The overall goals of the project were to lower the net cost of reducing fire danger in forested areas of the central Sierra Nevada, California, and improve the feasibility of utilizing removed biomass for useful energy. The Scope of Work and Activities included the following items:

I. List CDF as a Sponsoring Member of the California Biomass Collaborative.

II. Identify equipment – currently in commercial use, under development, or previously tested or used – that can or has potential to be used for harvesting forest biomass in site and stand conditions common to the Central Sierra Nevada, California. The primary purposes of the biomass harvesting are the mitigation of wildland fire hazards and the protection of watersheds.

III. Evaluate and report the costs, production rates and limitations of the identified equipment.

IV. Report findings and recommendations on the machinery evaluated.

V. Recommend improvements to existing or planned biomass harvesting equipment.

VI. If warranted, facilitate demonstrations of promising equipment that is not currently in use in the Central Sierra.

VII. Assess and research the development of biomass plants for electricity and heat generation and/or the production of biofuels, including small, portable biomass utilization plants that can be moved from harvest site to harvest site or concentration site to concentration site.

Items I-V are addressed below. We did not arrange equipment demonstrations. The assessment of conversion methods is covered in Peter Dempster’s M.S. thesis, available separately.
Accomplishments

I. Sponsorship

CDF was recognized as a sponsor on the California Biomass Collaborative’s website at http://biomass.ucdavis.edu/pages/sponsors.html.

II. Equipment with Potential for Harvesting Biomass

We collected hundreds of documents on biomass harvesting operations and equipment, including information from manufacturers and published and unpublished studies. We catalogued types of equipment and associated parameters.

Typically, harvesting activities are classified by activity such as felling, deliming, bucking, primary (stump to landing) transport, loading, chipping, secondary (landing to utilization facility) transport, etc. But a more basic and useful approach for evaluating equipment concepts might divide these activities into generic categories for which general objectives can be established. Basic functions include 1) gathering or acquiring, 2) processing and 3) transport. (Gathering could also be considered a process.) These functions are in many cases at least partially independent. A feller-buncher gathers (by reaching out and grabbing trees), processes (by severing trees), and transports (by moving trees into bunches). A cable yarder gathers (when choker setters hook logs) and transports (during lateral inhaul and inhaul). A tally of types of equipment is summarized in Table I.

Table I. Types of biomass harvesting equipment categorized by primary harvesting activity, indicating all associated harvesting activities and machine functions.

<table>
<thead>
<tr>
<th>Primary Activity</th>
<th>Comminution</th>
<th>Densification</th>
<th>Extraction</th>
<th>Felling</th>
<th>Loading</th>
<th>Processing</th>
<th>Transport</th>
<th>Gathering</th>
<th>Processing</th>
<th>Transport</th>
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<tr>
<td>chipper-forwarder</td>
<td>x</td>
<td>x</td>
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<td>chipper, based at the landing</td>
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<td>chipper, woods-mobile</td>
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<td>chipper-truck, woods-mobile</td>
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<td>roll splitter</td>
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### Table I (continued).

<table>
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<th>Primary Activity</th>
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<td></td>
<td>Communion</td>
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<td>Densification</td>
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</table>
Table I (continued).

<table>
<thead>
<tr>
<th>Primary Activity</th>
<th>Functions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Processing</td>
<td>Comminution</td>
</tr>
<tr>
<td>chainsaw</td>
<td>x</td>
</tr>
<tr>
<td>topwood processor</td>
<td>x</td>
</tr>
<tr>
<td>topwood processor skidder</td>
<td>x</td>
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Transport (secondary)

<table>
<thead>
<tr>
<th></th>
<th>Functions</th>
</tr>
</thead>
<tbody>
<tr>
<td>chip van</td>
<td>x</td>
</tr>
<tr>
<td>log truck</td>
<td>x</td>
</tr>
<tr>
<td>multi-use trailer</td>
<td>x</td>
</tr>
<tr>
<td>rail</td>
<td>x</td>
</tr>
<tr>
<td>residue trailer</td>
<td>x</td>
</tr>
<tr>
<td>roll-on/roll-off container</td>
<td>x</td>
</tr>
<tr>
<td>self-loading log truck</td>
<td>x</td>
</tr>
<tr>
<td>setout trailer</td>
<td>x</td>
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</tbody>
</table>

A. Comminution

Most forest residue is too large to be utilized directly in most energy conversion processes, with the notable exception of David Ostlie’s Whole Tree Burner (Ragland et al., 2005), so it typically is chipped or hogged/ground into smaller bits. Comminution also creates material that can readily be handled in bulk, possibly even in a flowable form for transport through pipelines (via air or water). For residues and small whole trees, it also increases the bulk density (Table II).

Table II. Solid volume factors of comminuted materials.

<table>
<thead>
<tr>
<th>Material</th>
<th>Solid Volume Factor (SVF), %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tops and branches</td>
<td>15-30</td>
</tr>
<tr>
<td>Small, uncompacted whole trees</td>
<td>25-40</td>
</tr>
<tr>
<td>Larger whole trees</td>
<td>30-45</td>
</tr>
<tr>
<td>Hogged (ground) fuel</td>
<td>35-45</td>
</tr>
<tr>
<td>Chipped residues or whole trees</td>
<td>35-45</td>
</tr>
<tr>
<td>Chipped roundwood</td>
<td>40-50</td>
</tr>
<tr>
<td>Chunked wood</td>
<td>35-55</td>
</tr>
<tr>
<td>Pellets</td>
<td>45-60</td>
</tr>
<tr>
<td>Tree-length roundwood</td>
<td>60-70</td>
</tr>
<tr>
<td>Short-length roundwood</td>
<td>60-75</td>
</tr>
</tbody>
</table>


Basic dry densities for common Sierra conifers range from about 20 to 30 lb/solid ft³ (Forest Products Laboratory, 1987). Chips and ground materials decay faster in storage than do chunks or uncomminuted material such as whole trees or bundles, or bales of slash.
Most chippers used at forest sites in North America are located at roadside and chip directly into chip vans (Figure 1). Some, on tracked or rubber-tired undercarriages (Figure 2), e.g., the Track Bandit (Bandit Industries Inc., no date), are self-propelled and capable of traversing forest terrain, but most of these are used to comminute material to be left on site. They could, however, blow material into separate chip forwarders.

Chipper-forwarders carry a chip container on the same chassis as the chipper and can transport chips to roadside or they can collect material while chipping and then dump their container into a chip forwarder (Figure 3). These machines are equipped with booms and grapples to pick up and feed felled material. They are popular in parts of Scandinavia (Bjorheden, 2007; Frisk, 2002; Molbak and Kofman, 1991) and have been used to some extent in eastern Canada (Guimier, 1989). Processing costs for residues on the cutover are rather high (Kvist, 1988). Drum chippers are less sensitive to dulling of the knives by dirt than are disk chippers.

A chipper-forwarder can obviously transport its own loads to roadside, and this is optimal at relatively short forwarding distances. At longer distances, however, the chipper would be underutilized because much of the cycle time would be spent traveling empty and loaded, so in these situations it’s preferable to pair the machine with a chip forwarder. Alexandersson (1984,
cited by Pottie and Guimier, 1986; Alexandersson, 1985) found production rates for a Bruks 1001CT chipper-forwarder alone to be 3-4 dry tonnes/PMH at 150 m and 2-3 dry tonnes per productive machine hour (PMH) at 500 m. The chipper had an 18-m³ bin. Adding a chip forwarder at the longer distance increased productivity to 4-6 odt/PMH and had a cost advantage of about 20% compared to the single-machine option. The breakeven distance for one versus the pair of machines was 230 m. The capital cost for the chip forwarder was only a third of that for the chip-forwarder.

The primary (and more expensive) machine’s on-board bin provides the buffer that allows it to continue operating while the forwarder is shuttling between the road and the chipper. A woods-mobile chipper without a bin, however, must be paired with two chip forwarders in order to keep the chipper busy at any forwarding distance. Which is preferable? This is an optimization problem, and a look at agricultural situations is informative. For less-dense crops such as cotton and those such as grain where the yield per harvesting hour is not so high, harvesters are designed with on-board containers to provide a buffer. With crops harvested at high rates, such as tomatoes and silage, material is delivered directly into containers attached to shuttle vehicles. Short-rotation tree crop harvesting has tried both approaches, with self-contained storage considered preferable at short distances and for low-productivity harvesters. But agriculture and short-rotation forestry (which is also agriculture) have an advantage that fuel reduction operations do not: they clearcut and therefore have lots of space to queue and exchange shuttle vehicles. Without this, an on-board buffer is the only way of ensuring the chipper will be well utilized. This, along with the capability to work efficiently at short distance without shuttle vehicles, seems adequate justification for an on-board container. Most if not all European woods-mobile chippers are equipped this way.

The above observations about on-board bins and operation with or without a chip forwarder apply as well to the feller-chippers and feller-chipper-forwarders described later.

During the last decade, chipper-trucks have been developed in Finland for situations where the amount of material at a site doesn’t warrant the move-in of a separate chipper (Hakkila, 2004; Figure 4). As does a self-loading log truck, a chipper-truck pays a penalty in higher hourly cost and reduced payload, but in some cases these may be offset by eliminating the chipper and move-in costs. One of the chipper-trucks – the MOHA/SISU – was capable of in-woods travel as well as on-highway (Asikainen and Pulkkinen, 1998). It carried a roll-on/off container and was considered better than a two-machine combination (woods-mobile chipper and transport truck) for transport distances up to about 30 or 40 km. A prototype chipper-forwarder capable of on-road travel was developed in the United Kingdom (Ecoenergy Limited, 2001)

Chunkers cut material into larger bits than do chippers and therefore expend only a half or a third as much energy per unit solid mass as do chippers (Arola, 1983). Under natural convective airflow, chunks were found to dry more rapidly than chips due to lower resistance to airflow. Chips dried faster with forced air, but required more flow energy to reach the same moisture content (Sturos et al., 1983). Several chunkers were in production or being tested in the mid-1980s (Pottie and Guimier, 1985), but few are available at present, probably due to a lack of interest in chunks.
FERIC recently reported the use of a single-grip processor to buck tops of processed trees into 25-cm chunks (Forrester, 2004). The chunks were transported in demolition containers to a plant where they were hogged. The study anticipated that time and cost could have been saved by producing longer (1-m) chunks, with no loss in transport efficiency.

With the decline in the market for pulp chips, many contractors have replaced chippers with hogs or grinders, primarily because the latter use blunt force trauma to comminute and therefore don’t require maintenance to sharpen or replace dull knives. The penalty is more energy (on the order of 2-8 times as much) to comminute to the same size (Jones and Associates, 1981a, 1981b).

Experimental devices called roll splitters were tested to partially crush small stems and thereby remove water and speed passive drying (Curtin et al., 1987, DuSault, 1985a). They would not express moisture unless the initial moisture content was above 50% wet basis, but split stems did dry very quickly. Some tests found the material would also rapidly rehydrate if rained upon. The mechanical breakdown of stems by the rollers was expected to help with any subsequent baling or other compaction operations.

The Forest Engineering Research Institute of Canada (FERIC) developed a prototype Logging Residue Processor (LRP) during the 1980s to comminute large material at roadside (DuSault, 1985b). The machine had a shearing rotor or chunker for primary comminution and a hammer hog to further reduce size.

A residue shear was tested in the intermountain west for producing firewood (Johnson and Lee, 1988), and stump splitters are used in Finland so stumps can be more fully cleaned of soil and rock and be more efficiently transported to biomass plants (Figure 5). We don’t consider either of these types of devices to be relevant for the central Sierra.
B. Densification

As noted above, many devices densify in addition to other modifications. Baling doesn’t reduce size of individual pieces, but increases density and also creates uniform packages that can be more readily handled than loose residues (Figure 6). Unlike chips or hog fuel, bales can be transported on flatbed or shortwood trucks. There was considerable interest in balers during the early 1980s (Fridley and Burkhardt, 1984, Schiess, 1981, Schiess and Yonaka, 1983, Walbridge and Stuart, 1981) and there is renewed interest on a small scale for handling residues from cut-to-length operations and material from fuel reduction operations on small parcels in the wildland-urban interface or WUI (Dooley et al., 2006, 2008; Lanning et al., 2007).

A simple and inexpensive device for assisting the loading of chips into railcars was found to pack up to 13% more material into the same volume than did front-end loaders (FERIC, 2005). It would not be of benefit in woods operations where weight rather than volume generally constrains truck payloads when hauling fresh chips.
Various devices have been tested in Scandinavia and elsewhere for compacting truckloads of whole trees, tree sections and residues. Some are mounted on the trucks while others are detachable and rely on, or are adapted to, loading equipment (Carlsson, 1981, Larsson, 1982a). Danielsson et al. (1977) found that green (54% moisture content, dry basis) pine branches and tops required pressures of 220 kPa to effectively compact them to 80% SVF, while pressures of only 10 kPa were required to compact dry (20% MC) material to 64% SVF.

C. Extraction

Agricultural tractors are commonly used in small-scale (woodlot) forestry in parts of the world where terrain conditions allow. Although tractors are cheaper than most skidders, they are small and have low power, so they carry small payloads and travel slowly. Other issues include ground clearance, safety and woods-worthiness on rough terrain (Folkema, 1985). Tractors can be equipped with winches for hauling turns of 1-3 m³, but payload capacities can be increased to 5 m³ or more by adding a trailer with bogie suspension (Folkema, 1986). Some trailers have powered wheels to increase traction, and others are equipped with grapple loaders (Folkema, 1987). Arches for tractors are available, e.g., from Future Forestry Products (now LogRite Tools).

ATVs have been employed to transport wood, but for safety reasons it has been recommended that the total weight of a trailer and load not weigh more than the ATV and driver (Dunnigan et al., 1987). This would limit payloads to 800 pounds or so, but substantially larger loads have been reported or advertised for ATV-towed trailers or arches, e.g., 2000 lb (Dunnigan, 1990) or even 5000 lb (Moore, 1991). At even smaller scale are devices such as the Swed Caddy walk-in-front mini tractor (450 lb, 7 Hp, 2 mph, 2000 lb load capacity; Northeastern Technical Division Production Efficiency Committee, 1985) and Blue Ox human-powered arch (Altman, 1987), for which it is claimed a person can haul loads of up to 600 lb.

Continental Biomass Industries manufactures a conversion unit for forwarders, called a Brush Transport System, which increases capacity when carrying slash and small whole trees by compacting the material after loading (CBI-Inc., 2006) (Figure 7).

Cable yarder with carriage and chokers: A huge variety of cable yarders are available, although declines in harvest volumes over the last decade have reduced the number of North American manufacturers of purpose-built yarders to one – Madill Equipment (Madill Equipment, no date) – with a couple of others willing to produce a machine on order. Small yarders are available on special order from abroad (such as Koller, through Johnson Industries in Canada, (Johnson Industries Ltd, no date), or from the manufacturer in Austria (Koller Forsttechnik, no date)), and converted excavators are now quite common for cable yarding, e.g., the Yoader and Timbermast’r (Jewell, 2005a and 2005b). Yarders are used on steeper terrain where tractive skidding or forwarding is either infeasible or considered to have too much environmental impact. In most cases, therefore, trees will be felled by hand and be distributed throughout the treatment unit. To gather these, the yarding system must be capable of moving material laterally from within the stand to the skyline corridor. Locking, sequencing or line-operated slackpulling carriages are being replaced in many cases by self-powered, radio-controlled carriages because the latter can be used with simpler yarders and offer the rigging crew more control.
When small trees are scattered it may be difficult to accumulate large payloads. Biller and Peters (1987) invented a locking carriage that had two loadlines so twice as much area could be accessed for each turn. Their specific device didn’t work well because the two loadlines twisted between the carriage and their connection to the mainline, but the concept has potential.

Cable yarder with grapple: In some cases it may be possible to use machinery to fell and bunch or fell and process trees prior to cable yarding. Alternatively, trees or logs might be prebunched with a small winch. If through one of these means all the trees or logs are located adjacent to the yarding corridors, lateral yarding is not required. It also may be possible to use a grapple instead of chokers, eliminating much of the labor requirement and the time to set and release chokers. Cable-operated grapples are commonly used in Canada on clearcut operations. A combination cable/hydraulic grapple was recently developed by Eagle Carriage and Machine (Eagle Carriage and Machine Inc., 2008).

“Zig-zag” cable systems were imported from Japan and saw a brief period of interest (Miyata et al., 1987; Miyata and Aulerich, 1988; tested in several places in California including the Shasta-Trinity NF, Shingletown and Tahoe NF during the late 1980s and early 90s). They can be used on flat or steep ground. Such a system utilizes a capstan to drive an endless loop of cable continuously at slow speed around an area being treated. The cable passes through a series of closely spaced, open-sided blocks (pulleys) arranged in a zig-zag pattern to support the cable above the ground, but within reach of the crew members. A crew member drags or carries a piece of wood to the cable, ties a piece of twine around one end, lifts that end and ties it the twine to the moving cable, which then urges the wood on its way to the landing. The system is cheap ($10k purchase price and $3 per hour in the mid-1980s, Miyata et al., 1987). In the existing configuration, the system can only be used with pieces small enough to be dragged and lifted by hand. As this involves the use of human horsepower to move wood at a cost of on the order of $100 per horsepower-hour, it is in most cases not an economically justifiable system. Miyata et al. (1987) reported that two workers could yard 15 to 20 m³ in a day with 6 PMH.
A chip forwarder is similar to a log forwarder (described later), but has a bin to hold chips produced by a woods-mobile chipper within the stand. Chip forwarders are employed in some parts of Scandinavia, but not much elsewhere. As noted above, they are useful for long distances.

Loader booms and, more recently, processing heads have been mounted on cable yarders to allow the yarder operator to conduct a second activity while otherwise idle, which is generally the majority of the cycle time in partial-cutting operations, especially when radio-controlled carriages are used (Figure 8). These additions eliminate the need for second machines, but do not of course allow the machines to work at separate locations. That is not an unusual need for a loader, where trucking may lag behind the yarding operation somewhat.

![Figure 8. Yarde-processor.](image)

Source: McMass Industries

The Syncrofalke yarder-loader also incorporates automation of outhaul and inhaul to free the yarder operator to concentrate on loading during more of the yarding cycle. A computer controls most of the outhaul, delivering the carriage to the point of the previous turn. At that point, the choker setters take over control. The computer again comes into play on inhaul, stopping the carriage just before it reaches the landing to prevent safety problems (Visser and Pertlik, 1996).

Self-propelled carriages such as the Konrad Woodliner and TLD Gauthier Tele-Carrier require a skyline (and possibly a smaller static traction cable) but no moving lines such as a mainline or haulback, therefore are less capital-intensive than conventional cable yarders (Jamieson, 1999; Stampfer et al., 1998). Because the only power available is that in the carriage, however, and more power comes at the expense of a heavier carriage and therefore reduced payload capacity, these carriages are more likely to be competitive with conventional yarders where loads can be yarded downhill with the assistance of gravity. Downhill yarding usually requires a different roading scheme and can produce more damage to reserve trees than uphill yarding. Self-propelled carriages have been found to be less productive than conventional yarders, but the reduced productivity can in some cases be offset by the lower capital and operating costs (Corteau and Heidersdorf, 1991; Foronomics, 1998; Visser et al., 2001).

A conveyer belt is an ideal device for moving material – it can transport continuously and can be loaded to capacity all the time (if material is available to it). The problem is getting the conveyer
to the wood or vice versa. Also, conveyers typically require substantial setup time. We understand a conveyer system was proposed for fuel reduction operations on sensitive sites in the Tahoe Basin, but never came to fruition because of the above drawbacks. It may be possible to solve the setup problem with clever design. For example, a conveyer for transporting farm produce was recently developed in Great Britain (Gizmag, 2006). Up to three hundred feet of conveyer can be pulled into place by a tractor, then be inflated and ready for operation in minutes. This particular conveyer would not stand up to the loads imposed by logs or trees.

Crawler tractors were first developed for use in agriculture in the Sacramento-San Joaquin delta, but were soon found to be quite capable at log skidding. They preceded the widespread use of rubber-tired skidders by decades. Tracked machines travel slowly but can transport large loads, and they can travel on steeper slopes than can rubber-tired machines. Environmental concerns have limited steep-terrain skidding, and the shift to smaller trees has reduced the cases where the large pull capacity of crawlers can be put to use, so crawlers are less prevalent than in the past. Many sides employ a mix of rubber-tired machines and crawlers, with the latter handling construction of skid trails and landings, and skidding on steeper patches.

Forwarders – essentially off-road trucks – are the most common means of primary transport in Nordic countries, and parts of eastern Canada. They are also used in areas of the U.S. where small trees and relatively gentle terrain allow. They were introduced into California in the early 1990s (Hartsough et al., 1997), but never took hold to a large extent. At present, we believe two contractors in California (both in the Sierra) own forwarders. While these machines typically carry processed logs of 20 feet or less in length, they have been used to transport slash (Pottie and Guimier, 1986; Klepac et al., 2006), short whole trees and tree sections with branches (Jylha, 2004; Kvist, 1988). In some cases the forwarders have been equipped with grapple saws to buck the trees to shorter lengths when necessary. Jylha (2004) obtained load weights of 56% of capacity on a forwarder transporting tree sections of Scots pine. Long forwarders, e.g., from ARDCO (ARDCO, no date) are available to accommodate whole trees or tree sections.

