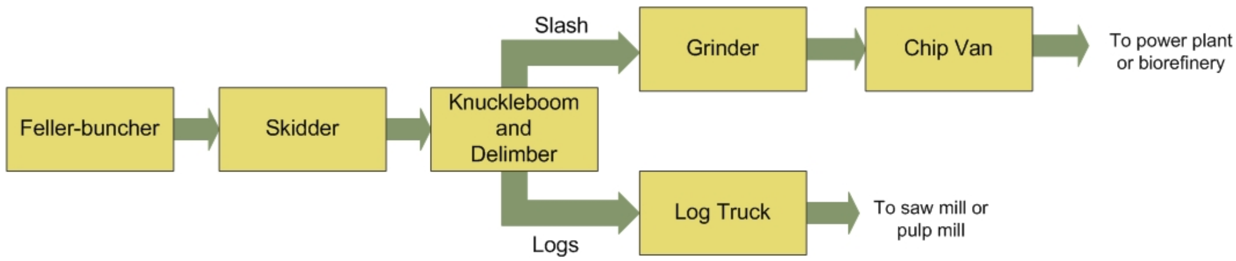

Figure 12. Integrated residue collection by whole-tree harvesting.

In a recent study by Adebayo et al. (2007), a whole-tree harvesting approach was compared with cut-to-length harvesting (see Section 3.1.3). The whole-tree harvesting system had a slightly higher hourly machine cost, yet its higher productivity resulted in lower production costs compared with the cut-to-length system. Although these results were based on log costs, the conclusions can be extended to include non-merchantable wood because the only additional costs for residue collection in an integrated system are transport costs.

Figure 13. Skidder transporting trees to a yard where a knuckleboom and delimber is delimbing, topping, and sorting (D. Brad Blackwelder, INL).

Whole-tree harvesting also includes utilization of entire trees, including branches and tops. Harvesting whole-trees for bioenergy uses can be integrated with timber harvest operations. A study by Watson et al. (1986) compared one-pass and two-pass harvesting methods for small diameter trees and larger timber. In the one-pass approach, a feller-buncher separated trees into piles of energy wood and piles of roundwood. Both types of piles were skidded to a landing and processed during the same time period. In the two-pass method, the feller-buncher maneuvered around merchantable trees to cut the energy wood first. The energy wood was piled in the forest and allowed to dry for several weeks while the merchantable timber was harvested. They concluded that the one-pass method resulted in better utilization of the wood and the lowest costs. However, a disadvantage of this method was that biomass was delivered at higher moisture contents because it was not allowed to dry before extraction from the forest and chipping. They also found that of all steps in the energy wood supply chain, felling costs were highest, indicting that advancement in felling machines offer the best opportunity to improve the feasibility of harvesting small diameter material. Although this study was performed over two decades ago, conventional forest harvesting equipment has changed little during that time and the conclusions drawn remain valid.

3.1.3 Integrated Residue Collection with Cut-to-Length Logging

Cut-to-length harvesting is another highly integrated option for logging operations (see Figure 14). Cut-to-length logging is the most common logging method in European countries, including Finland (Leinonen 2004). Cut-to-length harvesters, such as the John Deere 1270D shown in Figure 15, are equipped with a versatile head that grips the tree while cutting it at the base. The harvester head then rotates so that the tree is turned parallel to the ground and spiked rollers feed the tree through the delimbing device. As the tree is fed through, a saw embedded in the harvester head cuts the log into specified lengths. Typically, residues are piled in front of the harvester's tracks to serve as a mat for the harvester as it progresses through the forest. This makes cut-to-length logging well-suited for wet or sensitive areas where the slash mat can protect the ground from the harvester (Leinonen 2004). Logs are stacked alongside the harvester's path to be collected by a forwarder and extracted to the landing. In operations where no-merchantable wood is harvested for energy, residues could also be stacked alongside the machine's track for later collection.

