14

Woody Biomass Logistics

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14.1 Introduction

The economics of using woody biomass as a fuel or feedstock for bioenergy applications is often driven by logistical considerations. Depending on the source of the woody biomass, the acquisition cost of the material is often quite low, sometimes near zero. However, the cost of harvesting, collection, processing, storage, and transportation from the harvest site to end users can be quite expensive. In many cases, the combined cost of logistics will exceed the delivered value of the resource by a substantial margin. Therefore, it is highly important to the economic success of any bioenergy project that the logistics of bringing the woody biomass to the consuming facility be optimized to the greatest extent possible.

Optimizing the logistics for woody biomass fuels and feedstocks can best be accomplished in the planning stages of the project. If the consuming facility is improperly located with respect to the geographic distribution of the woody biomass resource, the project will likely suffer a continuing economic burden in the form of excessive transportation costs. Furthermore, the design of any woody biomass-consuming operation is generally best served by providing for as much feedstock flexibility as the operation's core conversion technology permits. That is to say that a wider range of feedstock species, form, particle size, ash content, and moisture content will be preferable from an economic standpoint. Increased feedstock flexibility expands the usable resource base, which in turn will serve to reduce risk and uncertainty in feedstock supply. Diversified feedstock supply chains may also reduce procurement costs by avoiding competition for biomass with other users, such

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as pulp mills and pellet manufacturers. Investments at the consuming facility in storing, processing and drying the woody biomass to the extent required by the conversion technology can offset the logistical disadvantage of performing these functions in the field.

14.2 Overview of the Woody Biomass Supply Chain

The woody biomass supply chain varies by region and land ownership type. The primary sources of woody biomass are federal, industrial, state, and private forests managed for a variety of objectives. Ownership and management objectives affect the availability, volume, and quality of biomass harvested, as do forest age, the type of woody biomass being harvested, tree species present in the forest, and the type of harvesting system. For example, short-rotation hybrid poplar energy crops, pre-commercial thinnings in pine plantations, wood utilized from fuels-reduction treatments to reduce the risk of catastrophic wildfires, and logging residues from industrial silviculture all produce different yields and quality of woody biomass. Moreover, the details of the supply chain depend heavily upon the material specifications of the final, delivered product for a particular end use or conversion process. For example, some drop-in liquid biofuel conversion processes that rely on digestion are well suited for delivery of high moisture content materials, while other processes, such as densification to pellets or briquettes, may require both low ash content (e.g., $<1\%$) and low moisture content (e.g., $<12\%$). Thus, to some extent, the specifications of the end product dictate the nature of the supply chain, including: (1) the characteristics of the raw material, (2) the number and types of preprocessing steps required to meet feedstock specifications, (3) the cost effectiveness of alternative transportation modes, and (4) the area of the procurement region needed to supply the facility.

14.2.1 Sources and Scale of Temporal Variability

The theoretical temporal variability associated with three biomass supply options is shown in Figure 14.1, representing conversion to densified biomass from multiple rotations of a dedicated short-rotation woody crop, two intermediate thinnings from a stand grown primarily for sawlog production, and logging residues utilized only during final harvest in a sawlog production system.

From Figure 14.1, it should be evident that there is an interaction of temporal and spatial variability at play in utilizing woody biomass from forestry activities that may be less relevant for agricultural crops. In particular, woody biomass from stand thinning operations and logging residues from an intermediate or final harvest may be spaced as much as an entire rotation length (25–100 years) apart at any fixed point on the landscape. Thus, in order for woody materials from logging residues to adequately supply annual demand for a depot or conversion facility, spatial rotation of management activities between the stands that make up an estate ownership or management area is needed. Accurate characterization of the frequency of treatments performed, types of woody biomass available, spatial pattern, and transportation network associated with projected annual utilization within a draw region is critical for long-term supply planning.

Two common ways to manage long-term supply planning in well-regulated, managed forests are *area control* and *volume control*. Strict area or volume control are most easily applied in even-aged silvicultural systems growing a single cohort of trees from the

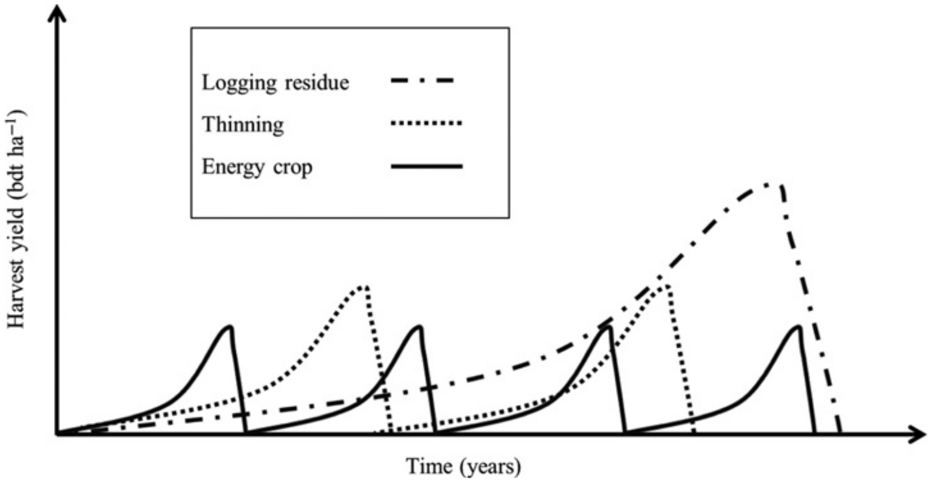

Figure 14.1 *Comparative relationship between harvest yield and time for three different woody biomass sources.*

regeneration phase to final harvest, it is the harvesting of the primary sawlog crops that result in logging residues utilized for woody biomass. Area control is realized when, for a given estate area of size A hectares and a stand rotation length of N years, A/N hectares are harvested each year. *Volume control* refers to the case in which a fixed target sawlog volume, (V + G)/N, is harvested over the rotation length, N, from all standing timber volume (V) plus growth (G) over that time period. For example, in the inland northwestern United States, it is assumed that the yield of useable woody biomass from terminal harvest logging residues falls between 0.5 and 1.5 bone dry tons (BDT) per 1000 US board feet, or 2.4 m^3, of sawtimber volume. Depending on regional variability, a typical mature stand might have between 15 000 and 25 000 U.S. board feet (15–25 MBF) per acre (0.4 ha) or more. At moderate residue concentration, in a productive and mature stand in the inland northwest, approximately 25 BDT of logging residues might be available for every 0.4 hectares of sawlog volume harvested, or 61.75 BDT per hectare. Thus, yields from harvesting potential available woody biomass are considerably larger, more spatially variable, and less frequent than yields from agricultural crops on a per unit area basis.

14.2.2 Preprocessing in the Woody Biomass Supply Chain

As will be evident in Section 14.4, there are a large number of established and emerging equipment options for harvesting and in-woods preprocessing of woody biomass. The level of preprocessing that occurs and the point at which it occurs in the supply chain have important impacts on supply chain efficiency because transportation costs, whether from stump to landing, landing to depot, or over long distances by rail or barge, are affected by the energy and mass density of the material. In general, supply chains that reduce the particle size, ash content, and moisture content of woody biomass close to the harvest location have the greatest transportation efficiency. This is because more densely packed densified, dried biomass contains the highest energy content per unit volume or mass (BTUs m^{-3}, BTU ton^{-1}). To address this characteristic of the woody supply chain, a number of specialized harvesters and forwarders have evolved that process, comminute, and densify biomass in the woods, immediately after harvest, to varying degrees. These include, for example, slash bundler forwarders, self-feeding chipper-forwarders, and even mobile depot units that dry, grind, and densify regional woody biomass supply at tactical scales (e.g., 3–4 years within a draw area) before moving to another location. Some of the more common harvesting and combined harvesting and processing equipment types currently available are described briefly and generally in Section 14.6.

Most woody biomass currently used or being actively studied in the context of biofuels and bioenergy development is derived from three major source categories: dedicated short-rotation woody crops (SRWCs), thinning materials, and logging residues.