Small radio-controlled prebunching winches allow full payloads of small, scattered trees to be accumulated prior to moving in a large cable yarder. They would essentially replace the lateral yarding elements of the cycle for the large machine, thus speeding the latter’s productivity. Some prebunching winches were commercially available in the past (e.g., LeDoux et al., 1987) but we know of none being manufactured at present.

Residue collector forwarder: FERIC developed a prototype for picking up down residues from a cutover, comminuting them and transporting them to roadside (DuSault, 1985b; Pottie and Guimier, 1986). The machine, called the RECUFOR, employed a horizontal-shaft rotor with curved teeth to pick up material and force it through a fixed set of knives, producing chunks of approximately 30 cm in length. The concept was dropped because of the movement at that time towards wholletree harvesting, and the machine was converted into the LRP mentioned above.

Clambunk-grapple skidders have three advantages over traditional grapple skidders that allow them to carry larger loads: 1) the load is carried further forward on the machine, transferring more weight to the wheels and thereby increasing traction and decreasing drag force of the skidded tops, 2) a large inverted grapple mounted above the rear wheels can hold more trees than
a traditional grapple behind and between the rear wheels, and 3) a separate boom-mounted loading grapple allows the machine to pick up trees from a larger area without having to back up to them (Figure 9). These skidders are currently manufactured by Fabtek, Tigercat, TimberPro and Trans-Gesco, while Valmet is apparently introducing one soon.

![Figure 9. Clambunk skidder. Source: TimberPro Inc.](image)

Cable skidders are appropriate for areas where trees are felled by hand and traffic is to be confined to designated skid trails, and for winching trees out of other areas that can not be traversed by equipment such as riparian areas or short-steep pitches.

Grapple skidders are the bread-and-butter primary transport machines for mechanized harvesting in California and much of North America. They are highly productive when loads are accumulated by feller-bunchers, can access more terrain than can forwarders, and produce little environmental impact if used by conscientious operators under appropriate conditions.

**D. Felling**

Chainsaws can be used to fell just about anything, but being jacks of all trades they are not very good for dealing with small trees. They are the only options for trees too large for machines, and on terrain where machines are deemed unacceptable.

Combination harvester-forwarders, sometimes called harwarders, were initially developed in Scandinavia for small parcels (Figure 10). A single machine reduces move-in costs because only one truck load rather than two is required to deliver the system to the site. However, the single machine costs more to purchase and operate than either of the two separate machines. Early versions had interchangeable heads. The harvester head was mounted on the boom while the machine cut and processed all the trees on a unit. It was then swapped for a grapple with which the machine collected the processed logs. Harvesting productivity is typically slightly less than for a harvester because of the interference of the forwarder bunks. Overall stump-to-landing cost, not considering move-in, is therefore higher than for a two-machine system. Some newer versions have single heads that can both harvest and load (Asikainen, 2004; Talbot et al., 2003). Some also have bunks that can be rotated about the vertical axis, allowing logs to be more easily...
processed directly into the bunks rather than onto the ground, eliminating rehandling of the logs and increasing productivity (Wester and Eliason, 2003).

Figure 10. Harwarder. 
Source: Pinox Oy

The current crop of harvester-forwarders were preceded some decades ago by the Koehring Short Wood Harvester, a huge machine produced in Canada in the late 1960s and early 1970s to fell, limb and buck small trees and transport the logs to roadside. Felling and bucking, however, was accomplished with shears (which cause some crushing damage) and all logs were cut to 8-ft lengths, so the product was acceptable only as pulpwood. The higher value of some of the material as sawlogs forced operators to switch to systems that could produce both sawlogs and pulpwood (Clow and MacDonald, 2001).

Feller-bunchers are very common in much of North America. A drive-to-tree machine, based on a three-wheel, four-wheel or tracked undercarriage, has a felling head attached to the front of the prime mover, so the machine must maneuver to each tree to be cut, and move while carrying cut trees to the spot where they will be bunched. This limits such machines to slopes of less than 20% or so. While there is a good bit of terrain in this category in California, most contractors must purchase equipment they can keep operating over the full range of conditions they will experience during the whole season, which for ground-based harvesting in the Sierra typically includes intermediate slopes as well as gentle ones. Therefore drive-to-tree machines are not seen much in California.

Swing-to-tree feller-bunchers may also be mounted on tracked or four-wheeled undercarriages, although most used in California are on tracks. The felling head is mounted on a boom which can be extended and swung to reach trees while the prime mover remains in one spot. The machine is therefore more stable while felling and bunching, allowing it to operate on steeper slopes than a drive-to-tree machine. Some models are equipped with self-leveling cabs, so the cab and boom are on horizontal platform even when the carrier is on slopes of up to 50%. Although these versions are more expensive than others, they are the most common for feller-bunchers in California because they can cover the full range of conditions seen in treatment units.
Jylha (2004) proposed a feller-bundler that would incorporate an accumulating felling head that could crosscut when necessary but not delimb, and a compacting and binding device to produce bundles of tree sections. The target was energywood from thinnings, expected to average about 10cm dbh and 0.05 m$^3$/tree. Bundles would then be transported by standard forwarders and on-highway trucks for chipping at the energy plant. A prototype of such a machine, called the Fixteri, has been developed by Biotekki Oy, and incorporates automated production of bundles of standard length (Figure 11). Based on the first trials, the machine is being redesigned. Production rate must double to be economically attractive (Jylha et al., 2007).

Selective feller-chippers and feller-chipper-forwarders: A few Scandinavian trials in the 1990s explored the possibility of replacing the boom-mounted grapple on a woods-mobile chipper-forwarder with a felling head so trees could be cut in selective thinnings and comminuted by the same machine. Felling was found to limit the productivity, so the combination could not be justified (Asikainen, 2004; Stén 2001). With current high prices of energy, there has been renewed interest as evidenced by the development in 2006 of the Valmet Combi BioEnergy, which has a chipper and 27-m$^3$ bin mounted on a self-propelled chassis (Figure 12). The felling head has a shear for cutting biomass trees and can hold multiple small trees. It also has a chainsaw, feed rolls and delimming knives for felling, delimming and bucking of roundwood. It
appears to be felling-limited for the very small sizes of trees diverted to the energy stream in Finland, however, and at 190 Hp would have limited capacity as a chipper compared to those typically utilized at roadside in the U.S.

Swathing feller-chippers and feller-chipper-forwarders: Some feller-chipper approaches have relied on non-selective swath-type felling devices rather than boom-mounted cutting heads. This simplifies the operator’s task and is feasible if the material to be cut is in the machine’s path rather than to the side. The Nicholson-Koch harvester was intended to fell and chip within a seven-foot swath all non-merch trees up to 18” in diameter remaining after a clearcut and collect and chip harvest residues and other down material as well. It was only effective with the latter if the material was oriented parallel to the machine’s direction of travel (Sirois, 1981, cited by Johnson 1989). It blew chips directly into one of a pair of chip forwarders while the other shuttled to roadside and back. The GP Jaws III was a contemporary machine of similar concept and power (600 Hp versus 575 for the N-K) but lower observed productivity (6 GT/PMH versus 26 for the N-K; Johnson, 1989). The Pallari harvester was developed in Finland for cutting, chipping and forwarding brushwood. It used a slow-speed rotary shear so as to be less sensitive to rocks than other cutting mechanisms. Chips were loaded into large bags rather than into a bin. The concept was brought to Canada and developed into the prototype Crabe Combine. It cut stems up to 15 cm in diameter (Sutherland, 1984). Another machine, combining a Cimaf head on a Scorpion base, was marketed in the late 1980s for cutting, chipping and forwarding (in an onboard bin) small trees and brush (Cormier, 1989). A public-private partnership in Texas developed a feller-comminutor for mesquite (Texas Farm Bureau, 2006). This device utilizes a standard brush cutter to fell the trees. The cutter’s prime mover tows and powers a second machine that uses a flail rotor to pick up and comminute the mesquite and deliver it to an onboard bin. The Texas group decided it was easier to fell and comminute separately, in contrast to previous efforts that had attempted to fell and comminute mesquite with the same head (Felker et al., 1999; McLauchlan et al., 1994; Ulich, 1983). Projected production rate is 5-10 acres per day, with 15 (we assume green) tons per acre.

An effort by North Carolina State University and a manufacturer (FECON Inc, 2008) has produced another cutter-chipper-collector based on an existing masticator design (Gregg, 2007; Figures 13a and 13b). It aims to remove understory material of up to six inches in diameter and has being tested on the Croatan National Forest in stands averaging up to 20 green tons per acre of this biomass. The first prototype was effective at collecting some material, but a high percentage was thrown out of the cutterhead’s shroud rather than being conveyed into the collector and therefore was left on site. The head is being redesigned with a larger collection volume behind the cutter and with other changes based on experience with the first version (Roise, 2008).

A machine developed around 1980 also felled a “swath” but the operator had to move the cutting shear laterally to each tree by positioning it along a track on the front of the prime mover (Bryan, 1980).

Other comminutors and brush cutters such as those described by Windell and Bradshaw (2000) might lend themselves to collection of the cut material.
Feller-forwarders of various sizes were produced by Koehring in the 1970s and 1980s (Figure 14). These very large machines cut trees with a boom-mounted head and dropped the whole trees into a bunk behind the cab. When full the machine traveled to roadside and offloaded the trees by tilting the bunk to the back, as would a dump truck. These machines were designed to clearcut relatively small trees from large areas on gentle terrain. They were expensive to transport on public highways because they had to be disassembled, but were ideal for large, contiguous blocks in areas such as eastern Canada. The Koehrings have been largely phased out due to a shift away from clearcutting of large units.

A “harvester”, as the term is now commonly used in forestry, refers to a machine that fells, delimbs and bucks trees into logs. It is the first of a pair of machines, the second being a forwarder, that makes up the mechanized “cut-to-length” (CTL) system. This system is prevalent in Nordic countries, parts of eastern Canada and elsewhere. As noted previously for forwarders, harvesters were introduced in California but have not captured a substantial part of the operations.
Over the past decade or so, Scandinavians developed harvester heads that would cut multiple small stems before processing them. These are somewhat similar to the accumulating feller-buncher heads developed in North America in the 1970s. They were shown to have higher productivity than single-stem heads, but have not gained much ground until recently due to apparently unfounded concerns about delimbing quality and length measurement accuracy (Thor and Thorsen, 2007). They have gained dramatically in popularity in the last year or so (Thorsen, 2008).

A tree puller head for drive-to-tree carriers was developed and marketed by Rome Equipment in the 1970s (Grillot and McDermid, 1977). It was similar to a feller-buncher head, but sheared lateral roots belowground so the majority of the stump could be extracted along with the tree. The device could not accumulate multiple trees before bunching. We do not consider stump removal to be desirable in the Sierra.

E. Loading

Chip dump/van loader: In most cases, hog fuel or chips are loaded directly into a van or transport container by the grinder or chipper. Another option is to deposit material into a stationary buffer which can load vans or containers when they become available. This approach might be utilized at a satellite processing yard.

Articulated, rubber-tired front-end loaders are highly productive and, equipped with log forks, can handle logs or whole trees on landings that have substantial surface area.

Excavator-based log loaders work extremely well on landings where space is very limited, such as when cable yarding on steep terrain to a truck road with no constructed landing other than the road surface.
F. Processing

As with felling, a chainsaw can process essentially any tree; no limb is too large to remove, and no trunk is too large to crosscut (if a large-enough bar is available). But for smaller trees, chainsaws can’t compete with mechanized processing in terms of productivity or cost, assuming the mechanical equipment can be fully utilized.

Researchers on the upper Midwest developed two prototypes, called a topwood processor and topwood processor-skidder, to buck bulky, spreading tops of hardwood trees into pieces that could be readily transported to roadside (Christopherson, 1983; Christopherson and Barnett, 1985). The latter machine also skidded the processed material. Given the scarcity of such hardwoods in fuel reduction operations in the Sierra, we won’t further consider these concepts.

G. Transport

Payloads may be limited by laws restricting the gross vehicle weight (GVW) or by the volume capacity of the specific vehicle. On-highway GVW limits depend on number or axles, wheels and spacing, but maximums for single vehicles are set by states or countries. Within California, maximum standard load – for an eighteen-wheel tractor/trailer – is 80,000 lb. Elsewhere in the world, legal on-highway loads range as high as 130,000 lb, and off-highway loads in Canada may be as large as 675,000 lb for truck-trains (FERIC, 1990).

Chip vans come in various sizes, but those in California are typically selected to reach legal weight capacity before they max out on volume. There is a tradeoff because a larger van has slightly higher tare weight and therefore less weight capacity than a smaller one, but this penalty is small compared to the case if a van reaches volume capacity first. If chips are very dry, as they might be if produced from trees that were dead for a few years, they may fill the cubic volume of a standard van before the weight limit is reached.

Chip vans don’t track the truck very well because the pivot point between the truck and trailer is far forward – at the fifth wheel. Therefore roads must be wider and/or have shallower curves than those for the stinger-steered log trucks typically used in California and the rest of the west coast of the U.S. and Canada. The U.S. Forest Service San Dimas Technology and Development Center is working on a stinger-steered chip van that would be able to access areas that cannot now be reached with standard vans (Haston, 2008).

Residue trailers: Uncompacted, uncomminuted residues such as tops and limbs are relatively fluffy and therefore will not fill a standard chip van to weight capacity. Scandinavian efforts have developed special high-volume vehicles, some equipped with compactors, for residues (Axelsson and Bjorheden, 1991). These probably would not satisfy length restrictions in California, nor would they be able to traverse many forest roads. They also have greater tare weights and therefore approximately 10% less payload weight capacity than standard log trucks.

Standard “west-coast” log trucks have trailers that are steered from a pivot point far behind the drive axles, allowing the trailer wheels to closely track those of the truck. When hauling log loads of 32 or longer, they can readily be loaded to full weight capacity before reaching volume
limits. For shorter logs (16-20 feet), a “short logger” hauling one load on the truck and another on the tractor can max out at legal weight. Alternatively, a short logger conversion, e.g., one produced by General Trailer (General Trailer Parts LLC, no date) can be added to a west-coast truck-trailer.

In some cases, standard or modified log trucks have been used to transport whole trees or tree sections with limbs, but there may be a substantial weight penalty because of the fluffy nature of material (Figure 16). Zundel (1986) found that standard log trailers loaded with whole-tree Jack pine carried only 44% of the merchantable volume on trailers loaded with limbed tree lengths.

Self-loaders: In some cases, such as small treatment units or when the production rate of the stump-to-road operation is very low, it’s hard to justify having a loader on site. Self-loading trucks provide an option, but cost more than conventional trucks and have lower payloads because they must carry the loader as well (Garland and Jackson, 1997; Figure 17). In Scandinavia, manufacturers produce self-loaders that can be decoupled from the truck after use, avoiding most of the payload penalty for all but the last load out of a unit (Axelsson and Bjorheden, 1991).
Setout trailers: Conventional chip vans can be decoupled from the truck’s fifth wheel and left on site for later loading, but stinger-steered log trailers cannot. Where roads allow, log trailers that attach to fifth-wheel tractors can be used to haul long or short logs.

Multi-use trailers: Most vehicles transporting material from the woods travel empty on the backhaul. In some cases, loaded backhauls may be possible, with or without some detour. FERIC evaluated multi-use trailers capable of hauling either logs or chips. In British Columbia, for example, they estimated that such vehicles could save $3 million dollars per year by hauling logs from the woods to sawmills, chips from the sawmills to pulp mills, and then returning empty to the woods (Brown and Michaelson, 2003). The net benefit clearly depends on the markets available (roundwood, pulp, energy), locations of facilities with respect to the woods and road network, and transport alternatives such as rail between facilities.

Roll-on/off containers: Trucks with or without trailers and hauling interchangeable containers can be used in place of chip vans where small amounts of chips, hog fuel or residues are being produced (Axelsson and Bjorheden, 1991). Trucks without trailers can haul containers on roads that are not up to chip van standards (Rawlings et al., 2004) (Figure 18). But the higher costs of extra containers and smaller payloads – especially with single containers with approximately 50 cubic-yard capacity versus chip vans of 90-100 cubic yards – creates a severe cost penalty. Hauling the first empty containers to be set out also has an additional cost because there is no load for the return trip. A recently developed container is tapered and can therefore be stacked (when empty) inside another for transport to the site (Thomas, 2008).

Figure 18. Truck with single roll-on/off container.  

Rail transport (and in the extreme, barge or ship transport) has considerably lower incremental cost per mile than on-highway transport. Biomass transport by itself will almost certainly not justify the installation of new rail lines, although transfer stations at existing spurs might extend the feasible transport distance in some specific cases.
III. Costs and Production Rates for the Identified Equipment

A. Individual Activities

For this purpose we must estimate several parameters for each type of equipment, including:

- Production rates, as a function of tree/piece size and other key variables
- Costs per unit of time, including those of ownership, operation and maintenance
- Operating constraints such as slope and tree size

Net cost of fire hazard reduction operations can be stated in several ways: cost per acre treated, cost per ton of material removed, cost per estimated reduction in loss, etc. Any of these can be translated into another by applying the appropriate conversion factor for a specific area in question. For purposes of this project – focusing on materials handling equipment – it seems best to select cost per unit of material treated or removed as the basis.

\[
\text{Net cost} = \text{harvest cost} - \text{product value}
\]

Where harvest cost is generalized to include all stand-to-utilization-facility operations such as felling, in-woods transport, processing and on-road transport.

Product value depends on type and character of product, and these can be affected by harvesting activities. For example, whole trees can be chipped, or delimbed and debarked and then chipped, or delimbed and bucked into roundwood. For a given mix of markets and product values, decisionmakers can determine the optimal allocation of raw material if they know the costs of various harvesting alternatives.

The harvesting supply chain usually involves more than one piece of equipment; the overall system cost is ultimately what is important. In some cases, e.g., where one activity such as felling is well buffered from subsequent activities such as skidding, the cost for one activity can be estimated without regard to other activities. In others where activities interact, such as chipping and chip transport, one activity influences the costs of another: chipping rate influences the productivity and cost of hauling, and availability of trucks affects the idle time of the chipper and therefore overall productivity.

Good engineering design practice attempts to break large problems into small, functionally independent parts so arrays of simpler solutions may be generated first for the subproblems, then combined and possibly consolidated to develop a more nearly optimal solution to the overall problem. We took a similar approach here, looking at elements of systems (and individual pieces of equipment) rather than complete systems. We are more likely to unearth ways of improving existing systems by dissecting them than by evaluating them as holistic black boxes.

For any activity:

\[
\text{Cost per unit of production*} = \frac{\text{cost per unit time}}{\text{production per unit time}}
\]

* bone dry ton (BDT) or other unit such as cubic foot
Time can be measured in years, days, hours or other units. The type of time must also be defined: scheduled time is that during which an operator or crew associated with a machine is being paid, while productive time is that during which the equipment is performing useful work, variously defined. The ratio of productive time to scheduled time is defined as utilization (UT). We focused on time in productive machine hours (PMH) or scheduled machine hours (SMH).

\[
\text{Cost per time} = \text{owning cost (depreciation + interest + insurance + property taxes)} + \text{operating cost (maintenance + repair + fuel + oil + lubricants + supplies)} + \text{labor cost (wages + burden)}
\]

\[
\text{Depreciation cost, $/PMH} = \frac{\text{initial cost} - \text{salvage value}}{\text{life, PMH}}
\]

Interest, insurance and taxes (IIT) costs can be approximated by:

\[
\text{IIT, $/PMH} = \text{IIT rate, \%/year} \times \frac{((\text{initial cost} + \text{salvage value}) / 2)}{\text{(UT \times SMH per year)}}
\]

\[
\text{Labor cost, $/PMH} = \text{crew size} \times \left(\frac{\text{average wage, $/SH}}{1 + \text{burden rate}}\right) / \text{UT}
\]

It is simple to include all cost elements in a spreadsheet for calculating hourly costs, and we did just that. For more conceptual analyses, however, it is easier to visualize if only the most important factors are included. For most harvesting equipment (chainsaws are notable exceptions), all three cost elements – owning, operating and labor – are significant contributors to the total cost, so they cannot be ignored even for simplified analyses.

When equipment is held for several years as is typical for harvesting operations, salvage values are relatively low compared to initial costs and can be ignored for first approximations. Maintenance and repair costs are described in much of the harvesting literature as fractions of depreciation costs (M&R fraction). We used this same approach. For all activities with the exceptions of comminution and secondary transport, the costs of fuel, oil, lube and supplies are relatively small compared to other costs. Wage rates are rather consistent across most types of equipment (chainsaw operators felling trees being the notable exception), as are burden rates, so the key element affecting hourly labor cost is the size of the crew associated with a piece of equipment.

For most harvesting activities, time can be broken into fairly definite cycles. For example, a secondary transport cycle usually includes four elements: travel empty, loading, travel loaded, and unload. With these cyclic activities:

\[
\text{Productivity, BDT/PMH} = \frac{\text{BDT handled per cycle}}{\text{PMH per cycle}}
\]

### 1. Results Based on Empirical Studies

We collected information from numerous empirical studies on the production rates of the more common biomass harvesting equipment such as feller bunchers, skidders, harvesters and forwarders, and several less common machines such as residue bundlers. Information on feller bunchers was taken from Gingras (1988, 1996), Gonsier and Mandzak (1987), Greene and

With this and other information such as repair and maintenance cost estimates and utilization rates (Brinker et al., 2002) entered into the Fuel Reduction Cost Simulator or FRCS (Fight et al., 2006), we used the machine-rate approach (Miyata, 1980) to estimate costs for several types of equipment considered relevant to California conditions.