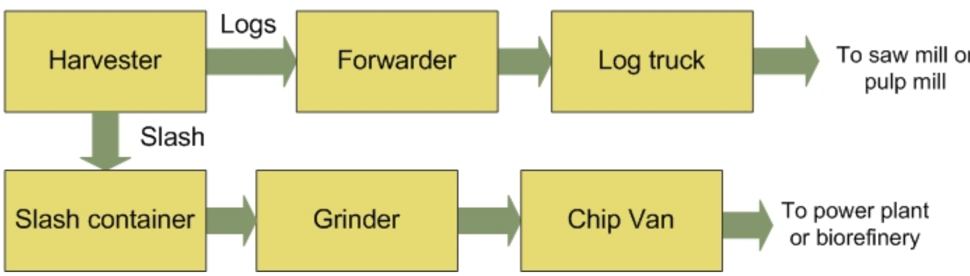

Figure 14. Integrated residue collection by cut-to-length harvesting.

Figure 15. Cut-to-length harvesting. A John Deere 1270D harvester falls a tree, delimbs it, and cuts logs to a desired length with the same head (John Deere).

Cut-to-length systems are most suited for logging larger trees ((Huyler and LeDoux 1999, Klepac et al. 2006). In a recent study evaluating the Timberjack 1270 harvester for fuel reduction treatments, Klepac et al. (2006) found that harvest costs for wood (residue collection not included) was dramatically affected by tree size. Harvesting trees 7.6 to 12.7 cm (approximately 3–5 in.) in diameter was cost prohibitive. Costs for trees larger than 12.7 cm (5 in.) in diameter decreased dramatically so that the cost of harvesting 36-

cm (14-in.) trees was essentially negligible compared to other components of the supply chain. With regard to harvest time, the harvester is the limiting machine (Klepac, et al., 2006) and was outperformed by the forwarder (Figure 16) by about two to one for producing sawlogs and five to one for collecting tops and limbs. The efficiency of cut-to-length harvesting systems can be increased by employing appropriate techniques. A study by Nurmi (2007) compared harvester operations where residues were piled in front of the machine (typical method), to one side of the road, or to both sides of the road. Stacking residues to one or both sides of the road significantly improved collection times and yield of residue recovery compared with stacking residues on the road in front of the harvester. However, stacking residues in the path of the harvester is believed to minimize soil disturbance and compaction.

Figure 16. Forwarder stacking logs in a bunk. Forwarders are specialized machines that load logs, haul them from the forest, and unload them at the landing. Unlike skidders, forwarders carry logs clear of the ground (Komatsu).

3.2 PREPROCESSING

Before woody biomass can be fed into a reactor at the refinery, two important preprocessing steps must occur: comminution and drying. Comminution (size reduction) is necessary to prepare the material for the reactor. Following comminution, machines specially designed to handle chipped biomass is required in all subsequent steps of the supply chain. Therefore, when and how size reduction occurs has a significant impact on the overall efficiency of the operation. Drying is another preprocessing operation that increases the stability of biomass during storage and increases its value.

3.2.1 Comminution

Comminution of woody biomass is a prerequisite step for all biofuel conversion technologies. Grinders in assorted configurations are available for introducing and grinding feedstocks. The material size is reduced by cutting (knife milling) or blunt impact (hammer milling). Grinders may be fed by a belt or top fed with a loader. Large-diameter, large-scale grinding is typically performed by a hammer-mill, top-fed tub grinder (see Figure 17). Particle size is an important consideration in grinder selection. Larger particles (greater than 2.5 cm) produced by disk chippers, hammer hogs, and tub grinders are best suited for pulping and particle board production. Energy production systems require particles less than 2.5 cm (1 in.) in diameter that can be obtained using a hammer mill. In a review of size reduction technologies for woody biomass, Naimi et al. (2006) concluded that two stages of size reduction, a coarse grinding (to particles greater than 2.5 cm (1 in.) in diameter) followed by a fine grinding (less than 2.5 cm), are needed in most energy production applications.

Figure 17. Large tub grinder (Vermeer).

Size reduction can occur at any point in the supply chain, from the stump to just prior to feeding into a reactor or boiler. Where residue grinding occurs is largely dependent on the logging operation equipment and site. Grinders can be mounted on a truck, trailer, or on tracks enabling them to access many logging sites. For smaller material on smaller sites, trailer mounted horizontal belt fed knife mill chippers are most appropriate.

Comminution drastically changes the properties of woody biomass, which determines the equipment needed for each subsequent step of the supply chain. Wood chips require very different handling and transportation equipment than do loose residues or logs. Solid containers or chip vans are needed to haul wood chips. Although this additional specialized equipment increases costs, the significant increase in material bulk density typically offsets these costs compared to hauling loose residues. The size reduction process can also change the moisture content of the material. Fresh green material typically has a moisture content of about 55%. Grinding can reduce moisture content by 5–20%.

