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Contents

Equipment and systems for the recovery, transportation, and processing of woody biomass for energy: synthesis of the literature 1982-2002

Abstract

The Forest Engineering Research Institute of Canada (FERIC) conducted a literature search on the recovery, transportation, and processing of forest biomass into fuel. This report presents a summary of findings of the literature search, which includes both Canadian and international publications.

Keywords

Biomass, Recovery, Processing, Transportation, Fuelwood, Energy, Costs.

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Introduction

Over the last thirty years in Canada, considerable research, both of a fundamental and applied nature, has been undertaken on the recovery, transportation, and processing of forest biomass into fuels or chemicals. During the early 1980s, the federal government initiated a program, Energy from the Forest (ENFOR), that supported research on the topic of forest biomass recovery and processing. FERIC participated in the program and developed, evaluated, and reported on several recovery technologies (Du Sault 1985). This research effort was in response to major national concerns about oil supply. During this same period, the International Energy Agency (IEA) also funded programs to investigate forest biomass use (Pottie and Guimier 1986).

More recent concerns about CO_2 emissions have stimulated renewed interest in utilization of biomass for energy in Canada. New research funding initiatives have developed, as well as the need to ensure past research results are fully utilized. Scarce funding could be wasted if researchers and funding agencies are not aware of past efforts.

This literature review is intended to allow today's researchers to build on the research results from the past two decades. The study was funded by Natural Resources Canada's POL 4.2.5 program. The study consisted of a summary of findings, which is presented here, and an annotated bibliography[1] of research undertaken in the last twenty years on recovery, transportation, and processing of forest biomass into fuel.

Results

The search for literature located 153 reports and articles that met the search criteria. This literature includes both Canadian and international publications and is categorized in this report under four main headings: Recovery, Transportation, Processing,

[1] Ledrew, K; Clark, M; Hedin, I. Equipment and systems for the recovery, transportation, and processing of woody biomass for energy: an annotated bibliography 1982–2002. FERIC, Vancouver, B.C. Internal report IR-2004-03-01. Available upon request.

and Economics. Although many reports covered two or more of these topics, they are only included in one category. Richardson et al. (2002), which is described in the Economics section of this report, is one of the most comprehensive publications addressing bioenergy from forests. Its eight chapters, written by 28 contributors from around the world, focus on the sustainability issues associated with forest biofuels, and discuss fuelwood characteristics, production of forest energy, cost of wood energy production, environmental and social implications, and policy and institutional factors.

Recovery

For the purpose of this literature review, recovery is defined as the collection of forest biomass at the harvest site to facilitate subsequent transportation or processing. Recovery can occur at the stump, roadside, or landing. Eighty-one reports and articles were found on this topic.

Some studies are concerned entirely with recovery activities while others also include the transportation and/or processing aspects. This section groups the literature that provides a general review of recovery equipment and systems, and then categorizes the remaining literature based on the type of primary product usually recovered at the harvest site, including harvesting residue (e.g., branches, tops, and short pieces of log defect); bales (i.e., compressed harvesting residue); chunk wood ranging from 5 to 10 cm; hog fuel; and chips.

General review of recovery equipment and systems

During the 1980s, funding to investigate forest biomass recovery for energy prompted several general reviews, with seven of these presented here.

Gilliusson (1984) outlined the research funded by the IEA program.

FERIC conducted several comprehensive studies, and reviewed equipment and systems available for biomass recovery. Guimier (1985) described the equipment available in that year by machine type, manufacturer, product, distributor, and country of origin. Pottie and Guimier (1986) reported on equipment for the harvesting and transportation of harvesting residues. This was a comprehensive report on equipment with potential application for Canada and elsewhere. The authors made recommendations to develop an integrated approach to harvesting logs and biomass; develop equipment to reduce biomass into chunks or compact into bales; and investigate specialized hauling rigs to carry biomass with optimum loads.

Baldini (1987) described biomass recovery from short-rotation forest, thinning, and harvest residues, and described recovery equipment from agricultural tractors to steep slope cable yarders.