Numerous factors can affect productivity, so we varied two important variables - tree size and slope – and held skidding, forwarding or yarding distance (one-way) at a representative value of 500 ft. For in-forest activities we considered three values of surface slope: 10, 30 and 60%. Some equipment is not applicable on the steeper slopes (30 and/or 60%), so the slopes we included were equipment-specific.

For purposes of the developing representative productivity and cost graphs, we covered a range of tree diameter at breast height (DBH) of 4-10”, and used a representative diameter-weight relationship shown below (Table III). For in-forest activities we also needed to assume representative levels of removals (trees per acre) and, as a consequence, total tons per acre in the trees to be removed, also shown below. (Due to in-forest processing and breakage, the total weight removed is somewhat less than the total available, with the percentage loss depending on the system.)

Table III. Representative diameter-weight relationship for DBH from 4” to 10”.

<table>
<thead>
<tr>
<th>DBH, in</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total weight per tree, green lb</td>
<td>125</td>
<td>212</td>
<td>326</td>
<td>469</td>
<td>642</td>
<td>848</td>
<td>1088</td>
</tr>
<tr>
<td>Trees/ac removed</td>
<td>500</td>
<td>350</td>
<td>250</td>
<td>190</td>
<td>150</td>
<td>120</td>
<td>100</td>
</tr>
<tr>
<td>Total GT/ac in trees removed</td>
<td>31.3</td>
<td>37.1</td>
<td>40.7</td>
<td>44.5</td>
<td>48.2</td>
<td>50.9</td>
<td>54.4</td>
</tr>
</tbody>
</table>
Productivity and cost results for various equipment types are shown and described below.

![Drive-to-tree Fell & Bunch](image)

**Figure 19.** Representative productivity and cost of drive-to-tree feller bunchers versus tree size, on 10% slopes. Drive-to-tree machines are generally limited to gentle slopes because of stability problems on steeper terrain.

Productivity for drive-to-tree feller bunchers is very sensitive to tree size, increasing by a factor of approximately five across the displayed range of tree size (Figure 19). This is primarily due to the character of these machines, which are piece-handlers, driving to each tree cut, no matter what the tree size. Because the equipment must be sized to the largest tree to be cut, it is not possible to downsize the equipment very much when attempting to remove smaller as well as larger trees. Even if downsizing were possible, the economically optimal machine size is not substantially smaller for small trees than for larger because machine stability and production rate are more sensitive to machine size than are capital costs and hourly costs.

Productivity changes by a factor of three or so over the range of tree size, also due to the piece-handling character of the functions associated with the boom (Figure 20). Unlike the move-to-tree machines, the undercarriage travel for swing-boom machines is not piece-related, accounting for the lower sensitivity of productivity to tree size. However, the swing-boom machines have higher capital and hourly costs due to their greater complexity, therefore their cost per ton is higher than for drive-to-tree machines over most of the range of tree size.

Chainsaw operations are very sensitive to tree size, by a factor of seven across the considered range, because of the piece-handling aspect of moving to and preparing the tree for felling and the cross-sectional area (rather than volume) effect on felling times (Figure 21). While chainsaws have much lower productivities than do feller bunchers, they are cost-competitive because of their negligible capital costs and therefore low hourly costs (mostly labor). From a system standpoint, however, chainsaws provide none of the downstream benefits produced by mechanized felling and bunching, and are some of the most dangerous equipment in harvesting.
Figure 20. Representative productivity and cost of swing-boom feller bunchers versus tree size and slope.

Figure 21. Representative productivity and cost of felling with chainsaws versus tree size and slope.

Empirical studies of felling alone show little or no effect of slope, because fellers tend to walk on the contour between trees rather than up and down slope. (More extensive studies would probably be able to detect significant increases in time on steeper slopes.) Not having to process the felled trees allows the saw operators to avoid many of the difficulties they might otherwise encounter on more rugged terrain.
Figure 22. Representative productivity and cost of felling, limbing and bucking with chainsaws versus tree size and slope.

As with chainsaw felling, the combination of felling and processing is very sensitive to tree size (by a factor of 7 to 9 in the relationships shown above, Figure 22). In addition to the piece-handling aspect of moving to and preparing the tree for felling, there are cross-sectional area effects on felling and bucking times. Measuring and delimming are length-related rather than volume-related.

Chainsaw felling and processing is much less productive than mechanized cut-to-length harvesting, but again is cost-competitive because of the low hourly cost. When the whole system is considered, however, chainsaws are disadvantageous for small trees.

The productivity of skidding of bunched trees is rather insensitive to tree size; our representative cases show an increase of only 30-40% across the 4-10” range of tree size (Figure 23). This is true because skidders do not handle individual trees; they pick up bunches and transport grapple loads of multiple trees. For larger trees the load weight may be power-limited; for smaller ones it is constrained by the cross-sectional area of the skidder’s grapple, but skidders can compensate for smaller loads somewhat by traveling at higher speeds, also allowing them to operate near a power-limited condition while loaded.

Loading and unloading times are relatively short, the former effect being a result of the mechanized bunching (a full load might consist of as little as a single bunch) and the latter due to the simplicity of dropping a skidded load from a grapple. As a consequence, total skidding time per load is close to directly proportional to skidding distance, other factors being equal. To illustrate, for the 10” trees and 10% slope case and 500-ft skidding distance, loading and unloading represents only about a quarter of the cycle time, and only about a minute per green ton. As explained later, this contrasts with the case for forwarding.
Figure 23. Representative productivity and cost of skidding bunched whole trees versus tree size and slope.

In contrast to skidding of bunches, the productivity of skidding of unbunched trees is fairly sensitive to tree size, increasing by a factor of three or so over the considered range of tree size (Figure 24). This is primarily due to the loading element of the skidding cycle for unbunched trees: a machine that should be power-limited is relegated to a piece-handling mode while collecting scattered trees that must be carefully maneuvered from between the leave trees. For the smallest trees, unbunched skidding of unbunched trees is only a quarter as productive as skidding of bunched trees, and yet the skidder configurations and hourly costs are essentially identical. This is a glaring example of the potential effects of one activity (felling in this case) on a subsequent one (skidding), even when there is no interactive delay between the two activities.

Figure 24. Representative productivity and cost of skidding unbunched whole trees versus tree size and slope.
Yarding productivity when handling unbunched trees approximately doubles over the range of tree size (Figure 25). Yarding is less sensitive than is skidding (of unbunched trees) because several small trees can be accumulated on the same lateral outhaul-hook-lateral inhaul sequence, so the yader is not operating in a piece-handling mode. Chokers can be preset for a subsequent turn while the previous turn is being transported to the landing and unhooked, so the serial hooking time can be less sensitive to the number of pieces hooked than if the logs were choked during the hook element.

Yarding productivity is not very sensitive to slope because, unlike tractive operations, there is no efficiency loss due to slippage, nor concern about stability on steeper ground.

While cable yarding is somewhat more productive than skidding of unbunched logs, it is nevertheless somewhat more expensive. This is due to the higher capital cost of a yarding system compared to a skidder of similar power, and the substantially larger crew required for yarding. While a grapple skidder requires a crew of one – the operator – a yader involved with partial cutting (versus clearfelling) requires at least two people – the operator and a choker setter – and possibly several more: a hooktender to lay out rigging for subsequent corridors, multiple choker setters and/or a rigging slinge, and a chaser to unhook chokers at the landing. Whether the yadering crew has two or more people, some crewmembers are idle during a portion of most yading cycles while waiting for activity that is not under their control to be completed. In contrast, a grapple skidder operator is fully occupied during all normal elements of the skidding cycle.
Figure 26. Representative productivity and cost of chipping whole trees versus tree size.

Based on the limited number of empirical studies considered, chipping productivity approximately doubles across the considered range of tree size (Figure 26). In concept, chippers are limited by either cross-sectional area of the material being fed or by machine power, so little sensitivity to tree size might be expected. However, many more small trees must be fed to achieve the same feed rate in terms of weight (approximately ten 4” trees to equal the weight of one 10” tree), so the operator and infeed grapple capabilities are more limiting than power for the smaller trees.

Cut-to-length harvesters are sensitive to tree size, with productivity increasing by a factor of six across the range of tree size (Figure 27). Harvesters share this sensitivity with other felling methods and for similar reasons: the acquire and fell functions are piece-handling rather than volume- or weight-limited. The rate of processing (delimbing and bucking) is generally limited by a linear throughput speed, with stops for each bucking cut. As volume and weight throughput are more affected by diameter and cross-section than length, the processing rate is also relatively sensitive to tree size as indicated by DBH.

Processing accounts for a substantial portion of each harvesting cycle. The above results apply to single-tree harvesters, on which all included empirical studies were based. Some relatively new multi-stem harvesting heads have the potential to increase production rates for small trees.

The productivity of CTL forwarding increases relatively little – by a factor of about 1.4 – from the small end to large end of the range of tree size (Figure 28). This is a result of the CTL harvesting activity, which converts trees of all sizes to logs of uniform length. Because forwarders can be fully loaded with small logs or large logs, the travel empty and travel loaded elements of each cycle are not affected by tree size. Only the loading and possibly unloading involve handling of the logs by the boom and grapple. When loading, it is generally easier to pick up more weight in a single grapple load if the logs are larger, so loading is somewhat
affected by average log size and therefore tree size. Unloading is not impacted greatly by log size because the logs to be unloaded are neatly compacted within the bunks of the forwarder.

![CTL Boles Harvest graph](image)

**Figure 27.** Representative productivity and cost of felling and processing with a cut-to-length harvester versus tree size and slope.

![CTL Boles Forward graph](image)

**Figure 28.** Representative productivity and cost of forwarding cut-to-length logs versus tree size and slope.

The sensitivity shown above is partly indirect; based on our assumptions, there is less total log volume and weight to be removed per acre for smaller trees. This results in the forwarder having to travel a longer distance while accumulating a full load. Loads are usually accumulated on the
return to the landing, so travel while loading may displace some travel loaded, but the additional starting and stopping while accumulating the load has an adverse effect on cycle times. Unlike skidding, the time to forward a load increases much less than proportionally with travel distance within the typical operational range. This is a result of the substantial “terminal” times involved with loading and unloading, each of which requires at least several and in some cases dozens of grapple loads. For the 10” trees and 10% slope case (at forwarding distance of 500 ft), loading and unloading account for roughly two-thirds of the total cycle time, and approximately two minutes per green ton.

Several factors affect the overall productivities and costs of skidding and forwarding: loading and unloading times, load sizes (generally four to six times as large for forwarders than with skidders), travel speeds (slower for forwarders) and hourly costs (30-50% more for forwarders than for skidders of similar power). In general, forwarding cost per ton is less sensitive to distance than is skidding cost (due primarily to the much larger load size), but forwarding is costlier than skidding at short distances (due to the large loading and unloading time per ton). For our representative case with 10” trees on 10% slope, skidding and forwarding break even at a rather long one-way travel distance of about 1500 feet.

The results for cable yarding of CTL logs are based on only one empirical study, so they are less precise than for other activities. Productivity is estimated to increase by a factor of three from small to large trees (Figure 29). A substantial portion of this is probably due to the indirect effect of our assumption of removing less material per acre when handling smaller trees. When yarding CTL logs, a single choker is placed around a whole pile of logs created by the harvester, so there is no direct effect of log size on load size. With smaller trees, however, the harvester may create more piles, each of less volume.

![Yard CTL Boles](image)

**Figure 29.** Representative productivity and cost of cable yarding of cut-to-length logs versus tree size and slope.
Based on the one study, yarding of CTL logs is estimated to be 20% less productive than yarding unbunched trees for smaller trees, and 40% more productive for larger trees. The latter makes sense, as the accumulation of logs makes it easy to hook the turn. The former may be valid or an anomaly. Conceptually, it doesn’t make sense to cut very small trees into smaller pieces before handling them: they should be combined rather than divided. This argues for the result being valid. On the other hand, the harvester did accumulate logs in small piles, so the result for the smallest trees could be suspect.

Yarding of CTL logs is both less productive and considerably more expensive (three to seven times more on 30% slope) than skidding of bunched trees. This is caused by the inherent disadvantages of cable systems: high capital cost and relatively large, underutilized crews (due to unavoidable interactive delays between the yarding cycle elements).

![Chip CTL Boles](image)

**Figure 30** Representative productivity and cost of chipping cut-to-length logs versus tree size.

As with chipping whole trees, the productivity of chipping of CTL logs approximately doubles from the small to large end of the range of tree size, and for the same reasons (Figure 30). In addition, chipping of short logs is less productive because of the additional feeding activity (by operator and grapple loader) necessary to supply a given weight of material. Essentially, the infeed method rather than the chipper is the limiting element.

The effect of tree size on bundling is not very large – productivity decreases by about 15% from the smallest to largest trees – and is indirect, being the effect of residue weight removed per acre (Figure 31). It is related to our assumptions about the numbers of trees removed per acre, average tree weight and the fraction of total tree weight that is removed by the CTL harvester during processing. The third point is important here: smaller trees have a higher percentage of weight in the unmerchantable top and branches than do larger trees. The net effect for the representative assumptions is: residue weight removed per acre decreases as average tree size increases, from
about 9 GT/acre with 4” trees to 5 GT/acre for 10” trees. If residue weight per acre were the same for different tree sizes, the bundling productivities would also be very similar.

![Graph](image)

**Figure 31.** Representative productivity and cost of bundling in-forest residues left by cut-to-length harvesting versus tree size.

![Graph](image)

**Figure 32.** Representative productivity and cost of forwarding bundled in-forest residues left by cut-to-length harvesting versus tree size and slope.

As for bundling, the apparent effect of tree size on the productivity of bundle forwarding is purely the effect of the amount of residue per acre (Figure 32). If fewer bundles are scattered over each acre, the forwarder must travel farther to accumulate a full load. If the residue volume
per acre was constant, so would productivity. Bundling is a great equalizer, and produces uniform packages that can be readily and efficiently handled by a forwarder, independent of the sizes of the trees from whence the residues came.

![Chip Bundled CTL Residues](image)

**Figure 33.** Representative productivity and cost of chipping bundled residues versus tree size.

Productivity of chipping bundles is unaffected by tree size because all bundles are created approximately equal – in weight, length and diameter (Figure 33). The slight increase in cost with tree size (about 4%) is due to the assumption that a somewhat larger chipper will be used if larger trees and their residues are being chipped. (A larger chipper may not be necessary.)

2. Conceptual Evaluation of Equipment and Systems

Based on the generic evaluation of costs described above, we can identify factors that result in low cost per dry ton, given other factors are the same:

- Low initial equipment cost
- Long equipment life (in productive hours)
- High utilization rate
- High scheduled time per year
- Low maintenance and repair fraction
- Small crew size
- Large cycle weight, BDT
- Short cycle time

Some of these provide rather obvious ways of improving the situation. For example, scheduled time per year can be increased by operating over a longer season or by double-shifting. Where weight is a possible limiting factor, such as in on-highway transport, dry weight per cycle might
be increased by pre-drying of material. But influences of the other factors are not obvious because they are usually coupled: reducing crew size associated with a cable yarder may decrease average cycle weight or increase cycle time. A more revealing approach is needed.

It can be useful to generate conceptual/theoretical ideals for various harvesting activities and then compare the identified types of equipment with ideals to highlight potential areas for improvement. Beginning with the three basic functions – gathering, processing and transport – identified in (II) above, we described what might make a machine perform these functions better.

**Objectives (i.e., more or less is better) for functions**

To improve (reduce) the ratio of machine cost to production rate, one should attempt to:
- Maximize the use of the (load-carrying or other weight-unit throughput) capacity of the equipment.
- Maximize utilization of the machine’s power, defined as average power output over the duty cycle divided by rated power.
- Maximize work efficiency of the equipment, defined as useful work done over energy consumed.
- Improve the equipment’s utilization rate by minimizing interactive delays.
- Maximize the duty cycles of the components of the equipment.
- For multifunction machines, maximize the parallel (rather than series) operation of functions.

To reduce cycle time:
- Minimize acceleration and deceleration (versus continuous motion).

To reduce crew size for a given level of productivity:
- Substitute sensors and/or machine intelligence and control for human control.
- Minimize the mental complexity of the task so an operator’s productivity can be increased.

To maximize utilization rate:
- Minimize interactive delays between activities.

To reduce labor cost per cycle volume:
- Maximize the labor duty cycle (active time per scheduled time)

At the machine or system level, to reduce time and cost per ton:
- Minimize handling or double-handling of material.
- Minimize fixed move-in costs per ton.

To minimize time per ton for in-stand gatherers/acquirers:
- Maximize the area that can be covered per unit time = travel speed * swath width.

To minimize owning costs:
- Maximize equipment life

To minimize operating costs:
- Minimize maintenance and repair fraction

The combination of a taxonomy and organized means of evaluating current methods provided a logical approach for identifying existing deficiencies and ways to remedy them.
Examples for the Gathering Function

- Maximize the use of the weight throughput capacity of the equipment. Ideal might be a grain combine header; grapples that pick up a constant cross-section of pieces of a given length are good; a shear head that cuts one stem at a time is not good for stems substantially smaller than the machine’s capacity.
- Maximize utilization of the machine's power, defined as average power output over the duty cycle divided by rated power. Ideal might be a variable-speed combine, where speed can be increased if crop density is lower.
- Maximize work efficiency of the equipment, defined as useful work done over energy consumed. (Probably not a valid measure for gathering.)
- Maximize the duty cycles of the components of the equipment. Ideal is a machine such as a grain combine in which most components work simultaneously and continuously.
- Minimize acceleration and deceleration (versus continuous motion). Ideal is a constant-velocity combine header or another type of swath harvester. Feller-bunchers (especially drive-to-tree) or loading grapples that start and stop, and move back and forth are not so hot.
- Substitute sensors and/or machine intelligence and control for human control. Ideal might be a load-sensing, constant-power, adjustable-speed combine with height-sensing and automatic height adjustment. A feller-buncher or loading grapple for which the operator must do all the sensing and manipulate complex controls is at the bottom end.
- Minimize the mental complexity of the task so an operator's productivity can be increased.
- Maximize the labor duty cycle (active time per scheduled time). Ideal is a fully occupied crew, such as a combine operator (or maybe even an operatorless combine).
- For gatherers, maximize the area that can be covered per unit time = travel speed * swath width. Ideal would be a wide swath and high speed, e.g., a two-row tomato harvester is better than a one-row machine if travel speeds are equal. For a tree plantation, an excavator-based feller-buncher that can reach five rows but travels slowly may be as good or better than a single-row harvester that travels relatively fast.

Examples for the Processing Function

- Maximize the use of the weight throughput capacity of the equipment. Ideal might be a chipper being fed a constant, full cross-section of material. Single-stem delimbers aren’t utilized fully when tree diameter is below the machine’s capacity.
- Maximize utilization of the machine's power, defined as average power output over the duty cycle divided by rated power. Ideal might be a stationery chipper being fed at maximum capacity.
- Maximize work efficiency of the equipment, defined as useful work done over energy consumed: Chippers with sharp knives are efficient; hammer hogs are less so.
- Maximize the duty cycles of the components of the equipment. Ideal is a chipper.
- Minimize acceleration and deceleration (versus continuous motion). Ideal is a chipper. Hotsaw-equipped feller/bunchers are better than intermittent saws or shears.
• Substitute sensors and/or machine intelligence and control for human control. Ideal might be a diameter- and length-sensing processor head, with a matrix of log values by diameter and length.
• Minimize the mental complexity of the task so an operator’s productivity can be increased.
• Maximize the labor duty cycle (active time per scheduled time). Ideal is an operatorless chipper.

Examples for the Transport Function

• Maximize the use of the (load-carrying or other) capacity of the equipment. Ideal is a fully loaded conveyer belt; chip vans have good capacity utilization while loaded if cubic volume is not limiting due to low density of material; log forwarders get high marks, skidders get low marks for small trees because grapple area becomes limiting (Figure 34).

![Figure 34. Conveyer at biomass power plant. Source: Peter Dempster](image)

• Maximize utilization of the machine's power, defined as average power output over the duty cycle divided by rated power. Ideal is a fully loaded constant-speed conveyer belt, or constant-power belt with adjustable speed; cable yarders do poorly, skidders are in between.
• Maximize work efficiency of the equipment, defined as useful work done over energy consumed. Ideal is a fully loaded constant-speed conveyer belt (or constant-power belt) that raises a load, with a high efficiency drive train. (If there is no lifting, useful work could be zero. An alternative measure would be ton-miles per energy consumed.)
• Maximize the duty cycles of the components of the equipment. Ideal is a machine such as a conveyer in which all components work simultaneously and continuously.
• Minimize acceleration and deceleration (versus continuous motion). Ideal is a constant-velocity conveyer.
• Substitute sensors and/or machine intelligence and control for human control. Ideal might be a load-sensing, constant-power, adjustable-speed conveyer with no operator.
- Minimize the mental complexity of the task so an operator’s productivity can be increased. Ideal might be an automated rail system where the operator provides only oversight. The other extreme might involve a machine with a manual transmission traveling around obstacles on rough terrain.
- Maximize the labor duty cycle (active time per scheduled time). Ideal is a fully occupied crew, such as a cross-country truck driver.
- For gatherers that collect distributed material. Maximize the area that can be covered per unit time = travel speed * swath width.