3.2.2 Drying

Reducing the moisture content of biomass increases its energy density and makes it more friable, lowering the energy cost of grinding. Although mechanical drying of biomass is typically not feasible, transpirational drying in the forest or landing may be beneficial. As previously mentioned, in a two-pass harvesting system residues can be stacked in the forest and allowed to dry before extraction. A study by Nurmi (1999) found that while biomass is drying in the forest, defoliation occurs. The leaves and needles fall to the ground replenishing the soil with vital nutrients. This also eliminates a material that degrades quickly in storage compared to the woody portions of the tree. Defoliation also occurred in material stored at the landing, but to a lesser degree.

Drying increases the stability of wood chips in storage. Whole tree wood chips stored in piles have been known to self-heat if the moisture level is greater than 24% (note that self-heating is also dependent on factors such as tree species and pile size). Dry biomass has a reduced amount of biological activity and, thus, lower dry matter loss during storage.

3.3 TRANSPORTATION

Transportation of biomass occurs at several points along the supply chain. For low bulk density material such as wood residues, transportation can account for as much as 30% of the total collection costs

(Andersson et al. 2002). Therefore, selecting a transportation mode has a large impact on the overall costs and efficiency of the biomass supply chain. As woody biomass progresses along the bioenergy supply chain, changes in terrain, roads, and format of the material necessitates transfers to different transportation modes. Primary transportation includes the distance from the stump to the grinder. This is followed by secondary transportation of chips from the grinder to the end user or to a larger chip van for long distance transportation. Handling the biomass to transfer from one vehicle to another adds an expense that should be carefully evaluated.

3.3.1 Primary Transportation

Primary transportation covers the distance from the stump to the grinder. This segment of the transportation network requires specialized off-road equipment as it covers rough and often steep terrain. In conventional logging operations, moving timber from the stump to the landing is typically accomplished with a skidder or forwarder. If residues are collected along with timber in an integrated whole-tree harvesting system, the tree with both timber and tops and limbs remains intact while being dragged from the forest with a skidder (see Figure 18, left). In fuel reduction operations or two-pass harvesting systems, small diameter wood is collected and transported independently of timber in a modified forwarder (sides added to prevent loss of material) or off-road dump truck. New methods of bundling biomass can utilize typical logging equipment such as forwarders. Figure 18 (right) shows bundles of wood residues being handled much like logs (see Section 3.6.2 for more information on bundling and baling biomass).

Figure 18. Primary transportation options for biomass. Forest residues may be transported (left, John Deere) along with timber from the stump to the landing in whole-tree harvesting with a skidder, or independently of the timber and (right, U.S. Forest Service) can even be packaged so that it can be handled with conventional logging equipment.

3.3.2 Secondary Transportation

Secondary transportation is considered to be movement of the woody biomass from the landing to the end user or to another mode of tertiary transportation. The distance of secondary transportation is dependant on highway distance to user facility and access to the landing. Smaller chip vans can often access less remote landings. If a chip van can reach the landing, chipping directly into the chip van and hauling the biomass to the end user is the least expensive option (Rawlings et al. 2004). Often, large chip vans (92 or 113 m^3; 120 or 148 yd^3) cannot reach grinders on remote landings. In this case, dump trucks or roll on/off containers can be used as in Figure 19 (see Section 3.6.1). If the facility is nearby, these containers can economically be used to transport chips directly to the plant.

Figure 19. Secondary transportation of woody biomass. When chip vans cannot access remote landings, roll on/off containers can be used to haul wood chips to the utilization facility or to a larger truck (Montana Community Development Corporation).

3.3.3 Tertiary Transport

Transportation of more than 16-24 km (10–15 miles) on improved roads is more economical with large capacity vehicles such as 92 or 113 m^3 (120 or 148 yd^3) chip vans. Wood chips can be loaded into these large vehicles from small chip vans that carry it from the grinder at the landing. However, it is most economical to centrally locate the grinder in a place that is accessible to the large vehicles, transport whole slash to the grinder, and deposit wood chips directly into the large van (Rawlings, et al., 2004).

