

---

# **Compilation of State-of-the-Art Mechanization Technologies for Short-Rotation Woody Crop Production**

November 6, 1996

Prepared by

Bruce Hartsough and David Yomogida  
Biological and Agricultural Engineering Department  
University of California  
Davis, CA 95616

under

Work Agreement WO4062-05  
Electric Power Research Institute  
3412 Hillview Avenue  
Palo Alto, CA 94303

EPRI Project Managers  
Jane Turnbull and Evan Hughes

and

Cooperative Agreement USDA-19-95-060  
USDA Forest Service Southern Research Station  
Auburn University, AL 36849

Forest Service Project Manager  
Bryce Stokes

---

## SUMMARY

This report reviews the current state of mechanization of operations, from establishment through harvesting and transportation, for short-rotation hardwood plantations. Given that essentially all of the high production plantations in the U.S. are intended for pulp production, with residues for energy as a secondary product, the report focuses mainly on approaches for producing trees greater than 3 inches DBH (diameter at breast height), although technologies for smaller trees intended solely for energy are also reviewed. Possibilities for improvement are also discussed.

Planting of more widely-spaced plantations for pulp is generally still done by hand. For closer-spaced energy plantations, mechanical planters are used. Agricultural seedling transplanters have been successful, and machines intended specifically for planting hardwood cuttings have recently been developed in Scandinavia. Cultural operations -- fertilization, weed control and pest control -- are carried out with traditional agricultural equipment, ranging from backpack sprayers to small all-terrain vehicles, agricultural tractors and implements, to aircraft. Given the amount of effort that has gone into developing equipment for a wide variety of agricultural operations, and the similarities between establishment and cultural operations for SRWC and other agriculture, improvements in these operations are more likely to be incremental than substantial.

To date, conventional forestry equipment and methods have been employed for all operational harvesting, processing and transportation of SRWC in the U.S. for pulp production. These operations are highly mechanized with the most common utilizing feller/bunchers, grapple skidders, a chain flail delimeter/debarker/chipper and chip vans. Another replaces the flail/chipper and vans with irongate delimiters, log trucks and a drum debarker. All deliver clean chips to pulp mills. Residues from the flail/chipper or drum debarker may be comminuted with a tub grinder or hammer hog and transferred to an energy production facility by van or conveyer.

Conventional forestry equipment is probably not optimal for SRWC plantations; it is used by default because it is productive and reliable. The amount of SRWC harvested has not justified the full-cycle development of specialized equipment for larger trees, i.e., greater than 3" DBH. But the conditions in SRWC plantations -- flat, obstacle-free ground, small trees of uniform size growing in straight rows, uniform road spacing (in many cases), short transportation distances to the mill (in some cases), small branches and bark characteristics which differ from those of conifers -- all suggest that SRWC harvesting, processing and transportation can be carried out in different and cheaper ways.

Equipment manufacturers and researchers have pursued numerous alternatives for harvesting smaller trees (less than 3" DBH) for energy production. Some of the most recent efforts in Scandinavia have been highly successful and have nearly reached the end of the development cycle. The best machines are based on well-developed harvesters for traditional crops such as corn or sugar cane, and involve relatively minor developments, such as headers specifically designed for harvesting small diameter hardwoods. Small, closely-spaced trees are not tremendously different than sugar cane or corn, which accounts for the relatively rapid success of the development efforts with the modified agricultural harvesters. In contrast, projects involving

purpose-built machines designed from the ground up for small SRWC have mostly been terminated.

For small trees, harvesting concepts may be classified as cut-and-chip by one machine, cut-only, or cut-and-forward. Cut-and-chip appears to be the best option, because the bulk chips are cheaper to handle than whole trees, and because the harvester is smaller and has less idle time than a combination harvester-forwarder. (With cut-and-chip machines, separate machines usually carry and transport the chips.)

One apparent improvement for harvesting large SWRC involves continuous-travel harvesting, to replace the stop-and-go, back-and-forth (or swing-and-return) motion of conventional feller/bunchers. The readily negotiable terrain and straight rows are amenable to continuous straight line travel, which in theory should be faster (for the same machine power) than any other alternative. (Note that essentially all agricultural harvesters and the successful machines for small SRWC all travel continuously.) Many continuous-travel prototypes have been built for larger trees, most of them for natural stands. None of these has met with much success, for a variety of reasons. The most promising machines, the National Research Council of Canada FB7 and FB12, were intended for SRWC for energy, but funding for their development was terminated in the mid-1980s due to the drop in energy prices. Renewal of efforts with these or similar concepts would benefit all producers of large SRWC, but the task is not as easy as with smaller SRWC because of the larger mass and higher center of gravity of the bigger trees.

Several machines with multiple functions are available or have been tested for larger trees in conventional forest handling. Examples include feller/chippers, feller/chipper/forwarders, feller/delimiter/buckers (called harvesters in conventional forest terminology), feller/delimiter/debarkers, and feller/delimiter/debarker/chipper/forwarders. Some of these are successful, many are not. Multi-function machines tend to require fewer operators, be less reliable and may not utilize the components as fully as single function equipment, but this depends on the combination. For SRWC, combinations with potential benefits include feller/loaders, feller/chippers and feller/forwarders. In addition, equipment capable of both primary (i.e. within the plantation) and secondary (on-road) transportation would eliminate unloading and reloading at roadside.

Improvements in processing (delimiting/debarking/chipping) might include a better alternative to the inherently inefficient chain flail, and an economical means of upgrading whole-tree chips for use by pulp mills. The Massahake process being developed in Finland may prove to be the latter.

A list of “ideal” harvesting/processing/transportation systems for large SWRC might include the following two examples (and others):

- 1) Continuous-travel feller/chipper, combined primary/secondary chip transport, and separation of clean chips from residues
- 2) Continuous-travel feller/loader, combined primary/secondary transport of whole trees, delimiting/debarking, and chipping.

Both systems could be used to produce either pulp chips or, by eliminating the separation step, whole-tree chips for energy.

## TABLE OF CONTENTS

1. INTRODUCTION .....	1
2. ESTABLISHMENT OF CROPS.....	3
2.1 SITE PREPARATION .....	3
2.1 PLANTING.....	4
2.2 DRIP LINE MACHINES .....	6
3. CULTURAL OPERATIONS .....	7
3.1 MANAGEMENT PROGRAMS.....	7
3.2 FERTILIZATION.....	8
3.3 WEED CONTROL.....	9
3.4 PEST CONTROL.....	11
4. HARVESTING/HANDLING.....	12
4.1 EFFECT OF TREE SIZE.....	12
4.2 OVERVIEW OF HARVESTING SYSTEMS FOR SRWC PLANTATIONS.....	12
4.3 MACHINE UTILIZATION.....	18
4.4 CONVENTIONAL FORESTRY EQUIPMENT .....	18
4.41 Tree-to-tree feller/bunchers .....	18
4.42 Cut-to-length harvesters .....	19
4.43 Skidders.....	19
4.44 Forwarders .....	20
4.45 Loaders .....	21
4.5 SRWC HARVESTING MACHINES (FOR DBH LESS THAN 3").....	21
4.5.1 CUT-AND-CHIP HARVESTERS .....	22
4.5.1.1 Valley Forest Products Precommercial Thinner (VFPPT).....	22
4.5.1.2 Texas A&M Harvester .....	23
4.5.1.3 Bord na Mona .....	23
4.5.1.4 Gandini Bioharvester 93.....	24
4.5.1.5 Austoft Sugar Cane Harvester.....	24
4.5.1.6 The Claas (695) Jaguar Harvester .....	25
4.5.1.7 John Deere Harvester.....	26
4.5.1.8 Salix Maskiner Harvester (“The Bender”).....	27
4.5.1.9 New Holland “719” .....	28
4.5.2 CUT-ONLY HARVESTERS.....	29
4.5.2.1 Virginia Polytechnical Institute/Department of Energy (VPI/DOE) Harvester..	29
4.5.2.2 University of Hawaii Biomass Harvester .....	29
4.5.2.3 National Research Council of Canada (NRCC) FB2 .....	30
4.5.2.4 National Research Council of Canada (NRCC) Coppice Harvester.....	30
4.5.2.5 Loughry Coppice Willow Harvester .....	31
4.5.2.6 Frobbesta Harvester.....	31
4.5.2.7 Empire 2000.....	32
4.5.2.8 Nicholson Harvester .....	33
4.5.2.9 Energiskogsmaskiner AB (ESM) Harvester.....	33

4.5.3 CUT-AND-FORWARD HARVESTERS .....	34
4.5.3.1 <i>Brunn AIB SRICB Harvester</i> .....	34
4.6 SPECIAL-PURPOSE HARVESTING MACHINES (FOR DBH GREATER THAN 3”) .....	34
4.6.1 CUT-AND-CHIP HARVESTERS.....	35
4.6.1.1 <i>Nicholson-Koch Mobile Harvester</i> .....	35
4.6.1.2 <i>Pallari Harvester and Canadian Crab Combine</i> .....	36
4.6.2 CONTINUOUS-TRAVEL FELLER/BUNCHERS.....	36
4.6.2.1 <i>U.S. Forest Service (USFS) Harvester</i> .....	36
4.6.2.2 <i>A-Line Swather</i> .....	37
4.6.2.3 <i>Missoula Technology and Development Center (MTDC) Harvester</i> .....	37
4.6.2.4 <i>National Research Council of Canada (NRCC) FB7</i> .....	38
4.6.2.5 <i>National Research Council of Canada (NRCC) FB12</i> .....	40
4.6.3 CUT/CHIP-AND-FORWARD HARVESTERS.....	40
4.6.3.1 <i>Georgia Pacific Biomass Harvester</i> .....	40
4.6.4 CUT-AND-DELIBM/DEBARK HARVESTERS .....	40
4.6.4.1 <i>Bell SP35 Harvester</i> .....	41
4.6.4.2 <i>Lako/Kato Grapple Harvester</i> .....	41
4.6.4.3 <i>Waratah 240 HTH</i> .....	42
4.6.5 CUT/DELIBM/DEBARK/CHIP-AND-FORWARD HARVESTERS.....	42
4.6.5.1 <i>(Bruks) IF 300 Chipmaster Harvester</i> .....	42
5. PROCESSING -- DELIMBING/DEBARKING/CHIPPING.....	43
5.1 CURRENT DELIMBING/DEBARKING/CHIPPING PROCESSES FOR PULP WOOD PRODUCTION...43	
5.1.1 <i>Irongate Delimbers</i> .....	43
5.1.2 <i>Harvesters, Boom/Stroke Processors and Roll Processors</i> .....	44
5.1.3 <i>Drum Debarkers</i> .....	44
5.1.4 <i>Chain Flail Delimber/Debarkers</i> .....	44
5.1.5 <i>Ring Debarkers</i> .....	46
5.1.6 <i>Chippers</i> .....	46
5.2 THE MASSAHAKE PROCESS .....	47
6. TRANSPORTATION.....	47
6.1 TYPES OF TRANSPORT VEHICLES .....	47
6.2 MAXIMUM PAYLOAD LIMITATION .....	48
7. RE-ESTABLISHMENT OF CROPS.....	49
7.1 RE-ESTABLISHMENT ALTERNATIVES .....	49
7.2 COPPICE THINNING MACHINERY.....	50
7.3 STUMP REMOVAL MACHINERY.....	51
7.3.1 <i>Cavaceppi Machine</i> .....	51
7.3.2 <i>Rome TX-1600 Tree Extractor</i> .....	51
7.3.3 <i>Stumper</i> .....	52
7.3.4 <i>Wick-Bartlett Stump Harvester</i> .....	52
7.3.5 <i>Pallari Stump Harvester and Modified Pallari Stump Harvester KH120</i> .....	52
7.3.6 <i>Rockland Roto Lifter</i> .....	53
7.3.7 <i>Additional Stump Harvesting Machines</i> .....	53

8. SRWC COSTS AND POTENTIAL IMPROVEMENTS .....	54
8.1 COST BREAKDOWN FOR SRWC PRODUCTION .....	54
8.2 CONTINUOUS-TRAVEL FELLING.....	56
8.3 COMBINING MULTIPLE FUNCTIONS INTO A SINGLE MACHINE .....	57
8.3.1 <i>Feller/Loaders</i> .....	57
8.3.2 <i>Feller/Chippers</i> .....	58
8.3.3 <i>Feller/Forwarders</i> .....	58
8.3.4 <i>Other Combination Machines</i> .....	59
8.4 DELIMBING/DEBARKING/CHIPPING.....	59
8.5 TRANSPORTATION.....	60
8.5.1 <i>Lighter Chip Vans</i> .....	60
8.5.2 <i>Combined Primary and Secondary Transport</i> .....	60
8.6 STUMP HANDLING.....	61
REFERENCES.....	62

## LIST OF TABLES

TABLE 1: VARIOUS HARVESTING MACHINES FOR TREES WITH A DBH LESS THAN 3 INCHES .....	22
TABLE 2: AUSTOFT STUDY RESULTS .....	25
TABLE 3: CLAAS STUDY RESULTS .....	26
TABLE 4: JOHN DEERE HARVESTER STUDY RESULTS .....	27
TABLE 5: SALIX MASKINER HARVESTER STUDY RESULTS .....	28
TABLE 6: FROBBESTA HARVESTER STUDY RESULTS .....	32
TABLE 7: EMPIRE 2000 STUDY RESULTS .....	33
TABLE 8: VARIOUS HARVESTING MACHINES FOR TREES WITH A DBH GREATER THAN 3 INCHES .....	35
TABLE 9: LAKO/KATO GRAPPLE HARVESTER MACHINE PERFORMANCE.....	42
TABLE 10: COSTS OF RE-ESTABLISHMENT ACTIVITIES .....	50

## **LIST OF FIGURES**

FIGURE 1: VARIOUS BIOMASS CHIP/FUEL PRODUCTION SYSTEMS.....	16
FIGURE 2: ESTIMATED PRODUCTIVITY OF THE FB7 .....	39
FIGURE 3: EXAMPLES OF VARIOUS SECONDARY TRANSPORT VEHICLES .....	48
FIGURE 4: VARIOUS ENERGY CROP PRODUCTION COSTS .....	55

## 1. INTRODUCTION

The use of hardwood for pulp in the United States increased from 31% to 39% of the United States' total hardwood production supply from 1976 to 1990 (McDonald and Stokes, 1993). The United States Department of Agriculture (USDA) Forest Service predicts that, by the year 2000, pulpwood will account for approximately 50% of the total hardwoods consumed in the United States. This increasing demand, along with the reduction in harvest from public lands, has encouraged the pulp and paper industry and researchers to investigate the feasibility of using short-rotation woody crops (SRWC) as a source of hardwood pulp.

Another potential user of SRWC is the biomass energy industry. The United States Department of Energy (DOE) is committed to diversifying energy production technologies for the United States to offset the dependency on domestic and foreign fossil fuel resources. Diversification can reduce the shock of sudden fossil fuel price fluctuations and can increase the dependability of electric generation systems. One such technology currently supported by the DOE is biomass energy production. Dedicated feedstocks from SRWC plantations are currently viewed as a potential means of ensuring a stable supply of fuel to biomass power plants in the United States. Countries such as Sweden and Brazil have already realized the benefits of biomass energy production through dedicated feedstocks. But since the cost of electricity through natural gas, coal, and oil fuels are relatively low in the United States, biomass energy production is currently perceived as unattractive; this perspective will change as economic, environmental, and social conditions change. To prepare for the eventual demand, ground work in SRWC production must be laid for both the pulp and energy industries.

According to Hohenstein (1994), most lands in the U.S. currently in food crop production could produce SRWC with high yield. In 1991, the USDA reported that there were 400 million acres of cropland in the U.S. Of this total, Graham (1994) found that 225 million acres could be used for the production of SRWC, producing yields of at least 5 tons/acre/yr with current technology.

The Soil Conservation Service (SCS) projected that only 220 million acres of the 400 million acres of land currently used in agricultural production will be required to meet the domestic and export agricultural demand in 2030. This means that 180 million acres could potentially be used for the production of SRWC. However, approximately 75% of this is located in the Great Plains or Mountain Regions (Hohenstein, 1994). These areas are not very suitable for SRWC production, because of low rainfall levels or uneven terrain. Thus, approximately 40 million acres of land would be in regions suitable for SRWC production. Due to this and other constraints, 20 to 40 million acres of cropland could be converted to SRWC production in the near future without displacing conventional crops in a significant way (Hohenstein, 1994).

Since SRWC production in the United States is currently more economically viable for the pulp industry than for the energy industry, most of the approximately 50,000+ acres of operational plantations are intended primarily for pulp production (McDonald and Stokes, 1993). Therefore, this report centers on the production of trees with diameters at breast height (DBH) ranging from 3" to 10"; trees with a DBH less than 3" are not suitable for pulp production, since the ratio of wood to total biomass (wood, bark, branches, and foliage) is low for small trees, and the pulping of chips from these trees results in shorter fiber lengths and lower pulp yields. The fraction of total above ground biomass from SRWC plantations that can be used for pulp production is approximately 75%, and the remaining 25% -- the tops, limbs, and bark -- may be used for fuel. Therefore, this report focuses on Eucalyptus and Populus (poplar or cottonwood) tree species, which have been looked upon more favorably for SRWC pulp production. Salix (willow) species, which have been grown for energy production in Sweden and other countries, will not be addressed heavily in this paper. The major objective of this report is to review the current technologies in the mechanization of producing SRWC trees greater than 3 inches DBH (diameter at breast height). This includes a review of various machinery which may be utilized in the growth, harvesting, transportation, and re-establishment phases of SRWC production. Special attention centers upon the mechanization potential of harvesting, since harvesting cost is relatively large and has the greatest potential for improvement. The "harvesting" section includes a description of potential harvesting schemes, using conventional forestry machinery as well as specialized machinery for harvesting SRWC stands. Next, individual specialized

harvesters are reviewed for harvesting trees less than 3 inches DBH and then for trees greater than 3 inches DBH. Other topics addressed in this report include: various machinery for plantation establishment, fertilization developments, delimiting/debarking developments, transportation improvements, re-establishment alternatives, and opportunities to reduce the costs of SRWC production.