Equipment or system-level examples:

- Maximize the utilization of the components of the equipment. Single-function machines such as feller/bunchers and skidders get higher marks than multiple-function machines such as combination harvester/forwarders unless the multiple functions work in parallel.
- Minimize interactive delays between activities. Ideal is any buffered equipment such as a combine or a conveyor with a large infeed bin and large output storage. Systems with buffers between activities, such as cut-to-length harvesters and forwarders, do well.
- Minimize double-handling of material. Ideal might be a chip van loaded by a chipper so no separate chip loader is needed. An even better example is a chain flail debarker-chipper. A cut-to-length harvester head is good because it grips a tree only once before conducting multiple operations – felling, delimbing and bucking, but the rest of the cut-to-length harvesting system, which involves handling multiple small pieces downstream of the harvester, is not so good. (Better to leave trees whole for as long as possible so handle fewer pieces. An analogy: Use high-speed, low-torque components as far along a mechanical drivetrain as possible.)
- Maximize the time during which the operator is using the brain. Harvesters do well; chippers with operators do not.
- Minimize the mental complexity of the task so an operator’s productivity can be increased. Hand-in-glove or other intuitive controls are preferable than, say, a bank of separate control levers, one for each cylinder or motor on a feller/buncher, harvester or loader.
- Minimize fixed move-in costs per ton. Ideal might be a log truck that has no move-in time. CTL is better than a whole-tree system that involves more equipment.
- Maximize equipment life. Ideal might be a cable yarder because it sits in one place most of the time while working, therefore it sees relatively low wear and tear. A stationary chipper is another good example.
- Minimize maintenance and repair fraction. Ideal might be an irongate delimber. Cable yarders, especially those equipped with clutch-and-brake drivetrains (versus hydrostatic) have low repair costs because of their relatively static locations and simple drivetrains.

Limits on throughput/productivity

Another way of gaining insight about equipment capabilities is to look at what limits a concept’s throughput, especially when dealing with smaller stems to be addressed in fuel reduction operations. Some of the more obvious limits:
• Power. This obviously limits production for most equipment at some point in the production cycle, but in most cases is not limiting for smaller trees.

• Diameter capacity. Many pieces of equipment – feller bunchers, harvesters, processors and chippers, for example – have upper limits on the diameters of trees or logs they can handle; a few such as grapples have lower limits, but the lower limits may not come into play very often because the equipment will handle multiple small stems or logs.

• Weight capacity. Log trucks and chip vans are limited by legal weight restrictions; other equipment such as swing-to-tree feller bunchers or loaders are limited by design to maximum loads that vary with reach.

• Volume capacity. Chip vans may be limited by cubic volume capacity rather than legal weight if the bulk density of the chips or other material being handled is low. Volume limits are more restrictive for small trees and residues because of their lower bulk density.

Other limits are less obvious but very important when utilizing given equipment for a range of tree sizes.

• Length throughput capacity. Some equipment, such as a ring debarker for a sawmill, processes single logs at a fixed linear speed. Therefore if the average log diameter drops by a factor of two, the volume throughput of the debarker drops by a factor of four.

• Cross-section area handling capacity. Some equipment is limited by the area of material it can hold or process. For example, a grapple skidder is limited by the area of its grapple opening in situations where power or pull are not limiting. Volume-handling capacity per turn is therefore proportional to length of the trees and is less for smaller trees.

• Piece throughput capacity. A non-accumulating feller/buncher is a good example of a piece handler. It can cut a relatively fixed number of trees per hour independent of tree size. Since tree volume is roughly proportional to the cube of tree diameter, volume-handling capacity of this type of equipment may drop by up to a factor of eight when the average tree size is decreased by a factor of two.

Machines that can operate at their weight capacities or power limits whether trees are large or small might be considered ideal configurations. Those that handle a relatively fixed number of pieces per time are clearly the worst for dealing with a range of tree sizes. One of the biggest challenges and opportunities for developers of new equipment is to shift from piece-handlers and other configurations that are piece-size sensitive, to designs that can handle small trees as effectively as larger ones. The measures of the various objectives and limits are summarized in Table IV.

We used this evaluation procedure to compare types of equipment that carry out similar activities.

From Table I we selected three felling-only machine categories: chainsaw, drive-to-tree feller buncher and swing-to-tree feller buncher. We added a variation – a hot saw cutting head versus an intermittent cutting head such as another type of saw or a shear – as another option for the swing-to-tree machine. As a “close to ideal” machine we also included a prototype harvester – the Hyd-Mech FB-12 – developed under contract to the National Research Council of Canada in the 1980s to harvest energy plantations of single-stem short-rotation woody crops such as poplar
or sycamore, of up to 12” butt diameter. The Hyd-Mech was intended to harvest straight rows of trees on relatively flat ground so the concept not directly applicable to forest biomass harvesting in California.

We then assigned values (0 = worst possible, 10 = best possible) to each of the first ten measures listed in Table IV for each of the three functions (with the exception of transport for the chainsaw which is not generally used to bunch trees) and for the overall machines. The results of this example evaluation are displayed in Figures 35 through 38. They show substantial differences between the types of equipment on certain measures, helping identify potential areas for improvement to existing equipment.

We evaluated extraction equipment from Table I in a similar fashion (Figures 39 through 41).

Table IV. Matrix of measures of objectives by function.

<table>
<thead>
<tr>
<th>Measure</th>
<th>Gather</th>
<th>Process</th>
<th>Transport</th>
<th>Overall Machine</th>
</tr>
</thead>
<tbody>
<tr>
<td>Use of (load weight-carrying or other throughput) capacity</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Utilization of machine's power</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Work efficiency</td>
<td></td>
<td></td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Duty cycles of components</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>Parallel use of components</td>
<td></td>
<td></td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>Acceleration and deceleration</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
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<tr>
<td>Sensors/machine intelligence vs. human control</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Mental ease of the task</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Labor duty cycle</td>
<td>x</td>
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<td>Area covered per unit time</td>
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<td>Interactive delays</td>
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<td>Handling/double-handling of material</td>
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<td>x</td>
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<tr>
<td>Fixed move-in costs per ton</td>
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<td>x</td>
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<tr>
<td>Equipment life</td>
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<tr>
<td>Maintenance &amp; repair fraction</td>
<td></td>
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<td>x</td>
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<tr>
<td>Limits (Weight, Volume, Area, Length, Piece)</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td></td>
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</tbody>
</table>
Figure 35. Comparison of the efficacy of five different types of felling equipment for several measures related to the move-to-tree function.

Figure 36. Comparison of the efficacy of five different types of felling equipment for several measures related to the cut function.
Figure 37. Comparison of the efficacy of five different types of felling equipment for several measures related to the bunching function.

Figure 38. Comparison of the efficacy of five different types of felling equipment for several measures related to overall machine operation.
Extraction: Gather (Pick Up Load) Function

Figures 39a and 39b. Comparison of the efficacy of 14 different types of extraction equipment for several measures related to the gathering function.
Figures 40 a and b. Comparison of the efficacy of 14 different types of extraction equipment for several measures related to the transport function.
Figures 41a and 41b. Comparison of the efficacy of 14 different types of extraction equipment for several measures related to overall machine operation.
B. Systems Approach

With this approach we began with the harvesting and utilization activities that must or may be accomplished and look at possible paths through the network of activities.

Design Principles

Figure 42 shows possible processes (modeled as nodes) and material forms (links) as material is transferred from one process to another in forming possible treatment systems. When designing a system from scratch, or trying to improve on an existing system, it is beneficial to begin with a set of basic design principles, somewhat in parallel with the objectives mentioned previously. We propose the following, to be used in identifying areas for improvement in existing systems.

1. Use the human brain and machine brawn. A person can generate on the order of a fifth of a horsepower for long periods. If the cost of that person with overhead is $30 per hour, the cost per unit of power output is well over $100 per horsepower-hour. In contrast, a 200-Hp skidder has an hourly cost, including operator, of approximately $100, for a cost per unit of power of well under $1 per horsepower-hour. Activities that require substantial power, such as moving wood, clearly should be carried out by machines rather than humans. Systems such as zig-zag yarding systems that require humans to move wood are working at extreme economic disadvantages. In addition, as a skidder is reduced in size and approaches the zero end of the power scale, it approaches the human cost-to-power ratio. This is one reason the optimal size of machine does not decrease in direct proportion to the size of the trees or logs being handled.

2. Take advantage of economies of scale. In most cases, the capital and operating costs of equipment do not increase in direct proportion to size, so the cost per capacity decreases as capacity increases. To give a simple example why, consider a spherical tank. The volume of the tank increases with the cube of its diameter. The material needed to fabricate the tank is mostly in the shell, but the surface area of the shell increases with only the square of the diameter rather than the cube. The moral is: use higher capacity equipment if the capacity can be reasonable well utilized.

3. Fully utilize payload weight capacities, in contrast to volume capacities. For energy feedstock, value is based on energy content. For woody biomass of a given moisture content, energy content depends on weight, not on bulk volume. The energy content per weight may be increased by drying or by converting to another material such as bio-oil.

4. Densify on-highway loads, to a point. Transport is constrained by several legal limits including gross weight. Vehicle height, width and length also are limited, and the product translates into a volume limit. While permits can be purchased for special cases where the limits can’t be met, the associated costs make these economically unattractive for everyday operations. Standard vehicles have rather uniform tare weights and cubic volume capacities. For example, a chip truck might have a payload limit of 50,000 lb (80,000 lb gross limit – 30,000 lb tare) and a volume capacity of 2700 cubic feet (100 cubic yards). The weight limit can therefore be reached if the material bulk density is about 18.5 lb/ft$^3$ or greater. Based on reported densities for various materials (Figure 43), it’s clear that some materials such as pellets are over-densified for transport in a standard chip van, while others such as uncomminuted slash exact a large penalty in payload and therefore should be densified prior to transport.
Figure 42. Network of possible processes (nodes) and forms of material (links) between standing trees and utilization facilities.
Figure 43. Density of various forms of woody biomass, assuming 50% moisture content, wet basis, except for pellets (10% moisture content).

5. Handle small pieces in bulk or in big packages. Piece-handlers require approximately the same amount of time to handle each single piece, independent of piece size. For example, a fork transports a piece of pizza to the mouth in the same amount of time, no matter whether the piece is a half-inch square or four square inches. A feller-buncher is somewhat similar, although accumulators allow the handling of more small pieces before bunching (Figure 44). Since tree volume (and weight if solid density is constant) is approximately proportional to the cube of diameter, the weight handled per time diminishes dramatically as tree diameter decreases. Length handlers such as ring debarkers or stroke delimbers have an approximately constant linear throughput rate (Figure 45). Volume (and weight) throughput is proportional to length times cross-sectional area, so it is proportional to the square of diameter. Area handlers such as grapple skidders transporting small trees are limited by the cross-section area of the grapple: more small trees than larger ones can be held in the grapple (Figure 46). Volume, however, is the product of length and area, and tree length for small trees may increase in almost direct proportion to diameter. Volume handlers such as forwarders are limited by the width of the bunks, height of the stakes and lengths of the relatively short logs loaded, all of which may be independent of tree diameter (Figure 47). The weight on a forwarder, however, will depend on the bulk density of logs. Weight handlers are ideal because they are insensitive to either piece size of bulk density. A barge, for example, can in theory be loaded until its weight limit is reached. Materials of lower bulk density can be accommodated by adding relatively light side panels to the barge (Figure 48).
Figure 44. Example of a piece-handler – a feller-buncher
Source: Bruce Hartsough

Figure 45. Example of a length handler – a ring debarker

Figure 46. Example of an area handler – a grapple skidder.
Source: Bruce Hartsough

Figure 47. Example of a volume handler – a forwarder.
Source: Bruce Hartsough

Figure 48. Example of a weight handler
Figure 49. Harvester-chipper-forwarder - a barge.
Source: Raffaele Spinelli

Source: University of Aberdeen 1998
6. Minimize rehandling. When possible, avoid setting down and picking up pieces multiple times. A cut-to-length system may handle the same piece four times before the material is in a chip van: once by the harvester, twice by the forwarder (loading and unloading) and once by the chipper. In contrast, a harvester-chipper-forwarder cuts, chips and blows material into a chip container while handling each tree only once (Figure 49).

7. Fully utilize humans, machine power and machine components. Ideally the duty cycles for all elements of a system should be 100% on. A conveyor belt is a good example to emulate. Traditional cable yarding represents a case where neither the labor nor machinery is very well utilized because of interactive delays between the elements of the yarding cycle: outhaul, lateral outhaul, hook, lateral inhaul, inhaul, and unhook. The issue of utilization of components is critical for multifunction machines. The ideal situation, and therefore where a multifunction machine is attractive, utilizes all functions simultaneously. A delimer-debarker-chipper is a good example (Figure 50). In contrast, a machine where the functions act sequentially, i.e., only one at a time, has difficulty competing with a multi-machine system because the multi-function machine is almost certainly more expensive than any of the single-function machines of the same capacity. Early combi harvester-forwarders were good examples because they operated at any one time as either a harvester or a forwarder. Such machines have lower move-in cost than a multi-machine system, but this is only beneficial for very small treatment units.

8. Move continuously rather than starting and stopping. If a machine has a fixed maximum speed, it can cover a given distance faster if it doesn’t repeatedly start and stop. In addition, acceleration requires energy; some energy available when decelerating is lost to heat when braking, so each start-stop cycle has a net energy cost.

9. Use humans to make decisions and take actions that cannot be automated; use computers to deal with other decisions/actions. Some decisions require information on multiple parameters, and evaluation algorithms that may be difficult to automate. Selecting which trees to be cut in a fuel-reduction treatment in a naturally regenerated stand is a good example. Other activities may be easier to carry out with a “robot”, e.g., moving cut trees to a bunch or bunk, or processing a cut tree (Figure 51).
10. Recognize that tradeoffs almost always exist. It is usually impossible to simultaneously optimize all of the multiple objectives; a gain in one area may be offset by a loss in another. Weighting of multiple objectives – especially by combining into a single objective function such as maximization of net worth – is a clear approach when feasible. But the overall optimum may depend on the specific situation. Take the narrow issue of cost per green ton of skidding versus forwarding as an example. Skidders travel faster, both empty and loaded, and require less time per ton to load and unload. They also have lower capital and hourly costs, but carry much smaller payloads than do forwarders when handling small trees. Because of the tradeoff between payload and other factors, skidding is less expensive at shorter distances, while forwarding is cheaper at very long distances (Figure 52).
Base Case Systems and Possible Changes

Based on the above and using the empirically derived results from Section III(A)(1) above, we developed stump-to-truck costs for four “base case” systems, selected because they are either common in California or elsewhere for biomass-only trees, and/or because they have been advocated and therefore provide good illustrative situations with which to compare other options or potential improvements. We then considered all the other possible paths through the network shown in Figure 42. Those considered to be of interest or to have potential are discussed below as offsets to the base case system to which they are most closely related. Elements such as transportation alternatives that are relevant for multiple base-case systems are discussed later.

For simplicity, we have confined this evaluation to biomass-only trees, assuming they will be comminuted before conversion into a final energy product. Many of the results apply to integrated harvesting (roundwood plus energy material) situations as well. Integrated systems are generally considered less expensive than two-pass systems (e.g., Watson et al., 1986). Some experienced observers of California conditions also feel it would be best to remove all material in one pass with a machine sized for smaller trees, then do any processing at the landing or further downstream (Carlson, 2003). Occasional larger trees could be felled and partially processed with chainsaws.

The four base cases\(^1\) are:

1. Ground-Based Whole Tree, consisting of a combination of swing-boom feller-bunchers and grapple skidders, and a chipper at the landing
2. Ground-Based Cut-to-Length (CTL), consisting of a combination of harvesters and forwarders, and a chipper at the landing
3. Cable Yarding Whole Tree, including chainsaws for felling, a skyline yarder and a chipper
4. Removing Surface Fuel (slash or pre-existing), with a slash bundler, forwarder, and a chipper at the landing.

We have ignored system balancing in our analyses, i.e. how many of each type of equipment would make the best configuration and which activity is limiting. While balancing is an important aspect, especially for specific harvest units, the best combination depends on average tree size, skidding distance and other factors, and clever contractors will work around imbalances by operating the most limiting equipment for extra hours or moving more productive equipment to other units.

To consider “average” system imbalances, we have incorporated an average utilization rate, defined as the ratio of productive hours to scheduled hours, into the analysis for each type of equipment.

Stump-to-plant costs for the four systems under one scenario are shown in Figure 53 for illustration purposes.

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\(^1\) In the first three systems, a delimer-debarker-chipper (DDC) can be substituted for the chipper if bole-only chips are required for purposes such as pellet production. The residues (bark and branches) produced by the DDC can be comminuted by a tub grinder for use as feedstock for another process.
Figure 53. Representative stump-to-plant costs for the four base-case systems under one specific scenario: removing 190 trees per acre averaging 7” dbh (a total of 45 green tons per acre), with a one-way extraction distance of 500 feet on a 30% slope (60% for cable yarding) and a 50-mile one-way haul.

Base-Case System 1. Ground-Based Whole Tree

Combined stump-to-truck costs are shown below (Figure 54).

Figure 54. Representative stump-to-truck costs for the base-case ground-based whole-tree system (feller-buncher, grapple skidder and chipper) on 10% and 30% slopes.
Changes Related to System 1

A) Drive-to-Tree Feller-Buncher (Figure 55).
Deficiencies addressed: Under-utilization of expensive swing-boom machines on gentle terrain. As noted above, purchase prices, hourly costs and costs per ton are higher for swing-boom machines than for drive-to-tree machines due to the complexity of the former. Most contractors in California purchase swing-boom machines because of their versatility; with the exception of the Cascades region, it has in recent years been difficult to find a steady diet of work on gentle slopes. If more fuel reduction work was carried out, some contractors would be able to specialize on easier terrain, reducing the cost of biomass removed from that easier ground by approximately $2 per green ton.

B) Continuous-Travel Feller Buncher
Deficiencies addressed: Piece-handling nature of feller bunchers; start-stop action of feller bunchers; need for the operator to continuously control the boom. Continuous-travel machines have been developed for short-rotation willow plantations and are extremely productive (Figure 56). In trees of 2-3” dbh, these machines may fell (and chip) on the
order of 50 green tons per hour of travel down the crop rows (Hartsough and Spinelli, 2002). This shows that productivity does not have to be low for small trees, if the trees are handled “in bulk” rather than as individual pieces, and if the machine travels continuously rather than starting and stopping at each tree. Clearly, fuel reduction thinnings of natural stands are not harvests of even-aged short-rotation plantations: trees must be selected from either side of the skid trail as well as from within the trail, and are not located on uniform or otherwise predictable spacing. But the trees are substantially larger than in willow plantations, so fewer must be cut. For example, if trees average 200 green pounds (about 5” dbh), cutting eight per minute will produce about 50 GT/hour. How might this be accomplished? A first step in this direction might be boom-tip control, where the operator indicates where the felling head should go rather than controlling multiple boom functions. This might speed up felling somewhat. In a semi-automated system, the machine operator might select trees to be cut by “painting” them with a laser. This rate – eight per minute – is certainly within the range of human capability. Given the known locations of the standing tree and the trail, the machine’s computer would then direct the boom out, cut the tree and bunch it. Proximity sensors on the head could be used to help avoid hitting leave trees. A machine equipped with two booms and felling heads, one each on the left and right, should be able to keep up with the operator’s designation rate.

A more advanced automation scheme might allow the operator to select the leave trees, typically fewer than those to be removed in a fuel reduction operation, and sense and remove the rest. Such technology is not available in the woods yet, but the elements have been demonstrated on equipment such as the vehicles competing in the DARPA Challenge. To demonstrate the possibilities, we assumed a feller buncher with two upper limits: 1 mile per hour travel speed, and 1000 trees per PMH, cutting 30 feet on either side of the trail centerline. We assumed the hourly cost would be twice that of a conventional self-leveling swing-boom machine. Based on these results, we estimate the potential benefits to be on the order of $2-4/GT (Figure 57).

![Figure 57. Estimated felling and bunching costs for drive-to-tree and continuous-travel Feller bunchers versus the base-case swing-boom feller bunchers.](image-url)
C) Long-Reach Swing-Boom Feller Buncher
Machines must be designed for the worst-case scenario, whether that be the largest tree or steepest slope it must address. In the case of boom-equipped machines, load requirement at maximum reach is also a worst-case scenario. U.S.-manufactured feller bunchers commonly reach only 25 feet or so, while harvesters may reach 30 or 40 feet or more. (Most harvesters don’t hold trees upright, so they can get by with rather slender booms.) A Japanese research group, however, developed a feller buncher for thinnings that could reach over 60 feet and fell trees up to 16” at the butt (Parker, 1999; Figure 58). It accomplished this by using an intermediate foot between the inner and outer sections of the boom. Another approach might employ a caster wheel at the end of the boom to support the felling head, thereby eliminating much of the moment on the boom and carrier. This would either result in a slimmed-down and somewhat less expensive machine for the same reach, or a longer reach for the same cost. Such a machine would allow trails to be located at wider intervals, and for larger bunches to be made for skidding. The longer reach and wider trail spacing would be especially beneficial when pairing a feller buncher with a cable yarder, due to the significant fixed cost of moving the yarder from one corridor to another.