14.3 Woody Biomass from Dedicated Energy Crops

Woody biomass from purpose-grown energy crops offers the opportunity to positively affect logistics costs in several ways. One of the most obvious is the opportunity to reduce transportation costs by geographically concentrating the source of the material, in the form of plantations, close to the consuming facility. Secondly, and even more impactful, would be the higher productivity of the energy plantations versus wood derived from natural stands. Producing more biomass per acre means less acres required to sustain operations, resulting in shorter haul distances for the woody biomass fuel or feedstock. Therefore, it can be seen that highly-productive energy plantations, grown in close proximity to the consuming bioenergy facility, offer an excellent opportunity to minimize the logistical complexity and cost of sourcing the woody fuel or feedstock.

Dedicated woody energy crops currently represent only a minor source of biomass for energy, although it is expected that energy plantations will become an increasingly important source in the future. Harvesting systems for woody biomass from energy plantations remain somewhat developmental and will need to be adapted to the specifics of the regime being considered. Specifically, the number of stems, spacing and tree size are important determinants of feasible harvesting solutions, production, and costs.

Short-rotation woody energy crops from genera such as the willows (*Salix* sp.), pines (*Pinus* sp.), poplar (*Populus* sp.) and Eucalyptus (*Eucalyptus* sp.) provide important SRWC crops. SWRC crops differ from pulp or sawlog stand thinnings and logging residues as biomass sources in that the sole purpose of intensive energy crop plantations is biomass production. By contrast, thinning materials and logging residues from silvicultural treatments in forestry are a secondary product, after sawlogs or pulp. Poplar energy wood crop rotations are short, from 7 to 15 years [1], and stands are established primarily through cuttings. Willow rotations may be even shorter (3–4 years). Because poplar and willows can also be regenerated well in coppice systems, coppice regeneration systems can also be deployed for both crops. Coppice systems are those in which stump sprouts or "suckers" re-sprout from stumps to establish the new stand of woody crop following harvest.

The systematic row-crop spatial location and small diameter of short rotation woody energy crops are conducive to agriculture-style harvesting with short-rotation woody harvesters. These purpose-built machines are forage harvesters with harvesting heads that can handle woody stems, typically less than 5 inches (12.7 cm) in diameter at breast height (DBH). A major advantage of using short rotation woody harvesters is that the resulting material delivered to roadside is a chip that is ready for transport without further preprocessing, that is, a single pass system. A further advantage of short rotation woody crop harvesters over the equivalent, conventional timber harvesting equipment (e.g., small excavators with harvester heads), is that they are able to conduct continuous travel harvesting, rather than stop-and-go felling of individual stems [2].

Although dedicated SRWC harvesters are the most promising emerging modern equipment for woody energy crops, a variety of conventional logging equipment has been evaluated in the context of woody biomass. Feller-bunchers and single-grip harvesters designed for sawlog production have been evaluated, as have a variety of forwarding systems. Mobile harvester-chipper-forwarders with knuckleboom harvester arms, chipper-forwarders, slash forwarders, slash compactors, and slash bundlers all have potential use with short-rotation crops. However, these systems tend to have either lower overall hourly production or higher hourly logging costs compared to modified swath harvesters because they require multi-stage processing. The many harvester-chipper-forwarders now available for woody biomass tend to be designed for larger diameter stems than are achieved in short rotation crops, and are better designed for intermediate thinning treatments in stands being grown for pulp or sawlog production. Unlike SWRC harvesters that have evolved from forage harvesters, the harvester-chipper-forwarder style machines tend to be designed for single approach harvest. That is, they have a harvester head mounted on a knuckleboom arm that is used to fell one or more stems, and the stems or bunch of stems are fed into the conveyor-feed mouth of an internal chipper. They are not able to perform continuous travel harvesting, but instead must stop intermittently.

14.4 Woody Biomass from Stand Thinning

In contrast to SRWC biomass, woody biomass from stand thinning is obtained from intermediate treatments in forest stands managed for sawlog or pulp production, or managed for non-market values like recreation and wildlife habitat that may be enhanced or protected by thinning treatments. In forestry, thinning operations are partitioned into *pre-commercial* and *commercial* thinning. Pre-commercial thinning incurs a cost, typically requiring investment of \$100–150/acre (\$247–371/ha), but generally results in better growth and higher production for the stand over the rotation. In addition, pre-commercial thinning is often used to reduce fire risk or manage insects and disease, regardless of impacts on long-term commercial output. Commercial thinning treatments are deployed in even-aged silvicultural systems, when feasible, 10–20 years before a terminal harvest. At this point in stand growth, stems are large enough to yield at least one small diameter sawlog, and revenue from the sale of merchantable sawtimber outweighs the logging costs associated with operations. At some critical threshold price, or under certain financial incentives, markets for woody biomass may help to further offset logging costs and help to make commercial thinning financially viable in stands where it otherwise might not be through supplemental revenue.

A number of supply chain pathways have been explored for thinning materials to be used for biofuels or bioenergy that are low in both ash and moisture content. In southern pine plantations, thinned stems are typically harvested with wheeled feller-bunchers that are able to proceed through plantation rows in alternating fashion, removing a stem from the left, then one from the right, and so forth. Pre-bunched stems may then be collected by a grapple skidder or forwarder. Or, in order to reduce the moisture content of stems for subsequent processing, pre-bunched stems may undergo in-woods drying before being removed for processing. Efforts to reduce the ash content of woody materials from thinning operations have evaluated extraction methods that fully support stems using forwarders or wheeled loaders, minimizing dragging and resulting soil contamination associated with grapple skidding.

In the western United States, a major potential source of biomass is thinning materials removed from fuel treatment operations on national forests. Frequently these types of treatments result in net costs, with relatively low value material removed from treatment units. Recent analysis of U.S. national Forest Inventory and Analysis data [3] using the BioSum model has shown that fuel treatment costs in the western United States range from very moderate (e.g., \$100/acre) to infeasible (>\$10 000/acre) on the landscape, depending on logging system used, topography, and transportation distance to utilization facilities. Remote stands on steep slopes that require cable logging or specialized equipment for treatment tend to be prohibitively expensive to treat.

14.5 Logging Residues

In most cases, woody biomass derived from the forest for energy applications today comes from either roundwood timber or forest residues recovered in conjunction with conventional harvesting activities. Certain bioenergy applications, including energy pellets, require or prefer clean fiber feedstock with very low bark content and soil contamination, which results in low ash content of the final product. Also, certain biofuel conversion technologies, specifically certain biochemical platforms, are best adapted to narrowly specified clean fiber feedstocks, often of a single species or species group. When clean fiber is required, conventional harvesting and debarking systems for pulpwood and other small diameter timber are commonly employed. These could include conventional longwood systems for delivering tree-length material to the conversion facility or in-woods chipping operations. In the former case, the timber would typically be debarked and chipped at the conversion facility. In the latter case, debarking would occur in the forest, usually by means of a flail debarking system, close-coupled to the chipper. In this case, clean chips are normally blown directly from the chipper outfeed into a chip van for delivery to the plant.

Logistics associated with utilizing woody biomass from slash, tops, and unmerchantable stem portions produced as a by-product of logging operations depend on the type of harvesting method used. The majority of logging in North America uses ground-based harvesting systems, with a variety of skidder or forwarder types. However, on steep slopes (>40%), cable logging is required. Industrial forest ownerships in the western United States and Canada most commonly require a mix of ground-based and cable logging. The difference in systems has important implications for the cost of extracting woody biomass. In general, cable logging operations are both more expensive and less productive than ground-based logging operations. Landing sizes tend to be smaller due to the steep terrain, and logging roads are more difficult to navigate with conventional chip trailers. In particular, curve radii engineered for conventional log trucks in the western United States may not be suitable for possum-belly chip trailers. A variety of emerging options to productively transport biomass on low volume forest road networks designed for roundwood transport are described in Section 14.7. In this environment, it is rarely cost effective to handle logging residues using cable systems.