## **2. ESTABLISHMENT OF CROPS**

### **2.1 Site Preparation**

Essentially all SRWC operations employ conventional agricultural equipment and methods when preparing areas for planting. James River operates short rotation hardwood plantations in Mississippi and Oregon. In Mississippi, site preparation on their flood prone areas includes two discings with an Amco scalloped pan disc pulled by a Caterpillar Challenger 65 tractor, and ripping (Portwood, 1994). James River's Lower Columbia River Fiber Farm in Oregon is mostly on diked floodplain sites along the Columbia River (Kaiser, et al, 1994). Site preparation includes ditching, installing drain tile on the wetter spots, four to five plowing or discing passes, mechanical spading and rototilling.

Scott Paper is planting sycamore seedlings on upland agricultural and natural woodland sites in Alabama (Morgan, 1994). On the woodland sites, they shear residual trees, rake, disc twice, and apply lime. On the agricultural lands, they disc and rip.

In the north-central U.S., hybrid poplar plantations are established on agricultural sites (Netzer and Hansen, 1994). Preparation is carried out with large tractors, plows, cultivators, discs and harrows. The majority of Brazilian eucalyptus plantations are also located on former agricultural areas. Site preparation may include removal of stumps and other residue with root rakes mounted on crawler tractors, ripping and simultaneous placement of fertilizer in the rips, which become the planting rows (McNabb, 1994).

Boise Cascade Corporation has been planting hybrid poplar on agricultural land along the upper Columbia River in Washington (Wierman, 1994). The soils are very sandy and the summer climate is hot and dry. To prevent wind erosion, Boise Cascade prepares planting strips with a rotovator and leaves untilled strips of a cover crop between.

Simpson Timber's eucalyptus plantation is sited on marginal agricultural lands in California (Rydellius, 1994). Summers are hot and dry, so irrigation is required, but the heavy soils are not prone to wind erosion. Bare land is ripped; two Caterpillar D9s in tandem allow three ripper shanks to be mounted on the second tractor. After ripping, the underground portion of the irrigation system is installed and the ground is left over the winter. Two passes with a disc are made in April, followed by emitter line installation and planting.

## **2.2 Planting**

SRWC plantations intended for biomass energy production are established at high densities, i.e. 10,000 to 20,000 cuttings per hectare, to fully occupy the site as soon as possible and maximize yield of biomass. For these high density biomass energy plantations to become economically attractive, a much higher rate of planting than possible with hand planting is required. For a large number of cuttings to be planted in a relatively short time frame in the spring, mechanical planters appear to be the best options. According to Christopherson et al (1989), a four-row mechanical planter tested in the U.S. can plant about 3,000 cuttings per hour at 3 foot by 3 foot spacing. A similar six-row planting machine developed in Sweden has been able to plant 5,000 cuttings per hour. Similar rates of production in Canada and the U.K. have been obtained using mechanized agricultural planters. Willow and poplar cuttings may be planted modified vegetable planters (with a slightly lower productivity) as well as specially developed equipment (Culshaw and Stokes, 1995).

To date, the country with the most advanced equipment for planting is Sweden; developments include the Wilstrand machine, the Frobbesta machine, the Salix Maskiner Four-Row Step Planter, and the Superprefere planter from France. The Superprefere requires one person for

each row being planted (2, 4, or 6 rows) to place cuttings in the machine. The machine inserts the cuttings into the furrow and packs soil around them. According to Christopherson et al (1989), this machine worked well in organic and light mineral soils but less efficiently on heavier clay soils. The Wilstrand machine, with one operator, can plant approximately 4,500 cuttings per hour per row in soil that has not been tilled. The Frobbesta machine is a two-row planter, taking cuttings fed by two persons, or from an automated feeder supplied by one person (Culshaw, 1993b). This planter inserts the cuttings into a slot in the soil made by a coulter, and the spacing of the cuttings is controlled by the feeding rate. The Salix Maskiner Four-Row Step Planter has been demonstrated widely in Sweden and England and will operate at 1.7 acres/hr, using willow cuttings.

In Denmark, two general types of planting machines have been developed for willow plantations: (1) machines to make the planting furrows and mark the planting locations for the willow and (2) machines to plant the willow cuttings (Ledin, 1992). The furrow maker, developed by Dansalix, forms the planting furrow and marks the locations for planting; cuttings are then hand planted. For the automated planting of willow, three different types of machines have been developed: two by Hvidsted Energy Products and another by Lydum Energy Crops. All three are drawn by agricultural tractors on three-point hitches. One of the Hvidsted planters is equipped with four furrow makers; two operators seated on the machine plant the cuttings in the four rows. This machine had a productivity of about 5 acres/day (Ledin and Alriksson, 1992). A second Hvidsted machine has two planters seated on the machine and plants only two rows at a time. The productivity of this machine was reported to be about 2 acres/day. The four-row Lydum Energy Crops planter uses ammonia injector tines to open the planting furrows; four seated operators feed cuttings into the planting heads. This machine was reported to have a productivity of about 2 acres/day (Ledin and Alriksson, 1992).

According to Christopherson et al (1989), a unit manufactured by Mechanical Transplanter Company in Michigan is primarily intended for seedlings, but it can plant 20 to 30 cm long hardwood cuttings. Through repeated field trials, this machine had an established productivity of nearly 2,000 cuttings/hour/planting head; up to six heads can be mounted on a tractor. In

contrast, a commercial hand-planting crew of five people operating in Minnesota and Wisconsin averaged about 1,640 cuttings/person/8-hour day.

Plantations intended for fiber production are established at much lower densities, i.e. 1000 to 2000 trees per hectare, because of the need to grow larger trees for high quality pulp. Hand planting is currently used at the Simpson Tehama Fiber Farm in California, Boise Cascade in Washington, and Potlatch Corporation in Washington to ensure that seedlings are placed in zones wetted by the drip emitters employed in their irrigation systems. Boise Cascade tested a modified mechanical asparagus planter but abandoned this approach because the seedlings could not be located near enough to the drip emitters (Wierman, 1994).

Many sites are wet during the planting season, so machine planting is infeasible (Portwood, 1994; Kaiser, et al, 1994). Hand planting is also preferred because the productivity of automatic planting machines has not been shown to justify the required capital cost.

In the north-central U.S., poplar cuttings have been planted by hand and by machine, e.g. a tractor with two single-row continuous furrow planters (Netzer and Hansen, 1994). Scott Paper, in Alabama, machine plants on woodland sites, and hand plants on former agricultural lands (Morgan, 1994).

In the future, the development of higher productivity planting machines for hardwood stands would benefit the SRWC industry. For drip-irrigated sites, planters must also be designed to sense wet spots near drip emitters so that seedlings can be planted in optimum locations.

### **2.3 Drip Line Machines**

According to a Lake Company Irrigation Systems (Anonymous, 1986) sales brochure, drip hoses on single-row, 3-point hitch-mounted drip hose layout machines (typically used for vineyards) have been installed at speeds up to 4 mph. Manufacturer's reported maximum capacities for these machines are about 25,000 ft/hr. Similarly, Lake indicates that drip lines on three-row, 3-

point hitch layout machines have been installed at speeds up to 4 mph with maximum capacities of 75,000 ft/hr. Three-row machines are more suitable for large acreages. For the removal of drip lines, the manufacturer estimates that single-row large-reel takeup machines have maximum capacities of approximately 2-4 acres/hr.

In a study by Coates (1985), the field capacities for tube installation were found to range from 4.30 acres/hr to 4.57 acres/hr for run lengths of 840 feet and 3960 feet, respectively, and run widths of 25 feet and 10 feet, respectively. Field capacities for tube retrieval machines were found to range from 3.76 acres/hr to 8.43 acres/hr for run lengths of 500 feet and 560 feet, respectively, and run widths of 19.4 feet and 19.0 feet, respectively. The labor requirements for the installation and retrieval of drip lines were found to be high, and it was speculated that the capital investment of drip line machines might be reduced if one machine was developed to perform both the installation and retrieval of the drip lines.

One possible problem during drip line retrieval is drip line breakage. Simpson Tehama Fiber Farm, however, has not experienced this problem during trial harvesting of their eucalyptus stands. Drip lines were found to be quite usable after the first rotation period (Richter, 1996).

### **3. CULTURAL OPERATIONS**

#### **3.1 Management Programs**

A range of management programs have been proposed for SRWC plantations from low-intensity to high-intensity. The choice of which management program to follow depends on the desired crop production rate, economics, soil fertility, and water resources available.

A typical low-intensity management scheme uses no fertilizers, irrigation only in the first year (or not at all), and weed control in the first year and in the year after the harvest. A low input approach will naturally result in relatively slow tree growth and an optimal rotation age of ten years or so. With high-intensity management, trees achieve more rapid growth because of

additional irrigation, fertilization, and/or weed control. Trees can be harvested every five to eight years. Most commercial SRWC plantations are currently managed using high-intensity schemes.

### **3.2 Fertilization**

In drip-irrigated plantations, soluble fertilizer can be added to the irrigation water, focusing fertilizer at the plant's root system. This not only reduces the amount of fertilizer required, but also eliminates the costs of alternative methods of application. Currently, Simpson, Potlatch, and Boise Cascade on the west coast and a few companies in the southeast are applying fertilizer through drip irrigation systems in their SRWC plantations.

Another option for fertilization is the use of sludge and waste water. This would provide nutrients for SRWC plantations, and a means for the disposal of sludge wastes. The use of pulp and paper mill sludge has been employed for years in eastern Canada on hybrid poplar plantations (Wilstee, 1994), and a New Zealand meat packer is using eucalyptus to dispose of effluent from a processing plant (Lowe, Sims and Cooper, 1994). Also, treated municipal waste water has been successfully used to irrigate hybrid poplar plantations in British Columbia. Drawbacks associated with this, however, include the possible buildup of heavy metals in the soil. Hence, a testing of the sludge and waste water along with the nutrient requirements of the plantation should be made before employing wastes for fertilization.

Biomass ash from direct-combustion biomass power plants is yet another option for fertilization. According to Tiangco (1988), wood ash is advantageously disposed of by incorporating it back into agricultural soil. Tiangco asserts that many past experiences utilizing soil incorporation have been successful in countries such as Sweden and Rhodesia. However, in the past, a biomass power plant in California had been fined for selling toxic ash as a soil amendment to an agricultural grower, and was required to remove the contaminated ash. Hence, care should be taken when utilizing biomass ash as a soil amendment.

For plantations which are not drip irrigated, conventional ground-based agricultural fertilizer spreaders or applicators can be used during the year of establishment or regeneration. In subsequent years, fixed-wing aircraft or helicopters are the only viable options for closely spaced plantings. For example, on some sites in the north-central U.S., nitrogen fertilizer is applied in the third year and later, by cyclone applicators carried by helicopters, small tractors or all-terrain vehicles (Netzer and Hansen, 1994).

### **3.3 Weed Control**

Ledin and Alriksson (1992) noted that weeds are one of the most severe problems during the establishment and early growth of SRWC plantations. Research has shown that effective weed control should usually incorporate a combination of mechanical and chemical techniques. In some areas, experience has indicated that mechanical weed control is the better treatment process for poplar stands during the establishment phase, in others a combination of cultivation and pre-emergent chemicals is preferred. After planting, chemical weed control or a chemical/mechanical combination is preferred, since mechanical techniques may not be effective within rows.

Equipment for mechanical weed control is generally the same in most countries. Furthermore, conventional agricultural equipment used for row crops such as corn and beans works well for SRWC plantations (Christopherson et al, 1989). One significant disadvantage of most mechanical cultivators is their inability to remove weeds within rows. There are exceptions; a machine with light tines mounted on a conveyer belt running across the rows of the trees can operate within the rows without causing significant damage to willow stands (Culshaw, 1993a).

For chemical weed control, herbicides may be applied manually or with machines. Manual application equipment includes the use of hand-held wick-like devices to wipe herbicide on weeds, and backpack sprayers. Most herbicides are applied by shielded mechanical spraying devices which are pulled behind a tractor or an all-terrain vehicle. One disadvantage, however, of chemical weed control is the sensitivity of short rotation hardwoods to damage from many of the herbicides commonly used in agriculture and forestry (Christopherson et al, 1989). Another

disadvantage is that dry weather may cause the herbicides to be ineffective, and excessive rain or moisture may leach the herbicides into the soil which may ultimately damage the trees.

Herbicides must also be labeled for use with the specific crop.

At Scott Paper in Alabama, herbicides are used to control competing vegetation; SRWC plantations established on woodland sites are aerial sprayed, while farm tractors are used to apply herbicides on the agricultural sites. Mechanical weed control is not used (Morgan, 1994).

Vegetation control on James River's Mississippi operation consists of herbicide applications and two to three cross-cultivations during the first year, one cross-cultivation during the second, and none in subsequent years (Portwood, 1994). Cultivation is carried out by tractors pulling discs and equipped with front-mounted field cultivators.

At James River in western Oregon, control of competing vegetation is critical to obtain maximum growth and survival of hybrid poplar, and to eliminate cover for voles which can kill trees as old as four years (Kaiser, et al, 1994). Herbicides are used before planting, and mechanical vegetation control (small discs, rototillers and dynadrives) and/or herbicides applied with backpack sprayers are used after planting if needed.

Weed control in the north-central U.S. is accomplished with herbicides and cultivation (Netzer and Hansen, 1994). Boom sprayers and rotary hoes are used during the first year or two. Compact tractors pulling small single-row sprayers, narrow discs, mowers, shovel cultivators or combinations of implements and sprayers work effectively later in the rotation.

At Boise Cascade's plantations in eastern Washington, weed control is the most important consideration to obtain maximum yields, but relatively little control is required during the growing season due to the lack of precipitation (Wierman, 1994). Pre-emergent is applied to the planting strips before rotovating, broadcast application is used to control grass and to control annuals late in the dormant season, and shielded sprays or wick applications are used between

the rows during the growing season. Mechanical cultivation has not been successful because of damage to the drip lines.

For preplant weed control in Brazil, herbicides are replacing mechanical cultivation (McNabb, 1994). Herbicides are applied immediately after planting, either to a 1 m band with a tractor-mounted boom sprayer, or broadcast from ground or aerial equipment. Further weed control during the first year involves rotary mowing between the rows and manual weeding with machetes or hoes within the rows. Beyond one year, shading by the tree crowns provides adequate control of competing vegetation.

The University of California, Davis is using machine vision to identify plants for weed control in California's agricultural industry (Tian and Slaughter, 1993). In field testing, a device for distinguishing tomato seedlings from weeds could identify tomato seedlings successfully 61% of the time. Another algorithm separates green plants from soil. These approaches have potential to increase the speed of herbicide application, and reduce herbicide volume and application costs, in many crops including SRWC. A similar machine vision system might be used for thinning coppice sprouts.

Another option for weed control is the use of mulch, but this is generally more expensive than mechanical control or herbicides. Materials for mulch include polyethylene plastic, shredded bark, wood chips, and grass clippings. Caution must be taken if organic mulches are used, since they may over-acidify the soil or deplete nutrients such as nitrogen.

### **3.4 Pest Control**

SRWC may be damaged by domestic livestock, rodents, deer, and insects. Young trees are more vulnerable than well-established trees. Donaldson (1988) recommended inspecting young trees frequently so that the impacts of pests will be minimized with early control. An effective weed control program will also help reduce rabbit and gopher damage. Fencing or tree guards are effective in areas with high deer or rabbit populations, but in most cases these are prohibitively

expensive. Trees such as poplars and eucalyptus are especially vulnerable to damage from rodents and grasshoppers. Minimizing the costs of short rotation forestry may include measures against pests and diseases in some areas. However, as in the case with fertilization and irrigation, the measures must not be too costly. Ledin and Alriksson (1992) suggested that the best way to handle pests and diseases is to use tolerant and resistant plant material.

Conventional agricultural methods of applying pesticides, including ground-based sprayers and spreaders, and aircraft, are appropriate for SWRC. In the north-central U.S., insecticides are applied from the ground by boom or airblast sprayers, although aerial application is required when trees are taller than 5 m (Netzer and Hansen, 1994). Boise Cascade applies systemic insecticides through their drip irrigation system (Wierman, 1994).