Figure 58. Long-boom feller-buncher.
Source: Parker 1999

D) Chainsaw Felling and Skidding of Unbunched Trees
Deficiencies addressed: None, but we felt we should address the question.
To corroborate what is probably obvious, our estimates show this less-mechanized option is substantially costlier than the fully mechanized base case (Figure 59), primarily because of the large amount of time and cost required for the skidder to assemble a turn of unbunched small trees.
Figure 59. Stump-to-landing costs of felling with chainsaws and skidding unbunched trees versus the base-case felling and bunching followed by skidding of bunched stems.

E) Feller-Skidder
Deficiencies addressed: Repeated handling of trees by the feller buncher and skidder.
As for a combi harvester-forwarder (harwarder) versus a two-machine harvester and forwarder system, a combination feller-skidder cannot have a cost benefit on relatively large treatment units unless the multifunction aspect eliminates some activity that would otherwise be carried out by separate feller bunchers and grapple skidders, or conducts activities in parallel. Time eliminated might include part of what a feller buncher spends moving trees to create large bunches for a skidder, as all trees could now be dropped directly into the skidder’s clambunk grapple. Loading times for conventional skidders are so short that any reductions here are likely to be negligible, and the activities – felling and skidding – would essentially be carried out sequentially rather than simultaneously, assuming current felling technology. The machine is more expensive than either a feller buncher or a skidder, and it would be operating as one or the other at any given time rather than as both machines simultaneously. We have no data on feller-skidders, but information on Koehring feller-forwarders gives some idea of potential. Legault (1976) studied the massive Koehring KFF, carrying loads averaging 75 trees and 19.5 m³ (approximately 17 GT). Levesque (1985) observed the downsized K2FF with loads of near 10 m³. In five separate studies or sub-studies in these two reports, production rates averaged 53-106 trees/PMH and 8.6-22.4 m³/PMH.

Improved felling technology, as hypothesized above for the continuous-travel feller buncher, might make a combined feller-skidder more attractive by allowing the felling and travel activities to occur simultaneously rather than in sequence. The machine would travel empty to the end of the trail, turn around and cut while traveling back to the landing. But our assumed higher hourly cost for the automated felling capabilities would make this a very expensive skidder, so we doubt this concept has much potential.
F) Selective Feller-Chipper-Forwarder (paired with a separate Chip Forwarder at longer distances)

Deficiencies addressed: Repeated handling of trees by the feller buncher, skidder and chipper; underutilization of the weight capacity of the skidder when handling small trees; interactive delays between machines when buffers run out.

The tradeoffs with a multifunction feller-chipper using current technology did not justify this combination when trialed in the form of the Chipset chip harvester in Finland during the mid-late 1990s (Asikainen, 2004). While the felling and chipping activities could in theory operate simultaneously, the piece-handling-limited felling productivity was considerably less than the capacity of the chipper. The Chipset was capable of handling material up to about 14” diameter, but sound whole trees of that size would not have been chipped for fuel in Scandinavia because of their higher value for other products. In California, larger trees (although not 14-inchers) would be chipped for energy, so the felling productivity might more nearly match the capability of the chipper. The Chipset is no longer in production, but a similar machine, the Valmet Combi BioEnergy, has been introduced recently. We have no definitive literature, but some information indicates production rates might be on the order of 5-10 bdt per hour for this 190-Hp machine (Siuro, 2007, Biologistiikka Oy, 2005). If production has been limited by felling very small trees and processing many of them into more valuable roundwood rather than chipping them, the production potential could be substantially higher under California conditions, i.e. where somewhat larger trees would be chipped. But one study would indicate the rates above are near values observed for landing-based chippers of similar power (Johnson, 1989).

While we do not have a good cost estimate, the machine must be more expensive than a feller buncher, chip forwarder or chipper of equal capability, but almost certainly not as expensive as three separate machines. And it has only one operator. If felling and chipping can both be productive, the cost per ton might be less than that for two separate machines, and since chip forwarders carry full loads regardless of the sizes of the trees, the primary transport would be rather efficient. The Valmet literature indicates a time of 3 minutes to transfer chips from the feller-chipper to the forwarder (Biologistiikka Oy, 2005). Assuming a similar time to offload to a van and a payload of 6 bdt (12 GT) in the 35-yd3 container, the terminal times are only a half minute per green ton, better than for a grapple skidder with small trees, and substantially better than for a log forwarder. Travel times should be similar to those for a log forwarder, making the extraction cost rather low. Our cost calculations, based on the rather fuzzy data available to us, show no advantage over the base-case system (Figure 60), but this option warrants more attention as subsequent information on the Valmet Combi BioEnergy and similar machines becomes available.

Given the type of multifunction machine, when the felling device is broken, the chipper is idled, and vice versa. Interactive delays of some kind between the primary machine and the chip forwarder are unavoidable: the only buffer between the two is the on-board bin. While the chipper can forward if the forwarder is down, the forwarder can not accomplish anything when the chipper is down.

Chip forwarders have rather high centers of gravity, as do log forwarders, so they are restricted to travel up and down the fall line on steeper terrain. Log forwarders have been used successfully
in California and certainly in the Pacific Northwest, so chip forwarders might be able to access a substantial part of the area designated for ground-based fuel reduction operations.

Figure 60. Estimated stump-to-truck costs for a single-machine system (feller-chipper-forwarder) and a two-machine system (feller buncher plus chipper-forwarder) versus the base-case three-machine system (feller buncher plus skidder plus chipper).

G) Grapple Skidder with Large Grapple
Deficiencies addressed: Underutilization of the weight capacity of the skidder when handling small trees.
Small trees are short. To get the same weight of small trees in a skidded load, more basal area must be carried. Since trees must generally be grappled by the butts to avoid breakage, the only way to get more trees in a grapple when it is already full is to increase the size of the grapple. There would be a slight payload weight penalty to pay with more iron, but not a substantial one. We ran a simple simulation of a larger grapple by assuming a combined hourly cost and/or cycle time penalty of 10%, and a payload advantage of 100% for trees of no weight, diminishing to no payload advantage for 1-GT trees. Based on this simple model, the cost advantage might be approximately $1-2/GT (Figure 61).

Clambunk skidders may have much larger grapples than do conventional skidders, but these grapples are inverted and therefore require a separate loading boom and grapple on the machine to transfer trees from the ground to the clambunk (Figure 62). This increases loading (but not offloading) time per ton substantially compared to that for a regular grapple skidder, and therefore the fixed cost per ton, versus the variable cost that increases with skidding distance. The latter is rather low for a clambunk because of its large load, so in a fashion somewhat similar to that for a short-log forwarder, a clambunk skidder out-competes a regular skidder at longer distances. The breakeven distance is shorter for a clambunk than for a short-log forwarder because the former’s loading and (especially) unloading times are so much less. Examples of clambunk skidders may be seen at TimberPro.com (Timberpro, 2004) and Tigercat.com (Tigercat, no date) (both accessed April 2008).
Figure 61. Estimated skidding costs for a machine equipped with a larger grapple versus those for a skidder with a standard grapple.

Figure 62. Small clambunk skidder.  
Source: Raffaele Spinelli

H) Whole-Tree Forwarder
Deficiencies addressed: Underutilization of the weight capacity of the skidder when handling small trees.
A standard-configuration skidder with a large grapple has both advantages and disadvantages compared to a whole-tree forwarder (Figure 63). The center of gravity of the load is near the ground, so the machine is relatively stable on slopes. Loading time is very short if an adequate number of large bunches can be reached, but it may be difficult to assemble an adequate load. The skidder dragging a large number of stems may cause some damage to reserve trees, and of course sweeps organic matter off the skid trail.
On the other hand a forwarder long enough to hold whole trees would have difficulty turning around or backing down a trail. Existing whole-tree forwarders are used in clearfell operations where backing and sharp turns are not necessary. One option might be to piggyback a trailer with rear bunks onto the front bunks, using either the loading grapple as on a self-loading truck or a hydraulic device such as that used on some logging trucks in Australia.
I) Chipper-Forwarder (paired with a separate Chip Forwarder at longer distances)
Deficiencies addressed: Repeated handling of trees by the skidder and chipper; underutilization of the weight capacity of the skidder when handling small trees; interactive delays between the skidder and chipper when buffers run out.

Chipper-forwarders (Figure 64) have been in existence for a considerable time; Wellwood (1979) mentioned machines with containers capable of carrying 4-6 tonnes, and producing 4-8 green tonnes/hour. Biomass for energy from forest thinnings in Denmark is almost exclusively produced by chipper-forwarders (Molbak and Kofman, 1991). Spinelli and Hartsough (2001a) reported results for small chipper-forwarders. Pottie and Guimier (1986) cited a study that found a Bruks 1000CT drum chipper (160 kW, on a 100-kW forwarder chassis) to be twice as productive at the landing as when processing residues on a cutover: 5.6 versus 2.8 odtonnes/PMH. (The issue of bringing residues to the landing was not considered in this comparison.) Mitchell et al. (1989) studied thinning of young stands in Great Britain. Chipping and extraction costs for a stand-mobile chipper-forwarder were only 30% of those for skidding whole trees and chipping at roadside, apparently due to underutilization of the load capacity of the skidder when dealing with very small trees, and underutilization of the chipper at the landing because of the low skidding productivity. Because of economies of scale, larger machines are preferable if they can be fully utilized. Silvatec (Silvatec, 2005.) produces a 278-Hp chipper-forwarder with a 16-m³ bin, capable of chipping material up to 35cm in diameter. Logset (Logset, no date) previously manufactured a 360-Hp chipper with 17-m³ side-tipping bin that could be mounted on Logset forwarders. It also had a diameter capacity of 35cm.

A combination chipper-forwarder, following a feller buncher, should have most of the advantages of the feller-chipper-forwarder while avoiding the disadvantage of having to closely match the productivity of the felling and chipping functions on the same machine. Trees can be felled well in advance of chipping, eliminating interactive delays between the machines. It has for some time been considered the most promising in Denmark for biomass thinning (Suadicani, 1989, cited by Twaddle et al. 1989). Our simulations, however, showed it to be less advantageous than either the base-case system or a combination feller-chipper-forwarder (Figure 60). Relative to the latter, the chipper-forwarder performed comparatively well for the smallest trees we considered because felling was more limiting than chipping. For 10” trees, however, we believe that felling would be as rapid as chipping, therefore putting the felling head on the chipper-forwarder may not impact productivity.
J) Selective Feller-Bundler
Deficiencies addressed: Repeated handling of trees by the feller-buncher, skidder and chipper; underutilization of the weight capacity of the skidder when handling small trees; interactive delays between machines when buffers run out; degradation of chips during long-term storage.
A prototype feller-bundler is under development in Finland for very small trees (Figure 65). Substantial upsizing would be required for California conditions. Bundling is more costly than direct chipping, but can be advantageous if seasonal operations require long-term storage and the material degrades substantially if in chip form.

Base-Case System 2: Ground-Based Cut-to-Length (CTL)
Combined stump-to-truck costs for the system consisting of harvesters, forwarders and a chipper are shown below (Figure 66).
In North America, CTL systems are generally considered more expensive than whole-tree systems (Adebayo et al., 2007; Gingras, 1996; Gingras and Favreau, 1996). This is especially the case if it is desirable to remove the majority of the harvest residues from the unit, as is likely the case with fuel reduction operations. Even in the Nordic countries, where CTL systems are most popular, field studies and systems analysis have shown whol-tree operations to be more cost-effective than CTL followed by residue recovery (Asikainen, 2004).

Changes Related to System 2

A) Harvester with Multi-Tree Head
Deficiencies addressed: Low utilization of the capability of the harvester’s processing capability (a length-handling device) when dealing with small stems.

The machine cuts multiple smaller trees before processing them, thus saving considerable processing time (Figure 67). Lilleberg (1990) found that processing time per tree decreased by about 40% when two trees were processed rather than one, and by 50% when three or four were handled rather than one. Bergkvist (2003) reported a study of a single-stem head that had been modified for multiple trees. When felling and processing trees of approximately 0.06 m$^3$ (2 ft$^3$), the multi-stem capability increased productivity by 36% (trees per hour) and 18% (volume per hour, because trees processed while in the single-stem mode happened to be slightly larger). Gingras (2004) tested a Waratah HTH-470HD head with trees averaging 0.10 m$^3$ (3.5 ft$^3$). Harvester productivity increased by 21-33%, and the head handled multiple stems on 30-40% of the cycles. Other European studies have reported on multi-stem feller buncher heads for very small trees harvested for energy. The concept is common in the U.S., but the European heads are designed for harvester booms, so we feel the results in terms of trees handled would be similar for multi-stem harvester heads. Kärhä et al. (2005) tested the Narva-Grip 1600-40 (Pentin Paja Oy, no date). Between 73% and 96% of the stems in various stands were accumulated rather than bunched singly. Spinelli et al (2007) studied two accumulating Timberjack heads – the TJ 720

**Figure 6.** Representative stump-to-truck costs for the base-case ground-based cut-to-length system (harvester, forwarder and chipper) on 10% and 30% slopes.
and TJ 730, with cutting capacities of 20 and 30cm, respectively. They were 50% more productive than non-accumulating heads. When felling trees averaging 6.7 cm dbh, the TJ 720 averaged 2.6 trees per cycle. We have used this information to estimate that a multi-stem head would increase harvester productivity by 50% for 4” trees, 25% for 6” trees and not at all for 8” trees. With these assumptions, the cost savings would be $20/GT for the smallest trees and $5/GT for 6” trees (Figure 68).

![Multistem harvester head](image)

**Figure 67.** Multistem harvester head.

Source: Bergkvist 2003

![Harvester costs per ton](image)

**Figure 68.** Harvester costs per ton for a machine equipped with a multi-stem head versus a conventional head.

B) Forwarder with Roll-On/Off Chassis

Deficiencies addressed: Multiple handling of small logs by the forwarder. While roll-on/off trucks and containers (Figure 69a) have been used in numerous on-road applications and in off-road situations for chips, only recently have they been tested for use with log forwarders. Results are not yet available, but should be shortly (Thomas, 2008). The most time savings would occur if loaded log bunks (Figure 69b) were transferred from a forwarder to a transport truck, rather than offloading the logs from a conventional forwarder to the ground and
then rehandling them again to load the truck. Even in the chipping scenarios we’ve posed, use of roll-on/off bunks would eliminate the unloading time by the forwarder. This scheme would be practical if chipping was rather close-coupled to forwarding, so the number of bunks required for the buffer between the forwarder and chipper could be kept to a reasonable value. The chassis and additional bunks would add some capital requirement and therefore increase hourly cost a bit, but this would be offset by increased productivity. We estimate the cost benefits to be approximately $1-2/GT (Figure 70).

Figure 69a

Figure 69b

Figures 69a and b. Forwarder equipped with roll-on/off chassis and a) container or b) log bunks.

Sources: TimberPro Inc. and Cky-Ber Enterprises via Larry Swan

Figure 70. Estimated forwarding costs for a machine equipped with a roll-on/roll-off chassis and bunks, a machine that has capability to load logs while traveling, and a conventional forwarder.
C) Continuous-Travel Forwarder with Continuous-Feed Loading
Deficiencies addressed: Piece-handling nature of forwarder grapples; start-stop travel of forwarders while loading; need for the operator to continuously control the boom and grapple. Logs produced by harvesters are generally windrowed in rather predictable rows alongside the forwarder trail, and they must be delivered to a known location – the log bunk. Agricultural hay-bale pickup machines have similar although somewhat simpler challenges and can travel continuously at reasonable speeds without requiring the operator to tediously pick up each bale (Figure 71). Some examples may be seen at http://www.tubeline.ca/Products/Technobale/ (Tubeline, no date) or http://www.newholland.com/home.asp (New Holland, no date) (both accessed July 2008). Although no continuous-feed loading device for logs exists at present, it should be relatively easy to automate this activity, compared to automating something such as selective felling. We simulated a continuous-feed machine by eliminating the loading times (while stopped; representative values are 10-15 minutes per cycle) from four empirical studies for which cycle times had been reported in considerable detail. We retained the observed travel while loading (on the order of 3 minutes per turn) and other elements. We also assumed such a machine would have an hourly cost that might be roughly a third more than a conventional forwarder. Based on these assumptions, we estimated a net benefit of $2/GT for larger trees to $5/GT for the smallest trees compared to a conventional forwarder (Figure 70).

![Continuous-Travel Hay Bale Transporter](image)

Figure 71. Continuous-travel hay bale transporter.
Source: New Holland

D) Harwarder with Rotating Bunk
Deficiencies addressed: Multiple handling of small logs by the system.
In a conventional CTL system, each piece is handled at least three times before it reaches a truck: once by the harvester and twice by the forwarder (loading and unloading). Newer harwarders with processing/loading heads and rotating bunks can eliminate most of the loading activity by processing most logs directly into the bunks. Talbot et al. (2003) conducted a detailed simulation of two harvesters: a Valmet Combi that could process directly into a fixed bunk, and a Ponsse Dual that operated first as a harvester, then as a forwarder. The Combi outproduced the Dual under all conditions. Asikainen (2004) reported that the productivities of either machine operating in single-function fashion were less than the equivalent single-function machine’s productivities due to the impossibility of optimizing the multi-function machines for each
activity. Without considering move-in, costs for the Combi and Dual were 15-20% and 10-15% higher, respectively, than those for a two-machine system. For the specific move-in assumptions stated in the study, the harwarders were less expensive than two-machine systems when less than approximately 30 m$^3$ (about 25GT) were removed from a harvest unit. Although not considered explicitly in these studies, Talbot et al. (2003) noted that either type of harwarder is at least superficially a self-balancing system in that the machine is busy until the unit is finished, while a two-machine system may require more hours by one than another, e.g. the harvester if small trees are being processed and forwarding distances are short. But the harwarder’s hidden imbalance relates to successive activities rather than simultaneous. For example, the harvester is idle while the machine is forwarding logs.

Wester and Eliasson (2003) tested a harwarder with a combination processing and loading head and a rotatable, tiltable bunk that allowed more logs to be processed directly into the bunks. The rotation capability increased productivity by 6% in clearfell and 20% in thinnings. There was less gain in clearcutting because in that case many of the logs could be processed directly into a fixed bunk. Not considering move-in, the harwarder with rotating bunk was about 20% and 35% more expensive in thinning and clearfell, respectively, than a two-machine system. Under the given move-in scenario, the systems broke even at 87 m$^3$ (about 25GT).

**Base-Case system 3: Cable Yarding Whole Tree**

Combined stump-to-truck costs for the system consisting of chainsaws for felling, a skyline yarder with lateral-yarding capability and a chipper are shown in Figure 72.

![Figure 72](image)

**Figure 72.** Representative stump-to-truck costs for the base-case cable system (chainsaws, cable yarder and chipper) on 60% slopes.
Changes Related to System 3

A) Swing-Boom Feller-Buncher and Yarding of Bunched Trees
Deficiencies addressed: Poor utilization (low duty cycle) of the cable yarder; poor utilization (low duty cycle) of choker setters and rigging slinger.

Much of the duty cycle for a cable yarder operating in partial cuts with small trees is devoted to accumulating several scattered small trees to assemble a reasonable payload. The lateral outhaul, hook and inhaul activities require almost no power and essentially no activity from the crew members at the landing, especially if the carriage is radio-controlled. Lateral outhaul and hook require manual labor at the carriage, generally two or possibly three people, but these people are idle during the rest of the cycle (lateral inhaul, inhaul, unhook and outhaul). On intermediate terrain where a feller-buncher can be used but where tractive transport equipment cannot, mechanized felling creates bunches at the skyline corridor and thereby eliminates lateral yarding. A single choker can be placed around a whole bunch, if the bunch is properly sized and if the feller buncher places the trees so a choker hole is available under the bunch. MacDonald (1990) observed yarding of whole trees, most of which had been mechanically felled and bunched. (Trees on steeper pitches were felled by hand.) Two yarding approaches were compared: a dropline carriage with hand-set chokers and radio-released choker bells; and grapple yarding (Figure 73). The latter was cheaper at short distance because of the very short terminal times, especially the short grappling time relative to the time to set chokers. At distances greater than 150m, use of chokers was preferable because the choker setters could hook more trees than the grapple could pick up. Since inhaul times dominated the cycles at these longer distances, the benefits of the larger choker payloads more than offset the extra cost of choking.

![Figure 73. Grapple carriage.](source)

Source: Eagle Carriage and Machine Inc. 2008

We simulated the combination of felling-bunching and yarding with a dropline carriage, and also felling-bunching and grapple yarding. The net benefits of these are estimated to be about 20% ($3-40/GT) and 30% ($5-50/GT), respectively, for the average yarding distance of 500 feet assumed for our base cases (Figure 74).
Figure 74. Estimated stump-to-landing costs for four alternatives and the base-case cable yarding system (chainsaws and cable yarder with chokers). The modified systems include 1) feller buncher and cable yarder with chokers, 2) feller buncher and cable yarder with grapple, 3) a combination feller-buncher-yarder and 4) harvester and cable yarder with chokers.

B) CTL Harvesting and Yarding of Logs
Deficiencies addressed: Poor utilization (low duty cycle) of the cable yarder; poor utilization (low duty cycle) of choker setters and rigging slinger.
As does felling and bunching, this combination also eliminates the accumulation and lateral transport phases of yarding (Visser and Stampfer, 1998). It would only be advantageous compared to felling and bunching if it was desired to leave the tops and limbs in the woods. Drews et al. (2001) studied a harvester in combination with a yarder. Based on the results of that study, we estimated the cost-per-ton disadvantage of the harvester-plus-yarder combination to be about 25-100% compared to the base-case system (Figure 74), primarily because large fractions of the weights of the smaller trees are not recovered when using a CTL harvester, substantially increasing the cost per recovered ton.