Twaddle et al. (1989) reviewed biomass recovery technology internationally, with a New Zealand perspective.

Gingras (1995) summarized the body of work done during 1992–1994, including a literature review of potential recoverable material as a function of harvest system; an analysis of factors affecting chipping quality and productivity; a comparison of firewood processing technologies; a review of small-tree and residue harvesting methods; a description of prototype combination machines for recovering roundwood and biomass; and an update of harvester head development for multiple tree handling in Nordic countries.

Brunberg et al. (1998) described a project to expedite the development of technology and methods for enhanced bioenergy harvesting systems. Examples included

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ISSN 1493-3381

multi-tree felling heads for small wood, compaction equipment for logging residues, and heavy duty chippers. An interesting method starting to evolve at that time was the bucking of pulpwood at larger diameters, and utilizing long tops for biofuel. Adoption of new technology can both increase the volume of biofuels and the net profits of logging.

Harvesting debris

Publications on biomass harvesting systems and equipment are numerous, with 39 found.

Brown et al. (1983) reported on two trials of double entry logging of old-growth timber in the Pacific Northwest region of the United States. A large cable yarder was used to recover the heaviest merchantable logs on the first entry and a smaller yarder followed to recover both the smaller merchantable logs and the biomass.

Christopherson (1983) presented results on a prototype machine recovering hardwood logging debris in southeastern United States.

Stokes et al. (1986) evaluated a feller-buncher, grapple skidder, small tractor, and chipper system in a three-year-old sycamore stand. Costs could be reduced with a smaller chipper. The feller-buncher did little stump damage—important for coppicing. The tractor caused less skidding damage than the large skidder.

Host and Lowery (1983) described a fuelwood harvesting system that consisted of a feller-buncher, skidder, and chipper which operated in salvage and thinning operations. Economics depended on proximity to market.

In Europe, Bonicelli (1985a, b) discussed the design features and use of small biomass forwarders in France. Abeels (1987) compared energy values from different types of biomass (cereals, and coniferous and deciduous trees), and discussed different harvesting methods and their economies of operational scale. Curro and Verani (1987) reported on coppice harvesting trial productivities by extraction phase for mechanized systems.

Van Landegherm and Gasquet (1987) evaluated a forestry tractor, the Scorpion, for harvesting biomass. Productivity depended on site and stand conditions, and market value. The machine was versatile and therefore could be used in other applications when markets are low.

Integrating the harvesting of logs and biomass was a common theme in many reports. Hassler et al. (1983) proposed integrating the harvesting of forest products, including fuelwood. They found larger diameter stands were necessary to produce fuelwood economically with three people (handfalling, yarding, and chipping operators at roadside).

Johnson (1982, 1983) and Johnson and Lee (1982, 1986) reported on biofuel recovery being done concurrently with cable harvesting. Concurrent recovery is advantageous when the piece size of sawlogs and slash is similar. The major disadvantage is congestion at the landing. Miller et al. (1985) reported on the same topic, and compared one-pass and two-pass harvesting systems to produce biofuels from hardwood and pine stands. The two-pass system had high costs when biomass levels were low.

In Japan, Minamikata (1987) described methods of harvesting and processing forest biomass, including cable yarding, skidding, thinning, and chipping. Total removal of biomass was not recommended due to its importance to regeneration.

Mitchell et al. (1987) used a systems analysis approach to compare the range of equipment available for harvesting early thinnings. The authors derived the cost of producing fuelwood chips, and made recommendations for further study of promising techniques. Mitchell and Zibetta (1989) described trials and development work subsequent to the previous study.

Du Sault (1985) reported on the development and trial of the prototypes of two biomass processing machines, called the Recufor and the Logging Residue Processor (LRP). The Recufor (Figure 1) was designed to recover logging residue left on the forest

Figure 1. The Recufor was designed to recover logging residue left on the forest floor, to comminute this material, and to transport it to roadside. The high cost of owning and operating the machine compared to the low value of the biomass prevented commercialization of the unit.

floor, and to comminute this material and transport it to roadside. The LRP was developed as a self-propelled machine to recover and reduce the roadside residues after full-tree delimbing. The report covered the design, development, and field testing of these prototype machines. They were never commercially developed because the capital and operating costs of the equipment were too high for the low market value of the fuelwood. Hamilton (1984) also described these machines and Novak (1986) described the results of a modified LRP.