## **4. HARVESTING/HANDLING**

### **4.1 Effect of Tree Size**

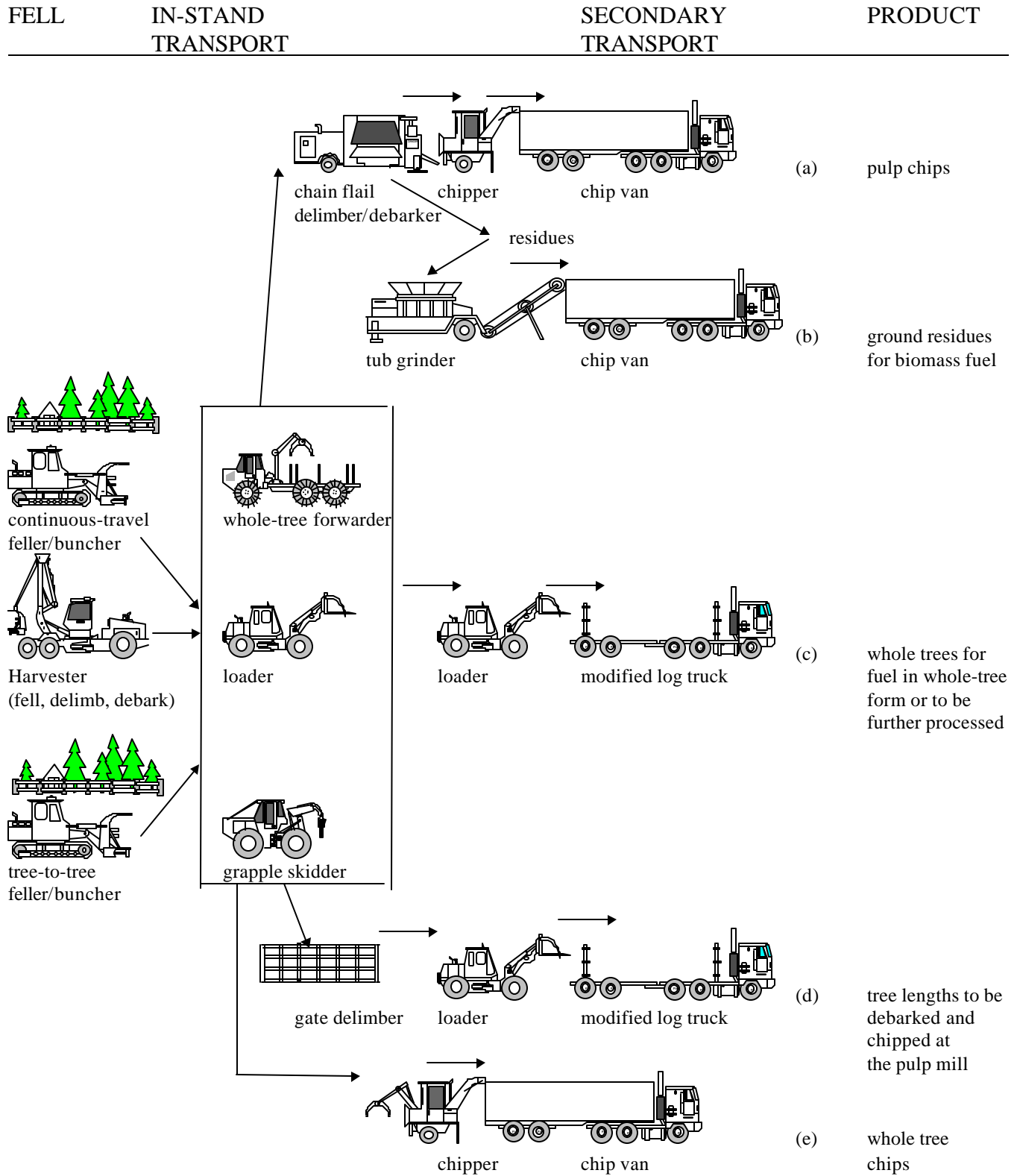
The economically optimal rotation age is a function of several factors: growth rate of the stand, costs of planting and cultural operations, harvesting and handling costs, and discount rate. A key consideration for economic optimization is the harvesting cost, and how it varies with tree size. Generally, costs are less for larger trees. For example, Stokes et al (1986) found that the minimum economic tree diameter for one SRWC plantation situation was about 6 inches when utilizing conventional feller-bunchers and skidders. Harvesting costs decrease with tree diameter because (a) the increase in the tree mass decreases the felling and skidding cost (\$/BDT) and (b) the increase in volume removed from the harvest site decreases the machinery move-in costs per BDT.

### **4.2 Overview of Harvesting Systems for SRWC Plantations**

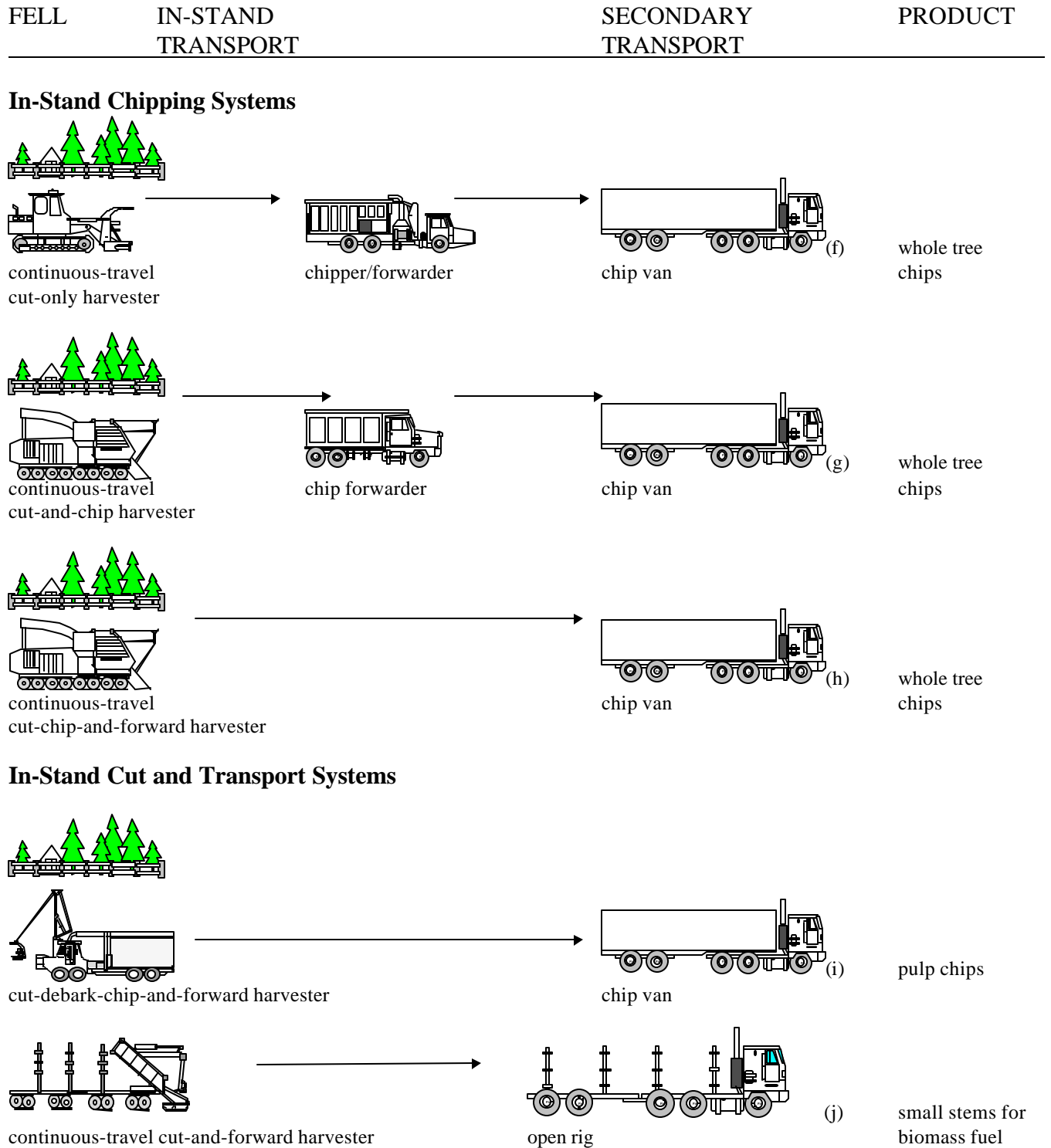
Various harvesting systems have been suggested for SRWC plantations for pulp production and biomass energy production. A system may be composed of the five general steps: (1) felling,

(2) in-stand transport (primary transport: skidding or forwarding), (3) delimiting/debarking (only for pulp production), (4) chipping, (5) and fuel/chip transport (secondary transport). Two or more of these steps may be combined together in one operation, making the system more compact, and utilizing less equipment. For instance, Figure 1(f) shows a system in which the chipping and forwarding processes are combined together in one operation. Additionally, some of these five steps may not be necessary in the production of biomass fuel. For instance, Figure 1(c) shows that the delimiting/debarking and chipping processes are not present in the production of whole-tree biomass since delimiting and debarking is not necessary for the utilization of the woody products in direct-combustion, and chipping is not included when the trees are to be burned in whole tree form. Figure 1 includes the more conventional systems and some of the more economically attractive options for fiber/fuel production.

**Figure 1: Various Biomass Chip/Fuel Production Systems**



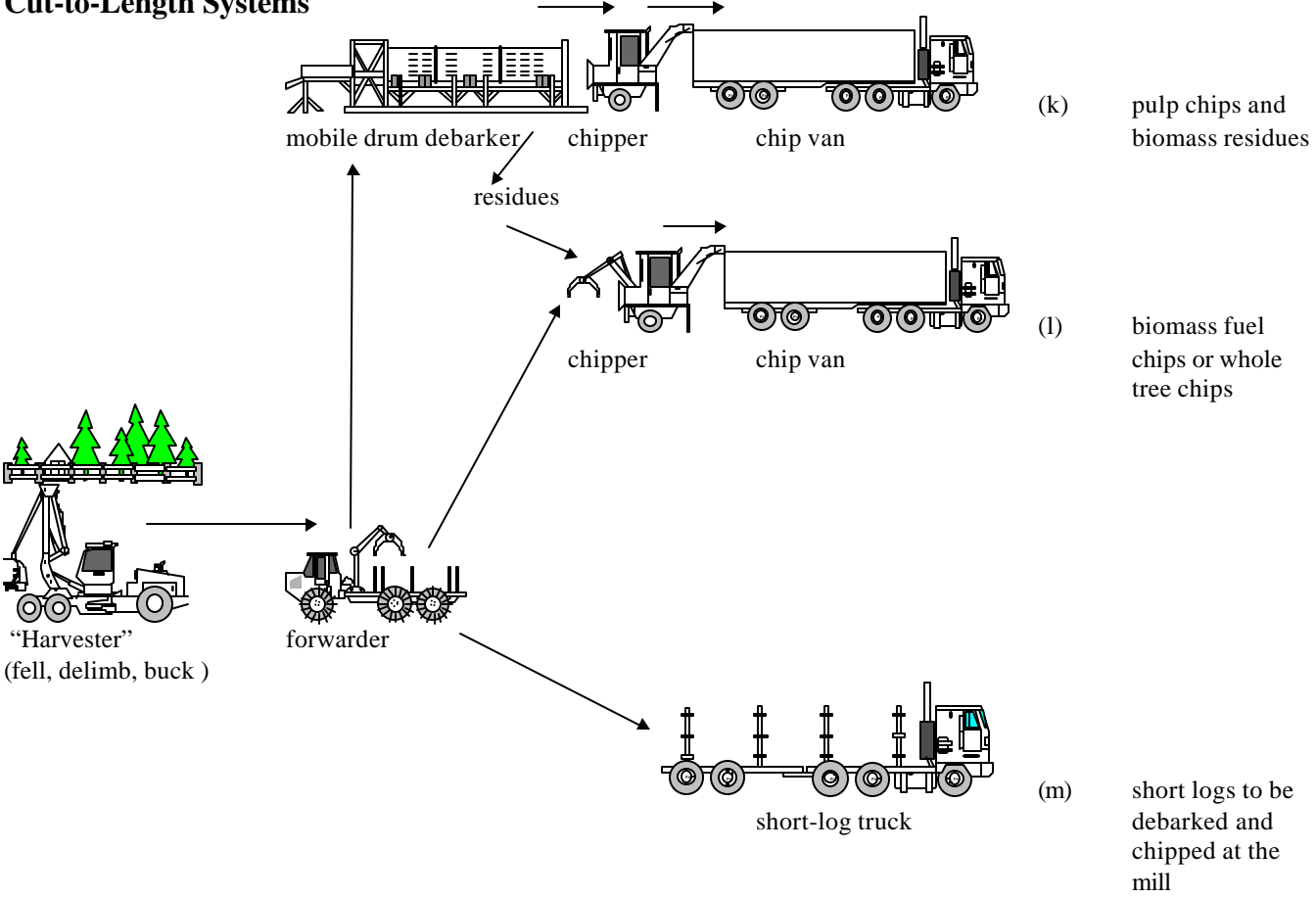
**Figure 1 (continued): Various Biomass Chip/Fuel Production Systems**



**Figure 1 (continued): Various Biomass Chip/Fuel Production Systems**

FELL	IN-STAND TRANSPORT	SECONDARY TRANSPORT	PRODUCT
------	-----------------------	------------------------	---------

**Cut-to-Length Systems**



Figures 1(b), 1(c), 1(e), 1(f), 1(g), 1(h), 1(j), and 1(l) illustrate possible biomass fuel production processes, where delimeter/debarkers are not needed. (Systems 1(e), 1(f) through 1(h) and 1(l) could also produce pulp-quality material, if the whole-tree chips were upgraded with the Massahake process, described in section 5.2.) Figure 1(g) represents processes that utilize continuous-travel “cut-and-chip” harvesters for the production of biomass fuel. Figures 1(a) through 1(e) represent conventional harvesting systems in which skidders, whole-tree forwarders, or loaders may be used for in-stand transport.

Figures 1(k) through 1(m) illustrate cut-to-length harvesting schemes, where the trees are bucked after being felled. These processes are currently used in the harvesting of trees for pulp production; but in most cases cut-to-length systems have been shown to be more expensive than whole-tree systems because of the extra processing and handling of multiple pieces per tree. Because forwarding cost is less sensitive to distance than is skidding cost, cut-to-length systems may compete with whole tree systems when the primary transport distance is relatively long. But since most SRWC plantations have fairly dense road networks, the primary transport distance is relatively short, and hence cut-to-length systems are expected to be less economical than the chip/fuel production systems found in Figures 1(a) through 1(e).

Figure 1(c) illustrates the “whole-tree” process, described by Schaller, et al (1993). It is a possible means of reducing the cost of biomass fuel sent to a direct-combustion biomass power plant. In this process, trees are felled, placed in trailers, transported to power plants, and placed in drying stacks. Delimiting, debarking and chipping are not included in this process, since (1) residues may be efficiently utilized as biomass fuel and (2) the power plant is assumed to be capable of burning trees “whole”. This process could also be used for supplying woody material for pulp production by delimiting, debarking, and chipping the whole trees at the pulp mill or at the central processing facility. However, as noted later in the section on transportation, special log trailers would probably need to be developed to safely and legally haul whole trees on public roads, and payload weights may be less than those for chips.

With the exceptions of the continuous-travel feller/buncher, components of the systems shown in Figures 1(a) through 1(e), and 1(k) through 1(m) are proven in forest harvesting operations. Prototypes of continuous-travel machines, whether they be feller/bunchers or harvesters, have been developed, but few are operational at this time.

### **4.3 Machine Utilization**

The production rate for a harvesting system composed of several machines working in series is limited to that of the least productive machine in the system. There are several ways to balance the individual capacities of the machinery in a system to make the system more efficient. One way is to increase the productivity or increase the working hours of the least productive machine. Another way is to use multiple machines, e.g. two skidders instead of one. Balanced harvesting systems have the lowest costs since the machines are more fully utilized.

### **4.4 Conventional Forestry Equipment**

SRWC harvesting mechanization in the U.S. has been geared towards the paper/pulp industry with byproducts targeted, in some cases, for biomass energy production. The relative scarcity of harvesting machinery developed specifically for SRWC plantations has necessitated the use of conventional forest harvesting equipment. However, these machines are designed for rough terrain and are therefore somewhat oversized and more rugged than required for most SRWC applications. The utilization of smaller and lighter harvesting machines would not only lower the up-front capital costs but would also lower the associated operating and maintenance costs. These, however, must be considered along with the productivity of the machinery.

#### *4.4.1 Tree-to-Tree Feller/Bunchers*

Tricycle or articulated rubber-tired drive-to-tree feller/bunchers are by far the cheapest commercially available machines for felling and bunching trees in the 5” to 10” DBH range, to be followed by skidding, whole-tree forwarding or woods-mobile chipping. They cause more soil

disturbance than other felling methods, and can't load forwarders or trailers. Rubber-tired or tracked limited-area (excavator-style) feller/bunchers are more expensive than drive-to-tree machines, but they can travel in a single track, causing very little surface disturbance. They could probably load trailers in the field.

Feller/bunchers may utilize shears to sever trees from the stumps; shears are somewhat slower than saws but they are cheap and robust, and they can cut at or even below the ground level, maximizing fiber recovery. Chainsaws and intermittent circular saws produce clean cuts, which may be important if coppice regeneration is desired, but saws are more expensive than shears. Continuous-rotation or "hot" circular saws are fastest and are necessary for continuous-travel machines, but are most sensitive to contact with soil.

#### *4.4.2 Cut-to-Length Harvesters*

Harvesters are much more expensive than feller/bunchers, but are used in many countries or regions where it is desirable to leave residues on site rather than accumulating them at roadside or using them for fuel. They also cause almost no site disturbance, and can create a mat of slash that is traveled on by the forwarders which transport the log lengths to roadside. They have been used to simultaneously delimb and debark eucalyptus. The disadvantages include the extra cost of processing trees into shorter lengths, and the extra downstream costs of handling the multiple smaller pieces.

#### *4.4.3 Skidders*

Rubber-tired grapple skidders are obviously overbuilt for most SRWC plantations; the heavy guarding for machine protection, extreme axle or frame oscillation capabilities for rough terrain, low gearing for handling slopes, and decking blade may have little or no utility. Because trees are dragged on the ground, skidding disturbs the soil surface and requires more tractive effort than does forwarding. Some soil is mixed with the trees, especially in wet conditions, leading to higher ash contents; no problems are known to have been reported with soil levels on either

pulpwood (where the soil is removed during debarking) or trees harvested for fuel. For fuel, alkali derived from soil is far less mobile during combustion than the biological ash (Jenkins et al, 1996), and therefore causes relatively little fouling on boiler tubes.

Skidding is often recognized as a major cause (second only to roads) of soil disturbance in conventional harvesting operations, with 50% to 75% of the skid trails considered compacted. Lighter machines have less impact. Wasterlund (1992) stated that 5 to 10 ton machines with a real mean ground pressure of 8.7 to 10 psi could possibly give an acceptable level of soil disturbance. High tractive forces and slip may result in twice as much soil disturbance as produced by ground pressure alone. Therefore, it's not surprising that calculations have shown that it is better to carry the load, e.g. on a forwarder, than to skid, if soil disturbance is an important consideration.

In a number of studies, rut formation, soil compaction, and the water infiltration rate were found to be influenced by the number of trips. According to Wasterlund (1992), the first trip often contributes more than 50% of the damage compared to the next 10 or 20 trips.

To mitigate this problem, skid trails have been used to minimize the area exposed to compaction forces. On agricultural soils, where stumps have been removed and rock content is low or non-existent, compaction may be mitigated by ripping or disking and/or rototilling. The costs and timing of these operations must be considered, but soil disturbance is probably much less of a concern in SRWC plantations, where site preparation is relatively easy, than in conventional forests.

#### *4.4.4 Forwarders*

The use of a log-length forwarder causes less damage to the stand and has been shown to cause less soil compaction and disturbance than a skidder. Also, the use of forwarders may cause less damage to stumps than do skidders. However, stump damage is not currently a major consideration when harvesting SRWC plantations for pulp material, since replanting is

considered to be more economically attractive than coppice regeneration for pulp production. As noted above, the cut-to-length harvester and forwarder system is generally more expensive than whole tree systems because of the extra handling of the multiple short pieces.