C) Endless-Loop Yarder
Deficiencies addressed: Poor utilization (low duty cycle) of the cable yarder; poor utilization (low duty cycle) of choker setters and rigging slinger.
The standard cable yarding cycle – outhaul, lateral outhaul, hook, lateral inhaul, inhaul and unhook – is far from ideal in terms of utilization of both equipment and labor. Yoshimura and Hartsough (2007a) proposed a number of conceptual variations to improve duty cycles by adding a second skyline and carriage to the yarder, adding a second carriage that traveled on the same skyline as the first, or using an endless-loop, continuously moving traction cable (Figure 75). Konrad (Konrad, no date) offers a second-skyline (Duo) option on its Mounty yarders, with the second to be used in conjunction with a Woodliner self-propelled carriage for downhill yarding of timber above the road while the conventional skyline scheme is working below the road (Figure 76). Endless-loop systems including the Japanese zig-zag and Austrian Timberveyor
have been used or proposed. With either of these, the moving line had to be located almost directly over the material to be yarded, or wood had to be moved by hand to the line. The former is possible with clearcutting; the latter makes very poor use of expensive human labor. While it is not clear how to best accomplish lateral yarding with an endless-loop system, one possibility might employ a movable capstan driven by the traction cable to power a lateral-yarding cable. The movable capstan unit might also act to hold the traction line down near the ground so loads could be attached to it. Although many problems would have to be solved to bring such a system to the operational level, Yoshimura and Hartsough (2007a) projected that it might more than double yarding productivity. Simply applying this differential to conventional cable yarding costs gives upper bounds on potential benefits of $10-25/GT, depending on tree size.

D) Feller-Buncher-Yarder
Deficiencies addressed: Poor utilization (low duty cycle) of the cable yarder; poor utilization (low duty cycle) of choker setters and rigging slinger; setup time required to rig each skyline corridor.

Tailblocks, tailtrees and intermediate supports must be rigged in advance of yarding for conventional skyline yarders. By using a feller-buncher as the tailhold and having the yarder transport trees as soon as the feller-buncher cuts them, the former machine can be fully utilized, and the latter could get by with a crew of only a few people. This system might not have any deflection and therefore no lift capacity, so a skidding sled or caster-wheeled pan could be used to prevent hangups and possible rutting. (The Chuball was a passive, solid-wheeled device tested on the east coast for selective logging with a single-drum yarder. It was lowered down the slope to logs to be yarded, then winched back up the hill.) Alternatively, a small towed vehicle with steerable wheels, radio-control and a video camera could be maneuvered around obstacles by the yarder operator while the yarder is towing the vehicle and payload to the landing. Our preliminary analysis of this concept indicated it might reduce costs by over half compared to the base-case system (Figure 74).
E) Yarder-Chipper
Deficiencies addressed: Poor utilization (low duty cycle) of the cable yarder operator and chipper at the landing.
Although we know of no yarder-chippers in existence, the concept parallels those of the MM Forsttechnik Syncrofalke and Konrad Mounty yarder-loaders or yarder-processors. We assumed the combined machine has a purchase price intermediate between that of a yarder and a yarder plus a chipper, and productivity is the same as for a conventional yarder. We believe this is quite feasible, especially if the yarder has automated inhaul and outhaul similar to the Syncrofalke (Figure 77).

![Yarder-processor with automated outhaul and inhaul.](source: Konrad GmbH]

Miscellaneous Cable Yarding Possibilities

LeDoux et al. (1987) reported productivities for prebunching with a radio-controlled winch. Several other attempts have been made to utilize winches to prebunch for yarders, but none has been economically successful in the long run. The added cost and trouble of prebunching with a small winch has not been adequately compensated for by the reduced costs of yarding bunches. Prebunching with a small winch is an example of relatively poor utilization of the human because the human is paired with a low-power mechanical device that is used to transport material.

Biller and Peters (1987) invented a two-loadline carriage and contracted with Christy Manufacturing to produce a prototype. This particular model did not work well due to twisting of the two loadlines between the end of the mainline and the carriage, but the concept has potential for increasing payload size, possibly by using two internal dropline drums inside a motorized carriage, or using one internal drum and a mainline-dropline.

While a conveyer is an ideal device for moving material – it can transport continuously and can be loaded to capacity all the time (if material is available to it) – the problem is getting the conveyer to the wood or vice versa. The Timberveyor was a system employing an endless loop of chain for yarding trees. It was manufactured in Austria by Steyr in the 1970s, but apparently did not gain a significant market. The zig-zag cable yarding system (Miyata et al., 1987; tested in several places in California including the Shasta-Trinity NF, Shingletown and Tahoe NF during the late 1980s and early 90s), which can be used on flat or steep ground, has the same benefits.
(good utilization of the machine’s power and duty cycle) and disadvantages (using humans to move material to it) as a conveyer. In addition, conveyers and zig-zag systems require substantial setup time. A conveyer for transporting farm produce was recently developed in Great Britain (Gizmag, 2006). Up to three hundred feet of conveyer can be pulled into place by a tractor, then be inflated and ready to operate in minutes. A more robust conveyer would be required for transporting logs or trees.

Base-Case system 4: Removing Surface Fuel (slash or pre-existing)

While thinning of standing trees can diminish the potential for wildfire severity by increasing height to the live crown and decreasing crown density, it is now recognized that surface fuels also play major roles in fire behavior (Agee and Skinner, 2005, Peterson et al., 2005). In fact, if a first treatment substantially reduces ladder fuels, subsequent treatments may focus primarily on surface and near-surface fuels if conducted at relatively frequent intervals. Prescribed fire is certainly one option for such subsequent treatments, but human health issues as well as concerns about escape will probably limit the area that can be treated with fire. This will leave room for practical mechanical means of removing surface fuels.

Parker and Stine (1979) reported on the collection of non-merchantable material after logging of a selectively harvested area. The operation used a grapple skidder to collect material and produced over 20 dry tons per acre of pieces down to a 4” by 4” minimum size. In most of today’s situations, the type of material remaining on site after harvesting would not justify the use of a grapple skidder.

Combined stump-to-truck costs for the system consisting of a slash bundler, conventional forwarder and a chipper are shown below (Figure 78). This system could be used to collect some of the pre-operation surface fuels as well as the tops and limbs produced by a harvester.

![Figure 78. Representative stump-to-truck costs for the base-case residue collection system (bundler, forwarder and chipper) on 10% slopes.](image-url)
Changes Related to System 4

A) Harbundler
Deficiencies addressed: Inefficient handling of small pieces of slash by means of a boom and grapple.
Combining a slash bundler with a harvester would allow the limbs and tops of processed trees to fall into a bundler infeed chamber rather than onto the ground, eliminating the need to pick up the pieces with a separate machine and eliminating the second operator as well (Yoshimura and Hartsough, 2007b). Harvesting and bundling are both activities with semi-continuous duty cycles, and both can proceed simultaneously rather than in succession, so a harbundler seems to be a good application of the multifunction approach. Preliminary trials with such a machine are under way in Scandinavia (Bergkvist, 2007a). We simulated such a device, assuming it would cost more than a harvester and would slow harvesting productivity somewhat due to the need to process stems over the bundler. Taking the incremental cost of this approach versus a standard harvester and dividing by the tons of biomass bundled gives a cost that can be compared with that of an independent slash bundler. Our simulation indicated the harwarder might reduce costs of slash recovery by approximately $5-10/GT (Figure 79). A harbundler would address activity fuels (tops and limbs of trees being harvested) but would not be applicable to pre-existing surface fuels.

![Figure 79. Estimated costs for bundling when using a combination harvester-bundler versus a residue bundler.](image)

B) Continuous-Feed Bundler
Deficiencies addressed: Inefficient handling of small pieces of slash by means of a boom and grapple.
No agricultural forage producer would consider collecting hay with a boom and grapple, nor should small pieces of forest residue be handled with a grapple.
C) Swathing Feller-Chipper-Forwarder (with a separate Chip Forwarder at longer distances)
Deficiencies addressed: Inefficient handling of small pieces of slash by means of a boom and grapple; multiple handling of material.
As noted previously, machines have been developed to cut and comminute small trees and brush. An experimental shear-equipped feller-chipper could process 1 to 1.5 trees per minute with stems of 7-8”, or about 8 cords/day (Bryan, 1980). The prototype Pallari harvester produced 1.7-3.5 dry tonnes/PMH in thinnings in Finland (Hakkila and Hannu, 1980). It and its successor in Canada – the Crabe Combine – had slow-speed, rotary shear cutting heads so they could operate on relatively rocky sites. The Cimaf brushcutting head on a Scorpion prime mover was designed to cut brush, coppice sprouts and other small trees. The developers claimed a capacity of 80 m³/day (Cormier, 1989).

Some swathing cutters – those configured with horizontal-shaft cutting and comminuting rotors – can process slash and standing material. A mesquite biomass combine on a 135-Hp tractor produced 4-5 (assumed green) tons/hour while processing and forwarding trees up to 6” diameter at speeds up to 2mph (Ulich, 1983). The productivity of the prototype NCSU/FECON harvester (FTX440 base, 440 Hp engine, FECON Inc., 2008) while processing understory vegetation has improved with experience (Figure 80). Best results to date have been approximately 7GT/hour while traveling (Roise, 2008). Understory vegetation in these stands has varied between 5 and 15GT/acre. Density of overstory trees has been the key factor affecting productivity, with higher production rates in stands that are more open and therefore allow the harvester to travel on a straighter trajectory. At a value of $18/GT for the delivered biomass, the development group anticipates the equipment will break even at a production rate of 10GT/PMH. The machine is being redesigned with a larger collection shroud so a higher percentage of the material will be recovered rather than being ejected.

Figure 80. Stand before and after treatment by the NCSU/FECON biomass harvester.
Source: Joe Roise

The NCSU/FECON machine and the various prototype mesquite harvesters point towards the possibility of using similar machines in California in fuel reduction applications where masticators have been employed in the past. Fixed-head masticators, such as the FECON machine adapted to collection in North Carolina, are the easiest to convert, and these styles have some use in California settings. Excavator-based heads are more common here, however,
because of obstacles and uneven terrain (Figure 81). Adapting these for collection would be more complicated because of the circuitous path that must be followed by the material from the head, along the boom and back to a container. The Valmet Combi Bioenergy feller-chipper-forwarder uses a pneumatic system rather than kinetic energy of the chip to transport chips along a multi-angled path. The same approach might be used for masticated material. Many of the masticators described by Windell and Bradshaw (2000) might lend themselves to conversion, although rotor-style cutters seem more likely candidates than do disk configurations.

D) Slash Forwarder, Chipping of Loose Slash at the Landing
Deficiencies addressed: If material is going to be transported in chip form rather than as bales or bundles, forwarding slash for chipping at roadside eliminates the need for the expensive bundler. Minor modifications to a standard forwarder – extra stakes, wider bunks and outward-angled stakes – can allow such a machine to carry more slash, but load weights are still low unless material is compacted (Pottie and Guimier, 1986). Productivities reported by some early studies were in the 3-4.5 dry tonnes/PMH range (Larsson, 1982b; Mellstrom and Thorlind, 1981). A recent study (Klepac et al., 2006) gave similar results: 160 cubic feet of solid volume/PMH (less than a quarter the productivity of the same machine on the same units when transporting sawlogs), assuming a solid volume factor (not measured) of 0.1. The reported volume would translate into a weight of approximately 4GT/PMH. Bolding and Lanford (2005) compared the productivities of a forwarder moving merchantable logs versus small trees and residues. For the latter material, both payload and productivity were a third of those for merchantable logs.

More advanced slash forwarding machines incorporate some means of compacting material, and sheet-metal sides and bottom to better hold small pieces (CBI Inc., 2006; Hakkila, 2004; Figure 82). Collection time per ton is still high with these machines due to use of a boom and grapple. For example, in Klepac’s 2006 study, loading time alone required approximately 4 minutes per green ton.

E) Chipper-Forwarder (with a separate Chip Forwarder at longer distances)
Deficiencies addressed: Eliminates the expensive bundler if chips can be transported.
Stand-mobile chippers equipped with booms and grapples are used in southern Sweden to process down material on cutovers (Kvist, 1988; Bjorheden, 2007). Guimier (1989) reported some use of Bruks chippers in eastern Canada. Asikainen and Pulkkinen (1998) found that a chipper-forwarder was about 10-20% cheaper for collecting and comminuting residues than was forwarding slash to the landing and then chipping or grinding it.

F) Continuous-Feed (Swathing) Chipper-Forwarder (with a separate Chip Forwarder at longer distances)
Deficiencies addressed: Inefficient handling of small pieces of slash by means of a boom and grapple; multiple handling of material.
Du Sault (1985b) reported on tests of the RECUFOR, a 240-kW machine equipped with a 6ft-long by 6ft-diameter rotor for picking up and comminuting on-site residues to chunks of approximately 30cm in length. The machine also had a 43-m$^3$ bin for storing and transporting the biomass. The prototype produced 2.4 dry tonnes/PMH, but improvements were anticipated to increase productivity to 4.5 dry tonnes/PMH, still too low to be economic. Travel speed while collecting was about 0.6 km/hr. Capital costs for the machine were estimated at that time to be CN$400k.

Chipping or Grinding

Several studies have reported the use of chippers or grinders for comminuting limbs and tops piled at roadside. Bowater Newfoundland Limited (1983) found it extremely difficult to feed residues to a chipper that was not equipped with an infeed table and therefore obtained very low production rates (12 green tons/day). Johnson (1989) used several previous studies to develop a relationship between disk chipper power and production rate, which varied ranged from 10 GT/PMH for 200-Hp machines to 52 GT/PMH for 550-Hp chippers. Desrochers et al. (1995) obtained 13.5 and 31 bdt/PMH with 550-Hp and 815-Hp drum chippers, respectively. Asikainen and Pulkkinen (1998) observed 11.5 od tonnes/PMH for a 267-kW drum chipper and 9-10.5 od tonnes/PMH for a 481-Hp tub grinder. It was difficult to feed larger tops into the tub grinder. Desrochers (1993) also reported on tub grinders. Rawlings et al (2004) reported 22 bdt/hr for a 475-Hp Universal Refiner (top-feed, vertical-shaft) grinder.

Baling

Baling has at least three advantages compared to comminution and at least two major deficiencies. On the positive side, much less energy is required for baling a given mass, so less power is required per unit mass throughput rate. Bales or bundles, especially rectangular ones, can be transported without a container. Chips or ground fuels decay in bulk storage and do not dry, while bundles are reported to be very stable and to dry somewhat in storage. These advantages are partly or completely offset by the need to comminute the bundles at some point downstream and the extra time per ton required to handle bales versus chips once the latter are in a bulk container. Walbridge and Stuart (1981) developed a successful prototype rectangular baler for forest residues. This machine was further tested by Schiess and Yonaka (1983) in the Pacific Northwest, where it produced bales of 505-656 green kg/m$^3$. Schiess proposed an updated version that was estimated to produce 6.6 dry tonnes/PMH. Fridley and Burkhardt (1984) tested the use of a slightly modified Vermeer round hay baler for use with small-diameter trees and
achieved bulk densities ranging from 144-338 kg/m$^3$ (as-furnished weight). Lavoie et al. (2007) modified a towed round baler to cut, partially shred and bale willow in short-rotation plantations. Bale densities ranged from 111-167 dry matter kg/m$^3$, with green densities of approximately twice the dry values. Productivity was estimated at 8-12 green tonnes/hr while cutting, and 5-8 green tonnes/hr when field efficiency, wrapping and idle times are included. Dooley et al. (2006, 2008) is experimenting with producing large rectangular bales of forest biomass, primarily from small treatment units within the WUI. Dooley argues that baling on site preserves material that might be of higher value than energy chips. Bales can be transported to a central processing facility and dissected for recovery of various products.

**Other Comminution Options**

A) Chunking

Deficiencies addressed: Overuse of energy to comminute material into tiny pieces if not necessary; degradation of chips while in storage.

Wood can be reduced in size by slicing it with a sharp blade – as is done with chippers and chunkers – or by beating it with a blunter tool such as a hammer hog or stirrup flail. The sharp knife approach requires much less energy per unit mass to reduce material to a given size; some laboratory studies indicate the benefit might be a factor of 2-8 times less energy (Jones and Associates, 1981a, 1981b, cited by Pottie and Guimier, 1985). Field studies of full-scale chippers and grinders also show substantial differences. For example, Asikainen and Pulkkinen (1998) reported that a tub grinder and drum chipper produced approximately the same mass (dry basis) per hour, but the grinder had an engine that was almost twice as powerful. Chunkers produce bigger pieces than do chippers and therefore don’t make as many cuts or utilize as much energy per unit mass as do chippers (Figure 83). Arola (1983) observed energy consumption per mass of a half to a third of that for a chipper. Mitchell et al. (1989) found that, when processing small trees at roadside, chunking cost half as much per unit of material as did chipping. Johnson et al. (1989) obtained an average production rate of 15.7 dry tons per productive hour when processing trees averaging 6.6” dbh with a 310-Hp chunker. Chunks have less surface-to-volume ratio than do chips and therefore are probably likely to decay less rapidly than chips while in storage. Pottie and Guimier (1985) described several chunking concepts, although only two were in production at that time. At present, we are aware of only one manufacturer offering chunkers (Laimet, no date), although the company calls them chippers. These are of the conical-screw type, with power requirements ranging from 20-600 kW. Depending on the cutting screw’s pitch, the larger of these machines will generate chunks of up to 150 mm in length. If a process can use material larger than standard chips without further comminution, chunking makes sense. Assuming an approximately 50% cost reduction potential for chunking versus chipping as observed by Mitchell, the benefit would be approximately $0.8-1.5/GT. (This would apply for base-case systems 2 and 3 as well.)

The LRP combined a chunker for primary comminution and a hammer hog for further size reduction. It was anticipated that the 240-kW machine might process 24 green tonnes/PMH of piled slash (50% MC, wet basis; DuSault, 1985b). The machine had a loading grapple on a slideboom with 60-foot reach so no separate loader was required.
A study in British Columbia used a single-grip processor that was manufacturing sawlogs to “chunk” the unmerchantable tops into 25-cm lengths and deposit these into transport bins. The chunks were hauled to an energy plant where they were ground for fuel (Forrester, 2004). The cost of chunking was substantial - $CN91/bdt – but was expected to be reduced to $23/bdt if the tops were bucked to 1-m lengths rather than to 25 cm. A single-grip processor is clearly suboptimal for chunking, but use of the same machine to manufacture both sawlogs and chunks eliminates the need for a separate piece of equipment.

B) Chipping at the Utilization Facility
Some studies report that chipping at a powerplant or other fixed installation may be less than half as costly as in-woods chipping (Figure 84). The electric motors employed at mills are more efficient and cheaper to operate per horsepower-hour than are diesel engines. Throughput rates are generally higher, so labor costs per ton are less. There are no move-in costs, and the equipment can in theory be in operation almost 24 hours a day.
Chipping costs are not usually very substantial relative to other costs, however, so the advantage of chipping at the destination can be easily dissipated by higher transport or other upstream costs associated with uncomminuted material.

**Transport**

The base case for energy material involves use of a standard chip van of approximately 100 yd$^3$ volume, transporting material such as green chips or ground material that fully utilizes the payload weight capacity (25 tons or so) of the vehicle.

For a given starting point and destination, transport costs may be constrained by legal limits for weights, dimensions and speeds of on-highway vehicles. Road conditions such as sight distance, width, radius of curvature and bearing capacity also place practical limits on vehicle size, weight and speed. For example, Rawlings et al. (2004) reported average travel speeds (in miles per hour) for haul trucks of 60 on interstate highways, 50 on two-lane paved roads, 30 on graveled county roads and only 10.5 on logging roads. Pottie and Guimier (1985) noted that transport may be either volume-limited or weight-limited. For a vehicle of a given cubic volume and payload capacity, the loose density at which both capacities are fully utilized is:

$$D_{\text{loose BE}} = \frac{W_{\text{max}}}{V_{\text{max}}}$$

Where $D_{\text{loose BE}}$ = the breakeven loose bulk density between weight and volume limits

$W_{\text{max}}$ = legal payload capacity

$V_{\text{max}}$ = cubic volume capacity

For example, for a 100-yd$^3$ chip van with payload capacity of 25 tons:

$$D_{\text{loose BE}} = \frac{(25 \text{ tons})(2000 \text{ lb/ton})}{(100 \text{ yd}^3)(27 \text{ ft}^3/\text{yd}^3)} = 18.5 \text{ lb/ft}^3$$

This can be compared with the actual loose density for a given material:

$$D_{\text{loose}} = \frac{D_{\text{DB}}(\text{SVF})}{(1 - \text{MC}_{\text{WB}})}$$

Where $D_{\text{loose}}$ = loose bulk density

$D_{\text{DB}}$ = basic dry density

$\text{SVF} = \text{solid volume factor} = \text{solid volume/bulk volume}$

$\text{MC}_{\text{WB}} = \text{moisture content, wet basis}$

Two examples – green chips and dry slash – are illustrative. For both cases, assume $D_{\text{DB}} = 25 \text{ lb/ft}^3$. For chips at 50% MC and $\text{SVF} = 40\%$:

$$D_{\text{loose}} = \frac{(25 \text{ lb/ft}^3)(0.4)}{(1 - 0.5)} = 20 \text{ lb/ft}^3$$

The chip van will therefore reach weight capacity before it is completely filled. Predrying the material to anything above 46% MC before chipping would therefore increase the amount of dry material that could be transported. At 46% MC, the van would be maxed out on cubic volume, so additional drying would not increase the dry payload weight.
For slash at 40% MC and SVF = 20%:

\[ D_{\text{loose}} = \frac{(25 \text{ lb/ft}^3)(0.2)}{(1 - 0.4)} = 8.3 \text{ lb/ft}^3 \]

Primarily because of the low solid volume factor of this slash, the payload for a van would be less than half of the legal limit, indicating a need for substantial densification via comminution, compaction or some other means.