Hamilton (1987) described several conceptual machines to harvest biomass, and included estimated costs. He proposed that biomass harvesting would only be economical if conducted as an integral part of pulpwood and sawlog harvesting.

Reports in the 1990s and early 2000s included both evaluation studies as well as system studies. Hall (1995) described a fibre recovery system to collect and transport logging residues in New Zealand.

Alriksson (1994) reported on a new shear head for harvesting small trees that has improved positioning reach for thinning operations.

Pari and Iapichino (1995) described eight harvesting machines available to harvest short-rotation plantations. A new machine prototype was also studied.

Nurmi (1997) described a modified single-grip harvester that accumulated logging residues and piled them along the strip road for easy recovery. Compared to the conventional recovery method, residue volume increased by 25%.

Ryynanen (1996) studied six harvesters that could be mounted on the hydraulic cranes of agricultural tractors for thinnings. Harvesting productivities and costs were discussed.

Gingras and Favreau (1996) presented the results of a study comparing three harvesting systems: full-tree to roadside, cut-to-length, and full-tree chipping. They also analyzed the effect of hauling distance, moisture content, and machine utilization.

Spinelli (1996) reported on the test of an Austrian self-propelled harvester/chipper. The machine performed well in the short-rotation forests and showed potential. Spinelli (2001) described a prototype harvester in short-rotation energy plantations in North America. Spinelli and Hartsough (2001b) also discussed short-rotation plantations. They studied a front-end loader and grapple skidder used to extract whole-stem bunches to the landing. The loader was more productive than the grapple skidder.

Remler et al. (1998) reported on thinning with a chipper/harvester to utilize both fuel chips and logs. The machine had some design problems, and was able to operate only on level ground. Soil compaction may be an issue, but residual stand damage was avoidable.

Felker et al. (1999) reported on the development of a biomass harvester and field tests in the United States. Although the machine operated well in dense, smaller-diameter material (less than 10 cm), it was too light for the application.

Ryynanen (1999) reported on the assessment of a bioenergy program in Finland. During the time, the economics of biofuels improved in response to technological changes and tax structure. The production cost of fuelwood was reduced by 20% since 1992.

Eriksson and Nordén (1999) described the backlog of stands on lower productivity sites requiring cleaning. Cleaning in such stands is costly but the wood can be used for biofuels. The machine was an EnHar felling head mounted on an FMG 0470 harvester.

The stand consisted of 25-year-old Norway spruce and birch undergrowth with an average mean diameter of 5 cm. If the stand had been smaller, the operation would likely not have been profitable.

Eriksson and Rytter (2000) did a similar study to determine if fuelwood can be profitable in late cleaning of stands. A harwarder (combination harvester and forwarder) (Figure 2) was used to fell and forward the material to roadside for chipping. The researchers noted potential growth increment loss due to creation of strip roads and nutrient removal. One stand with larger-diameter beech was clearly profitable but the smaller-dimension stands were more costly to clean. In the smallest-diameter stand, cleaning using conventional techniques (motor-manual) was less expensive than using the harwarder.

Glöde (2000) discussed the cost of an integrated harvester for fuelwood and merchantable logs, and the potential reduction of fuelwood cost. He estimated cost reductions should be 40% compared to chipping systems, or 20% compared to baling systems. The machine proposed was a single-grip harvester with a compacting attachment.

From the product point of view and again with an integration perspective, Wigren et al. (1993) gives generally applicable fuelwood quality criteria: homogeneity of moisture content and fine fraction, and limited percentage of contaminants. He suggested that it is worthwhile to manage residue from the start of logging through to delivery.

Bales

Baling of harvesting and pruning residues has received attention from European researchers and equipment developers, with four reports identified.

Beach et al. (1985) described the development of a grapple infeed system for biomass balers. Amirante and diRenzo (1987) discussed a prototype pruning residue baler adapted from a straw baler.