3.4 HANDLING COMMINUTED WOOD

Handling systems are too often overlooked in planning woody biomass collection operations and biorefineries. However, Hakkila (2004) states that handling systems can be problematic, particularly when the receiving plant is not prepared for the special properties of wood chips. The capacity of the receiving station to unload trucks must be synchronized with the rate of utilization. Improperly sized handling systems slow and sometimes halt operations, adding undue cost and frustration. Selection of handling systems must take into account the particle size distribution and moisture content, making this step in the supply chain highly dependent on techniques used for grinding and storage.

Comminuted wood handling systems are highly variable and include screw augers, bucket conveyors, and pneumatic systems (Badger 2002). Most loading systems utilize an articulating arm with a grapple to feed slash into the grinder. A conveyer moves ground material directly from the grinder to the transportation device.

In delivery of wood chips to the refinery, large volume users of wood chips use hydraulic dumpers that lift and tilt whole trucks as in Figure 20. These systems can empty a semi-trailer in 3–5 minutes (Badger, 2002). Intermediate scale facilities may use semi-trailer dumping systems that require the trailer to be uncoupled from the truck. This process is more time consuming than whole truck dumpers. Smaller-scale facilities may utilize walking bed trailers that can unload in about 10 minutes. These facilities may also use small dump trucks for short hauls or unload a standard semi-trailer with a small, skid-steer-type, front-end loader (Badger, 2002).

Figure 20. Unloading wood chips at a processing facility with a semi-truck hydraulic dumper (National Renewable Energy Laboratory).

3.5 STORAGE AND QUEUING

Some areas of the country can harvest woody biomass year around, and long-term storage is not necessary. However, in other areas the supply and demand of woody biomass for ethanol production will be, at times, in an unbalanced state due to seasonal variations. In these locations, storage for a one to six month supply of biomass will be required. Storing clean chips (from delimbed and debarked trees) in large piles is standard practice in the pulp and paper industry. Storage of woody biomass when production exceeds demand is desirable for biorefineries, in that it provides a constant feedstock supply. Storage also offers an important advantage for suppliers. Adding this material buffer minimizes the strain on harvesting and transportation systems (Andersson, et al., 2002). This eliminates any need for overtime labor charges and reduces the risks associated with production halts due to equipment problems or severe weather events. Also, if stored properly, biomass dries while in storage which may increase its value.

A significant disadvantage for suppliers in developing storage systems is the high costs of building storage structures. DOE estimates that full-size lignocellulosic plants will process 635 tonnes (700 tons) per day of dry material. A minimum 10-day supply in a queuing pile at such a refinery would contain 6,300 tonnes (7,000 tons). This would require a storage yard of at least 4,400 m^2 (47,361 ft^2), assuming a maximum height of 10 m (32.8 ft).

Also, depending on the condition of the chips and the ambient environment, there is significant potential for material degradation during storage. Nurmi (1999) observed dry matter losses and increases in moisture content of wood chips stored for 1 year. This led to a recommendation that comminuted material be utilized as quickly as possible after grinding to minimize dry matter losses (Nurmi, 1999). Furthermore, whole tree chips (chips containing a large proportion of leaves and bark) have a propensity to self heat. Piles of such chips at industrial facilities have been known to cause fires (Springer 1979). Chips with a moisture content of greater than about 24% will self heat when placed in large piles, but this can be mitigated by keeping pile heights under 9 m (30 ft) and/or limiting the amount of time the chips are in the pile to less than 10 days (Garstang et al. 2002).

Fungi and bacteria begin to grow as soon as a pile of wood chips is formed (Andersson, et al., 2002). The microbial growth rate depends on temperature, moisture content, particle size, and composition. External factors such as the size of the pile and duration of storage also affect the growth rate. The particular microbes that tend to colonize wood chip piles do not have a significant effect on dry matter loss. However, they do produce microspores that can cause respiratory problems when inhaled (Andersson, et al., 2002). Microbial growth is typically slow in freshly harvested biomass because the temperature is low enough to inhibit growth. But, higher temperatures caused by heating in large wood chip piles favor rapid growth of fungi and bacteria. Handling uncomminuted material poses less health risk because fungal growth is much less than in chipped fuel.