Many forest roads in the western U.S. were designed for stinger-steered logging trucks that allow the rear wheels to track those of the tractor reasonably close. Conventional fifth-wheel trailers such as chip vans swing to the inside of the tractor when traversing curves and therefore may not be able to travel on roads designed for log trucks.

**Changes Related to Transport**

A) Roll-On/Off Containers

Deficiencies addressed: Interactive delays between the chipper and trucks. Such containers have been tested in forestry applications for three decades. Jones and Associates (1979, cited by Pottie and Guimier, 1986) described a two-container system with 90m³ bulk capacity that delivered 28m³ solid volume and 11.2 dry tonnes per load. Sinclair (1984, 1985) reported results of trials by FERIC of a 50-m³ container for transporting approximately 20m³ solid volume of logging residue. Time to drop off an empty container or pick up a loaded one was about 2-3 minutes. Time to dump a full container was about 5 minutes. Alexandersson (1985) hauled residues chips using two different container systems, one a hooklift (rear-loading), and the other a side-loading version. Loads averaged 84m³ loose and 34m³ solid volume (40% SVF). Rawlings et al. (2004) tested hooklift containers of 48-yd³ capacities. Thomas (2008) developed a stackable container system that allowed four empty containers to be transported on a hooklift truck with pup trailer. Axelsson and Bjorheden (1991, cited by Stokes, 1992) stated that changeable containers are used in place of chip vans on operations where chipping rates are low so that trucks are not delayed. They noted that the costs of extra containers and the slightly smaller payloads of containers versus chip vans (due to higher tare weights for similar capacities) limit the use of container systems (Figure 85).

![Figure 85. Truck with multiple roll-on/off containers.](image-url)
A1) Truck with Single Roll-On/Off Container
Deficiencies addressed: Roads that don’t allow access by chip vans due to horizontal or vertical curvature issues, or lack of turnaround spots; interactive delays between the chipper and trucks. Cost per hour for a single-container (40-50 yd³) truck is almost as much as that for a full-sized chip van (either requires a full driver) and travel speeds are similar, so at longer distances the reduced payload of a single-container unit results in much higher cost per ton than for a chip van. Rawlings et al. (2004) concluded, “For any given distance, a roll on/off container system is not competitive with a regular highway chip van, unless part of that distance is inaccessible to the chip van.”

Other relatively small vehicles such as dump trucks address the access deficiency, but introduce the same problem: small capacity. Johnson (1989) presented hourly costs for vehicles with 25 and 13-ton payloads. The cost for the smaller vehicle was 90% of that for the larger, so the cost per ton of payload would be 70% higher for smaller vehicle if round-trip times were the same. To further illustrate the point, we considered current costs for vehicles with one-, ten- and 25-ton capacities (Figure 86). There are clear advantages of using the largest-capacity option where constraints allow.

![Figure 86. Current costs for vehicles with one-, ten- and 25-ton capacities.](Image)

A2) Truck and Trailer with Multiple Roll-On/Off Containers
Deficiencies addressed: Interactive delays between the chipper and trucks.
Assuming highway-legal loads can be produced with either type of vehicle, if chipping or grinding rates are low it may be slightly more economical to comminute into containers than into vans (Figure 87). When woods-mobile chippers are employed, transferring chips into containers avoids what might be substantial interactive delays between the chipper-forwarder or chip forwarder and trucks.
Figure 8. Representative hauling costs for trucks with single and dual set-out, roll-on/roll-off containers versus standard chip vans as a function of one-way transport distance.

B) Hauling Loose Residues
Deficiencies addressed: Move-in cost for a chipper or grinder when the amount of material to be processed at a site is low.

The low bulk density of slash makes it impossible to fill a standard chip van or container to legal weight capacity. For example, Rawlings et al. (2004) recorded an average of 19,000 lb of slash at about 40% MC in 48-yd³ containers. Han et al. (2008) obtained an average weight of 3.85 tons of partially compacted slash (at 22% MC, assuming wet basis) in 40 yd³ containers that were designed for 10-ton payloads. Part of the issue in the latter case was the low moisture content, but even if the material had been at 50% MC wet basis, it would have only utilized 60% of the weight capacity. Transporting loose residues may therefore cost twice as much as hauling comminuted or otherwise densified material. Transporting single small containers compounds the issue. Rawlings et al. (2004) found that shuttling slash 2.5 miles on a woods road in a single container cost approximately twice as much per ton as hauling ground material 35 miles on a highway in a full-sized chip van. Axelsson and Bjorheden (1991) noted that residue loads of legal weight capacity can be generated by using special high-volume vehicles, by compacting or the combination of the two. However, either method increases tare weight. In Sweden, trucks for transporting low-density materials have approximately 10% less payload capacity than do standard log trucks (Figure 8).

C) On-Truck Compactors for Whole Trees or Tree Sections
Deficiencies addressed: Low utilization of weight capacity when hauling whole trees.
Zundel (1986) found that a conventional highway logging trailer used in Canada could hold only 44% as much merchantable volume when loaded with whole-tree Jack pine as when hauling delimbed tree lengths, highlighting a need for compaction. Pottie and Guimier (1986) described two types of on-truck compactors – those permanently mounted on the truck, therefore reducing payload, and removable devices. Carlsson (1981, cited by Pottie and Guimier, 1986) compacted
green tops and limbs, increasing SVF from 21.2% to 27.8%. Larsson (1982a, cited by Pottie and Guimier, 1986) used a detachable unit to compact tree sections, thereby improving SVF from 31.2% to 37.2%.

![Figure 88. Vehicle designed to haul loose residues.](image)

**Source:** Metsäteho in Hakkila 2004

D) Post-Felling Air Drying

Deficiencies addressed: Transporting water rather than dry matter. Until a chip van becomes volume-limited rather than weight-limited, decreasing the moisture content of material will increase the number of dry tons that can be transported in a load. For chips, the threshold between the weight- and volume-limited condition for a standard chip van might be around 40% MV (wet basis). Assuming that chips from freshly cut material are at 50% MC (wet basis), letting material dry to 40% MC after felling and prior to chipping would increase payload from 12.5 to 15 dry tons, decreasing costs by almost $4/dry ton (equivalent of $2/GT) on a 50-mile haul. Further drying would have essentially no benefit in terms of transport cost, but would increase heating value if drier material is acceptable for the intended conversion process. The effectiveness and rapidity of transpirational drying varies with species, exposure and weather conditions (Forrester, 1991; Stokes et al., 1987), in some cases lowering tree weight by almost half over seven weeks in the summer, while in others producing little loss over similar or longer periods.

Drying does have some incremental costs. One is the interest cost on the value of the delivered material over the average delay required for drying. The second is the cost of managing a two-stage operation rather than having all equipment on site at the same time.

E) Self-Loading Trucks

Deficiencies addressed: Move-in cost for a loaders on small units; interactive delays between loaders and trucks.

Garland and Jackson (1997) reported that standard self-loaders have 15-20% less payload and 10-25% higher hourly cost than conventional log trucks. Self-loaders typically have less lift capacity and power than separate loaders, therefore they require more time per volume while loading. These disadvantages are offset by the elimination of move-in and operating costs for separate loaders and interactive delays, i.e., the truck waiting on the loader or vice versa. They
can be advantageous where little volume is being removed from units, production rates are low and transport distances are short. As can be seen from Figure 89, the differential cost for a self-loader can be substantial. The self-loader would be competitive at shorter distances if the move-in cost for the stand-alone loader was approximately $5 per ton, for example a move-in cost of $250 dollars for a unit where only 50 green tons were to be removed.

Demountable self-loaders have been used in Scandinavia (Axelsson and Bjorheden, 1991, cited by Stokes, 1992). These reduce the payload penalty suffered by standard self-loaders, but require additional time to mount and demount. Demounting may not be a practical option when only a single load is to be removed from a treatment unit.

![Figure 89](image)

**Figure 89.** Representative loading and hauling costs for a self-loading log truck versus a log loader plus conventional log truck, not including move-in costs for the log loader.

F) Stinger-steered Chip Van
Deficiencies addressed: Roads that don’t allow access by chip vans due to horizontal or vertical curvature issues, or lack of turnaround spots.

The USFS San Dimas Technology & Development Center is working on an experimental truck that would marry a chip container with the same steering scheme as on West Coast log trucks and trailers, thus eliminating the curvature issues (Figure 90). Roseburg Forest Products is testing a similar vehicle in southern Oregon. Because the trailer would not be piggybacked while traveling unloaded, the requirement for large turnaround spots would still remain. Capital and operating costs for a commercial version of this vehicle would probably be slightly higher than for a conventional van, and payload capacity might be reduced somewhat, depending on the design of the container and the weight of extra steering components. However, the cost per ton should not be substantially more than for a conventional van, and would be on the order of half of that for a short truck with a single container.
G) Increased Legal GVW
Eason and Greene (2006) found that increasing GVW from 80,000 lb to 97,000 lb by adding a sixth axle as is allowed in some states would decrease transport costs, probably by about 9%. Siry et al. (2006) noted that on-highway GVW limits are close to 96,000 lb in Canada and 107,000 lb in Mexico. GVW limits in Nordic countries were 40 (Denmark), 56 (Finland), 50 (Norway) and 56 (Sweden) tonnes in 1991 (Axelsson and Bjorheden, 1991); Sweden’s limit has been increased to 60 tonnes (Lofroth, 2006). As a point of interest, off-highway log transport vehicle configurations may allow for loads that are an order of magnitude larger than on-highway loads. FERIC (1990, no date) reported a “truck train” with a GVW of 675,000 lb and payload of 440,000 lb.

H) Michelin X One Tires
This new wide tire replaces duals on tandem axles and also can be used on steering axles. An X One XZY 3 model has just been released for use with on/off-road applications such as logging (FERIC, 2008; Figures 91a and 91b). Michelin claims the tires (and single rims) reduce a truck’s tare weight by 800-1300 lb, and claim fuel savings of 2-8%. A test of the on-highway version of these tires found a fuel reduction of 10% (Surcel, 2007). If the weight savings translated into an increase in payload of 1000 lb (2%) and a fuel savings of 3% was realized, savings per net ton for California trucks would be about $0.24 + $0.07 = $0.31/net ton for a 50-mile one-way haul.
I) Smaller Engines
Ressaire (2006) reported that fuel accounts for about 30% of the cost of transport in Canada, therefore a focus on ways to improve fuel efficiency is warranted. He compared fuel consumption for a 12.5 l versus a 15.2 l engine for trucks with 35 tonne payloads. The smaller engine reduced fuel use by 5.5%, or about 0.001 gal/net ton-one-way mile. At $3/gallon and a 50-mile haul, savings would be about $0.14 per net ton. The smaller engine also weighed 300 kg less, so payload increased by about 1%. At a one-way distance of 50 miles, the payload gain would translate into an additional savings of about $0.10 per net ton. Total savings would therefore be about $0.24/ton.

J) Optimization of Equipment Selection and Operation
It is possible to utilize materials with higher strength-to-weight ratios for some components of transport vehicles: a pound of tare weight saved is a pound of payload gained (Guimier, 1999). Of course, exotic materials cost more, but the optimum level of sophistication may not be obvious. Among many other services to its members, FPInnovations (FERIC, 2008a, 2008b) offers two specifically related to transport. The SPEC+ computer program allows a user to compare changes to a base truck configuration, their initial costs, reduced operating costs and additional revenue over the vehicle’s life. In one example case, changes increased payload by 3 tonnes at an additional front-end cost of $40,000 but provided additional benefits of $100,000 over the five-year life of the truck. FERIC’s SmartDriver training package for truck owners and operators provides guidance on how to increase fuel efficiency, for example by optimizing the timing of gear shifts.

K) Tire Pressure Control
Deficiencies addressed: Low bearing strength of unsurfaced road surfaces when moist. Although wet/weak road surfaces are not typical problems in the Sierra, they are problematic elsewhere. Technology developed by the U.S. military some decades ago has been adapted to logging trucks and other heavy vehicles to allow tire pressures to be reduced when traveling off highway at relatively slow speeds. Lowered pressure reduces maintenance costs for both trucks and roads, as well as allowing truck traffic over roads that would not otherwise support traffic while wet. A description of a commercially available system is available from Tire Pressure Control International (Tire Pressure Control International Ltd., 2004).

L) Multi-Use Trailers
Deficiencies addressed: Empty backhauls for transport vehicles. Brown and Michaelson (2003) evaluated the use in Canada of trucks with trailers that could haul either logs or chips. Rather than a back-and-forth trip, the trucks would move logs from the woods to a sawmill, then chips from the sawmill to a pulp mill, then return empty to the woods. Savings obviously depend on the locations of mills with respect to each other and the woods. These multi-use trailers were projected to save $3 million per year in British Columbia.

M) Improved Truck Scheduling
Deficiencies addressed: Interactive delays between the chipper and trucks. Siry et al. (2006) suggested that waiting times at mills could be reduced by improved truck scheduling and dispatching. They noted that some countries have essentially no waiting times. The same argument might be made for reducing waiting times in the woods.
N) Rail or Pipeline Transport
Deficiencies: Limits to on-highway payload capacity per vehicle and operator. If convenient rail loading and unloading facilities are available, rail is an attractive option because the variable cost per ton-mile of moving materials by train is rather small. Pipelines are clearly advantageous for transporting water, petroleum and natural gas. Rail or pipeline infrastructure is expensive, therefore is economically feasible only for concentrated and continuous or relatively frequent flows. There may be some situations in the Sierra where rail transport of trees or chips may make sense for longer hauls. Kumar (2006) simulated pipeline transport of chips in a water slurry for delivery to a biorefinery, and concluded that a pipeline would be cheaper per ton-mile than trucking if transport volume exceeded half a million dry tonnes per year.

Automation
Interest in automation of forestry tasks dates back at least 20 years (e.g., Courteau, 1990), and some advances have been successful, at least on an experimental basis. For example, Bonicelli et al. (1989, cited by Asplund and Fukuda, 1993) developed a thinning machine that used laser and ultrasonic sensors to find target trees and position the harvester head, even while the base machine was moving. Theilby and Have (2007) developed an autonomous weeder for Christmas tree plantations. It is now competitive with weeding by hand and, by 2010, is expected to match herbicide application in economic attractiveness.

Remote Control is at the low end of the automation scale, yet it has some niche opportunities. For example, the Besten remote-controlled CTL harvester allows two forwarder operators to share the same harvester while eliminating the harvester operator (Figure 92). Under specific conditions of stand density and forwarding distance, this combination is less costly than a traditional combination of harvesters and forwarders or a harwarder (Bergkvist, 2006; Bergkvist et al., 2007). Remote control also has advantages in situations where an on-the-machine operator might be exposed to dangers such as rollover. In a non-forestry application, an ASV was remotely controlled to clear unexploded ordnance (ASV Inc., no date; Figure 93). A group in Idaho has developed a small remote-controlled vehicle – the Logg Dogg (Forest Robots LLC., 2006) – for forestry applications, although the advantages of this particular vehicle, other than the lower weight of an operatorless machine, are not apparent.

A second level of automation might be termed “smart” motion control, in contrast to manual control. This is particularly applicable to machines with multi-section booms. Under manual control, the operator manipulates a set of levers or joysticks, with each motion controlling one of several cylinders or motors to activate a particular joint on the boom or head. With “smart” control, the operator would simulate the desired motion, for example with an instrumented glove, and a computer would determine which valves to activate to obtain the desired result. Freedman
et al. (1995) reported on the Canadian ATREF project involving universities, industry and FERIC to develop coordinated control of the end-effector on a multi-purpose prime mover. Guimier (1999) stated that work at that time focused on boom-tip control, where the operator points a lever in the desired direction and the computer determines how to get there. Lofgren (2007) simulated boom-tip control for CTL harvesters and forwarders and estimated a 30% improvement in productivity as well as a more rapid learning curve for new operators. The system would substitute a single knob for the conventional two joysticks.

True autonomous equipment is the holy grail, but some experts feel that fully autonomous forest robots are rather unlikely (Guimier, 1999). Halme and Vainio (1998) stated that the technologies for robotics and autonomous vehicles already exist and are being employed in industries such as mining because of the large scale and substantial resources. They felt it was harder to migrate these technologies into forestry because most logging firms are rather small. In addition, forests are rather undefined environments when compared to agricultural or on-road settings. Another issue is the high development cost for a limited market. If it does eventuate, the first autonomous equipment may be for primary transport on predetermined paths, using a combination of gyroscopic dead reckoning and GPS or radio beacons as feedback inputs. Considerable advances have been made in automated guidance of agricultural vehicles, and efforts are being made to develop controllers for navigation in forests (Canning et al., 2004). Although the actual transport might be autonomous, loading and unloading might still be accomplished by humans (Asplund and Fukuda, 1993). Future automation is likely to allow operators to focus on “strategic decisions rather than on routine operating tasks” such as placing logs in piles, grabbing a tree for delimming or traveling in a straight line (Guimier, 1999). The operator will concentrate on activities that are more difficult to automate because they require perception, assessment and/or planning (Halme and Vainio, 1998).

Robots have been employed in fixed-base agricultural operations since the early 1980s, e.g., there are robotic mushroom harvesters that work 24 hours per day, but applications in the field have only been tested in the last decade or so (Grift et al., 2006; Figure 94).
Although the price of automated technologies for difficult environments is currently high, it is dropping rapidly. Events such as the DARPA Grand Challenge and international Intelligent Ground Vehicles Competition are advancing the state of the art. While in the past, single robots were operated by teams of humans, we are moving to the day when multiple robots will operate under minimal human supervision (Bellingham and Rajan, 2007). Some experts are working on flockbots, i.e., robots that work together to carry out tasks (George Mason University, 2005) (Figure 95).

Due to its piece-handling character, the felling of small trees in selective cutting is clearly the area that most needs the advantages of automation. At present, a human identifies each tree to be removed, then manually controls the machine to cut and bunch or process. In a semi-automated system, the operator would identify each tree to be cut, maybe by “painting” it with a laser, and the machine would take carry out the actual handling of the trees. A third level might involve multiple machines. In fact, Halme and Vainio (1998) expect the first semi-autonomous, multi-
machine system to be used for cutting and processing, with one human making high-level decisions and several machines carrying out the work. The operator might "paint" only the leave trees, and a fleet of cutter-collectors would then identify and handle the stems to be removed.

It is of interest to note that the ATREF project did not result in a commercial boom-tip control, but instead generated two training simulators – one for harvester operators and a second for forwarder operators – that run on personal computers and are available as a set for $3500 from Simlog in Montreal, Quebec (Simlog, 2008; Figure 96). Training simulators are also available from equipment manufacturers such as John Deere, Ponnse and Valmet.

![Training simulator for a personal computer.](image)

Source: Simlog

**Miscellaneous**

A) Angled Harvester Boom
A joint with a vertical pivot axis was added to the boom of a harvester, allowing the machine to angle to the right or left and thereby reach trees from one location that otherwise would have required repositioning of the carrier (Nordfjell et al., 2007).

B) Hybrid Powertrain
Volvo has purchased a small firm that developed the El-Forest, a series-hybrid forwarder (Figure 97). A 40-Hp diesel engine powers three generators connected to batteries and an electric motor in each of the forwarder’s six wheels (Green Car Congress, 2007). The battery buffer smooths the peaks in the duty cycle, allowing the small engine to run at maximum efficiency while still meeting the forwarder’s peak power demands. Regenerative braking by the wheel motors also conserves energy. As a result, the machine consumes only 3 liters per hour of diesel, versus 7 liters per hour for a standard forwarder producing at the same rate (Lofroth, 2006).
C) Multi-Shift Logging
Multi-shift operations are common in many countries including Australia, Brazil, Canada, Chile and Sweden. A recent analysis by Murphy and Vandenberg (2007), however, concluded that double shifts or longer shifts would result in less net revenue because, during night hours, higher levels of errors and accidents and lower productivity would more than offset the reduced hourly capital costs. It should be noted that the results are very sensitive to the assumptions made.

D) Slash Grapple
The USFS Missoula Technology and Development Center designed and fabricated a large, lightweight grapple for use by a helicopter or small cable yarder (Coyner, 2006). It appears the grapple, attached to a helicopter, would be useful for distributing erosion-control material over burned areas. It is not likely the grapple would be economically attractive as a means for collecting slash, unless material was pre-piled.

E) Delimbing and Debarking at the Utilization Facility
In cases were a mill can utilize residues as well as more valuable bolewood, it may conceptually make sense to keep trees intact until they reach the mill. For example, a cogeneration plant may be located at a sawmill and have adequate capacity to utilize tops and limbs as well as bark from the logs. It is common in Sweden to have energy plants at pulp mills. At these facilities and a pulp mill in Florida, whole trees and/or tree sections are delimbed and debarked on site by using drum debarkers. The lengths of the drums have been extended to provide the longer residence times needed to accomplish delimming as well as debarking (Twaddle et al., 1989; Watson and Stokes, 1987).