#### *4.4.5 Loaders*

Golob (1986) proposed the use of front-end loaders for transporting bunches of small whole trees to roadside. This is an option that would eliminate the soil disturbance caused by dragging of trees, however it is probably not feasible for longer trees, e.g. of 60 feet or longer, because of potential breakage and other problems when holding long, slender stems horizontally while supported only near the center.

James River Columbia River Fiber Farm in Clatskanie, Oregon is currently harvesting their poplar stands for pulp production with residues for biomass energy production, using the tree-to-tree feller-buncher harvesting scheme shown in Figure 1(a) and a tub grinder for processing residues as shown in Figure 1(b). Their configuration utilizes a tricycle drive-to-tree feller/buncher, rubber-tired skidders for drier terrain and tracked skidders for wetter ground. This method has proven to be the most economical currently available alternative for harvesting their stands. Simpson Paper Farm in Corning, California has successfully tested a similar system for eucalyptus.

### **4.5 SRWC Harvesting Machines (for DBH Less than 3")**

Trees with DBH values less than 3 inches are generally not suitable for pulp production; hence, this harvested woody material is usually used for biomass fuel. Two general schemes are currently employed for the harvesting of SRWC with DBH values less than 3 inches. One scheme is the “cut-and-chip” process (Figure 1(g)), and the other is the “cut-only” process (Figure 1(f)). Another process which has a significantly lower productivity than either the “cut-and-chip” or “cut-only” processes is the “cut-and-forward” process (Figure 1(j)), which is not widely utilized. According to Culshaw (1993b), recent tests have shown that the cost of

harvesting is minimized by using machinery which produces chips in a one-pass operation (“cut-and-chip” process). A summary of the various harvesting machines suitable for trees with DBH less than 3 inches is found in Table 1.

**Table 1: Various Harvesting Machines for Trees with a DBH Less than 3 Inches**

<u><b>Cut-and-Chip Harvesters</b></u>	<u><b>Cut-only Harvesters</b></u>
Valley Forest Products Precommercial Thinner	Virginia Polytechnical Inst./DOE Harvester
Texas A&M Harvester	University of Hawaii Biomass Harvester
Bord na Mona	NRCC FB2
Gandini Bioharvester 93	NRCC Coppice Harvester
Austoft Sugar Cane Harvester	Loughry Coppice Willow Harvester
Claas Jaguar	Frobbesta Coppice Harvester
John Deere Harvester	Empire 2000
Salix Maskiner Harvester (“The Bender)	Nicholson Harvester
New Holland “719”	ESM Energiskogsmaskiner AB (ESM)
 <u><b>Cut-and-Forward Harvester</b></u> Brunn AIB SRICB Harvester	

#### **4.5.1 Cut-and-Chip Harvesters**

##### *4.5.1.1 Valley Forest Products Precommercial Thinner (VFPPT)*

The VFPPT consisted of a cutting header mounted on a conventional skidder. Two counter-rotating circular saws severed stems, and a drum chipper reduced the severed stems to chips which were blown the length of the skidder into a container (Curtin and Barnett, 1986). A push bar mounted approximately 6 feet above and 3 feet in front of the saws, produced bending in the stems as they were cut. When severed, the stems consequently “jumped” into the chipper. Chips were then blown the length of the skidder into a container. However, during harvesting, stumps

were frequently pushed over, split, and debarked on one side, since the saw housing on the VFPPT was located relatively low to the ground. An auxiliary power source of 96 hp was used to drive the saws and chipper, resulting in a total power requirement of about 200 hp.

#### *4.5.1.2 Texas A&M Harvester*

The Texas A&M Harvester was primarily designed for harvesting mesquite. In this harvester, a Brown Bear Flail cutterhead mounted on a John Deere forage harvester cuts woody material, and an auger and blower conveys the comminuted material to a towed van. In 1994, testing on this machine was carried out in coppice regrowth stands. The harvester was capable of traveling about 2 mph and collecting most of the comminuted material. Another trial was carried out in a tree-year-old sycamore plantation, where the trees averaged a height of 15 feet and a diameter of 3.9 to 4.7 inches. In this trial, the cutterhead severed the stems from the stumps, but it could not capture and comminute the material. Culshaw and Stokes (1995) believe that redesign of the cutterhead may resolve this problem. This harvester is still under development.

#### *4.5.1.3 Bord na Mona*

The Bord na Mona consisted of a trailed unit pulled by a farm tractor in the 120 hp class and was designed to harvest Salix aquatica up to 3.3 inches in diameter (Curtin and Barnett, 1986). But this harvester had been shown to also work adequately for harvesting willow (Christopherson et al, 1989). Severing was accomplished by a pair of 3-foot diameter circular saws. The severed stems were then directed to the rear of the trailer by chain-mounted deflector bars, spring-loaded vertical rollers, a conveyor, and horizontal rollers. This conveying system fed the trees into two horizontal chopping cylinders that cut most of the trees into billets 6 inches long. The billets were then transferred to a flail which removed small branches before the comminuted material was conveyed into a 250 cubic feet container that could be hydraulically emptied at the edge of a field. The project did not proceed beyond the initial stages.

#### *4.5.1.4 Gandini Bioharvester 93*

The Gandini Bioharvester 93 consisted of a farm tractor with a felling/feeding/comminuting head fitted to the three-point hitch and a chip bin mounted on a steel frame on top of the tractor nose. For felling, a hydraulically powered disk saw was used; for feeding, two parallel augers, faced by a third parallel staggered auger, transport the stems to a horizontal disc chipper. After the chipper processed the woody material, the chips were blown into the 124 ft<sup>3</sup> bin. Dumping of the bin, directly into a truck, was hydraulically actuated.

According to Culshaw (1993b), several problems were identified. First, the feeding process was found to be the bottleneck of the harvester. For the future, the feed augers were to be replaced by parallel, opposing, multiple conveyor chains. Second, a more powerful tractor was suggested, to supply enough power for all hydraulic devices and the chipper. In addition to this, the new tractor was suggested to have lower gears, since the tractor speed exceeded the feeding and chipping speeds, resulting in material build-up in the assembly. Third, cutting might have been improved by using a larger saw disk. The Gandini project was terminated in 1994, in favor of other, more promising machines such as the Claas and Austoft (Spinelli, 1996a).

#### *4.5.1.5 Austoft Sugar Cane Harvester*

The Austoft harvests two rows of stems per pass. Two augers, at the front of the machine, feed the stems into either circular saws or bush disks for cutting; bush disks are preferred over circular saws in stony soil conditions. The severed stems are then picked up at the butts by a lifting roller and are then transferred to a series of rollers which convey the stems to a swinging knife billeting mechanism at the back of the harvester. The 1.6 inch to 2.4 inch billets are then transferred by a conveyer to a trailer. As an alternative, 35 cubic feet of chips may be stored on the conveyer until a trailer arrives. In January 1994, a series of twelve harvesting runs were carried out with the Austoft in the U.K.. The machine could average 0.91 acres/standard (std) hr or 9.2 ODT/std hr, assuming twin row planting and two-way working (Anonymous, 1994; a standard hour

includes allowances for servicing and personal breaks, but does not include downtime for unscheduled repairs; two-way operation involves the machine cutting while moving through the plantation, turning, then cutting on the return pass). Average travel speeds while cutting two rows spaced at 3 feet ranged from 1.3 to 2.4 miles/hr in stands averaging 7.7 to 13. ODT/acre. Table 2 summarizes the results of this study. In these tests, the Austoft was run on both uphill and downhill conditions. Productivity was not affected by travel direction.

Trials in Scandinavia and Europe indicate average productivities of around 20 green tonnes per hour (range: 10 to 30) for the Austoft (Spinelli, 1996b). The machine is robust and in its current configuration is likely to have high availability when harvesting SRWC. The tracked undercarriage gives it high mobility on soft soils, and it is capable of operating on slopes.

**Table 2: Austoft Study Results**  
( Adapted from Anonymous (1994))

Site	Working Method	Average Run (ft)	Spacing	Output (acres/std hr)		Output (ODT/std hr)	
				Actual	Without Blockage	Actual	Without Blockage
Castle Archdale (13.0 ODT/acre)	1 Way Reverse	160	3 ft + 3 ft	0.556	0.60	6.4	7.85
			5 ft + 2 ft	-----	0.68	-----	8.81
Castle Archdale (10.5 ODT/acre)	1 Way Travel Round	210	3 ft + 3 ft	0.447	0.48	4.2	5.10
			5 ft + 2 ft	-----	0.54	-----	5.71
All Sites (10.2 ODT/acre)	2 Way	450	3 ft + 3 ft	0.632	0.73	5.8	7.44
			5 ft + 2 ft	-----	0.92	-----	9.42
			5 ft + 2 ft	-----	1.0	-----	10.3

#### 4.5.1.6 The Claas (695) Jaguar Harvester

The Claas Jaguar is multi-purpose “cut-and-chip” harvester. The Claas was initially run with a slightly modified forage corn header, but the header frequently broke down and the feed control was not reliable (Culshaw and Stokes, 1995). Recently, Claas developed a purpose-built header, which is now available from Claas and is fully supported through their dealer network. The Claas blows chips into a chip forwarder which travels behind the harvester. Two forwarders are matched with one harvester so the harvester can operate essentially continuously. In December 1994, a series of tests were carried out in the U.K.. Travel speeds while cutting twin rows averaged 2.5 to 4.3 miles/hr in stands averaging 3 to 7 ODT/acre. Assuming twin row harvesting,

calculations indicated that the Claas 695 could achieve a two-way output of 8.6 ODT/std hr, assuming a yield of 7.7 ODT/acre (Anonymous, 1995). Table 3 summarizes the results of the December 1994 study.

Much higher production rates have been rumored for the Claas under Swedish conditions: 7000 cubic feet (on the order of 50 ODT) of chips per hour (Culshaw, 1993b), and 2.5 acres per hour while cutting (Wiltsee and Hughes, 1995). These higher rates, which must be adjusted downwards to reflect expected delays, could be due to better terrain conditions and higher crop amounts per acre. A more realistic estimate of average production potential may be on the order of 40 green tonnes per hour (Spinelli, 1996b). It should be noted that the Claas base machine, designed for forage harvesting, may have high maintenance requirements when fed a steady diet of SRWC. It works well on gentle slopes and frozen ground, but is not as capable on very soft soils or steep terrain.

**Table 3: Claas Study Results**  
(Adapted from Anonymous (1995))

Site	Working Method	Average Run (ft)	Between Row Spacing	Output (acres/shr)		Output (ODT/shr)	
				Actual	Without Blockage	Actual	Without Blockage
Parbold & Buckfast (5.13 ODT/acre)	2 Way Harvest	400	3 ft + 3 ft	0.74	0.99	3.81	5.07
		400	2 ft + 5 ft	-----	1.1	-----	5.70
		660	2 ft + 5 ft	-----	1.4	-----	7.10
Buckfast (4.90 ODT/acre)	Round Robin	540	3 ft + 3 ft	0.94	1.3	4.59	6.17
		540	2 ft + 5 ft	-----	1.4	-----	6.90
		660	2 ft + 5 ft	-----	1.5	-----	7.26

#### 4.5.1.7 John Deere Harvester

The John Deere Harvester is similar in design and method of harvesting to the Claas. Stems are cut by an interchangeable header and then chipped by a drum chipper, before being blown into collection trailers (Anonymous, 1995). In December 1994, the John Deere 6910 Forager with a Kemper corn header was tested in a series of 10 runs in the U.K.. An average productivity of 6.80 ODT/std hr was reported in 3 feet by 3 feet row spacings with stand densities of 13.1 ODT/acre, but the Kemper header was considered unsatisfactory for SRWC. Table 4 summarizes the results of this study.

**Table 4: John Deere Harvester Study Results**  
(Adapted from Anonymous (1995))

Site	Working Method	Average Run (ft)	Spacing	Output (acres/std hr)		Output (ODT/std hr)	
				Actual	Without Blockage	Actual	Without Blockage
Castle Archdale (13.1 ODT/acre)	1 Way	300	3 ft + 3 ft	0.52	0.52	6.80	6.80
	Reverse		2 ft + 3 ft	-----	0.47	-----	6.15
Castle Archdale & Swanbourne (10.7 ODT/acre)	1 Way	300	3 ft + 3 ft &	0.54	0.62	5.80	6.58
	Reverse		5 ft + 3 ft 2 ft + 5 ft	-----	0.52	-----	5.53
All Sites (6.92 ODT/acre)	2 Way	440	3 ft + 3 ft	0.74	0.99	5.13	6.84
		440	2 ft + 5 ft	-----	0.89	-----	6.16
		660	2 ft + 5 ft	-----	1.0	-----	7.19

In these tests, the machine was able to efficiently harvest down hill on 10% slopes with side sloped up to 17%. However, the harvester failed to climb a 10% slope in wet field conditions, with wheel slippage between 6% and 10%. Throughout the trails, the harvester had to be held above the desired cutting height of 4 inches, making operation difficult. This was done to ensure that the header did not dig into the ground as the forager pitched on the uneven terrain.

#### 4.5.1.8 *Salix Maskiner Harvester ("The Bender")*

The *Salix Maskiner Harvester* is designed to harvest twin rows of willow coppice, while attached to the three-point hitch of a reverse-drive Ford Versatile tractor. While harvesting, feed chains catch stems in the middle and pull them into the machine where the stems are folded and compressed into a huge 'sausage-shaped' mass. The resulting 'stem sausage' may be handled, stored, and processed as though it were a log. After the stems are compressed, they are drawn into a drum chipper by hydraulic feed rollers. The resulting chips are blown through a discharge shoot into hitched trailers or tractor trailer units. In December 1994, twelve test runs were made on the *Salix Maskiner* at four different sites in the U.K.. According to the Forest Authority (Anonymous, 1995), the *Maskiner Harvester* could achieve a two-way productivity of about 4.0 ODT/std hr, assuming a yield of 8 ODT/acre. The December 1994 test results are summarized in Table 5.

**Table 5: Salix Maskiner Harvester Study Results**  
**(Adapted from Anonymous (1995))**

Site	Working Method	Average Run (ft)	Spacing	Output (acres/std hr)		Output (ODT/std hr)	
				Actual	Without Blockage	Actual	Without Blockage
Castle Archdale (12.3 ODT/acre)	1 Way	130	3 ft + 3 ft	0.074	0.27	0.91	3.34
	Reverse		2 ft + 5 ft	-----	0.30	-----	3.64
All Sites (8.13 ODT/acre)	2 Way	340	3 ft + 3 ft &	0.25	0.44	2.00	3.62
			5 ft + 5 ft	-----	0.52	-----	4.22
			2 ft + 5 ft	-----	0.69	-----	5.62

In the 1994 tests, the harvester experienced traction problems on wet soils, and chains were required to maintain efficient harvesting. The addition of the chains greatly increased the traction so that the harvester was able to harvest on slopes of 10%. Another problem was the skid design for the harvesting head. The harvesting head was designed to skid along the top of hard, frozen ground; but with the wet, soft ground conditions the skids pushed into the ground under the weight of the header. To overcome this problem, larger skids were made to improve flotation of the header. Also, during harvesting, the header occasionally obstructed the operator's view of the crops, requiring high operator skill and concentration. To overcome this problem, a second person was used to signal the operator whether to lift or lower the header to suit the immediate ground condition (Anonymous, 1995).

#### *4.5.1.9 New Holland "719"*

The New Holland is a single-axle, single-wheeled trailed device with a header, powered by a towing tractor. The header may be detached and replaced by other units for different operations (Anonymous, 1994). The header used in 1994 test runs was designed to feed 2 rows of corn stems. Chain-driven teeth help feed the stems into horizontal reciprocating triangular cutting teeth, and a horizontal push bar is mounted on the upper chassis to aid the flow of the stems into the conveying system. The cut stems are gripped by a set of horizontal feed rollers, which feed the stems into a drum chipper. The drum chipper creates an airflow which blows the chips out of the discharge spout and into a trailer. In January 1994, the New Holland was briefly tested in the U.K. for harvesting poplar and willow (Anonymous, 1994). In willow stands, the New Holland

performed reasonably well, cutting single rows. The corn cutting headers severed the stems at 7.9 inches to 12 inches height, and the collecting mechanism was generally effective although the bushy nature of the willow caused bunching at the throat. Cleanly severed chips of 0.60 inch to 1.4 inch sizes were produced. In these tests, productivities were not measured.

## **4.5.2 Cut-Only Harvesters**

### *4.5.2.1 Virginia Polytechnical Institute/Department of Energy (VPI/DOE) Harvester*

According to Curtin and Barnett (1986), the VPI/DOE harvester was a continuous-motion harvester which was designed and built at the Virginia Polytechnical Institute in cooperation with the United States Department of Energy for harvesting stems up to about 3 inches in diameter. This machine severed the stems with two counter-rotating saws, conveyed the stems to a crusher for dewatering, and then dropped the crushed stems on the ground for drying and later recovery. This harvester was intended specifically for biomass energy production. Future versions of the harvester were suggested to be constructed to allow the system to be towed by an agricultural tractor (Christopherson, 1989), to eliminate power limitation and maneuverability problems, but a revised prototype was never built; this harvester is not being developed any further.

### *4.5.2.2 University of Hawaii Biomass Harvester*

A harvester was proposed by the University of Hawaii for cutting small-diameter trees, but this machine was never built (Paquin, et. al., 1989). This proposed harvester was conceptually supposed to use two circular saws to cut trees while moving in a continuous motion. After cutting, trees were to be moved from a standing position to a flat bed trailer hitched at the rear of the harvester.