Figure 21. Piles of wood chips to be used for energy. Piling wood chips is an easy, convenient method of storage, but piles should be designed to minimize self-heating, dry matter losses, and microbial growth (National Renewable Energy Laboratory).

Whole tree chips for energy, that must be stored more than 10 days, may need some form of treatment in order to avoid degradation and/or spontaneous combustion. At present, drying to less than 20% moisture is the only viable option for safe, long-term storage of whole wood chips. Clearly, drying the fuel will be an added expense, and dried fuel will need to be protected from rain with a shelter or covering. However, depending on the conversion technology to be employed, drier fuels may be worth the additional expense of drying. Some conversion technologies can operate at higher capacity and have higher efficiencies if the biomass is dry.

3.6 SPECIALIZED SLASH HARVEST AND COLLECTION SYSTEMS EQUIPMENT

Slash materials are typically less than a quarter of the density of solid wood (McDonald and Seixas 1997). Handling this low-density, low-value material reduces the productivity of all handling operations (hauling, skidding, and loading). Currently, the least costly method of harvest and collection of forest residue for biomass is in-woods comminution as part of conventional logging or thinning (Rummer 2004). Comminution operations are most efficient in situations where logs are extracted by skidding, the site has good road access, and there are large volumes of biomass per acre. Many sites where biomass could be recovered do not meet these criteria, and so to cost effectively recover biomass from most fuel reduction and forest health treatments, alternatives to in-woods chipping are needed. Improved methods of densification and/or transportation of woody residues would make biomass collection more feasible. Two recent technology developments to potentially reduce collection and handling costs are 1) specialized containers, 2) combined harvester/grinder, and 3) bundling/baling.

3.6.1 Slash Containers for Remote Landings

Currently, the most common method of slash harvest is in-forest chipping and loading into a chip van for transportation. Two problems with this method increase cost: (1) Chip vans are not made to access remote sites, and (2) the grinder has to be moved to the slash piles, slowing the chipping process (Rawlings, et al., 2004). Roll on/off containers are an alternative to transporting slash from the forest to the landing. Slash is loaded into the roll on/off container in the forest. When full, the containers are hauled to a centralized landing where a chipper has been stationed. Comminuted material is loaded into a chip van for over-the-road transport to the user facility. This method of slash handling is described in detail by Rawlings et al. (2004). Several roll on/off containers can be hauled to remote sites and dropped off. Leaving the containers on site improves system efficiency since fewer trucks are needed and those trucks being used can operate continuously rather than spend time waiting to be filled. Slash is fed into a grinder and then deposited directly into the containers. Full containers are picked up and brought to an area accessible by the chip van. This method allows much more slash to be accessed and keeps the grinder operating much of the time.

Figure 22. Transportation methods for wood chips. Chips can be loaded into (left) roll on/off chip containers in the forest for transport to the landing. From there, they can be hauled in (right) large capacity chip vans to the end user (Montana Community Development Corporation).

3.6.2 Integrated Harvester/Grinder

As previously discussed, comminution increases biomass bulk density, thereby decreasing transportation costs. An experimental approach to improving operation efficiency is to move comminution as far forward in the process as possible. A Finnish company has developed a forwarder/harvester with a grinder and chip container mounted on it for comminution at the stump (Figure 23). This machine (Valmet 801 Combi BioEnergy - http://www.biologistiikka.fi/index.html) is best suited for thinning operations. A single machine and the associated support equipment can manage about 283 hectares (700 acres) of small diameter trees.

Figure 23. A new, novel machine that integrates harvesting and grinding. The new Valmet 801 Combi BioEnergy system thins and chips hog fuel. It is also capable of delimbing and bucking smaller timber suitable for pulp and posts. The small size and capacities of this machine limit its productivity on many sites (Komatsu Forest).

3.6.3 Bundling and Baling

The costs of transporting low-density forest residues generated during integrated harvesting and forest thinning operations can inhibit their use as an energy feedstock. Bundling technologies have been developed in recent years by several forestry equipment manufacturers as alternatives to hauling loose forest residues or in-woods chipping. Slash bundles (also called composite residue logs, or CRLs) are considerably denser than loose residues making them less expensive to transport. Also, slash bundles are not as susceptible to dry matter loss and self-heating; thus, they can be stored until needed. Slash bundles are shaped and sized like typical logs and can be handled as such with existing equipment. Only simple modifications are needed to integrate slash bundles into existing logging operations. The primary consideration should be to cover loaded trucks to prevent loose material from coming dislodged during road travel (Cuchet et al. 2004).