14.5.1 Whole Tree Versus Cut-to-Length

As mentioned in the previous section, the distinction between cable and ground-based logging affects the production rate and cost of woody biomass utilization from logging residues. Within ground-based systems, feasibility of biomass extraction, production rates, and costs are further affected by the type of harvest and processing system in use. Whole tree harvesting that involves felling of stems with a feller-buncher, followed by grapple skidding or shovel logging to forward whole trees (including branches and tops) to roadside or a centralized landing, is, by design, paired with a processing method that accumulates loose woody biomass at the roadside. Processing with a grinder or chipper step at a landing or a concentration yard is then required, prior to subsequent transport. By contrast, in cut-to-length harvesting systems, stems are bucked into sawlogs in the woods by a feller-processor that delimbs and tops trees immediately after felling, at the location of the stump. Piled sawlogs are loaded by a log forwarder, which advances them to the landing. This process leaves the majority of logging residue in the woods following the initial harvesting and processing step (Figure 14.2), and thus requires an additional, separate slash bundler, slash forwarder, chipper-forwarder, or other equipment option to collect and move slash to the roadside. If slash is forwarded without processing, or is bundled and compressed for forwarding, it must then be ground or chipped at the roadside, a landing, or a concentration yard before transport. Figure 14.3 shows a small number of the many possible systems and equipment configurations available for moving logging slash from the woods to a conversion facility in whole tree and cut-to-length harvesting operations. From the figure, it is evident that there are various points at which comminution may occur, and the number of pieces of equipment that handle materials along the supply chain can range from very few to very many (Figure 14.4).

Figure 14.2 *Logging residue piled by an excavator. (Photo: © Keefe, 2013).*

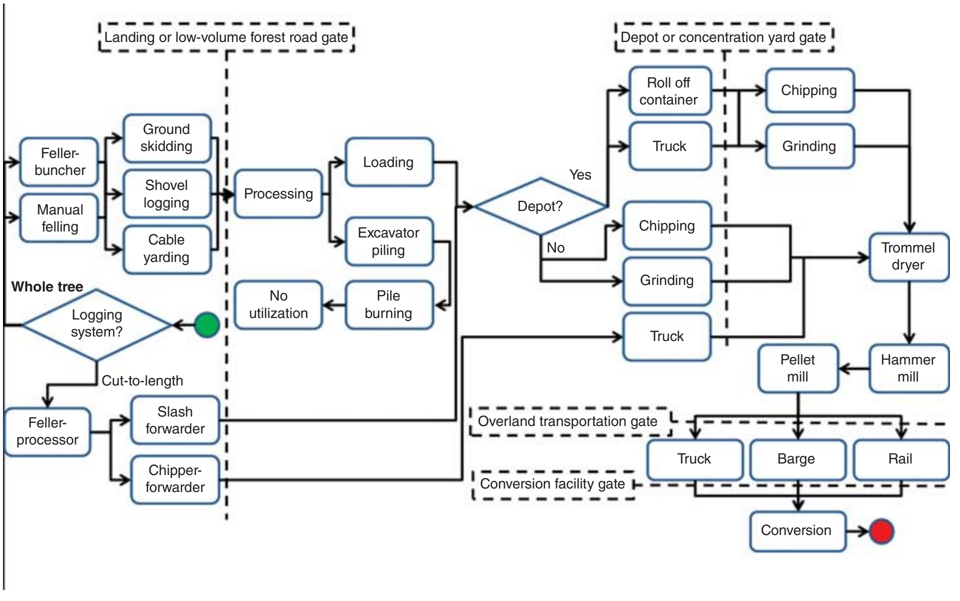

Figure 14.3 *Some examples of possible primary woody biomass supply chain alternatives for logging residues from conventional whole tree and cut-to-length mechanized industrial logging operations with a single, localized concentration yard and a depot to densify uniform feedstock woody biomass.*

Figure 14.4 *An end dump semi-trailer used to haul slash to a concentration yard. (Photo: © Anderson, 2013).*

When in-woods residues are collected by a self-feeding chipper-forwarder, then, depending on the system, they may be off-loaded directly from the chipper-forwarder to a chip van for subsequent transport. Open top 'roll-off' and hook lift containers are another useful option for advancing loose logging residues, either as a forwarder to advance residues to the roadside in cut-to-length operations, or to advance residues from the roadside to centralized concentration depots in whole-tree harvesting. Following a grinding or chipping step at the roadside or concentration depot, chips or hog fuel may be conveyed directly onto a chip trailer for transport to a processing facility (as part of the step, e.g., via equipment outfeed), or it may be piled and loaded at a later time. For example, a large chip trucking contractor in Idaho has developed specialized, large capacity wheel loader buckets for loading hog fuel onto chip trucks with higher production rates than could be achieved with a conventional loader.

14.5.2 Effect of Source on Feedstock Quality

Because logging residues are often laid or piled on disturbed, exposed soil during harvesting and processing, either in-woods or at the roadside, and may also be dragged along skid trails during extraction, the ash content tends to be high and affects the quality and value of this feedstock source. It is especially important that machine operators know if logging residues are going to be used as biomass rather than burned for disposal because they can work to minimize contamination in piling, especially on the landing. A number of post-harvest methods for reducing ash content in order to meet quality specifications of different biofuel and bioenergy processes exist. The most common methods are: (1) using rotary trommel screens to reduce the percentage of fine, inorganic materials that damage mill dies and increase ash content, and (2) downstream blending of feedstock from different material sources to meet quality specification standards. For example, if ash content of a residue feedstock is 5% and needs to be at or below 2% ash to meet quality specs for a particular conversion process, blending of 20% logging residue with 80% cleaner feedstock (for example, a one-pass agricultural residue, or clean pulp chips in pre-processing) can achieve a blended fuel with quality specification of 1.8 % ash content, though using higher quality feedstock in blending is likely to drive up costs.

Regulating moisture content of woody biomass feedstock from logging residues is an important research and development area. Depending on the season of the year, local climate, time between harvest and delivery, timing of processing, and species, the moisture content of cut slash and tops may vary from 12 to 50%. High or low moisture content may be desirable in final material specifications, depending on the conversion process. For example, aviation biofuels produced with a wet, thermochemical process are ultimately digested at high moisture content. For this reason, wetting dry feedstocks after transportation may be desirable for some conversion processes. In contrast, densification of uniform feedstock biomass into energy pellets requires dry material. Dried, ground biomass that is stored for subsequent use may actually regain moisture from ambient air prior to conversion, necessitating proper storage. Reduction in moisture content tends to reduce per unit transportation costs for biomass and may increase its value if end users pay for feedstock on a dry basis. From a technical standpoint, developing logistic supply chains that deliver feedstock with appropriate moisture content requires development and validation of predictive models that integrate tree and wood physiology (e.g., evapotranspirative drying as a function of local climate) with forest operations to consistently deliver a final product at required quality standards to meet conversion requirements. However, it may be more economically efficient to meet narrow feedstock specifications by centralized processing and drying at the facility rather than trying to meet them in the field.

14.6 Harvesting and Processing Systems and Equipment

There are a variety of harvesting systems in use in conventional forestry and short-rotation woody crop operations. This section describes the equipment used in conventional sawlog production operations from which thinning or logging residues may be derived, as well as short-rotation woody crop production equipment. When evaluating these equipment options working in sequence in biomass operations, the convention for establishing cost and production rates of equipment most commonly follows traditional *machine rate* methods, in which the hourly costs of equipment ownership and operation are partitioned into fixed and variable costs. Production functions are estimated using regression relationships developed from work sampling and time and motion field studies, with production in volume or mass per hour expressed as a function of stand (e.g., mean tree diameter, species, trees per hectare), site (average slope), equipment (machine payload capacity, horsepower), and operator variables as predictors. Logging costs for alternative supply chain components and equipment combinations are estimated by dividing machine rates, whether individually or summed over several machines, by the total production achieved in a specified time period. The result is cost per volume ($\$ \ m^{-3}$), or cost per unit mass ($\$ \ t^{-1}$). For example, if a feller-buncher has a machine rate cost of US\$140 per hour to own and operate, and averages felling and bunching of 10 cubic meters per hour, then the total logging cost is estimated to be $\$140/10 = \$14 \ m^{-3}$.