#### *4.5.2.3 National Research Council of Canada (NRCC) FB2*

The FB2 was a farm tractor attachment designed to handle small diameter coppice sprouts from plantations. Five major steps were involved in the harvesting process: (1) individual bulky coppice sprouts were gathered into the severing and accumulating mechanism, (2) the stems were severed, (3) the sprouts were accumulated in a holding area, (4) the accumulated stems were bundled, and (5) the bundle was discharged from the holding area (Curtin and Barnett, 1986). Gathering was accomplished by two chain-mounted paddles located approximately 6 feet above the severing mechanism. These paddles separated the coppice sprouts from adjacent rows and guided the sprouts into a collection mechanism. Stems were severed by a bandsaw, and forced into an accumulating area by pusher arms. After several clumps of sprouts were accumulated, they were mechanically tied and ejected from the accumulation area and laid perpendicular to the direction of travel. This harvester had been able to continually harvest 6-inch clumps while traveling 1.4 mph, using approximately 8 hp (Curtin and Barnett, 1986).

#### *4.5.2.4 National Research Council of Canada (NRCC) Coppice Harvester*

The NRCC Coppice Harvester consisted of a 53 to 67 hp tractor with a trailed attachment. Pairs of chains mounted with paddles were used to guide the coppice trees into the severing and conveying mechanism, while the Coppice Harvester traveled in a continuous motion. After the trees were severed by a reciprocating saw with M-shaped teeth, the trees were conveyed between two sets of rails, across the back of the harvester and discharged individually, perpendicular to the direction of travel. This harvester continually harvested multiple stems less than 5 inches in diameter in rows 3 feet apart. Initial tests on the first Coppice Harvester prototype were conducted during the winter of 1984/1985 and the results were satisfactory (Curtin and Barnett, 1986). One of the most difficult problems to resolve during operation was the synchronization of the forward speed of the harvester with the collection rate of the gathering chain.

#### *4.5.2.5 Loughry Coppice Willow Harvester*

Developed at Loughry Agricultural College in Northern Ireland, this machine was mounted on the 3-point hitch of a 55 hp farm tractor. The coppice stems are gathered by a pair of spring-loaded, counter-rotating, inclined augers that have rotating speeds slightly faster than the forward speed of the tractor. This causes the stems to lean towards the harvester as they are cut by a single 30-inch diameter circular saw. The stems are then collected in an upright position in a chamber at the back of the harvester. When the bundling chamber is filled with approximately 66 pounds of stems, they are separated from new stems entering the chamber and bundled with two twines. The tied bundle is then ejected from the chamber and may later be picked up and fed into a chipper (Curtin and Barnett, 1986). In February 1991, further tests on the Loughry Coppice Harvester were carried out on 2 and 4 year old willow stands and on 3 year old poplars at Swanbourne, U.K.. According to Ledin and Alriksson (1992), time study results showed a range of productivities from 1.72 to 4.41 green tons/pmh. In January 1994, two test runs were made on the latest version of the harvester, the Mk IV, in the U.K. (Anonymous, 1994). Both runs had to be abandoned due to blockages in the feeding system. With the relatively small amount of data collected, an average output of 0.044 acres/std hr (0.32 ODT/std hr) was calculated. During the 1994 studies, blockages of cut material accounted for 90% of the total cutting time. This percentage would have been much higher without the help of two mechanics. After further tests, researchers concluded that the Loughry was unsatisfactory for use in SRWC (Anonymous, 1995).

#### *4.5.2.6 Frobbesta Harvester*

The Frobbesta Harvester is a Swedish machine which was designed to simultaneously cut two 2.5 feet spaced rows of 2 to 5 year old willow coppice with 4 feet between pairs of rows. When cutting, the coppice is fed in by two counter-rotating paddle wheels and then gripped between a long inclined metal auger. The stems are then severed by two circular saws. The inclined auger then lifts and tilts the stems over a metal guide box, and the stems are released and fall

horizontally into a rear trailer platform. When the platform is full, the bundle of stems is pushed off. In January 1994, a series of 8 tests were carried out on the Frobbesta in the U.K. (Anonymous, 1994). The harvester was found to have a productivity of 1.97 ODT/std hr, assuming twin row planting and two-way working. The January 1994 test results are summarized in Table 6.

**Table 6: Frobbesta Harvester Study Results**  
(Adapted from Anonymous (1994))

Site	Working Method	Average Run (ft)	Spacing	Output (acres/std hr)		Output (ODT/std hr)	
				Actual	Without Blockage	Actual	Without Blockage
Dunstall Court (8.92 ODT/acre)	2 Way	500	3 ft + 3 ft	0.11	0.14	0.97	1.19
		500	5 ft + 2 ft	-----	0.24	-----	2.14
		660	5 ft + 3 ft	-----	0.36	-----	3.25
Swanbourne (8.16 ODT/acre)	1 Way Reverse	400	5 ft + 5 ft	0.14	0.200	1.1	1.63
		400	5 ft + 2 ft	-----	0.22	-----	1.84

There seems to be a discrepancy in the Table 6 data, in that at the actual spacings harvested by the one-way method gave higher outputs than the two-way method. The reason for this apparent discrepancy is that the one-way studies were carried out in rows spaced 5 feet apart, giving a slightly higher output than the two-way studies which were carried out on rows spaced at 3 feet apart (Anonymous, 1994). The main problem with this harvester was the auger mechanism; the auger edge tended to cut into and break poplar stems, jamming the auger.

#### 4.5.2.7 Empire 2000

Another self-propelled “cut-only” machine is the Empire 2000 which was built and demonstrated in Sweden. Front augers gather stems before they are cut by 2 circular saws and transferred into a conveyor which passes them to the rear of the harvester. After the stems are delivered horizontally to the collection chamber, they may either be transferred directly to a tractor and trailer or stored in the collection chamber for discharge at the end of the row. In December 1995, a series of fourteen tests were carried out on the Empire 2000 in the U.K. (Anonymous, 1995); the machine achieved an overall average productivity of 6.7 ODT/shr. Test results are summarized in Table 7.

**Table 7: Empire 2000 Study Results  
(Adapted from Anonymous (1995))**

Site	Working Method	Average Run (ft)	Spacing	Output (acre/std hr)		Output (ODT/std hr)	
				Actual	Without Blockage	Actual	Without Blockage
Castle Archdale (14.4 ODT/acre)	1 Way	140	3 ft + 3 ft	0.32	0.40	4.64	5.71
	Reverse	140	2 ft + 5 ft	-----	0.47	-----	6.43
Castle Archdale & Swanbourne (9.01 ODT/acre)	2 Way	650	5 ft + 5 ft	0.47	0.59	4.23	5.34
		650	2 ft + 5 ft	-----	0.86	-----	7.80
		660	2 ft + 5 ft	-----	0.94	-----	8.46
Swanbourne (6.88 ODT/acre)	Round Robin	720	5 ft + 5 ft	0.79	1.2	5.43	7.98
		660	2 ft + 5 ft	-----	1.8	-----	12.1
		660	2 ft + 5 ft	-----	1.7	-----	11.9

The tests identified several inherent problems, which prevented the Empire 2000 from being classified as a functional machine at that time.

#### *4.5.2.8 Nicholson Harvester*

The Nicholson Harvester, designed in Great Britain, is intended for 1 to 2-year-old willow but could also be suitable for 1-year-old poplar (Anonymous, 1994). Stems are gathered between two gates before being severed by two circular saws. After severing, the stems are transferred to a bundle chamber by pinch-belts. A stem counter automatically triggers a bundle tying and discharge sequence. If larger bundles are required, the stems remain loose in the collection chamber, where they are manually tied and retained for discharge. In January 1994, a test run was carried out on the Nicholson in the U.K. (Anonymous, 1994), indicating a productivity of 0.1 acres/std hr (no ODT/hr data was obtained). Blockages were a significant problem with this machine.

#### *4.5.2.9 Energiskogsmaskiner AB (ESM) Harvester*

Like the Frobbesta, the ESM Energiskogsmaskiner AB (ESM) Harvester carries bundles of sticks on a platform which may be tipped to form a stack.

None of the “cut-only” machines (ESM, Frobbesta, Loughry Coppice Harvester, and Empire 2000) are currently supported by major manufacturers, but developers are willing to produce machines to order (Culshaw and Stokes, 1995).

### **4.5.3 Cut-and-Forward Harvesters**

#### *4.5.3.1 Brunn AIB SRICB Harvester*

The Brunn AIB was a relatively large machine, which accumulated loads of stems up to 15,000 pounds. The large capacity of this harvester allowed the operator to devote most of the time to harvesting before having to engage the harvester to its transportation mode. This harvester cut stems and conveyed them to the bunk of a Brunnett forwarder. After the bunk was full, the Brunn then transported the stems to the roadside (Curtin and Barnett, 1986). The Brunn had low productivity and was relatively expensive.

### **4.6 Special-Purpose Harvesting Machines (for DBH greater than 3”)**

Trees with a DBH greater than 3 inches are suitable for pulp production for the reasons noted earlier. Four categories of machines have been suggested for the harvesting of these larger SRWC trees. One is a continuous-travel “cut-and-chip” process (Figure 1(g)), another is the “cut-only” option (Figure 1(a-e), with a continuous-travel feller/buncher), the third is the “cut/chip-and-forward” process (Figure 1(h)), and the fourth is the “cut-and-delimb/debark” process (Figure 1 (a-e) with the harvester). Another proposed harvesting scheme, which is probably less economical than those above due to lower productivity, is the “cut/delimb/debark/chip-and forward” process (Figure 1(i)). A summary of the various harvesting machines suitable for trees with DBH greater than 3 inches is found in Table 8.

**Table 8: Various Harvesting Machines for Trees with a DBH Greater than 3 Inches**

**Cut-and-Chip Harvesters**

Nicholson-Koch Mobile Harvester  
 Pallari Harvester  
 Canadian Crab Combine

**Continuous-Travel Feller/Bunchers**

U.S. Forest Service (USFS) Harvester  
 A-Line Swather  
 MTDC Harvester  
 National Research Council of Canada FB7  
 National Research Council of Canada FB12

**Cut/Chip-and-Forward Harvester**

Georgia Pacific Biomass Harvester

**Cut-and-Delimb/Debark Harvesters**

Bell SP35 Harvester  
 Lako/Kato Grapple Harvester  
 Waratah 240 HTH

**Cut/Delimb/Debark/Chip-and-Forward Harvester**

(Bruks) IF 300 Pulp Chip Harvester

**4.6.1 Cut-and-Chip Harvesters**

*4.6.1.1 Nicholson-Koch Mobile Harvester*

The Nicholson-Koch Mobile Harvester was primarily developed to recover biomass residues left by conventional timber harvesting systems in natural stands. In this machine, a horizontal felling bar cut standing trees, lifted the biomass off of the ground, and fed the biomass into a drum chipper (Curtin and Barnett, 1986). The chassis of the Harvester was a modified FMC skidder that was lengthened with an extra set of road wheels to provide extra space for required machine components. The gross weight of this machine was about 73,000 pounds, which resulted in a nominal ground pressure of about 10.7 psi. Study results for site disturbance when using this harvester showed that 32 percent of the harvested site was found to be significantly compacted. The Harvester was 33 feet long, 9 feet wide, and 15 feet high (Sirois, 1981). The felling bar,

with four cutter knives, felled standing trees, picked material off of the ground, and assisted in the feeding of the chipper. To further provide feeding of the chipper, the Harvester was equipped with vertical side rolls and a set of bottom feed rolls between the felling bar and chipper. Chipping was accomplished by a 48-inch cylindrical drum chipper, and chips were then blown into a trailing chip truck. Tests in 1980 indicated that the Harvester's felling bar was capable of felling pine up to 18 inches DBH, could fell both small and large trees, and pick up downed material off of the ground (Sirois, 1981). The Harvester's productivity was measured on one test stand (near zero slope and firm soil) containing mostly small residual pines averaging 6 inches DBH. The average production rate for this stand was approximately 1 acre/hr, yielding about 20 tons/hr. This harvester is not being developed any further.

#### *4.6.1.2 Pallari Harvester and Canadian Crab Combine*

In the Pallari Harvester, trees up to 4 inches in diameter are severed as a set of rotating sickles shear them against stationary anvils. Two vertical drums with triangular rotating inserts then direct the severed stems into a drum chipper (Curtin and Barnett, 1986). The Pallari Harvester provided the basic design for the Canadian Crab Combine; the latter, however, used larger sickle-feed mechanisms and a larger chipper. As a result, the Crab could harvest trees up to 8 inches in diameter. Both machines operated in a continuous motion. Neither is currently being further developed, but the Pallari is being manufactured in limited quantities in Finland (Hakkila, 1996).

### **4.6.2 Continuous-Travel Feller/Bunchers**

#### *4.6.2.1 U.S. Forest Service (USFS) Harvester*

The USFS Harvester is a continuous-motion harvester which was developed by the North Central Experiment Station Engineering Laboratory in Houghton, Michigan. This harvester consisted of a header attachment for a forestry skidder. Severing was accomplished by using a two-fluted milling cutter that was mounted in an assembly which allowed the cutter to retract if

the cutting rate was less than the forward speed of the harvester. After severing the stem, the cutter sprung forward to sever the next stem in the row. This “springing-retracting” action ensured that the harvester could move forward at a continuous rate. After the stems were cut, they were stored in a 14 ft<sup>3</sup> accumulating area and then discharged as a loose bunch (Christopherson, 1989). According to Thompson (1996), the USFS Harvester is no longer being developed.

#### *4.6.2.2 A-Line Swather*

The A-Line Swather was designed to harvest trees ranging from 4 to 8 inches DBH, in natural stands, in a continuous motion. Towed by a skidder, this machine consisted of a trailer with a side-mounted saw (Curtin and Barnett, 1986). As the Swather traveled along the peripheral face of the stand, the operator moved the trailer in and out to position the saw to cut the trees. Additionally, the operator could move the 36-inch diameter saw blade laterally a total of 12 inches without any changes in the direction by the skidder operator (Karsky, 1992). When the tree was severed, a rotating “bat” mounted on the trailer struck the tree about 11 feet above its trunk and directed the tree backwards into a V-shaped collection bed. Simultaneously, the butt of the tree was knocked forward by a trip chain mounted behind the rotating saw. When 1 to 2 cords of severed trees were collected in the bed, the trees were side-dumped away from the stand, so that the Swather’s path was clear for subsequent passes along the newly made stand face. In tests conducted in 1980, the A-line Swather achieved a production rate of approximately 300 trees/pmh (Curtin and Barnett, 1986). This production rate was considerably higher than a conventional feller-buncher working in naturally-regenerated small timber stands in relatively good terrain. Production potentials, however, were not fully realized, primarily because the machine was very sensitive to stand conditions, especially stand density. According to Karsky (1996), the A-Line is currently with the Prince Albert Paper Company but is not being used.

#### *4.6.2.3 Missoula Technology and Development Center (MTDC) Harvester*

The MTDC concept was based on the A-Line Swather but, following the suggestion of Bruce Hyde at Prince Albert Paper Company, had the collecting bunk and saw assembly mounted

directly on a TimberJack 520A prime mover (Karsky, 1992). The Harvester was tested in natural stands with most trees ranging from 3 to 8 inch DBH; there were also a few 14 inch diameter snags that were cut successfully by the harvester. Stand densities varied but averaged approximately 6,000 stems per acre. In one trial, the harvester's production rate was about 500 to 600 trees per hour.

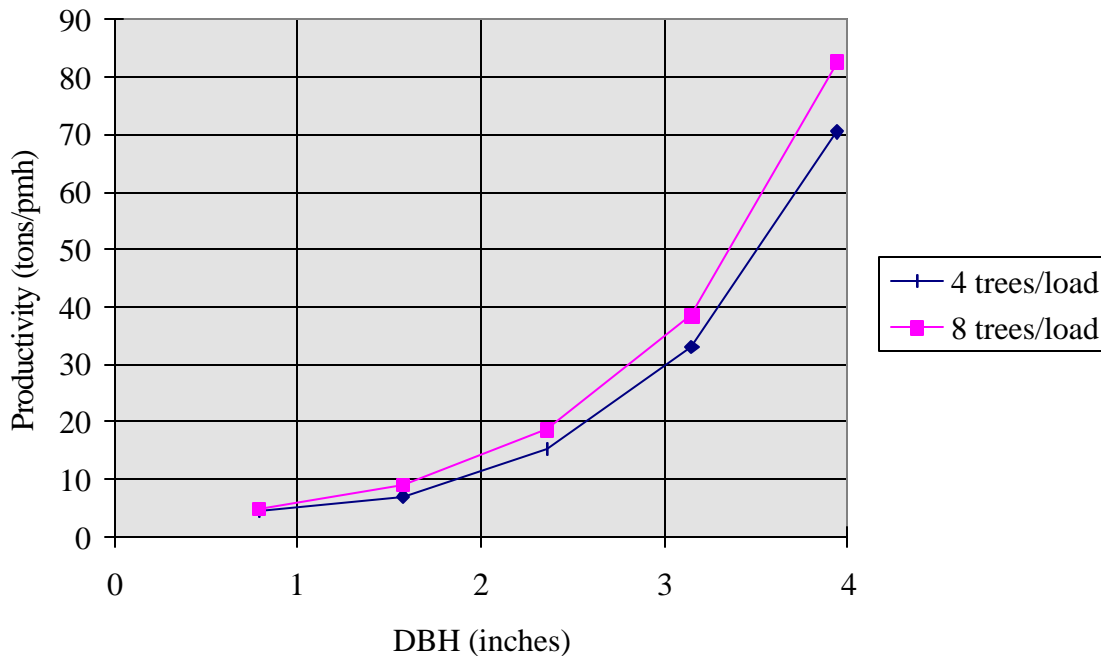
In September of 1990, a demonstration was held on James River Corporation's Fiber Farm in Clatskanie, Oregon. The MTDC Harvester left stumps of 3 to 4 inches; James River desired to have trees cut at ground level since coppice regeneration was not desired. During dumping, trees would occasionally remain in the bunk, decreasing the Harvester's productivity. Also, felled trees would bounce forward when they landed in the tree bunk, since the "trip chain" and "rotating bat" mechanisms did not guide the trees adequately. Consequently, after 3 or 4 trees were felled, the butts of the trees would begin to hang over the front edge of the bed. After several more trees were cut, the felled trees would hit the butts of the trees on the bed and fall forward rather than into the bunk (Kaiser, 1996). After this test, a "power roller" was added to the Harvester to force the felled trees past the cutting blade and back into the bunk. This addition was not field tested, and the MTDC Harvester is not currently being developed or used (Karsky, 1996).