John Deere is currently the only U.S. manufacturer of slash bundling machines (John Deere 1490D, formerly TimberJack 1490D). The John Deere 1490D is shown in Figure 24, left. Other manufacturers include World Wood Pac (Sweden) and Pinox Oy (Finland). The John Deere 1490D was first introduced in the U.S. in 2003 by TimberJack (acquired by John Deere in 2005). In 2004, it was estimated that 25 TimberJack 1490D slash bundlers were in operation in Finland and another 10 units in Sweden, the Czech Republic, Switzerland, France, Italy, Spain, and the U.S. (Karha and Vartiamaki 2006). The 1490D, based on an 8-wheeled TimberJack forwarder, features a bundling unit mounted on the rear frame that can be rotated right to left to pick up slash from either side of the road (Rummer, et al., 2004). The operator loads residue into the infeed deck with the crane. A pair of hydraulic rollers pulls the residue into the bundler cage where the material is compressed and slid through. At the outlet end, the bundle is wrapped and tied with sisal or polypropylene twine. The continuous procedure is halted momentarily while a “log” of specified length is cut. Slash logs are typically 3 m (~ 10 ft) long and about 60–80 cm (24–31.5 in.) in diameter (Packalen 2006). In a clear cut operation, the manufacturer estimates that, on average, 60 slash logs per acre can be produced. Actual collection rate will vary significantly with terrain and tree density.

Figure 24. Bundling logging residue. A (left) John Deere 1490D bundles logging residue which can then be (right) handled like logs at the landing.

Although, to the authors' knowledge, in 2007 there was only one John Deere bundler in operation in the U.S., bundling has been shown in a number of studies to be a promising technology for collecting forest residues ((Johansson et al. 2006), (Karha and Vartiamaki 2006), Rummer, et al., 2004,(Saarenmaa 2005). However, several areas of additional research and development are needed to improve its efficiency before widespread adoption of this technology will occur. Rummer et al. (2004) predicts that the additional cost of the bundler machine would make collecting forest residues cost prohibitive. However, they point out that if the value of bundling the residue for removal to aid forest management is considered (as opposed to burning, for example) bundling may be cost effective. Similarly, Karha and Vartiamaki (2006) concluded that although the costs of bundling collection systems currently exceed collection of loose residues or roadside chipping, if the costs of bundling can be optimized, bundling supply chains would be extremely cost competitive. Factors that have been shown to affect bundling performance are operator skill, slash density, and layout. As might be expected, the operator work method and experience are the primary factors in bundling productivity. In an efficient operation, over 50% of the total bundler work time should be spent loading residues (Karha and Vartiamaki, 2006). As bundling technology develops and becomes more widely adopted, worker competencies in operating bundlers will also increase. Another critical factor in bundling performance is the slash density and layout. Slash should be piled to one side of the road (Karha and Vartiamaki, 2006) in large piles containing at least 136 bone dry kg (300 bone dry lbs) (a full grapple load) (Rummer, et al., 2004). Bundling is most cost effective in areas with large amounts of logging residues.

There is concern among some that removing forest residues is not environmentally sustainable. In cut-to-length operations, residues are left in the path of the harvester to minimize soil disturbance and add nutrients to the soil. Slash bundling may not negate these beneficial effects as much as might be expected. In the study performed by Cuchet et al. (2004) only a portion of the logging residues were removed by bundling operations, leaving 50% or more for soil protection.

As the demand for energy wood increases, new residue packaging technologies, in addition to the slash bundlers currently on the market, will likely be developed. Forest Concepts, LLC of Auburn, Washington, is developing a prototype square baler, essentially a modified recycling baler, for woody biomass (Dooley et al. 2006). Preliminary tests show that the square bale concept can significantly reduce transportation costs for woody residues from forest thinnings and urban tree waste. The square bales can be hauled on typical flatbed trailers making them easy to transport via highway from the landing to the end user. A small, portable baler is especially promising for small logging or foresting thinning operations and for urban or residential areas that do not produce enough wood residues to justify purchase of a mobile slash bundler.