14.6.1 Harvesting

Though manual felling has largely been replaced by mechanized harvesting in many regions where gentle topography allows, it is still common on steep slopes in the western United States and other countries with mountainous terrain, where most mechanized single-grip harvesters and feller-bunchers in use are slope-limited (e.g., cannot operate on slopes >45%). Manual felling is also common when residual tree spacing is close enough to limit access and handling by large felling machines, in countries where forest operations are labor intensive rather than capital intensive, and as a component of cut-to-length operations focused on extraction of high value hardwood sawlogs and veneer, where poor bucking decisions can be extremely costly.

14.6.2 Single-Grip Harvesters

Single-grip harvesters ride on tracked, excavator bodies and have a hydraulic arm capable of felling, and usually processing, individual stems. The harvester may have a chainsaw felling head, a disk-like rotary cutting head that is variable speed or continuous (i.e., a “hot saw”). If the harvester is a feller-processor, it acts like a danglehead processor with hydraulic feed rollers that are capable of feeding the entire stem, horizontally, back and forth, in order to delimb the tree and buck it into sawlogs immediately following harvest. Feller-processors are commonly paired with forwarders, a woods machine with a hydraulic loader that carries multiple, fully supported sawlogs on a large trailer, as part of cut-to-length operations.

14.6.3 Feller-Bunchers

Feller-bunchers are similar to single grip-harvesters, but have the additional capacity to hold stems while additional felling cuts are made. The development of hydraulic accumulator arms that act like mechanical fingers on the felling head gives these machines the ability to hold one or more stems in place while a second or third is cut. Furthermore, this gives feller-bunchers the capacity to pre-brunch stems for a skidding or forwarding machine, without stopping harvesting.

14.6.4 Short-Rotation Woody Crop Harvesters

Short rotation woody crop harvesters, also called swath harvesters, are forage harvesters that are modified to harvest small diameter woody energy crops. These machines are typically able to harvest stems less than five inches in diameter. Stems are harvested and chipped, ground, or shredded, and fed through an auger to a trailer that is either pulled by the harvester or pulled by a second tractor driving in parallel.

14.6.5 Ground-Based Skidding and Forwarding

There are a variety of types of skidding and forwarding machines used to move whole trees, slash, or chips from the woods to a landing or roadside location in forestry. In the subsequent sections, traditional ground-based skidding and forwarding equipment types are described briefly, as are some specialized forwarders for woody biomass.

Ground-based log skidders may be tracked or wheeled machines. Log skidders are capable of working on moderate slopes (<40%) and may be configured as either cable or grapple skidders. Cable skidders have a large hydraulic winch on the back, which log ‘chokers’ are attached to, allowing multiple stems to be winched to the machine and elevated off the ground prior to skidding to the landing. Grapple skidders have a large hydraulic grapple on the rear of the machine that lifts logs off the ground for skidding (Figure 14.5). Cable skidders thus have the advantage of being able to pull felled trees out of areas that may be difficult for the machine to navigate, or preferable to avoid, such as streamside management zones (SMZs), while grapple skidders must be able to back up directly to bunched logs where they lay. Working under similar conditions, grapple skidders have higher production rates than cable skidders, and are more common. On the west coast of the United States (Oregon and Washington), shovel logging has largely replaced the use of skidders for ground-based yarding in industrial forest operations. However, skidders are still used commonly in the inland northwest and in the eastern United States.

14.6.6 Slash Forwarders and Chipper-Forwarders

There are several types of commercially-available slash-forwarders that are purpose built to forward woody logging slash and tops from in-woods locations to a landing or roadside pickup for subsequent processing or transportation. These machines include simple

Figure 14.5 *Conventional grapple skidder releasing a turn of small diameter logs. (Photo: © Keefe, 2013).*

forwarders with bunks for transport of loose logging residue, machines with inverted hydraulic grapples that compress slash in order to increase payload capacity, and forwarders with mechanisms for wrapping slash into large bundles.

Alternatively, a variety of self-feeding chipper-forwarders now exists that are able to pick up and chip logging residue in the woods. Slash is picked up with a hydraulic arm and grapple, self-fed to an in-feed conveyor or feed roller mechanism, chipped, and carried in an internal container to the landing. Because chipper-forwarders densify biomass from logging residues in the woods prior to transport, these machines tend to have higher production rates than slash-forwarders [4].

14.6.7 Shovel Logging

Shovel logging is the term used to describe a type of log or whole-tree forwarding in which a "shovel", "swing machine" or long reach hydraulic loader built for forestry advances stems toward roadside using a series of 2–3 "swings". Figure 14.6 shows a shovel logging system in which Douglas Fir stems are being advanced to a log landing using a shovel logging machine on moderate slopes, alongside a cable logging operation on steeper terrain.

14.6.8 Chippers

Wood chippers may be disk or drum machines and are available in a variety of sizes, from small, trailer-mounted models able to handle small diameter branch material, to mobile, whole-tree chippers that can process large diameter stems with high throughput in industrial operations. Whole-tree chippers may be paired with a separate loader or may

Figure 14.6 *Shovel logging to advance whole trees to the landing on moderate slopes near a standing skyline cable yarding operation in western Washington. (Photo: © Keefe, 2013).*

be self-loading. Tracked machines are able to work in the woods in order to minimize slash forwarding with a forwarder or excavator. Stationary machines work at a landing or concentration yard. Figure 14.7 shows a full mobile chipping unit processing commercially thinned stems at a log concentration yard in north Idaho. In general, chipping tends to work most efficiently when stems have high moisture content (i.e., "green" wood).

Fuel chips are most commonly used for thermal applications, such as boiler fuel, and for power generation. The presence of bark and foliage in the chips is generally not problematic in these applications, assuming that the presence of inorganic material can be controlled to reasonable levels. In addition, certain biofuel conversion technologies can utilize fuel chips, notably the thermochemical processes that gasify biomass or utilize some form of pyrolysis to convert the solid material to a liquid or gas.

14.6.9 Grinders

Unlike disk and drum chippers that slice and chunk wood into smaller particle sizes through cutting knives that slice fiber, grinders separate wood through a mashing and tearing or fibers. Thus, grinding may be more effective at lower moisture contents. Horizontal grinders such as that shown in Figure 14.8 have a rectangular open top for loading, with a conveyor and feed roller infeed that forces residues against the grinder, and then ejects hog fuel along an in-line conveyor outfeed. Vertical grinders, more commonly called "tub" grinders, have a large, cylindrical open top in which residues are loaded, and rely on gravity to feed the grinder.

Figure 14.7 *A complete mobile chipping unit processing de-limbed small-diameter logs from a commercial thinning operation into clean chips in north Idaho. The chipping is located at a concentration yard 2–3 miles from where the trees were harvested. (Photo: © Keefe, 2013).*

Figure 14.8 *A loader feeds a horizontal grinder, which in turn fills a high walled dump truck being used to haul biomass over a low volume forest road to a concentration yard. (Photo: © Anderson, 2013).*

Grinders, both of the tub and horizontal varieties, have an important place in the current infrastructure for woody biomass processing. The quality of the product resulting from grinders is generally of lower quality than a chipped product. Grinders tend to be more forgiving of soil and other contaminants, with the result that a higher proportion of these undesirable materials typically find their way into the product. Material processed in grinders is most often suitable for boiler fuel, in part because large biomass boiler systems tend to be less sensitive to ash content. Grinders are better adapted to locations where cut-to-length logging is common. In these operations, logging slash tends to be dispersed throughout the logging site. Logging residues are generally forwarded to the roadside or other locations where they can be accessed by the grinding equipment. Grinders are paired with a knuckle-boom loader and the outfeed discharges into a chip van of some sort. The ground product tends to be inconsistent in size and shape, and thus is not a preferred fuel or feedstock.

The choice of tub versus horizontal grinder is largely dependent on the type of material being processed. Tub grinders are better adapted to odd-shaped pieces, such as stumps, short bole sections, and the like. Horizontal grinders are more efficient at processing material with a more linear configuration, such as tree-length material or long tops and limbs. Horizontal grinders are capable of very high throughputs, making them efficient options where the product is acceptable.