#### *4.6.2.4 National Research Council of Canada (NRCC) FB7*

The NRCC FB7 was a continuous-travel harvester which consisted primarily of a 60 hp Versatile Tractor with a specially designed cutting/collecting/offloading header. All functions except driving and offloading were automatically sequenced by an on-board microprocessor. Also, once offloading was initiated by the operator, the remaining offloading process was automatic. As the operator moved the Harvester into a tree, sensors located in the cutting opening initiated the accumulation operation simultaneously with the severing operation. As the tree was severed by two 24 inch diameter, counter-rotating, inserted-tooth saws, the accumulator arm held the tree; and after the tree was fully severed, the accumulation arm pushed the severed tree away from the saw and into a holding area. After the holding area was filled with 8 to 10 trees, the

operator activated the offloading process: a grapple closed around the trees, swung them to the side, and placed them on the ground parallel to the direction of travel. The FB7 contained two holding areas and offloading mechanisms so that the operator could choose to which side of the machine the bunched trees would be offloaded. In January 1985, the FB7's performance was tested and evaluated in harvesting a three-year-old, short-rotation sycamore plantation. The productivity of the FB7 was found to be approximately 850 stems/hour (19 tons/hr) in the stand which had an average spacing between trees of about 6 feet and an average DBH of 2.5 inches (Stokes, et al., 1986). Figure 2 shows the estimated productivity of the FB7 over the range of stem diameters when collecting 4 trees/offload and 8 trees/offload. Very little stump damage resulted when the Harvester was operating properly. The FB7, however, encountered some operational problems. Aside from the minor breakdowns with the hydraulic components, sensor switches broke, leaves and vines built up in the head, and some of the computer components failed. These problems were expected to be overcome with only minor changes. Further development of the FB7 is no longer being actively pursued despite the very encouraging test results in 1985. The prototype is now at Massey University in New Zealand.

**Figure 2: Estimated Productivity of the FB7 (Adapted from Stokes, et. al., 1986)**



#### *4.6.2.5 National Research Council of Canada (NRCC) FB12*

The harvesting mechanization concept of the FB12 was the same as that of the NRCC FB7. The FB12, however, used a Hydro-Ax model 721 tractor as a prime mover and was a substantially larger machine weighing in at approximately 30,000 lb. This machine was expected to have a productivity of about 800 trees/hr when cutting tree sizes of approximately 10 inches to 12 inches DBH and 60 feet in height. Initial field tests on a ten-year-old hybrid poplar plantation near Kempville, Ontario and on a ten-year-old cottonwood stand near Vicksburg, Mississippi indicated that the FB12 had the potential of becoming a reliable and highly productive harvester. Initial field tests revealed that the FB12 was unable to efficiently hold large trees upright, because the grip on the stems was not firm enough. The prototype is currently in storage at Hyd-Mech Ltd. (the company that developed both the FB7 and FB12 under contract to the NRCC) in Woodstock, Ontario.

### **4.6.3 Cut/Chip-and-Forward Harvesters**

#### *4.6.3.1 Georgia Pacific Biomass Harvester*

The Georgia Pacific Biomass Harvester felled, chipped, and forwarded material while moving in a continuous motion through residual trees in natural stands. Woody material was severed by two counter-rotating cutters, and chipped material was fed into a bin towed by the harvester. According to Curtin and Barnett (1986), results demonstrated that the harvester could comminute standing stems up to 5 inches DBH, randomly distributed across the harvester's front, at rates in excess of 13 tons/pmh. This machine was never tested in SRWC plantations and is not being developed any further.

### **4.6.4 Cut-and-Delimb/Debark Harvesters**

A drawback of these machines is that all of the biomass residue is left at the felling site, which makes biomass recovery for energy production less economically attractive than if the residue

was located at a central collection site, i.e. adjacent to a drum debarker or chain flail delimeter/debarker, or on whole trees or chips delivered to a plant.

#### *4.6.4.1 Bell SP35 Harvester*

The Bell SP35 Harvester is an example of a non-continuous-moving harvester which fells, delimits, debarks, and bucks trees. After the SP35 fells a tree, rollers with helical flutes feed the tree through a set of knives. Delimiting and debarking is accomplished through both the pressure exerted by the rollers and the cutting action supplied by the knives. The helical flutes rotate the tree as it passes through the knives, aiding the debarking process. According to a Bell sales brochure, productivity of approximately 18 to 20 tons/hr has been achieved in eucalyptus stands, for an operation which includes felling, delimiting, debarking, and bucking (Anonymous, 1991).

#### *4.6.4.2 Lako/Kato Grapple Harvester*

Similar in concept to the Bell, the Lako/Kato Harvester is comprised of a Lako grapple harvester head mounted on a Kato excavator. The main components of the head are (1) a hydraulically powered chainsaw used to fell the tree, (2) 2 arms which clamp the tree in the head, (3) four hydraulically powered rollers to move the tree through the head, and (4) two arms with wrap-around knives for delimiting (Kerruish and Rawlins, 1991). The head is attached to the boom of the carrier through a free-swinging linkage, which allows the tree to fall immediately to the ground after the tree is severed. When the tree is falling, the operator cannot adeptly manipulate the tree to a great extent with the free-swinging linkage. For harvesting eucalyptus stands in Australia, the delimiting knives were removed and the feed rollers were surfaced with flat spiral bars, which were used for debarking. The performance of this machine with eucalyptus in Australia is summarized in Table 9.

**Table 9: Lako/Kato Grapple Harvester Machine Performance  
(Adapted from Kerruish and Rawlins (1991))**

<b>Location</b>	<b>Process Length</b>	<b>Total Time/Tree (min)</b>	<b>Trees/PMH</b>	<b>Volume (cubic feet/PMH)</b>	<b>% Bark Removed</b>
Smithton 1	short	1.28	47	410	70-80
	long	1.86	32	280	70-80
Smithton 2	long	1.40	43	420	70-80
	long	1.29	46	450	70-80
Smithton 3	short	1.00	60	200	75-85
Burnie	short	0.96	62	510	75-85
Waddamana	short	0.90	67	950	95-100

\* short -- approximately 18 ft, Long -- approximately 36 ft

#### 4.6.4.3 Waratah 240 HTH

The Waratah design is based on the Lako/Kato Harvester and is capable of processing logs up to 22 inches in diameter. According to Kerruish and Rawlins (1991), however, the Waratah has proved to be more robust, reliable, and efficient in removing bark than the Lako. Data on its debarking performance were taken at a number of eucalyptus thinning operations in Tasmania (Kerruish and Rawlins, 1991). When the head was used on stringy-barked species, the mean bark removal was 91 percent, where the mean debarking, delimiting, and topping time per tree averaged 0.71 minutes. In a June 1994 study on eucalyptus in New Zealand, the Waratah produced 31 tree-lengths (880 cubic feet) per productive machine hour (Gadd and Sowerby, 1995). Trees averaged 125 feet in height and 11 inches DBH.

#### 4.6.5 Cut/Delimb/Debark/Chip-and Forward Harvesters

##### 4.6.5.1 (Bruks) IF 300 Chipmaster Harvester

The Bruks IF 300 Chipmaster Harvester was another process-integrated continuous-travel harvester. The Chipmaster, however, added the delimiting-debarking process so that the chips could be used for pulp production. The prime mover for the Bruks was a forwarder. Trees up to

12 inches in diameter could be felled using a head on a long crane (Froding, 1989). Delimiting was accomplished by three delimiting knife sets, each consisting of one rigid and two moving knives, which were hydraulically controlled. Two vertical hour-glass rollers fed trees into a small flail debarker and finally into a disk chipper (Anonymous, 1989). Chips were then blown into a 530 ft<sup>3</sup> chip bin mounted on the back of the forwarder base, which could be dumped sideways, unloading the container in 2 to 3 minutes. All biomass residue was left in the stand, making biomass residue recovery for energy production impractical.

## **5. PROCESSING -- DELIMITING/DEBARKING/CHIPPING**

### **5.1 Current Delimiting/Debarking/Chipping Processes for Pulp Wood Production**

Delimiting and debarking is an essential process for supplying chipped wood to a pulp plant, since bark, small branches and foliage are undesirable in the pulping process. Delimiting of small trees is carried out by irongates or harvesters within the stand, stroke/boom or roll processors or chain flails at the landing, or in a few cases by drum debarkers. Currently, the two main types of debarkers used in the pulp industry are drum debarkers, typically used in short-wood harvesting operations and located at the pulp mill or a central processing yard, and chain flail delimiting/debarkers, which are typically used at landings to which skidders deliver whole trees or delimited trees. Ring debarkers are used mostly with sawlogs and are located at the sawmills, but ring debarkers for smaller trees have recently been developed and may have potential for pulp material.

#### *5.1.1 Irongate Delimiters*

Steel grates, resembling stout fence gates, are commonly used in the southeast U.S. to delimit trees intended for sawlogs and pulp logs. Grapple skidders back the tops of bunches of trees through the openings in the grate, stripping off the limbs. James River uses irongates to delimit their short rotation poplar at their plantation in Mississippi. The gates are effective for small stems because many trees can be delimited simultaneously.

### *5.1.2 Harvesters, Boom/Stroke Processors and Roll Processors*

These machines typically handle only one stem at a time, although two or three stems can be roughly delimbed by some processors. As noted above, harvesters leave residues at the stump where they are difficult to collect. Processors, if operated at roadside, can leave piles of residues that can then be comminuted and transported to an energy facility, but any of these machines is relatively expensive for very small trees and therefore not as popular as chain flails or iron gates for delimiting trees intended for pulp furnish.

### *5.1.3 Drum Debarkers*

Drums are used primarily for debarking, but several Scandinavian companies, and Proctor and Gamble in Florida, have used drums to delimit and debark conifer tree sections or whole trees. Drums are massive, so most are installed permanently at central processing yards or at mills. A few mobile models are available. Residues from drums are conveyed to hogs for comminution and use as fuel.

### *5.1.4 Chain Flail Delimiter/Debarkers*

Chain flails are capable of handling small trees effectively, because multiple stems can be processed simultaneously. Other advantages of flails are that they can be used at the landing, i.e. they are mobile and do not require much space, and they may (or may not, depending on tree characteristics) recover more pulpable fiber from branches and tops than some other methods. The main disadvantage is the inherently inefficient separation concept, i.e. using a blunt instrument to beat off the bark and limbs, which results in high chain costs and damage to the surface of the bole. Poplar is more easily broken than conifers, so smaller diameter chain must be used to prevent excessive breakage of tops.

Flails are generally coupled with the chipping process; that is, the wood from the delimit/debarker is directly fed into the chipper. In the past, experience has shown that chippers should be placed back about 6 feet from a separate debarker so that excess bark will fall

to the ground instead of following the wood into the chipper (Anonymous, 1993). In recent years, manufacturers have produced machines known as delimeter/debarker/chippers, which combine a chain flail and a disk chipper into a single machine. This eliminates the need for a second operator and machine.

Flail delimiting/delimiting and chipping is usually carried out at a landing in the field, so chips vans are then used to haul the chips to the pulp plant, and the flail residues can be collected for energy production. For instance, in tests at Simpson Tehama Fiber Farm the biomass residues from the flail were loaded by a clamshell grapple into self-unloading trailers and hauled to a direct-combustion biomass facility, Wheelabrator Shasta Energy, in Anderson, California, where they were further comminuted and then used as boiler fuel. At James River Corporation's Columbia River Fiber Farm, the flail residues are piled at the landing; after all the trees are processed, the residue piles are comminuted with a tubgrinder and transported by van to the pulp mill's power plant.

Chain flail delimiting and debarking is considered the bottleneck in converting trees to wood chips. Chipping costs, however, may also be reduced by increasing the debarking rate, since the debarking rate constrains the chipping rate. According to Hartsough and Richter (1994), this may be done by building a bigger and more powerful debarker, possibly with longer drums to allow more stems to be processed simultaneously. New delimeter/debarkers incorporate a third drum to increase chain-stem contact. Also, according to Watson and Twaddle (1990), many operators are using multiple chains on each opening on the flail drum to improve debarking. Using two chains on the drum has been shown to increase the life of the chains; thus, the decrease in bark content in using double chains has been shown to be achieved with little additional chain cost.

### *5.1.5 Ring Debarkers*

Ring debarkers are by far the most energy efficient of existing debarking methods, because they use knives rather than impact to remove bark, and are likely to cause the least bole damage. They are usually located in a permanent yard because of their size and the auxiliary conveyers coupled with the debarker. Although combination ring delimeter/debarkers have been developed, they were considerably more expensive and are not currently used. The main disadvantage of a ring is the single-stem processing and fixed lineal throughput rate for a given debarker. New designs for smaller stems have higher feed rates, but the rates are still fixed. If the distribution of tree diameters is reasonably narrow, then one could employ a ring which is optimized for the biggest trees that will be harvested and that is still economic for the smaller trees.

### *5.1.6 Chippers*

Chippers can be classified by type, which indicates the device on which the knives are mounted (disk or drum), size, and power source (electric motor or internal combustion engine). Essentially any chipper will produce material that is acceptable for the direct combustion energy market. The ideal pulp chip, however, has relatively tight size tolerances, and larger disk chippers are generally considered to produce the highest quality chips. The blade and anvil on a disk chipper can be set to control chip thickness, and bigger chippers with higher inertia travel at more uniform speeds. Large chippers at fixed installations are powered by synchronous motors and turn at essentially constant speed. Knives on chippers at fixed installations are probably less susceptible to damage from rocks and can be replaced at more uniform intervals. All these factors result in better chips from large fixed chippers than from small mobile chippers, so, from the standpoint of chip quality, it would be optimal if trees were transported to a central yard or a mill for processing. A large percentage of pulpwood is handled this way, but the remainder is chipped at landings after delimiting and debarking.

Drum chippers can process larger and less-uniform material than an equivalent-sized disk chipper. Knives on drum chippers are less susceptible to damage by rocks and dirt, and can be

sharpened many times without removing the knives, therefore drum chippers are commonly used to produce biomass fuel.

## **5.2 The Massahake Process**

The new Massahake process separates whole tree chips into clean chips and residues. It has been under development in Finland for several years, and is promising because it allows whole-tree chipping at the stump or landing, and also allows landing-to-processing facility transport of highway-legal, full-capacity chip vans. Other methods for upgrading chips have been tried over the last twenty years or so, but the Massahake process is substantially different from earlier concepts. It is comprised of the following steps:

(1) Undelimited trees or roughly delimited tree sections are chipped, (2) rocks and metals are separated from the chips, (3) disk screening is used to remove oversized material, (4) a Pocket-Roll screen is used to remove fines, (5) chips are ground to separate bark from the fibers, (6) a Pocket-Roll screen is used again to separate fines, (7) a pneumatic device is used to further reduce fines, (8) a Simco/ Ramic optical screening device separates the bark from the clean chips, resulting in two output streams: clean chips and hog fuel.

According to Gingras (1995), an industrial plant based on this process was nearing completion and start-up in Kankaanpaa, Finland, and was to provide birch chips to neighboring pulp mills and hog fuel to a district heating plant. The capital cost of this plant was estimated at 14.5 million FIM (about \$US 3 million) and had a rated capacity of about 1800 ft<sup>3</sup> / hr of loose chips .

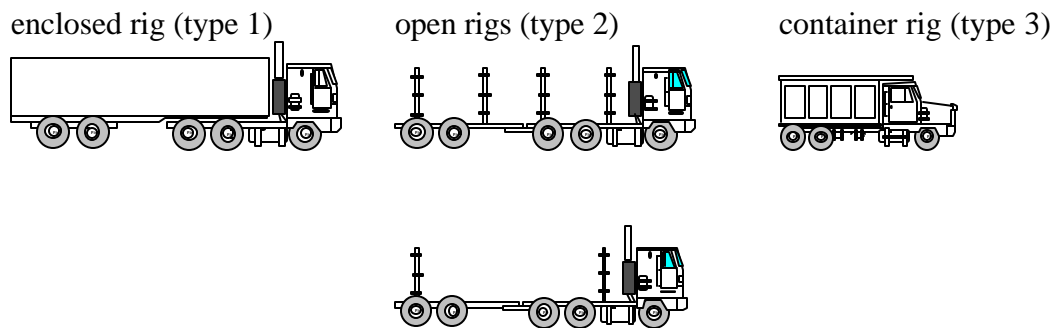
## **6. TRANSPORTATION**

### **6.1 Types of Transport Vehicles**

Transport of forest products is normally carried out by trucks. Various types are used depending on the kind of material transported and on the type of equipment they interface with in the woods and at the conversion site; the type of truck used is also dependent on the vehicles that are

available in a given region. Pottie (1986) classified trucks into 3 major categories: (1) enclosed rigs, (2) open rigs, and (3) container rigs. Figure 3 illustrates these various types of secondary transport vehicles. Types 1 and 3 are well suited for biomass consisting of small pieces and carried in loose form like chips, hog fuel, chunks, and split stumpwood. Enclosed rigs (or chip vans), however, are better suited for transport of wood chips, since they have larger payloads. Type 2 rigs are used to transport larger pieces of wood such as tree lengths or shortwood. With modifications Type 2 trucks have been used to haul whole trees, tree sections with limbs, or baled material (Axelsson and Bjorheden,1991).

**Figure 3: Examples of Various Secondary Transport Vehicles**



## 6.2 Maximum Payload Limitation

Each of the above configurations can be built with different numbers and arrangements of axles for the truck and trailer(s). This allows the transport of heavier loads while complying with public highway regulations on maximum gross vehicle weight distribution per axle. Currently, many states allow a maximum weight of 80,000 pounds for a five-axle semi-truck. This corresponds to a net payload of approximately 25 tons. In some states, much larger loads may be hauled legally.

For the transport of wood chips, another consideration is the maximum volume that the container can hold. The maximum load of a trailer is determined by either the weight limit or the volume limit of the load. Generally, for the transport of wood chips, the weight limitation seems to be the dominant limiting factor. If the weight limit is exceeded before the volume limit, then the

only way to transport more biomass in that same load would be to decrease the non-biomass weight. This can be done by either removing moisture from the biomass or reducing the tare weight of the truck/chip van. Removing water from the chips, however, is not desirable for the pulping process, since pulping chemicals diffuse into the wood chips better with higher chip moisture contents. Hartsough and Richter (1994), however, point out that recent reductions in log trailer weights indicate a potential for similar reductions in chip van weights.