F) Road Maintenance
Deficiencies addressed: Unnecessary road maintenance.
FERIC has developed a new software tool called Opti-Grade to decrease road maintenance costs. It relies on a vibration sensor and GPS unit mounted in a vehicle to identify sections of the road with incipient washboarding. In trials, the system has reduced grading hours by a third, yet maintained roads in better condition than previously (Favreau, 2007).
G) Equipment Tracking
Several years ago, FERIC developed the MultiDat recorder for mobile equipment. Equipped with a GPS unit, the recorder tracks equipment location, operating status and downtime. Operators enter codes to explain the causes of any downtime. Over 2500 of these units are in use, helping equipment owners better understand the performance of their machines and possible areas for improvement.

H) Nutrient and Organic Material Budget
Depending on the other long-term fluxes of nutrients and organic matter, there may be concerns about the amount of material removed in fuel reduction operations. In these cases, one approach is to leave a certain percentage of material. This might be “average” material, such as bunches of small trees or masticated small trees. Alternatively, it might be “selected” material that has higher concentrations of nutrients. For example, CTL systems leave limbs and tops within the stand. Stand-mobile chippers might be equipped with crude delimbing or topping devices that would drop a fraction of the branches or tops to the ground. Some disk chippers can be equipped with separators that differentiate a fraction of bark and foliage from clean chips. Chips might be screened, with fines left on site.

Small-Scale Operations

Jonsson (1987) defined small scale as 1) the use of small machines or 2) operation on a small unit. In general, small equipment has low productivity. Machine cost is less for smaller machines, but not in direct proportion, therefore the cost per unit volume is higher, especially when the fixed hourly cost of an operator (independent of machine size) is included. Numerous studies bear out the advantages of larger equipment. For example, Robe (1988) reported that a 170-Hp skidder was preferable to a 105-Hp skidder for thinning pine plantations. Sturos (1988) found that a 48-Hp mini-skidder out-produced a 28-Hp machine by over 50% when transporting small stems. A thinning system that incorporated a feller buncher and mechanical slasher was less expensive than one that utilized chainsaws for all felling and processing. Updegraff and Blinn (2000) noted the following disadvantages of small equipment, in addition to low productivity: relatively poor ergonomics, the need in many cases for modifications to meet safety requirements, and possibly an increase in the percentage of area trafficked by equipment. System balance may also be a concern for operations on small units, because the only practical ratios for equipment may be 1:1, whereas many ratios (1:1, 2:1, 3:2, etc.) may be feasible for large units.

The use of somewhat smaller equipment or a system with fewer machines may be justified for small units because move-in costs are lowered. But move-in cost contributes very little to the cost per ton on larger units, therefore the breakeven point between full-scale and smaller equipment tends to be at rather small size. For example, Gullberg (1993) found that, for a 20-km move-in distance, a forwarder was preferable to an ATV and trailer if the total volume removed from a unit exceeded about 10 m³ (about a third of a truckload). Lyon et al. (1987) evaluated numerous combinations and estimated that more-mechanized systems with more and larger equipment were cheaper down to units with 10 to 40 truckloads, depending on the assumptions.

We calculated move-in costs per ton for several systems, at two extreme move-in distances – 25 miles and 150 miles (Figures 98 and 99). At the shorter distance, move-in costs for all systems
with the exception of those employing helicopter yarding are less than a few dollars per green ton when more than 250 tons or so are removed from a unit. More importantly, the move-in cost differential between more mechanized and less-mechanized systems is less than a dollar per ton. For the 150-mile move, the same results hold true when more than 600 tons are removed from a unit.

Figure 98. Move-in cost per green ton for various systems, for a one-way move-in distance of 25 miles.

Figure 99. Move-in cost per green ton for various systems, for a one-way move-in distance of 150 miles.
Data on the size of harvest units on private lands in California from the approximately 4400 timber harvest plans approved from 2000 through 2007 are displayed in Figure 100. Approximately 14% of the plans covered areas of 25 acres or less, but less than one percent of the total area in harvest plans was in these smaller units (Figure 101).

Figure 100. Frequency and cumulative distribution of approved timber harvest plans by amount of area in each plan, 2000-2007.

Figure 101. Sum of area and cumulative distribution of area within approved timber harvest plans by amount of area in each plan, 2000-2007.
Assuming an average removal of 20 green tons per acre and a move-in cost of $1000 for a full-sized harvesting system, the cost for move-in would be less than $2 per green ton for over 99% of the harvest area in California, if future fuel reduction operations mirror the past THPs in area involved per operation. This $2/GT represents less than 20% of the stump-to-truck costs for a full-scale system. As noted above, small-scale equipment has lower move-in cost, but generally higher operating costs per ton due to diseconomies of the smaller scale. Unless the average size of treatment units drops substantially in the future, small equipment is likely to be optimal for only a tiny fraction of the area to be treated because the benefits of using smaller, less-mechanized systems to reduce move-in costs per ton are negligible for larger units.

Larger equipment and mechanized systems are probably optimal for most of the area to be treated, if other constraints allow them to be employed. This conclusion is validated by the intentions for harvesting as indicated in the approved timber harvest plans (Figure 102); for plans covering 25 acres or less where ground-based (tractor) extraction is prescribed, mechanized feller bunchers are mentioned in only a quarter of the plans. For larger areas, feller bunchers are prescribed in 40-90% of the plans.

Nevertheless, there is a wide array of small equipment available for those who are interested in using such equipment for very small treatment units. Excellent reviews are available for tractors and small skidders (Folkema, 1985), winches and trailers for farm tractors (Folkema, 1986, 1987), ATVs and ATV trailers (Dunnigan et al., 1987, Dunnigan, 1990; Figure 103). LogRite Tools (LogRite® Tools, 2004) offers a range of arches for ATVs and tractors. The bottom end of the scale is occupied by walk-in-front tractors, e.g., the 7-Hp Swed Caddy (APA, 1985) and human-towed arches.

Figure 102. Frequencies of designations of feller-bunchers and tractors in approved timber harvest plans of various sizes, 2000-2007.
The combination harvester-forwarder or harwarder was developed in Scandinavia for small units. Only one move-in load is required, and balancing is not an issue: the machine never has interactive delays. Stanturf et al. (2003) reported that an integrated system was being developed for mechanized fuel reduction operations on small units (less than 10 ha) at the WUI in the southern U.S. They anticipated that the system would consist of either a single multi-function machine or multiple small machines, in either case transportable in one load so as to minimize move-in costs.

Aesthetic aspects are important within the WUI and elsewhere as well. Eckley and Egan (2005) had people observe in-progress extraction operations by five different types of “machines”. They found that horses were considered preferable to all others, with tractors next. Skidders and bulldozers were approximately equal, and forwarders ranked lowest on most measures. Dooley et al. (2006) reasoned that systems for fuel reduction around homes should minimize on-site processing and associated noise and dust so as to be acceptable by residents. With this in mind, they developed a machine to produce rectangular bales of tree sections and brush, to be processed at utilization facilities (Dooley et al., 2008). The baler is no more obtrusive than a refuse collection truck. The density of the bales is high enough to produce loads of approximately highway-legal weight for efficient transport.

**Multi-Function Equipment**

As Asikainen (2004) described, combining multiple functions into one machine has possible advantages and disadvantages. The former include:

- Lower capital cost than two separate machines
- Fewer operators than with separate equipment
- Opportunities to eliminate repeated handling by separate machines

Possible disadvantages include:

- More expensive per hour than any machine handling subsets of the multiple functions
- Lower move-in cost per area since fewer machines to move
- Equipment is more complex
- Reliability of a machine is the product of the reliabilities of the components; unless each element is robust, a multi-function machine is likely to be down a lot.
- Difficult to optimize for any of the functions
- Greater size and weight than each of multiple separate machines

For very small units, the move-in issue favors multi-function equipment. For example, let’s assume a five-acre parcel with 25 GT/acre to be removed. If move-in costs $500 per machine and combining functions reduces the system by one machine, the move-in savings translates into a substantial $4/GT. But if the parcel has 50 acres and the transport expenses are only $250 per machine, the move-in differential is only $0.2/GT.

Ignoring move-in, multi-function machines are likely to be advantageous when all functions can work simultaneously, they are well-balanced in production potential, and the combined machine eliminates handling that would otherwise be necessary. A chain flail delimber-debarker-chipper is an example of a machine where the functions go on simultaneously and handling between physically separated equipment is eliminated. (Early chain flail delimber-debarkers paired with separate chippers required three pieces of equipment – a loader to feed the flail, the flail and the chipper – and two operators – one on the loader and another on the chipper.) Depending on season, tree size and species, the difficulty of bark removal and therefore the capacity of the flail may be more limiting than that of the chipper, but in general the two components are well balanced.

Older-style harwarders – those that operate strictly as a harvester and then change to forwarder mode – have no potential to produce at lower cost than a separate harvester and forwarder, each working at its own rate. Newer machines that process trees directly into the forwarding bunks make one handling serve two purposes (loading as well as processing) and may be less expensive than separate machines when forwarding distances are short (Bergkvist, 2007b).

A feller-chipper is another concept with potential because both functions can occur simultaneously. But the balance between these two functions is quite sensitive to tree size because felling rate is piece-limited while chipping productivity is mass-limited. Past experience in Finland found felling to be substantially less productive than chipping, but conditions in California, i.e. larger trees than in Finland going to biomass markets, might make the combined machine more attractive here.

**System Balance**

Balancing is an important issue for multi-machine systems. As noted above, we’ve ignored it in our cost calculations because, in practice, operators make adjustments to compensate for imbalances. We wish to comment on cases where underutilized equipment may not cause too much cost penalty. These are situations where a machine has low hourly cost due to low capital investment and no dedicated labor. For example, Bolding (2003), Bolding and Lanford (2005) and Westbrook et al. (2007) added relatively small chippers to operations to produce biomass chips. The chippers were idle much of the time, but because they were inexpensive and controlled remotely by operators of other equipment, the associated costs were not high.
Summary of Economic Potential of Changes to Base Case Systems

The estimated benefits of some changes to the base-case systems and for trees at the middle of the 4-10” dbh range considered are shown below (Figures 104 through 108). To put these in context, the representative costs for the base cases at this point are, as shown previously in Figure 53, approximately $30-50/GT including $12/GT for transportation.

**Figure 104.** Benefits of changes to the ground-based whole-tree system.

**Figure 105.** Benefits of changes to the ground-based CTL system.
Figure 106. Benefits of changes to the cable yarding system.

Figure 107. Benefits of changes to the system for collecting slash and surface fuels.
Figure 108. Benefits of changes to transport and comminution.

IV. Summary of Recommendations on Existing Machinery

Based on the comparisons with base-case systems we can summarize our recommendations for existing equipment as follows.

**Gentle Terrain**

For fuel reduction operations on terrain where tractive equipment can be used, the mechanized whole-tree system (feller-buncher, skidder and chipper) is the best current alternative because it is less expensive per ton than either than less-mechanized systems or the mechanized CTL system. In addition, it removes most of the tops and limbs from the stand while CTL systems leave tops and limbs in the stand and thereby increase the surface fuel load.

Small drive-to-tree feller-bunchers are less expensive per ton than self-leveling swing-to-tree machines but are limited to rather gentle terrain. More such machines could be pressed into service if the amount of fuel reduction activity is increased, providing steady work for this specialized equipment on easy ground.

Existing clambunk skidders or a conventional skidder with a large grapple appear to have potential for increasing the size of skidded payloads and decreasing skidding costs.

There may be some sensitive sites – stream environment zones within the Tahoe Basin for example – where skidding may not be acceptable. If managers wish to leave residues on site, the following modifications to standard CTL systems would reduce costs.

a) Employ multi-stem harvester heads. Extensive trials in Scandinavia have shown that these heads reduce the costs of handling small trees.
b) Utilize forwarders with roll-on/off chassis and log bunks to reduce the time and cost involved with multiple handling of small logs. Although such equipment is not yet part of the standard line of any manufacturer, modifications to standard forwarders have been carried out and are rather simple and inexpensive.

c) Consider harwarders on small units. Harwarders with multifunction (harvesting and loading) heads and rotating bunks are becoming competitive with conventional CTL systems, although it is unlikely they will have major cost advantages except on small units.

**Steep Terrain**

A whole-tree system on steep terrain would involve chainsaw felling, cable yarding and chipping. Felling is relatively cheap, but yarding of unbunched trees is very expensive.

Where terrain and soil conditions allow, replace chainsaws with self-leveling feller-bunchers to significantly reduce yarding costs. While bunched trees can be yarded with chokers, additional benefit can be gained by employing a grapple carriage.

Use semi-automated yarders such as the Syncrofalke to free the operator for other tasks during parts of the yarding cycle. This benefit can be utilized by incorporating combination yarder-loaders or yarder-processors into the system.

**Surface Fuels**

Collecting material distributed throughout a stand is very expensive. Where it must be done, employ existing bundlers if the material has the right characteristics (size distribution and moisture content) so that bundles will remain intact. Bundling is advantageous compared to immediate chipping or grinding if material is to be stored for long periods of time and would substantially degrade or spontaneously combust if stored in comminuted form. Bundles can be extracted on conventional forwarders, stored at the landing and transported on flatbed trucks equipped with stakes.

Alternatively, consider forwarders equipped with slash compactors to collect surface material and deliver it to roadside for comminution and transport in chip vans.

**Comminution**

Consider chunking. Chunkers require less energy per ton to comminute than do chippers, so they could be applicable if the downstream users can utilize material larger than standard chips.

**Transport**

Partially dry trees and residues prior to comminution and transport. Post-felling air-drying is the least expensive method of reducing transportation costs.
Consider roll-on/off containers. They have some potential to reduce transport costs in cases where the total time to hot-load and unload a chip van is longer than the total terminal times for a truck hauling multiple containers that fully utilize the highway load limit. An alternative, of course, is to use standard setout vans, and these are probably preferable to roll-on/off equipment where vans can be utilized.

Employ tracking, full-payload chip haulers on low-standard roads. The stinger-steered van being developed by the US Forest Service and a similar vehicle in use by an industry firm in Oregon appear to have major benefits in areas where road conditions will not allow the use of standard vans.

Adopt more efficient tires. Newly introduced wide tires (Michelin X One) may reduce costs by lowering both tare weight and rolling resistance.

Optimize truck design. The increased cost of fuel shifts the optimum size for a transport truck engine to a slightly smaller power. Careful comparison of options for other truck components, using an approach such as FERIC’s SPEC+ computer program, allows truck design to be optimized by trading off higher initial cost for lower tare weight and therefore higher revenue.

Miscellaneous

Utilize information technology to a greater degree. In addition to SPEC+, FERIC has developed a number of rather inexpensive tools that can improve forest operations. Among these are the Opti-Grade system that has been shown to reduce road maintenance costs while improving road quality, and the MultiDat recorder for tracking the operation and downtime on machinery.

Train operators. Simulators such as the Simlog products for CTL systems help new operators come up to speed more rapidly while eliminating much of the downtime caused by inexperienced personnel.

Consider baling for small-scale operations in residential areas. Baling at roadside eliminates much of the undesirable aspect of fuel reduction operations while producing unitized packages of biomass that can be efficiently transported to utilization facilities.

V. Summary of Recommended Improvements to Existing Equipment and for New Equipment

Gentle Terrain

The piece-handling characteristic of felling equipment is one of the major drawbacks identified for current harvest systems.

Develop automated felling and bunching equipment. A first step is boom-tip control. The next level might combine selection by the operator of trees to be removed with automated control of boom motion to cut and bunch. A higher level of sophistication would focus the operator’s
attention on selecting (the probably fewer) trees to be retained while automating the process of identifying and removing the rest. With either option, one operator might be able to “manage” two booms on a single machine, or multiple machines.

Add a support wheel to a feller-buncher head. This would eliminate the high cantilever load on the boom and carrier. This advantage could be used to 1) reduce the size and cost of boom-equipped feller bunchers and/or 2) increase the reach of feller bunchers, thereby increasing the size of bunches that can be created from one position and increasing the spacing between skidding or yarding corridors. This could be particularly attractive when mechanized felling can be employed prior to cable yarding.

Develop a continuous-travel feller buncher. This would have considerable potential to reduce costs per ton, yet is one of the most challenging development projects due to the conditions of selective harvesting in naturally regenerated stands.

Replace human-operated booms and end-effectors (cutting heads or grapples) with other means of acquiring and transporting (over short distances that a boom normally travels) small trees. Applications include felling and bunching, harvesting, grappling unbunched trees with a skidder, loading and unloading logs onto/off of a forwarder, feeding a chipper, and picking up slash to load a bundler or slash forwarder. There are two general approaches to this: dumb swathing and smart targeting. Swathers such as scrapers for soil; front-end loaders for wood chips, sand and gravel; non-selective agricultural harvesters for row crops and forage; harvesters for short-rotation trees; and the A-Line Swather for clearcutting stands of small trees (Heidersdorf, 1982) all use the dumb approach: they acquire whatever is in within the machine’s design swath width. Similar approaches seem feasible for activities such as picking up logs windrowed by a harvester along a trail, or collecting surface fuel from the path to be taken by the collector’s prime mover. Swathing within a stand to either side of a travel path is more challenging, but a swathing head mounted on a human-operated boom might be able to acquire multiple trees or pieces without the operator having to address each one separately. A further step might involve using sensors or input from the operator to identify areas that are off-limits (because a leave tree or piece of down woody material is located there, for example), and then having the swathing head cover the rest of the area. The smart targeting approach would identify each object to be acquired and robotically move the head to it. The mechanical equipment in this case would probably look very similar to that controlled by the human now.

Increase strip width. For a given production rate, increasing the width of the strip within which a machine can acquire reduces the required travel speed. Or, increased width at the same speed will increase productivity. In agriculture, harvest widths are increased as much as possible when conditions allow; twin-row tomato harvesters and multiple-head mower-conditioners are good examples of attempts to raise productivity.

Develop a whole-tree forwarder for partial cuts. A whole-tree forwarder with an accordion or piggyback rear axle and bunk may have similar or better potential for selective harvest conditions than a skidder with a large grapple because the trees can be confined within the bunks. The accordion or piggyback feature would allow the machine to turn around easily with in selectively harvested stands.
Develop a new loader for CTL forwarders. For CTL systems, costs for handling small trees could be reduced by developing an automated loading mechanism to replace the boom and grapple, allowing the forwarder to travel continuously as does a hay bale transporter.

**Steep Terrain**

An endless-loop yarding system – such as the zig-zag system but utilizing machine power rather than humans to move wood to the cable – has considerable potential to eliminate much of the interactive delay time inherent in conventional cable yarding.

Develop a combination feller-buncher-yarder to combine the advantages of bunching and of tethering the felling equipment on steep terrain.

Build a yarder-chipper. Combination yarder-loaders and yarder-processors allow the yarder operators to perform the second function during parts of the yarding cycle when they would otherwise be idle. A yarder-chipper, or a yarder-loader feeding a separate chipper, would provide the same advantage for a system producing comminuted energy feedstock rather than roundwood.

**Surface Fuels**

Keep track of the progress of the harbundler. If mechanized CTL systems are prescribed, the least costly way to collect the residues may be with a combination harvester-bundler. This concept is currently being tested in Scandinavia.

Develop a continuous-feed bundler. Current bundlers have been described as early technologies, with potential for large gains through improvements in collection of material and in bundle-making (Hakkila, 2004). A continuous-feed header similar to that for a hay baler would eliminate the need for the operator to use a grapple and boom to pick up relatively small amounts of material.

Track the progress of swathing feller-chipper-forwarders. Trials of the NCSU/FECON fixed-head masticator-collector show the promise of such machines (with separate chip forwarders at longer distance) to replace conventional masticators in conditions where the machine can traverse the whole area to be treated.

Develop a selective feller-chipper-forwarder. Many areas in California are too steep to be traversed by fixed-head masticators. Adapting the concept of the NCSU/FECON masticator-collector to a boom-mounted masticator would be challenging but rewarding if successful.
References


ARDCO. Forestry equipment. www.ardco.net/.


Bergkvist, I. 2003. Multitree-handling increases productivity in smallwood thinning. Skogforsk Results No. 3.


Bergkvist, I. 2007a. Personal communication with Bruce Hartsough.


Carlson, W. 2003. Personal communication with Bruce Hartsough.


Cormier, D. 1989. Personal communication with Bruce Hartsough.


EcoenergyLimited. 2001. Surefire wood fuel harvester development project. ETSU B/W1/00642/REP. ETSU/DTI.


FERIC. 2008. Michelin offers wide single tires for on-/off-road applications. FPInnovations.


Hartsough, B. R. Unpublished data on Morbark 22 chipper.


Haston D. - USDA Forest Service San Dimas Technology and Development Center. 2008. Personal communication with Bruce Hartsough.


Jamieson, S. 1999. When every last log counts: for some companies in fibre-strapped New Brunswick, by-passing the steep slopes is no longer an option. As a result they have turned to the skies. Canadian Forest Ind. (March).


Roise, J. North Carolina State University. Personal communication with Bruce Hartsough.


Thomas, C. 2008. Personal communication with Bruce Hartsough.