14.6.10 Portable Conveyors

Most equipment for primary harvesting and extraction in forestry has been designed for handling sawlogs or whole stems, which are single or multiple large, heavy objects. Relative to sawlogs, the material properties of woody biomass are very different, including small particle size and bulkiness. For this reason, use of portable conveyors for in-woods biomass handling applications, such as forwarding, have received some attention. Portable belt conveyors and continuous loop cable systems have important advantages over conventional skidding and forwarding equipment options. The continuous material flow properties of conveyors make it possible for high production rates to be maintained, regardless of turn distance [4, 5]. This differs from the production function for most skidding and forwarding equipment, which tends to decline with increasing turn distance. Set-up costs, or total equipment costs, tend to offset production gains associated with deploying conveyors for primary extraction to a landing or roadside. However, an additional advantage of conveyors is that many are able to handle bulky biomass in a variety of raw or comminuted forms, including, for example, chips, hog fuel, and unprocessed slash and tops. This flexibility makes it possible for portable conveyors to function as part of a variety of different system and equipment configurations.

14.6.11 Combined Harvesting and Processing Equipment

In addition to chipper-forwarders, there are now commercially available machines capable of harvesting, self-feeding, chipping, and transporting woody biomass. Though not commonly in use, these machines have the advantage of performing “single pass” utilization of thinned materials, when larger diameter (e.g., >5-inch DBH) must be processed.

14.7 Woody Biomass Transportation

Along with harvesting and processing costs, transportation costs are a major determinant of the delivered cost of woody biomass. Even after communition or compaction, woody biomass tends to be bulky and difficult to transport efficiently. The preferred approach, when possible, is to maximize net payload by using the largest trailer possible. For example, high-capacity chip tractor–semi-trailer combinations, also called chip vans, can exceed 19 m in length, 45 000 kg in gross vehicle weight, and 30 000 kg in net payload. Large payloads distribute the fixed costs of transportation over a larger amount of material and generally, though not always, result in greater input/output efficiency in variable costs, such as fuel consumption. Larger payloads also reduce operational delays associated with the loading and unloading of many small trucks compared to loading fewer large trucks. Though ideal from an operational standpoint, a number of factors constrain the use of these vehicles in woody biomass logistics.

14.7.1 Regulatory Considerations

In most places, regulations govern on-road trucking and limit vehicle dimensions and gross vehicle weight (GVW). Different laws may apply to different road segments along a route depending on local, state, provincial, and federal jurisdictions. For example, in some US states maximum GVW may be set at 45 360 kg, but vehicles greater than 36 290 kg are prohibited from traveling federal interstate highways, requiring smaller payloads or sub-optimal truck routing onto high GVW roads. Overweight and over-dimensions exemption permits are generally available but many jurisdictions bar such permits for cargo that can practically be divided into smaller loads, such as biomass. Even if overweight permits for divisible cargo are allowed, permit fees and transaction costs may exceed added revenue associated with larger payloads. In addition to GVW restrictions, seasonal road closures related to mud and snow conditions can limit transportation at certain times of the year. In general, these types of regulations have a direct influence on transportation options for both individual harvest sites and facility-specific transportation logistics systems.

14.7.2 Operational Considerations

There is also a close link between transportation options and material handling capabilities. At the harvest site, large open-topped chip van trailers can be loaded evenly by a conveyor, overhead hopper or front-end bucket loader. Closed trailers and box trucks, as well as trailers that cannot be approached from the side due to terrain or road conditions, must be loaded from the back. Depending on the particle size of the material and ejection range of processing equipment, it may be difficult to fill long compartments uniformly to maximize payload. Similarly, grapple loaders must have sufficient room to maneuver to efficiently load roundwood or compacted bundles onto long trailers. Unloading is discussed in more detail later in this chapter, but similar constraints apply to unloading biomass. Self-unloading configurations, including walking floor (Figure 14.9), side dump, end dump and belly dump trucks and trailers, carry smaller payloads than long, possum belly semi-trailers, but may be required if the end user does not have a hydraulic truck dump system on site. For

Figure 14.9 The back of a walking floor trailer that allows for automatic unloading of comminuted biomass. (Photo: © Anderson, 2013).

roundwood, self-loading log trucks equipped with a hydraulic grapple arm may be required if the log landing does not have a loader or forwarder on site.

Regulations and handling constraints apply broadly to all biomass supply chains but the forest sector is unique in the extent to which transportation logistics are dictated by harvest site characteristics. Plantations and native forests located on flat topography close to end users and accessed over high-speed, wide, paved roads with high GVW are obviously ideal for minimizing transportation costs. However, forested sites are frequently accessed over gravel or native soil low-standard forest roads that are steep, narrow and winding with limited turn-out locations for passing and turning around. In many cases, forest roads were designed for stinger steered log trucks and are inaccessible to the long, low clearance, high-volume tractor-semi-trailer combinations that maximize transportation efficiency for woody biomass. Road improvements can widen curves, flatten rough roads and reduce steep grades, but can rarely be justified by biomass extraction objectives alone and may be limited by regulation or forest management objectives. Recent innovations in stinger steering and rear axle modifications that allow a tighter turn radius than traditional fifth wheel semi-trailers with fixed axles have improved access to difficult sites by large semi-trailers. Such trailers are commercially available but cost more than conventional equipment. Short chip van tractor-semi-trailer configurations are also used to haul woody biomass on low-standard forest roads. Under especially challenging road conditions, shorter, higher clearance, and more maneuverable box trucks, dump trucks, roll-off bins, or tractor-trailers are an option. However, the smaller payloads carried by these vehicles typically translate to higher per unit transportation costs, which are intensified by long on-highway travel distances. In addition, if biomass has received some field drying before processing, smaller truck configurations tend to reach maximum volume before they reach maximum GVW. This is suboptimal from a logistics standpoint because it further reduces payload and increases per unit costs.

14.7.3 Concentration Yards

It is possible to combine the maneuverability of small trucks with the long-haul efficiency of large semi-trailers by using a concentration yard to improve logistics [6]. Concentration yards, also known as sort yards for roundwood, are intermediate transfer points where material is collected. In the forest sector, they typically serve to improve logistics in transportation, processing, storage and marketing. For sites that are inaccessible to large chip vans, smaller trucks can be used to transport material over forest roads to a site with better road access. Biomass can then be transferred to large trucks with higher payloads to cover long on-road distances to end users. Similarly, when harvest sites are widely dispersed, difficult to access, and have relatively small amounts of material to process, it is costly to move processing equipment from site to site. In this case, logging residues and roundwood can be transported from harvest sites to a central location, stockpiled, and then processed in large volumes, which increases processing efficiency. This logic can also be applied to pretreatments, which are discussed in more detail later in this chapter. In some cases, processing and pretreatment equipment cannot be transported to harvest units due to poor road conditions or design limitations, making a concentration yard necessary. In both cases, gains in transportation and processing efficiency must be balanced against added handling costs, with concentration yards requiring additional unloading, handling, and re-loading components. In general, the costs of double handing low-value material like woody biomass are very difficult to recover by improving transportation efficiency, unless transportation costs are extremely high.

Concentration yards can also provide off-site storage of raw material, either in its raw or processed/pretreated form. This may be an attractive option in areas affected by seasonal road restrictions that limit access to material at harvest sites for part of the year. In addition, though less relevant for woody biomass than for high value roundwood products, concentration yards can be used to improve efficiency in product marketing by separating aggregate deliveries of logs from harvest sites into fuelwood, pulpwood, and different grades of sawlogs for shipment to different facilities [7]. Typically, this is done on the log landing or at a facility that uses its log yard as a sort yard, shipping loads of logs to other facilities, but there are some conditions where it may make sense to incorporate this approach into woody biomass logistics. As with the storage and processing aspects of concentration yards, the added costs must be weighed against added revenues of product sorting and marketing. Though they are used in road-based logistics systems, concentration yards are a necessity when woody biomass is going to be transported by rail or ship. Though extremely rare because of its unfavorable economics, biomass removals by helicopter also require a concentration yard. For railroad transportation, rail-side concentration yards allow material to be stored on site and transferred efficiently into rail cars and shipped after sufficient material is stockpiled.