4. FUTURE DIRECTIONS

Currently, logging operations are designed to efficiently obtain merchantable lumber and not to gather and haul wood residues. However, new national initiatives to increase production of renewable fuels will greatly enhance the market for woody biomass. With this developing market, implementing new equipment and techniques to efficiently collect and process slash could be worthwhile for many timber operations. The uniform format concept was developed in recent years for agricultural residues to describe supply chain operations that lead to consistent, quality feedstocks for biorefineries. The following discussion addresses the technology and research path toward development of a uniform feedstock supply system design and improved feedstock logistics for forest resources.

4.1 TOWARD THE UNIFORM FORMAT CONCEPT

Within the report, *Lignocellulosic Biomass to Ethanol Feedstock Supply System Design and Economics for Herbaceous Biomass* (Hess et al., 2007), the challenges in developing feedstock supply systems are identified as (1) developing a uniform feedstock format supply system that connects the diversity of cellulosic feedstocks to a standardized feedstock supply system infrastructure and biorefinery conversion processes and (2) improving feedstock logistics, specifically the efficiency and capacity of feedstock supply systems.

The basis for a uniform format lignocellulosic biomass feedstock supply system design is presented in Hess et al. (2007). The uniform supply system concept considers all supply system elements from unharvested biomass to the point of insertion into the conversion process reactor. Within the uniform format system, feedstock diversity is handled as near to the point of harvest as feasibly possible (see Figures 25 and 26). This design concept models that of the current grain supply system, where crop diversity is managed at harvest allowing all subsequent feedstock supply system infrastructure to be similar for all biomass resources. The ability to standardize infrastructure is the key component in facilitating a true commodity system for lignocellulosic biomass.

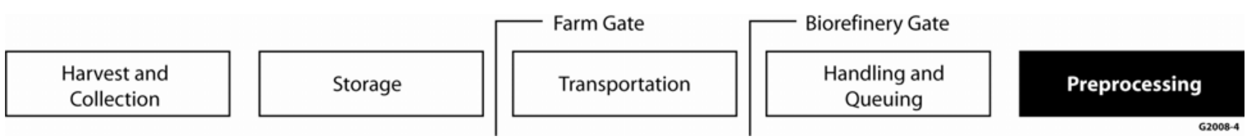

Figure 25. Pioneer supply system structure.

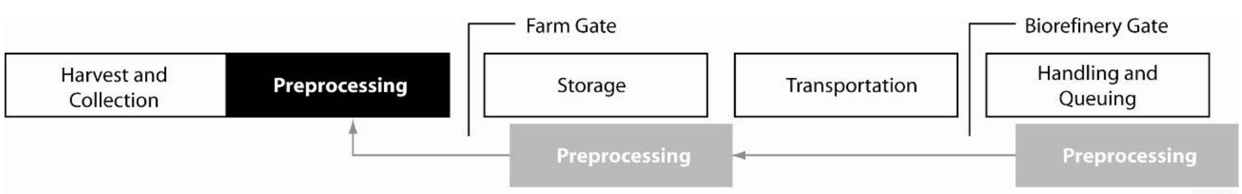

Figure 26. Uniform format supply system structure.

Forest resources represent significant diversity in terms of biomass characteristics and also the geography of resource locations. These factors create unique challenges in developing viable forest resource supply system designs. As mentioned previously, functional equipment and systems exist that are capable of capturing a wide range of forest resources across numerous physical terrains for use in the biorefining industry, but several constraining factors currently limit the large-scale implementation of the existing equipment and systems for application in an emerging biomass-to-biofuels market. These factors include the following:

- The operational economics, including equipment capacity, efficiency, etc., are unfavorable
- A high degree of specialization leads to high overhead and limited use case scenarios
- Multiple unit operations are necessary, which negatively impacts system efficiencies.

Focusing future technology development and research efforts on building a forest resource supply system design within the uniform format feedstock supply system concept is the key to addressing these constraints.

4.2 DEVELOPMENTS IN TECHNOLOGY AND LOGISTICS

Some major technology developments have been seen in recent years to improve the feasibility of collecting forest residues (see Section 3.6). However, more improvements in technology and logistics are needed to see the realization of a uniform format woody biomass supply system.