With delimbed tree lengths or shortwood from slower-growing natural stands, weight limits are almost always reached before volume limits. For whole trees or tree sections, considerable experience with conifers indicates that packing efficiency decreases, so payload weights are less than for chips or delimbed logs, resulting in higher transportation costs. Similar results might be expected with SRWC, and such was the case in limited tests with tree length short rotation poplar in western Oregon (Kaiser, 1994). However, limited trials with transporting hardwoods from natural stands on conventional trucks in the upper midwest resulted in payloads of 21 to 26 green tons; few problems were encountered with crowns and limbs or material falling from the whole tree loads (Schaller, et al, 1993).

In the transportation of logs or whole trees, trailer length may be another limiting factor. As with the weight limit, the trailer length limit also varies from state to state.

## **7. RE-ESTABLISHMENT OF CROPS**

### **7.1 Re-establishment Alternatives**

Focusing on the current major user of SRWC plantations, this section addresses techniques leading to merchantable wood for the pulp industry. Two methods of re-establishment are suggested: replanting or coppice regeneration. Replanting involves removing stumps, disking, reinstalling drip lines (if they are used), and planting; the coppice regeneration option involves reinstalling drip lines (if used), and coppice sprout thinning. In an analysis by Hartsough and Richter (1994), re-establishment costs for coppice regeneration were estimated to be slightly higher than replanting. Table 10 summarizes these results. Most of the costs for replanting in

this analysis were based on extensive experience with initial establishment at Simpson Tehama Fiber Farm; stump removal cost was an educated guess. The calculations, however, reflected only the re-establishment costs; they did not take into account any of the following growth or value differentials: 1) increased growth through the well-established roots in the coppice regeneration alternative, 2) increased growth rates of improved clones in the replanting alternative, or 3) higher values of the single stems in the replanting operation (assuming that thinning of coppice sprouts will not be completely successful) .

**Table 10: Costs of Re-establishment Activities  
(adapted from Hartsough and Richter, 1994)**

<u>Activity</u>	<u>Cost (\$/acre)</u>
A. Replanting	
Remove/Reinstall Drip Lines	66
Remove Stumps	52
Disk	21
Plant	<u>94</u>
Total	<b>233</b>
B. Coppice Regeneration	
Remove/reinstall drip lines	66
Thin Sprouts	<u>231</u>
Total	<b>297</b>

All companies that are already harvesting SRWC for pulp production are currently removing stumps and replanting at the end of their rotations rather than relying on coppice regeneration.

## **7.2 Coppice Thinning Machinery**

To date, no highly mechanized machinery has been developed for thinning coppiced woody crops; thinning must be carried out with chainsaws or hand-powered shears. A mechanized scheme might reduce the costs of thinning, although it is difficult to improve on the human for selecting and accessing the sprouts to be removed. This may be achieved through the

development of visual inspection machines to identify the most desirable shoot of a coppice woody plant. Visual inspection algorithms such as those developed by Tian and Slaughter (1993) might be modified for coppice sprout identification and selection.

### **7.3 Stump Removal Machinery**

In implementing the replanting alternative for re-establishment, tree stumps must be removed from the plantation so that new seedlings may effectively grow. Various machinery may be used to accomplish this.

#### *7.3.1 Cavaceppi Machine*

One stump extracting device was the Cavaceppi machine. This auger-like machine consisted of a cylinder of about 40 to 60 cm in diameter, driven by a 80 Hp tractor. Sharp teeth on the bottom of the cylinder cut the lateral roots as the cylinder rotated. Once the lateral roots were cut, the stump began to turn with the cylinder, and was then extracted. A productivity of about 250 stumps in 8 hours was possible (Walker, 1976).

#### *7.3.2 Rome TX-1600 Tree Extractor*

The USFS Southern Forest Experiment Station, in conjunction with Rome Industries, developed a tree extractor to harvest southern pines with the taproot attached. First, a horizontal knife blade cut into the stem near ground level, anchoring the Tree Extractor to the tree. A clamshell-hinged shear, powered by two hydraulic cylinders, was then forced about one foot below ground level, shearing the main lateral roots. At this point, two plates (one on each side of the shear) struck the ground to prevent further penetration of the shear. A hydraulic cylinder then raised the scissors grip about 9 inches while the plates remained stationary, wrenching the tree from the ground. Finally, the entire tree was lifted and bunched for skidding. During extraction, some soil and dirt clods could have been removed by either tearing with the extraction teeth or by using a scissors shearing device to trim the soil or humus material. Additional dirt and rocks

were removed by dropping the trees during bunching. The Extractor, mounted on a four-wheel front-end loader, had a production rate of approximately 1.1 to 1.9 trees (of 10 to 13 inch DBH) per minute (Walker, 1976). James River Corporation experimented with the Rome Tree Puller for the re-establishment of their plantation. According to Kaiser (1996), the Tree Puller was too slow, since it was designed for bigger stumps. Disking with a Rome TR24 disk was a more economical alternative for James River's conditions.

### *7.3.3 Stumper*

The Stumper was basically a curved plate with small teeth along the base. This was mounted on a tractor C-frame and was driven against the stump, concentrating the tractive pushing power on the Stumper surface. The teeth were driven below the ground level and the stump was pried up (Walker, 1976).

### *7.3.4 Wick-Bartlett Stump Harvester*

The Wick-Bartlett Stump Harvester was an attachment that mounts on a front-end loader. This harvester consisted of two hydraulic cylinders operating two shear blades, and was capable of extracting up to 20 stumps/hr with practically no size limit. This machine could take several bites on a very large stump to break it down and could have also been used in conjunction with bulldozer grubbing equipment to split stumps to be removed by the bulldozer (Walker, 1976).

### *7.3.5 Pallari Stump Harvester and Modified Pallari Stump Harvester KH120*

The base prime mover of the Pallari Stump Harvester was a 51 hp excavator (Walker, 1976). In this machine, a hydraulic cylinder activated a shearing blade against the extracting device, a two-pronged anvil, which split and cleaned the stump and roots. The maximum opening between the shear and anvil was 23 to 26 inches. Two 19 inch extraction teeth were also added to the underside of the anvil to aid in pulling. As with the Rome Tree Puller, some soil and dirt clods could have been removed during extraction by either tearing with the extraction teeth or using a

scissors-shearing device to trim the soil or humus material. Additional material was removed by dropping the stumps. In the collection process, the Harvester could have been equipped with a box or trailer for accumulating and transporting bunches of stumps and roots. The Modified Pallari Stump Harvester KH120 used a cutting anvil such that the extraction teeth were mounted opposite but parallel to the anvil prongs instead of perpendicularly to the anvil as in the original design. Preliminary tests on the Modified Pallari found a 40 percent increase in the productivity over the original machine (Walker, 1976).

### *7.3.6 Rockland Roto Lifter*

This machine was capable of extracting stumps only from row planted areas. The Rockland Roto Lifter consisted primarily of two two-toothed disks hydraulically controlled and was drawn by a bulldozer. The disks were aligned in a V-pattern so that radial plates on the periphery of the disks caused the disks to rotate when the tractor moved forward. As the stump was encountered by the Lifter, it became jammed between the disks. The rotating motion of the disks wrenched the stump from the ground. After the stump was extracted, the continued rotating motion caused the stump to be left behind the advancing machine (Walker, 1976).

### *7.3.7 Additional Stump Harvesting Machines*

The Elektro-Diesel Company in Sweden constructed the Swedish Rotryckare machine on a forest tractor chassis. This machine first lifted the tree complete with its roots from the ground and then cut the stump-root system off of the bole with a hydraulic chain saw (Hakkila, 1972). Another tree feller/stump extractor, the DK-1 Vepr, was developed in Russia for the T-100 GP crawler tractor. It had been used to push down trees at heights of approximately 6 to 10 feet, simultaneously extracting the roots from the soil. After extraction, the whole trees were then skidded to a landing (Hakkila, 1972). Another stump harvester was the Fowler, a pushing device specifically designed for uprooting trees. This machine incorporated a frame with tines to lift out the root system after the push bar had toppled the tree.

According to Walker (1976), studies have been done in Finland in using wheel loaders for extracting stumps. In one particular study, a 165 hp machine was fitted with a modified bucket consisting of two long extraction teeth with a cutting edge between. This machine was capable of extracting 50 stumps (averaging 14 inches in diameter) per hour. Another machine using a conventional logging grapple was able to extract 36 stumps/hr under the same conditions. Furthermore, A Hymac 580 C excavator equipped with a tine-like hook and leverage plate was tested in New Zealand in August 1975. This 95 hp excavator was capable of extracting pine stumps of up to 16 inches in diameter at a rate of 95 stumps/hr, but larger stumps caused the productivity to drop off sharply (Walker, 1976).

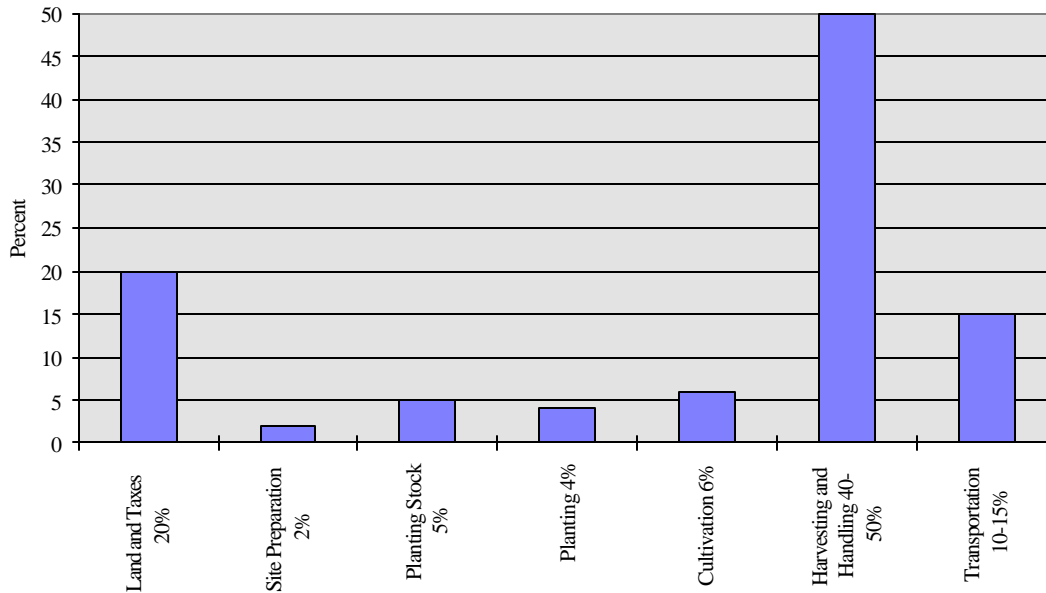
Obviously, most of the stump removal equipment described here would be prohibitively expensive for SRWC plantations. For example, assume a tree spacing of 10 feet by 10 feet, stump removal equipment cost of only \$50/hour and a removal rate of 100 stumps/hour (0.6 min/stump). The resulting cost in this example would be over \$200/acre. Because of this high cost, companies that are currently harvesting SRWC plantations are not recovering stumps. Instead, they are disking and incorporating the stumps into the soil as part of their site preparation operation for the next rotation.

## **8. SRWC Costs and Potential Improvements**

### **8.1 Cost Breakdown for SRWC Production**

The Electric Power Research Institute (EPRI) in 1995 developed a profile of various costs associated with the production of energy crops (Wiltsee and Hughes, 1995). Figure 4 shows these EPRI findings in a nutshell.

**Figure 4: Various Energy Crop Production Costs  
(Adapted from Wiltsee and Hughes, 1995)**



As shown in Figure 4, “harvesting and handling”, “land and taxes”, and “transportation” contribute the greatest costs for the production of energy crops for biomass energy production. This additionally is true for the production of SRWC for pulp production. The difference in these two schemes is that for energy crops, delimeter/debarkers are not needed, whereas wood for pulp production requires the wood to be delimetered and debarked before chipping. Hence, the “harvesting and handling” costs for pulp production are expected to be greater than the “harvesting and handling” costs for pure biomass energy crop production. “Land and taxes” costs may not be reduced through the implementation of technological advances (other than improved growth rates), whereas “harvesting and handling” and “transportation” costs may be reduced. Harvesting and handling has the greatest potentials for technological improvements to significantly lower the cost of woody material supplied by SRWC production.

Hartsough and Richter (1994) pointed out that conventional harvesting equipment has been primarily developed for forest conditions, where conditions such as rough and broken terrain with rocks, large stumps, and down logs exist. Additionally, these harvesting machines were generally developed for harvesting coniferous trees that are larger and less uniform in size than

trees produced on SRWC plantations. These machines are currently being used on SRWC plantations intended for pulp production, because the SRWC market has been too small to allow for development of systems that are ideally suited to short rotation conditions.

Improvements over the conventional feller/buncher-skidder-flail delimeter/debarker/chipper system may come in a variety of areas, some incremental and some dramatic. In the former category, delimiting and debarking improvements and reduction in truck/trailer tare weights hold some potential. More radical improvements are possible by developing effective continuous-travel felling equipment, by combining functions to eliminate multiple handling, and by the development of an effective and economic process to upgrade whole-tree chips to pulp quality.

## **8.2 Continuous-Travel Felling**

In the felling process, a reduction in cost may be possible by further developing continuous-travel fellers similar to the NRCC FB7 Harvester (Hartsough and Richter, 1994). Development of machines such as this would eliminate the stop-and-go, forward-and-backward motion inherent to conventional feller/bunchers. Impressive productivity results demonstrated by continuous-travel machines such as the Claas Jaguar for harvesting willow in Sweden support this view. Furthermore, based on the FB7 results (Stokes, et al., 1986) and Stokes' unpublished data on the FB12 performance, Hartsough and Richter (1994) estimated that current felling and bunching costs could possibly be reduced by 40 percent, assuming a purchase price of \$300,000 for the machine and an average traveling speed of 1.2 mph. Continuous-travel machines would also eliminate the repetitive aspects of the operator's job; with current feller/bunchers, operators cut and bunch 150+ trees per productive hour.

The FB7 cut at a rate of 1000 trees per hour while traveling down the row (Stokes et al, 1986) but the FB12 prototype had trouble with bigger stems because of stability problems when trying to hold the large stems loosely and keep them upright; positive control of upright stems is a necessity. The Claas and similar machines are successful in part because they do not have to resist large overturning moments from the crop trees. For larger stems, it would probably be

better to immediately lower the trees as soon as possible to lower the center of gravity; the trees could be held horizontally while more were accumulated, rather than holding them upright. This would reduce the size, weight and boom/head strength requirements for the felling equipment. An analogous situation is the comparison between feller/bunchers and feller/directors; the latter are much lighter for the same-sized tree because they do not attempt to keep the trees vertical.

Accumulated bunches could be dropped on the ground or offloaded onto trailers in the field. In the long run, continuous-travel machines of some type will be the best option, but they will involve development costs, which may be substantial.

### **8.3 Combining Multiple Functions into a Single Machine**

Two concepts -- feller/loaders and feller/chippers -- have the most potential, because each is relatively simple and could be applied in both the pulp and biomass fuel areas. (The size of the equipment would probably be smaller for the biomass market.)

#### *8.3.1 Feller/Loaders*

In many agricultural crops such as tomatoes and sugar beets, it is common for on-highway transport trailers to be loaded in the field by the harvester. A similar concept for tree harvesting and transport has been proposed by several individuals, including the proponents of whole tree burners (e.g. Schaller, et al, 1993). This is potentially one of the simplest and lowest-cost systems, and it would cause little soil disturbance on higher-strength soils. Existing excavator-style feller/bunchers could be used as feller/loaders initially, and an optimal continuous-travel machine eventually developed for short-rotation conditions. Transport issues associated with this system are discussed in the transportation section below.

### *8.3.2 Feller/Chippers*

This is a component of some of the simplest and possibly cheapest systems. For short-rotation (three-year) willow energy crops in Sweden, continuous-travel feller/chippers such as the Claas Jaguar are the best alternatives tested to date; they are superior to continuous-travel feller/bunchers or feller/forwarders because all processing is done by one machine, and the material is handled downstream as a bulk commodity rather than individual pieces. Production rates of these machines have been very impressive in some cases, on the order of those for conventional forestry equipment with large trees, even though the willow is less than 3" DBH. Chips are blown into separate chip bins, towed by agricultural tractors. The advantages are a minimum amount of equipment and minimum handling. The need for an effective chip/residue separation method, e.g. a proven Massahake process, is the biggest question mark for applying this concept in the pulp industry.

If it were possible to move chip vans through the field along with the feller/chipper, no chip forwarder would be needed. This is less of an issue than for whole trees because chip forwarders can rapidly transfer their loads to on-highway trucks, although the bulk density of transferred chips appears to be less than that of chips blown directly into a van.

### *8.3.3 Feller/Forwarders*

If on-highway transport vehicles cannot be towed through the field, then continuous-travel feller/forwarders may provide reasonable alternatives. Examples include the commercial Koehring KFF and the continuous-swathing A-Line and its descendent, the Missoula Technology & Development Center Swather. For natural stands, the big benefit of feller/forwarders is in combining felling and forwarding, not in continuous swathing. Given that SRWC trees are grown in straight rows, there is no need for a large diameter blade for cutting a swath, but productivity can be improved by using an automated cut-and-deliver-to-forwarding-bunk cycle instead of requiring the operator to repeat the motions for every tree.

### *8.3.4 Other Combination Machines*

A few feller/delimiter/debarker/chippers such as the MB-Trac and Bruks IF 300 have been developed (Froding, 1989), but they did not produce at rates that made them attractive. As with delimeter/debarker/chippers at the landing, the delimiting/debarking function is limiting.