14.8 Pretreatment

14.8.1 Mechanical and Chemical Pretreatments

Communition of woody biomass through chipping, grinding and shredding increases its bulk density, which improves transportation efficiency by allowing trucks to carry heavier payloads. Such processing also improves handling and storage by reducing particle size and increasing homogeneity, allowing material to be more efficiently handled by loaders, conveyors and other equipment. In the context of woody biomass logistics, pretreatment generally includes additional processing that further improves the transportation, handling, storage and end use characteristics of biomass feedstocks beyond typical communition methods. Physical, chemical and thermal pretreatments are all technically possible but vary significantly in their operational characteristics and commercial potential.

When end users of woody biomass have feedstock specifications that are outside traditional parameters for chips and hog fuel, additional drying, milling, chipping and screening can be used as pretreatments. For example, many distributed scale gasification systems require clean, dry, microchips as a preferred feedstock (e.g., low ash, bark-free chips less than 3 cm in size and 10% water by weight). The equipment to produce this high quality of feedstock from woody biomass is commercially available and widely deployed in industrial settings. More intensive debarking, chipping and screening are easily accomplished on a log landing, though these steps obviously incur additional costs. In-woods pelletization has also been explored as a pretreatment option, but remains difficult to do efficiently at distributed scales. Similarly, chemical pretreatments are widely used by cellulosic ethanol operations to reduce lignin content and improve sugar yields, but these techniques are not easily mobilized for field applications and typically involve liquid waste management and reprocessing that is almost impossible to do efficiently away from a large-scale facility. In contrast, there has been growing interest in using mobile thermal pretreatment technologies close to the harvest site to further improve transportation efficiency and produce renewable high-value bioproducts that can be shipped efficiently to distant markets, especially in areas characterized by long transportation distances. Though discussed here as a pretreatment option, thermochemical pretreatments can also be classified as biomass conversion technologies, especially when deployed at larger centralized facilities (Chapter 2).

14.8.2 Thermal Pretreatments

Among thermal pretreatment options, torrefaction, or pyrolysis of biomass in the 200–300°C temperature range, is closest to widespread commercial use [8]. Torrefaction produces a devolitalized, hydrophobic, high-carbon content product often referred to as torrefied wood. Several characteristics of torrefied wood make it more efficient to transport and store than untreated biomass, including lower water and oxygen content, higher energy density, hydrophobicity, resistance to decay, grindability, and relatively homogenous particle size. Torrefied wood is generally considered a solid fuel product suitable for combustion applications, including utility boilers and co-firing with coal, but may also be used in gasification and bioproducts manufacturing. Much attention has been paid to using torrefied wood as raw material in the manufacture of fuel pellets because low water content and high energy density are desirable for most energy applications. The sequence of processing can also be reversed, with wood pellets serving as the feedstock for torrefaction. However, this configuration is not a viable in-woods option due to the difficulty in efficiently downscaling pellet manufacturing, which is strongly subject to economies of scale in production, handling and transportation. In most torrefaction systems, once pyrolysis is initiated with an application of heat, the process is exothermic and self-sustaining, meaning the chemical reactions required to produce the end product will proceed without net additions of energy, such as heat from combustion of propane, natural gas or combustible gases produced by the reaction itself. This provides a deployment advantage for log landings that are close to the harvest site and typically distant from infrastructure. Another advantage is that torrefied wood can typically be handled by the same equipment used to handle and transport processed biomass, though initial cooling and additional dust control measures may be required.

Pyrolysis of biomass at higher temperatures (300–700°C) produces recalcitrant charcoal as well as volatile gases, a fraction of which can be condensed into liquid pyrolysis oil, also called bio-oil. Mobile pyrolysis systems have been examined as a pretreatment option for woody biomass but are not yet widely used in the forest sector [9]. The charcoal produced has most of the same favorable properties as torrefied wood and can be used in its raw form as solid fuel or as a feedstock for the production of other products, including chemicals, pellets, activated carbon and soil additives. The charcoal output of pyrolysis of biomass is commonly called biochar when it is used as an additive to improve the bulk density and nutrient and water holding capacity of soils. Pyrolysis oil can be used in its raw form as liquid fuel. However, because of its high oxygen and water content and low chemical stability, it is generally considered a crude product to be used in the production of refined (i.e., upgraded) biofuels and industrial chemicals.

Pyrolysis in this temperature range often produces residual tars, which can provide fuel for conversion, be sold as a commercial output, or handled as an undesirable waste by-product, depending on production objectives, equipment capabilities, and markets. Systems operating at the low end of this temperature range may be exothermic, similar to torrefaction systems, but fast pyrolysis units operating at higher temperatures are characteristically endothermic and require net additions of energy to sustain the thermochemical reaction due to their high heating rate and the relatively short residence time of the feedstock. Often this energy can be provided by combustion of producer gas generated by the system, which is generally composed of carbon monoxide, hydrogen, carbon dioxide, methane and other non-condensable gases. Because of the high temperatures and smaller feedstock particle size, which facilitate rapid heat transfer, the pulverized charcoal from fast pyrolysis systems can require significantly different handling than wood chips or torrefied wood – most often a cooling phase followed by containerization in drums, closed trailers, or large industrial bulk bags. Compared to biomass, pyrolysis oil is energy dense, and thus has the potential to improve transportation efficiency, but as a liquid product it adds material handing requirements that are unusual for most forest operations, including on-site liquid fuel storage, specialized trucking needs, and fire and spill containment preparations.

14.8.3 Locating Pretreatment Operations

As a component of woody biomass logistics, pretreatment can occur close to the harvest site, at intermediate processing and storage facilities such as concentration yards, or prior to use at the conversion facility. The location and timing of necessary pretreatment is highly dependent upon the end use and other components of the supply chain. However, several general considerations are worth mentioning here. In any logistics configuration, the value of pretreatment is likely to depend on the cost of the pretreatment weighted against the cost savings associated with increased transportation efficiency and the difference in delivered price between the treated and untreated materials. For example, when compared to green chips, torrefied wood produced from green chips at a harvest site may be cheaper to deliver on a cost per ton basis and may also command a higher delivered price attributable to its higher energy content. However, if the cost of the torrefaction operation is greater than the sum of transportation cost savings and new revenue, then the torrefaction preprocessing option is unlikely to be commercially viable.

Balancing the scale of operations is also important. Many existing pyrolysis and torrefaction technologies that can be deployed to forest settings have much lower material throughput (e.g., $1\ \mathrm{t\ h^{-1}}$) than grinding and chipping systems, which can produce up to $50\ \mathrm{t\ h^{-1}}$. When forest operations are bottlenecked through lower productivity preprocessing, gains in transportation and revenue may be erased by operational delays in the harvesting and processing components of the system. This is especially true of batch systems, where equipment may be idle during preprocessing periods. In addition, some technologies (e.g., refinery operations) benefit from clear economies of scale and cannot be effectively down-scaled for deployment to in-woods and concentration yard environments. Many of these challenges can be overcome with effective engineering, operations planning and logistics management, but others reflect the realities of preprocessing technology deployed in difficult operating environments.

14.9 Handling and Storage

Processed woody biomass is unloaded in different ways depending on the transportation method and capabilities of the concentration yard or facility to which it is delivered. High-volume operations, such as large combined heat and power boiler systems and electric power plants, typically use hydraulic truck dumps. These systems raise conventional tractor-semi-trailers vertically and use gravity to dump the contents of their trailers into a transfer bin, pit or bunker, or onto a ground-level pad. Once dumped, the biomass can be moved from the unloading area by drag chains, conveyors, wheeled front-end bucket loaders, or similar handling equipment. Paired with large-volume chip vans, truck dumps are an extremely efficient unloading system. However, they are costly to install and maintain, so they are generally found at facilities requiring hundreds of thousands of tons of feedstock per year. For smaller volume operations, such as distributed heating systems, self-unloading trailers are preferred. These trailers generally discharge onto a pad, where the material is moved by a rubber-tired front-end bucket loader. A variety of belly, side and end dump trailers are available for different truck and tractor configurations. However, walking floor (or live floor) self-unloading semi-trailers are a good option to maximize payload when a truck dump is not available or when the truck must unload in a covered

Figure 14.10 Woody biomass piled outdoors and loaded onto barges using a series of conveyors, prior to long-distance transport downriver. (Photo: © Keefe, 2013).

storage area or bunker with low overhead clearance that limits the use of side and end dump trailers.