4.2.1 Harvest and Collection Systems

The primary technology development needs for forest resource supply systems in support of the uniform format supply system concept are in harvest and collection. Harvest and collection systems for forest resources are already constrained in their operating parameters due to the multiplicity of forest resource feedstocks and the significant variation in terrain where these resources are located. As discussed previously, there are systems being developed and used that attempt to take advantage of the inherent benefits of a uniform format supply system through the integration of unit operations (e.g., Valmet 801 Bioenergy). The challenge is then to design equipment and systems that facilitate this integration within an operational framework robust enough to handle the variations associated with forest resources, while satisfying economic, efficiency, and capacity requirements.

Specifically, the following improvements in woody biomass harvesting technology would be valuable:

- Feller-bunchers and forwarders optimized for small diameter wood harvest
- Delimbers capable of feeding limbs and tops to a grinder
- Guidelines for configuring and locating landings to facilitate economical slash collection and grinding
- Specialized, integrated harvest equipment for slash collection and densification.

4.2.2 Integrated Preprocessing and Transportation

The integration of multiple unit operations to produce a low-cost product requires the development of robust models that accurately predict the consequences of unit-operation changes and the effect on other parts of the chain. Comminution of woody biomass is a form of preprocessing that improves handling, facilitates drying, and may lead to fractionation of the material. Woody tissues have different concentrations of elements and molecular constituents that impact potential conversion technologies. Separation of these fractions can increase the quality factors identified by the end user resulting in feedstocks that are tailored to a particular platform and increasing the value of the feedstock. Development of forest harvesting equipment that more efficiently integrates the harvest of both merchandisable timber and timber residues is needed. Additionally, equipment dedicated to the removal and collection of non-merchantable timber may be necessary in order to economically access the biomass resource.

The following transportation and preprocessing improvements would be quite beneficial to slash collection operations**:**

- Improve slash container handling characteristics and capacities
- Develop improved transportation of slash to centralized grinding location (conveyor systems, pneumatic systems, etc.)
- Develop trailers that facilitate drying of biomass during transit
- Optimize grinders for slash comminution
- Develop grinders that remove more moisture from the material.

4.2.3 Logistics

Forestry operations require large, expensive equipment. Thus, an important step in reducing costs is optimal utilization of this equipment. In developing a slash collection operation, several important, interrelated decisions must be made, which require a good understanding of equipment performance when harvesting and handling woody biomass. Contractors need better production rate information for equipment used in residue recovery in order to balance their operations (Mitchell 2005). Because equipment performance is influenced by moisture content, site characteristics, tree species, and the makeup of biomass (wood or foliage), ranges of production rates for various situations are needed.

More field-scale research is needed to fully explore ways that the woody biomass supply chain can be organized to reduce costs. For example, it was noted in Section 3.2.1 that Naimi et al. (2006) concluded in their research that two stages of grinding with different equipment may be needed to achieve the desirable particle size. Would it be cost effective to perform the first stage in the forest or landing and the final stage at the processing facility?

4.2.4 Environmental Impacts

Investigation of the environmental impacts of slash removal is another important future research direction needed to build the woody biomass market. Environmental impacts of removing forest residues will influence landowner decisions, policy development, and industry sustainability. The long-term effects of removing slash on soil nutrient dynamics, soil compaction, wildlife habitats, and water quality should be studied for various topographies and soil types across the U.S.

Slash removal is already known to have a significant impact on the state of the forest soil. Belleau et al. (2006) found that the amount of slash left on the forest floor was the main factor in determining soil nutrient dynamics. They found that slash increased soil acidity and improved cation availability. The presence of slash also affects soil compaction. McDonald and Seixas (1997) compared soil compaction caused by a forwarder when the slash density was 0, 10, and 20 kg m^{-2} in dry and wet soils. They found that the presence of slash did reduce soil compaction, particularly in drier soils, but the density of the slash had little to no effect. This seems to indicate that management practices could be developed in which a portion of the slash is left in the forest to improve soil quality while the rest is recovered for energy. More research is needed to further quantify these effects and develop forest residue collection best management practices.

New or modified equipment may also be developed to reduce environmental impacts of removing logging residues. (Gullberg and Johansson 2006) developed a modified grapple with a scarifying device attached. As the grapple picked up residues it also scarified the soil. Scarification aerates the soil and aids tree sprouting.

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