Feller/chipper/chip forwarders are similar to feller/chippers, but have their own integral chip bin. They may be reasonable options for small-tract, low-production operations where move-in costs are major considerations, but, in large tracts or dense stands, they are more expensive per ton than the two-machine combination (feller/chipper and separate chip forwarder) because the felling and chipping equipment is idle while the machine is traveling to dump a full bin at roadside. Also, they are designed for selective thinnings and have felling heads on booms to reach into the stands. Examples include the modified Brunnett, LOGSET (Hall, 1995), HAFO, Bruks and Silvatec/Hedelskebet machines developed in Scandinavia.

## **8.4 Delimiting/Debarking/Chipping**

Chain costs represent the single largest operating cost component for chain flail delimeter/debarkers. Stokes and Watson (1989) estimated that chain costs represent approximately 20 to 28 percent of the total flailing costs (\$0.8 to \$1.6 per BDT) assuming a life of 25 PMH per set of chains. But empirical tests on hardwoods in 1989, 1991, and 1994 have shown these early estimates to be low (Hartsough and Richter, 1994); chain costs may be as much as \$5/BDT of chips. This discrepancy may be due to the differences between the strength properties of bark on conifers and hardwoods. These differences might be exploited to design a more efficient debarking method for hardwoods.

Delimiting and debarking is considered the bottleneck in converting trees to wood chips. Chipping costs, however, may be reduced by increasing the debarking rate, since the debarking rate constrains the chipping rate. According to Hartsough and Richter (1994), this may be done by building a bigger and more powerful flail debarker, but a more efficient concept such as a fast ring debarker may be preferable in the long run.

## **8.5 Transportation**

### *8.5.1 Lighter Chip Vans*

Hartsough and Richter (1994) point out that recent reductions in log trailer weights indicate a potential for similar reductions in chip van weights. Lighter chip vans would allow more wood to be transported per trip, since the weight limit of the vehicle during transportation generally constrains the amount of wood chips which may be legally transported.

### *8.5.2 Combined Primary and Secondary Transport*

Given that highway trucks and/or trailers are loaded in-field for transporting agricultural crops, it appears feasible and highly desirable to do the same with SRWC, assuming that the trees or chips will be processed at a site other than the landing. This concept could be applied with log trailers, chip vans or truck/trailers for in-field and on-road transport, to be used in combination with feller/loaders or feller/chippers. No reloading would be required. Depending on soil strength, the trailers or vans could be towed in the field by standard on-highway tractors or by agricultural tractors. The Fast Trac in-field/on-road tractors from the U.K. (Hall, 1995) may be a higher-traction alternative to standard highway tractors.

A major concern is the feasibility of moving on-highway vehicles through the field while soils are wet. Compaction will certainly result; it can be alleviated with tillage. But it is unlikely that an unmodified on-highway vehicle can travel on many wet soils without becoming stuck. Options include central tire inflation (CTI) schemes, larger, lower-pressure tires, or load platforms that can be rapidly transferred from an in-field transporter to an on-highway vehicle. Storage buffers to supply the mills or plants during the wet season are alternatives to wet season harvesting, but debarking of stored trees is difficult, and chip quality decreases with storage time.

For transporting whole trees, load weight may or may not be a major economic concern for hauling cost, depending on the length of the haul and whether off-public-road transport is feasible.

Special trailers may be needed to prevent limbs and tops from extending beyond the legal load dimensions and to prevent small broken material from falling from the load. Effective whole tree trailers could probably be developed at relatively minor costs. The trailers might have:

- standard highway-legal bunks and stakes
- stakes which swing outward for loading, then swing in to compress the trees
- sheeted or boarded sides to prevent overhanging limbs
- a drop-bottom design, similar to some chip vans, to increase load volume. A trailer with this type of design was tested at Weyerhaeuser in the late 1970s.
- wide bunks and high stakes for hauling on private roads to the processing facility

## **8.6 Stump Handling**

Although past attempts to utilize stumps for pulp or energy have not been successful, the uniformity and smaller size of SRWC stumps may present less of an obstacle to favorable developments. Ideally, trees would be harvested and transported with stumps intact. Substantial development cost might be required in order to come up with an efficient tree puller. A feasible means of transporting trees with poorly packing stumps is difficult to envision, but stumps might be immediately separated from the trees, then collected and transported separately.

For recovery of stumps left after harvesting, a device similar to the Rockland Roto Lifter but sized for smaller stumps, might be attractive. It could possibly be equipped with machine vision to identify stump locations, allowing intermittent entry into the soil and reducing energy consumption and collection time.

## REFERENCES

- Anonymous. 1986. "Drip Hose Layout Machines" and "Drip Hose Retrieval Machines", Sales Brochures, Lake Company Irrigation Systems, Bakersfield, California 93303.
- Anonymous. 1989. "The solution to the thinning problem: Chipmaster!", Bruks News!, Bruks Mekaniska AB, Arbra, Sweden.
- Anonymous. 1991. "SP35 Harvester", Sales Brochure, Bell Ltd.
- Anonymous. 1993. "Timber Grown as Agricultural Crop Now in Harvest -- James River's Cottonwood Plantation Produces Chips for Paper", Timber/West, August. pp. 14-16.
- Anonymous. 1994. "First Field Evaluations of Short Rotation Coppice Harvesters", Report 11/94, Forestry Commission, The Forestry Authority, Technical Development Branch, Ae Village, Dumfries, DG1 1QB.
- Anonymous. 1995. "Second Field Trials of Short Rotation Coppice Harvesters", Report 1/95, Forestry Commission, The Forestry Authority, Technical Development Branch, Ae Village, Dumfries, DG1 1QB.
- Axelsson, Jan, and Rolf Bjorheden. 1991. "Truck Systems for Transportation of Small Trees and Forest Residues", in J. B. Hudson (ed), IEA/BA Task VI Activity 2, Integrated Harvesting Systems Workshop, Oregon & California, USA, June 3-8. pp. 60-87.
- Christopherson, Nels, Brian Barkley, Stig Ledin, and Paul Mitchell. 1989. "Production Technology for Short Rotation Forestry", International Energy Agreement (IEA) Report 89:1.
- Coates, Wayne. 1985. "Comparison of Equipment for the Installation and Retrieval of Drip Irrigation Laterals", ASAE Transactions 28(4):1173-1177.
- Culshaw, Damian. 1993a. "Summary of Presentations by the Swedish Hosts", in Damian Culshaw (comp), IEA/BA Task IX Activity 1 -- Status of SR Forestry Mechanization Worldwide, Workshop and Study Tour, Sweden -- March 2-4, 1993", IEA Report, ETSU, Harwell, Oxfordshire, OX11 0RA, United Kingdom. pp. 5-8.
- Culshaw, Damian. 1993b. "Study Tour Report", in Damian Culshaw (comp), IEA/BA Task IX Activity 1 -- Status of SR Forestry Mechanization Worldwide, Workshop and Study Tour, Sweden -- March 2-4, 1993", IEA Report, ETSU, Harwell, Oxfordshire, OX11 0RA, United Kingdom. pp. 62-75.
- Culshaw, Damian, and Bryce Stokes. 1995. "Mechanization of Short Rotation Forestry", *Biomass and Bioenergy*, Volume (9): 127-140.

- Curtin, Dennis, and Paul Barnett. 1986. "Development of Forestry Harvesting Technology: Application in Short Rotation Intensive Culture (SRIC) Woody Biomass", Tennessee Valley Authority, TVA/ONRED/LER-86/7.
- Donaldson, D.R., J.W. LeBlanc, R.B. Standiford, S. Gallagher, C.J. Jourdain, and G.E. Miller. 1988. "Seven-year Performance of Eucalyptus Species in Napa County", *California Agriculture* 42(6):19-20.
- Froding, Anders. 1989. "The Development of Pulp Chip Harvesters for Small Trees", in: Bryce Stokes (ed), Proceedings of an International Symposium, International Energy Agency/Bioenergy Agreement, Task VI -- Activity 3, Auburn University, Alabama, June 5-7. pp. 57-74.
- Gadd, Jonathan, and Tony Sowerby. 1995. "The Waratah 240 HTH -- Debarking and Logging Tree-Length Eucalyptus Regnans", New Zealand Logging Industry Research Organisation Report 20(1):1-5.
- Gingras, J.F.. 1995. "Recent Developments in Chip Cleaning and Cut-to-Length Harvesting Technologies in Finland", Forest Engineering Research Institute of Canada, Eastern Division, Internal Report: IR-1995-06-01, June 1995.
- Golob, T.B.. 1986. "Analysis of Short Rotation Forest Operations." NRCC No. 26014. Ottawa, Canada. Division of Energy, National Research Council of Canada.
- Graham, Robin. 1994. "An Analysis of the Potential Land Base for Energy Crops in the Conterminous United States", *Biomass and Bioenergy* 6(3):175-189.
- Hakkila, Pentti. 1972. "Mechanized Harvesting of Stumps and Roots", Metsantutkimuslaitoksen Julkaisuja 77.1, Helsinki, Finland.
- Hakkila, Pentti. 1996. Personal Communication with David Yomogida, May 21 & 24.
- Hall, Peter. 1995. "Harvesting and Utilisation of Logging Residue, John Balneaves Travel Award - 1995", New Zealand Logging Industry Research Organisation Special Report No. 18.
- Hartsough, Bruce, and Randall Richter. 1994. "Mechanization Potential for Industrial Scale Fibre and Energy Plantations", in Bryce Stokes and Timothy McDonald (eds), IEA/BA Task 9, Activity 1 International Conference, Mobile, AL, March 1-3, 1994. pp. 65-78.
- Hohenstein, W.G., and L.L. Wright. 1994. "Biomass Energy Production in the United States: An Overview", *Biomass and Bioenergy* 6(3):161-173.
- Jenkins, B.M., L. Baxter, T. Miles, Jr., and T. Miles. 1996. "Combustion Properties of Biomass", Proceedings, Engineering Foundation Conference on Biomass Usage for Utility and Industrial Power. Snowbird, Utah, April, pp. 17-47.

Kaiser, Charles. 1994. Personal Communication with Bruce Hartsough, March 1.

Kaiser, C.E., D.E. Rice, and K.R. Wallace. 1994. "Stand Establishment and Culture of Hybrid Poplars", in Stokes, B.J. and T.P. McDonald (eds), Proceedings of the International Energy Agency, Task IX, Activity 1 Symposium "Mechanization in Short Rotation, Intensive Culture Forestry"; 1994 March 1-3; Mobile, AL. Auburn, AL: US Department of Agriculture, Forest Service, Southern Forest Experiment Station. pp. 25-30.

Kaiser, Charles. 1996. Personal Communication with David Yomogida, May 2.

Karsky, Richard J.. 1992. "The MTDC Tree Harvester", United States Department of Agriculture, Forest Service, Technology and Development Program, 9251-2835-MTDC, August 1992.

Karsky, Richard. 1996. Personal Communication with David Yomogida, April 30.

Kerruish, C.M., and W.H.M. Rawlins. 1991. "The Young Eucalypt Report", CSIRO Bookshop, 314 Albert Street, East Malbourne, Victoria 3002. 272 p.

Ledin, Stig, and Agnetha Alriksson. 1992. "Handbook on How to Grow Short Rotation Forests", International Energy Agency Bioenergy Agreement Task V, Energy Forestry Production Systems Activity, ISBN 91-576-4628-7.

Lowe, Hamish, Ralph Sims, and Jim Cooper. 1994. "Utilization of Short-rotation Forestry for Fuelwood from an Effluent Disposal Scheme", in Stokes, B.J. and T.P. McDonald (eds), Proceedings of the International Energy Agency, Task IX, Activity 1 Symposium "Mechanization in Short Rotation, Intensive Culture Forestry"; 1994 March 1-3; Mobile, AL. Auburn, AL: US Department of Agriculture, Forest Service, Southern Forest Experiment Station. pp. 107-114.

McDonald, Tim, and Bryce Stokes. 1993. "Status of Short Rotation Forestry in the USA", in Culshaw, Damian (comp), IEA/BA Task IX Activity 1 -- Status of SR Forestry Mechanization Worldwide, Workshop and Study Tour, Sweden -- March 2-4, 1993, IEA Report, ETSU, Harwell, Oxfordshire, OX11 0RA, United Kingdom. pp. 21-44.

McNabb, K. 1994. "Silvicultural Techniques for Short Rotation *Eucalyptus* Plantations in Brazil", in Stokes, B.J. and T.P. McDonald (eds), Proceedings of the International Energy Agency, Task IX, Activity 1 Symposium "Mechanization in Short Rotation, Intensive Culture Forestry"; 1994 March 1-3; Mobile, AL. Auburn, AL: US Department of Agriculture, Forest Service, Southern Forest Experiment Station. pp. 89-96.

Morgan, T.H. 1994. "Industrial Short Rotation Intensive Culture Operations", in Stokes, B.J. and T.P. McDonald (eds), Proceedings of the International Energy Agency, Task IX, Activity 1 Symposium "Mechanization in Short Rotation, Intensive Culture Forestry"; 1994 March 1-3;

Mobile, AL. Auburn, AL: US Department of Agriculture, Forest Service, Southern Forest Experiment Station. pp. 1-4.

Netzer, D. and E. Hansen. 1994. "Establishing and Tending Poplar Plantations in the North-Central U.S.", in Stokes, B.J. and T.P. McDonald (eds), Proceedings of the International Energy Agency, Task IX, Activity 1 Symposium "Mechanization in Short Rotation, Intensive Culture Forestry"; 1994 March 1-3; Mobile, AL. Auburn, AL: US Department of Agriculture, Forest Service, Southern Forest Experiment Station. pp. 79-87.

Paquin, D., D. Singh, and T. Liang. 1989. "Development of a Biomass Harvester", ASAE/Canadian Society of Agricultural Engineering Meeting Presentation, ASAE Paper No. 89-7062.

Perlack, R.D., J.W. Ranney, and L.L. Wright. 1992. "Environmental Emissions and Socioeconomic Considerations in the Production, Storage, and Transportation of Biomass Energy Feedstocks", Oak Ridge National Laboratory, ORNL/TM-12030, July 1992.

Pottie, Michael A., and Daniel Y. Guimier. 1986. "Harvesting and Transport of Logging Residuals and Residues", Special Report N SR-33, Forest Engineering Research Institute of Canada, pp 24-64.

Portwood, C.J. 1994. "Utilization of Cottonwood Plantations", in Stokes, B.J. and T.P. McDonald (eds), Proceedings of the International Energy Agency, Task IX, Activity 1 Symposium "Mechanization in Short Rotation, Intensive Culture Forestry"; 1994 March 1-3; Mobile, AL. Auburn, AL: US Department of Agriculture, Forest Service, Southern Forest Experiment Station. pp. 21-23.

Richter, Randy. 1996. Personal Communication with David Yomogida, April 30.

Rydellius, J.A. 1994. "Growing *Eucalyptus* for Pulp and Energy", in Stokes, B.J. and T.P. McDonald (eds), Proceedings of the International Energy Agency, Task IX, Activity 1 Symposium "Mechanization in Short Rotation, Intensive Culture Forestry"; 1994 March 1-3; Mobile, AL. Auburn, AL: US Department of Agriculture, Forest Service, Southern Forest Experiment Station. pp. 53-56.

Schaller, Bruce J., David Ostlie, and Ronald Sunberg. 1993. "Whole Tree Energy Design, Volume 2: Program to Test Key Elements of WTE", Electric Power Research Institute, Hydroelectric Generation and Renewable Fuels Program, Generation and Storage Division, TR-101564, December 1993.

Sirois, Donald. 1981. "A Mobile Harvester for Utilization of Weed Trees and Residues", in Proceedings of the 1981 John S. Wright Forestry Conference, Weed Control in Forest Management, Purdue University, West Lafayette, Indiana.

Spinelli, Raffaele, 1996a. Personal Communication with David Yomogida, June 10.

- Spinelli, Raffaele, 1996b. Personal Communication with Bruce Hartsough, September 25.
- Stokes, B.J, D.J. Frederick, and D.T. Curtin. 1986. "Field Trials of a Short-rotation Biomass Feller Buncher and Selected Harvesting Systems", *Biomass* 11:185-204.
- Stokes, Bryce, and William Watson. 1989. "Field Evaluation of In-Woods Flails in the Southern United States, in Proceedings of IEA/BA Task VI Activity 2 Meeting, New Orleans, LA, May 29 - June 1. pp. 99-111.
- Thompson, Mike. 1996. Personal Communication with David Yomogida, May 2.
- Tian, Lei, and David Slaughter. 1993. "Computer Vision Identification of Tomato Seedlings in Natural Outdoor Scenes", 1993 International ASAE Winter Meeting, Chicago, Illinois, December 14-17, 1993, ASAE Paper No. 93-3608.
- Tiangco, Valentino. 1988. "State of the Art: Wood Ash Utilization", Agricultural Engineering Department, University of California, Davis, CA 95616.
- Walker, R.F.. 1976. "Stump Extraction and Utilization -- A Literary Review with Regard to Conditions in New Zealand", New Zealand Forest Research Institute Forest Establishment, Report No. 93, Rotorua, New Zealand.
- Walsh, Marie, Denny Becker, and Robin Graham. 1995. "Estimated Government Savings from Biomass Production on CRP Acres", *Energy Crops Forum*, Fall 1995, USDOE Biofuels Feedstock Development Program.
- Wasterlund, Iwan. 1992. "Extent and Cause of Site Damage Due to Forestry Traffic", *Scandinavian Journal of Forest Research* Vol (7): pp. 135-142.
- Watson, W.F., A.A. Twaddle. 1990. " An International Review of Chain Flail Delimiting-Debarking", IEA/BA Task VI, Activity 2, Aberdeen University Forestry Research Paper 1990:3.
- Wierman, C.A. 1994. "Management of Irrigated Hybrid Poplar Plantations in the Pacific Northwest", in Stokes, B.J. and T.P. McDonald (eds), Proceedings of the International Energy Agency, Task IX, Activity 1 Symposium "Mechanization in Short Rotation, Intensive Culture Forestry"; 1994 March 1-3; Mobile, AL. Auburn, AL: US Department of Agriculture, Forest Service, Southern Forest Experiment Station. pp. 57-63.
- Wiltsee, George A., Evan E. Hughes. 1995. "Biomass Energy: Cost of Crops and Power", TR-102107-Vol. 2, Electric Power Research Institute, Palo Alto, CA 94304, October.