Chipped or ground woody biomass can be stored in piles that are open to the weather (Figure 14.10). Obviously, moisture content is not a problem for conversion technologies that use wet chemical and biochemical processes, but even for thermochemical conversion processes where dry material is preferred, biomass harvested from green trees or logging residues that have received some field drying is unlikely to increase much in moisture content from precipitation when stored in piles outdoors. However, in most cases piles with high moisture content should be rotated to avoid degradation, which can change its physical and chemical properties, resulting in loss of energy content. Spontaneous combustion of green and wet chips can also occur if piles are allowed to remain outdoors without rotation for extended periods. This phenomenon is the result of microbial activity that produces heat, which can build up and cause combustion under some temperature, oxygen and moisture conditions. Regular rotation dissipates heat and changes pile conditions to make combustion unlikely.

Some woody biomass, especially residue from solid wood products manufacturing, has low moisture content as a result of kiln drying prior to final processing. In some cases, green woody biomass is dried prior to use, as in most fuel pellet manufacturing operations. Drying wood is expensive but elevates the recoverable energy content and value of the material. As a result, dry woody biomass should be kept in a dry condition using proper storage and handling procedures, which often include covered storage and short storage duration before use. Though spontaneous combustion and degradation are less of a concern with dry materials, dry biomass may require additional dust control, typically in the form of collection and exhaust systems that minimize fire, environmental and health risks. In general, the smaller the particles, the greater the need for such management systems.

For bioenergy facilities using roundwood delivered on log trucks or flatbed trailers, there are a variety of conventional options for unloading, handling, and storing wood. Log trucks can be unloaded by crane, either rotary or portal varieties, and easily stored in tall piles in a log yard. Unloading and storing wood in this fashion is an efficient option for high-volume operations and is commonly employed at conventional forest products manufacturing facilities. Grapple loaders and rubber-tired front-end log loaders can also be used effectively, although a larger land area is required due to the limited reach of the equipment. Log yards often employ both cranes and log loaders to stack and store roundwood. Low volume operations are unlikely to prefer roundwood as feedstock but can opt for grapple loading log trucks and a tractor or skidder to manage logs in the yard before processing.

14.10 Logistics Management

14.10.1 Delivered Cost and Woody Biomass Logistics

For facilities using woody biomass as a fuel or raw material, a central objective of logistics management is to reduce the delivered cost of the material. For woody biomass, delivered cost generally includes three core components: stumpage, forest operations costs, and transportation costs. Stumpage is the term used in the forest sector to denote the fee paid to owner of the raw material, typically the landowner. Stumpage costs are highly variable and regionally specific, but biomass generally has the lowest stumpage cost of any material removed from the forest. In contrast, operations costs for biomass, especially logging residues, can be quite high compared to large diameter roundwood. Operations costs include all on-site harvesting, handling, and processing, as well as handling and processing at intermediate transfer points, like concentration yards. Operations costs can be accounted for using a marginal costing approach, where biomass is considered a by-product of the production of high-value products that support most of the operations costs, or a joint product costing approach where biomass is considered a co-product and operations costs are proportionally allocated among all products, including biomass [10]. Transportation costs most often cover a single motor carrier transporting material from the harvest site to the end user, but may include multiple trucking segments, depending on logistics. If a short-haul transportation segment is required to bring slash or processed biomass from the harvest site to a nearby concentration yard, short-haul transportation costs may be included in operations costs, especially if the short haul is conducted by the logging contractor. In general, if the total costs of delivering woody biomass to a facility exceed the price that the end user is willing to pay, the material is left to decompose or burned on site to reduce fire risk and open growing space for regeneration. In some cases, the net costs of woody biomass utilization may be offset by revenues from higher value products if biomass use is uneconomical but desirable for other reasons. For example, utilization may be used as an alternative disposal method in situations where open burning is prohibited.

Different logistics costs may be borne by different organizations along the supply chain, or by a single firm in a vertically integrated operation. In locations where biomass supply chains are characterized by independent firms specializing in land investment, forest management, harvesting, transportation, and conversion, the details of cost structure are typically proprietary because efficient operations are a competitive advantage for competing firms. In this context, firms along the supply chain typically interact on price (e.g., stumpage price or gate price for delivered material). However, a number of different sources of information can be used to guide logistics management with regard to costs. The most important and reliable form of cost information is transaction evidence, or records of costs and prices from previous market transactions. In addition, in well-developed biomass markets individual firms are often surveyed by public agencies or industry organizations that aggregate market information, especially prices, into stumpage reports and other similar market data reports, which are available for free or for a fee. Government land management agencies sometimes have publicly available data and methods that characterize the value and costs of forest products from public land, including fuel wood and biomass. For forest operations, a large body of research is devoted to quantifying and improving the cost structure of woody biomass harvesting and processing. These data can be compiled to provide delivered estimates for a certain size and type of facility in a specific location.

14.10.2 Spatial Analysis of Woody Biomass Logistics

Many of the variables that determine the delivered cost of woody biomass have spatial attributes. Transportation distance is often cited as a critical constraint on the financial feasibility of biomass utilization but in a heterogeneous landscape the distribution, quality, ownership, management and accessibility of forestland also have spatial dimensions that influence biomass supply. The following section discusses the tools and approaches that are used to perform spatial analysis of feedstock supply to inform logistics. Though the techniques can be complex, their broad purpose is to help estimate how much biomass can be supplied to a specific facility at a given cost.

14.10.3 GIS

Facility managers typically take a large number of factors into consideration to build an optimal procurement plan to minimize woody biomass cost. In practice, those plans vary in detail from expert opinion and trial-and-error [11] to metaheuristic solvers that are incorporated into a geographic information system (GIS) [12]. While expert opinion is often used to minimize costs for an individual operation, it tends to produce substantial uncertainty when a supply chain is complex and compared to alternative operations occurring across vast landscapes over long periods of time. In that light, forest management, which typically covers large areas, has multiple objectives, delivers raw materials to many destinations, and utilizes long time horizons, often relies on building logistical costs into a GIS that can be used to compare multiple scenarios in a spatial and temporal manner.

In simple terms, a GIS is a collection of software procedures and data that use geometry as a primary relationship among records [13]. GIS data reside in a relational database structure that link records with one another based on primary keys and topological relationships. Within a GIS, real objects such as roads, harvest units and mills are symbolically represented as table records in either vector or raster form. Each record within a table stores descriptive information of each object (attributes) such as size, length, area, and cost along with a collection of coordinates that depict shape and location in the form of points, lines, polygons, or raster cells. Moreover, because an object's geometry (shape and location) is stored, spatial relationships such as proximity to, touching, adjoining, within, and containing can be used to relate attributes of neighboring objects to one another.

In the context of managing woody biomass supply chains, these objects represent the base components that can be attributed costs. For example, a polygon that symbolizes a 40 hectare harvest unit on a gentle slope located next to a primary road can be allocated costs related to the weight of the biomass collected, a skidder harvesting system, and primary road access. Allocating cost across a landscape within a GIS is straightforward and can be accomplished by defining a clear set of rules that constrain cost to specific locations based on a combination of spatially explicit factors. These rules are typically defined by setting lower and upper bounds (i.e., thresholds) on transportation distance, the types of equipment that can be used, and the amount of material that can be removed from a given location. Thresholds can be based on a wide range of factors including regulations, policy, management objectives, the physical limitation of equipment being used, transportation infrastructure, and the characteristics of the landscape, and should be derived in a manner that represents yes or no outcomes in terms of supply. Records or spatial locations meeting the defined thresholds can then be attributed a designated cost and mapped appropriately.

Commonly, logistics costs are based on rates such as dollars per unit of distance, area, or weight. While rates can be easily attributed to specific objects (e.g., harvest units), it can be helpful to convert rates to an absolute value when aggregating different sources of cost for an activity. For example, plotting total cost against total amount can provide useful supply curves. Again, within a GIS this process is straightforward, as long as there are estimates of distance, area, and weight for each of the different cost types. Common tables developed to store these kinds of estimates include vector and raster data sets that spatially depict woody biomass stocks, topography, road and stream networks, receiving facilities, and treatment units.

One of the most common ways to generate the geometry of objects within these tables is to use "heads up digitizing" and image interpretation where a technician manually converts maps and other imagery into a digital format that can be used in GIS [14]. For larger landscapes, though, this tends to be cost prohibitive. In those situations, remote sensing techniques are often employed to automate the creation of GIS data. Regardless of how an object's geometry is created, once it is defined it can be attributed with the base information needed to calculate absolute cost and biomass yield.

14.10.4 Estimating Biomass Stocks Across a Landscape

Estimating woody biomass feedstock across a landscape consists of three basic steps: (1) quantifying estimates of forest characteristics, such as basal area, trees, and woody biomass tons per acre across a landscape; (2) using those estimates to help determine where to apply actual or hypothetical silvicultural prescriptions; and (3) combining estimates of woody biomass with prescriptions to calculate potential treatment residues that can be utilized for fuel or raw material. Quantifying existing forest characteristics can be a substantial endeavor. Generally, this process consists of sampling areas on the ground and recording tree measurements, such as species counts, diameter at breast height (1.37 m), total height, live crown ratio, age, and percentage cull and breakage [15]. From these tree measurements, estimates of standing volume and weight are calculated using allometric equations. These measurements and calculations are then summarized based on sampling design to describe multiple aspects of a forest on a per acre basis. A common classical approach to quantifying existing forest characteristics uses stratified random sampling to relate summarized values to polygons within groups (strata) of similar forest types, stockings, and canopy cover [16]. With this approach, polygons and strata are generally created and labeled through manually defining boundaries of similar forest cover types, percentage canopy cover, and topographic position derived from aerial and satellite imagery. For larger landscapes where manual interpretation is impractical, image classification techniques are used to develop appropriate strata. Once strata have been defined, a random sample of polygons within each stratum is selected, visited, and sampled to derive mean estimates of forest characteristics for that stratum. Mean strata estimates are then attributed to each polygon within each stratum.

While this basic approach is still used in many analyses, mean estimates relate to the stratum as a whole and do not account for spatial variations within a given stratum. Furthermore, the coarse grain nature of this type of estimate may not be suitable for fine scale projects that utilize only small portions of strata. To address this issue, recent analyses have developed spectral and textural relationships between remotely sensed data and field measurements [17–19]. Using these relationships, estimates of biomass can vary as spectral and textural values change, thereby maintaining the spatial heterogeneity of forest characteristics at fine spatial resolution across the landscape.

After forest characteristics have been quantified for polygons or cells, they can be used to help determine where silvicultural prescriptions are applied across a landscape. The process of allocating these prescriptions to forested areas can be done in a similar manner as allocating logistical cost. Specifically, rules can be developed and applied using the attributes of spatial objects to identify polygons, portions of polygons, or cells that meet defined thresholds. Once allocated, these prescriptions can be combined with quantified forest characteristics to provide spatially explicit estimates of potential total woody biomass that can be removed from a given location. Finally, depending on the efficacy of the harvesting system and the merchandizing of the trees, treatment residues can be calculated for a given location. These residues represent the amount of potentially available woody biomass that can be utilized for energy and incorporated into potential woody biomass flows.

14.10.5 Estimating Transportation Costs Across a Landscape

Transporting woody biomass represents another important spatial aspect of logistics costs. Typically, these costs are derived as a series of rates relating to factors such as road speed, fuel consumption, machine hours, and payload. When combined with other costs, these rates can be converted to an absolute value based on hauling distance or time (trip) and the total number of trips required to transport the material. Within a GIS, hauling routes that minimize travel distance and time can be estimated for a route from a starting location (source of biomass) to an ending location (facility) using a road network, source and delivery points, and road network routing [20]. The total number of trips required to transport woody biomass from a given location can be estimated from the total amount of woody biomass available at that location, the associated densities of the woody biomass, and the payload of the truck-trailer configuration. Moreover, trip distance or time and number of trips can be tied together based on the spatial relationship between the source of woody material and the road network.

Minimizing travel distance and time between the source of biomass and a delivery site is straightforward within a GIS. However, on a forested landscape there are many potential sources of biomass for which to determine optimal routes to delivery sites. In this situation, it is easier to think of loading points along a transportation system that can be attributed a minimized trip distance and time. From loading points on the road network, polygons can be created that define the areas closest to each individual loading point, in an automated fashion (Thiessen polygons). Each Thiessen polygon can then be attributed with the transportation costs of its point on the road network, which can be efficiently related to estimates of biomass using spatial relationships.

14.10.6 Estimating Harvest Costs Across a Landscape

Similar to determining transportation costs across a landscape, harvesting costs are derived from rates such as fuel consumption and machine hours. Additionally, absolute costs derived from harvesting rates depend on the total amount and density of standing biomass. While the amount and density of biomass is typically quantified for polygons or a raster surface, the boundaries of those polygons or cells of the raster surface may not represent boundaries of areas that will be harvested. A separate spatial table that defines harvest unit boundaries is often needed to account for management objectives and the logistics of harvesting.

In practice, predicting the location of a harvesting unit boundary is difficult prior to its actual creation. However, within a GIS rules can be created that generalize harvesting policy, management objectives, and stochastic events to create potential harvesting units across a landscape. These rules can quickly become complex and can incorporate a wide range of factors, such as topography, proximity to streams, available tree biomass, maximum harvest unit size, proximity of harvest units to recently harvested land, fire mortality and beetle kill. Often, due to the complexity of building rules for harvest unit boundaries and the reliability of the outputs, a surrogate boundary table such as the Thiessen polygons described in Section 14.10.5 is used to represent harvesting units.

Once harvest unit boundaries are defined, rules and thresholds based on factors such as topography and soil condition can be used to determine the appropriate harvesting system. In addition, total woody biomass, densities, and residues can be calculated for harvest boundaries by spatially relating the geometry of each harvest unit to the estimates of biomass stocks. Absolute costs for the harvest unit are then calculated using the cost rates associated with the selected harvesting system and the weight of the residuals calculated from a treatment.

14.10.7 Planning

After determining harvest and transportation costs across a landscape, the two can be linked to one another through overlay analysis [21]. Specifically, absolute harvesting costs can be combined with absolute transportation costs based on estimates of woody biomass residues for a given harvest unit and the spatial proximity of that harvest unit to the closest loading area. These combined costs are attributed to the harvest unit and compared in relative fashion across the landscape (cost per acre or weight of material). Furthermore, estimates of available woody biomass residues for the harvesting unit are used to represent potential flow of material from that location. Using these costs and potential flows, questions such as how much woody biomass is available across a landscape, where are the least expensive areas to procure woody biomass, from which locations is it profitable to market woody biomass, and are there timing components related to harvest locations that can reduce logistical costs, can be answered in a relatively quick and easy manner.

When utilizing base data and rules to derive cost and potential woody biomass flows from a landscape, it is important to consider the scale and the level of precision needed to answer these types of questions. Base data and rules that are too coarse may not provide an adequate level of detail to properly estimate woody biomass and flows. On the other hand, too fine a scale may present issues related to finding and developing complete data sets, digital storage space requirements, and total processing time and memory it takes to perform spatial analyses for the landscape of interest. Once defined for harvesting units, these costs and potential flows can be used to plan harvesting schedules across both space and time for a given landscape. Multiple simulations depicting various policies, objectives, and conditions can be compared to evaluate the impacts of decisions made based upon the constraints of those criteria. Moreover, if objectives and constraints can be spatially represented in a relative fashion they, can be optimized across the landscape to minimize logistic costs and maximize woody biomass flows. Such analysis can help reduce biomass supply costs, especially in complex procurement environments.

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