Figure 2. A harwarder (combination harvester and forwarder) has been developed in Scandinavia to fell and forward material to roadside. In this picture, the harwarder is producing pulp and sawlogs.

Figure 3. A Timberjack Energy Wood Harvester 1490D biomass bailer mounted on a forwarder. One of these units was tested in 2003 by the U.S. Forest Service.

Davner (1996) reported on a SkogForsk system analysis study by Andersson and Nordén on a forwarder-mounted baler. The baler created cylindrical bales that were 1.2 × 1.2 m in size and weighed about 600 kg. The machine could produce 15 bales per hour. The compression factor of the bales doubled the payloads for both the forwarder and secondary transporter.

Andersson et al. (2000) described two new Swedish balers manufactured by Fiberpac and Wood Pac that compact logging residue into cylindrical bales called Composite Residue Logs (CRLs). CRLs, about 3 m long by 0.75 m in diameter, provide an energy output of about 1 MWh. They can be handled with the same forwarding and trucking equipment used for round logs.

In 2003, the U.S. Forest Service conducted a trial of a Timberjack Energy Wood Harvester 1490D (Figure 3) in Washington, Idaho, and Montana. The objective was to determine if this equipment could bale logging residues for transport and sale to energy facilities at an economical cost. Interest in the equipment was high, and the equipment was demonstrated later in the year in both British Columbia and Alberta. Preliminary information is available on the U.S. Forest Service website,[2] and indicates that the equipment's productivity ranges from 6.5 to 10 bundles per hour, depending on the site and residue conditions.

Fuelwood

Oakley and Manning (1984) described a portable shear-type residue processing system. They tested the machine in a logyard and at a logging site. The system can produce economic fuel at the logyard but not at the logging site. Sinclair (1984) reported a productivity at the logging site of one-quarter that of the logyard.

Cavalli et al. (2001) described the productivity of a fuelwood processing system which included a splitting machine and bucking saw. Processing times for one ton of fuelwood varied between 40 and 54 minutes.

Figure 4. The production of hog fuel from sortyard residues (Forrester 1996).

Figure 5. Trommel screen used to classify material entering a water separation unit (Forrester 2000).

Figure 6. Peterson Pacific 2400 portable hog mill converting harvesting slash to hog fuel in northern Alberta (Forrester 2003).

Chunk wood

Mattson et al. (1985), Arola et al. (1988), Danielsson (1988), Nurmi (1988), and Sturos (1988) all described chunking. These reports are summarized in the Processing section of this report.

Hog fuel

Smyre (1985) tested a horizontal-feed hog mill and found it suitable for large dimension wood waste as well as stringy material. It required less horsepower than a top-fed hog, and its knives required less maintenance than a knife hog.

Forrester (1993, 1996) studied hogging at logyards (Figure 4). He found that some material in these yards is suitable for hog fuel, but that some components must be removed prior to hogging. The reports contain information on material composition, equipment productivity, and product analysis.

In two additional reports, Forrester (1999, 2000) described separation equipment (trommel and screens, single knife destoner, and waterbath) and their effectiveness in removing mineral components from logyard debris. Figure 5 shows a trommel that he studied. Later, Forrester (2003) examined the feasibility of recovering logging slash for conversion to biofuels (Figure 6). Delivered hog fuel cost was compared to the cost of natural gas.

Desrochers (1993) presented two case studies evaluating the use of tub grinders to recover forest residues at roadside. Tub grinders proved to be particularly effective in processing residues from delimber/debarker/chippers and fairly effective at

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[2] Website address: http://www.fs.fed.us/fmsc.sdu/biomass/bundling/index.php.

processing two-year-old residues from stroke-delimbers, and ineffective in treating green residues from stroke-delimbers. Desrochers (1998) reported on a production cost study of a Maxi-Grind tub grinder, in a large-scale trial funded by ENFOR to collect and transport residues from the grinder.

Fuel chips

Chipping can occur at the stump site, on the roadside, or at centralized locations to maximize machine utilization.

Filipsson (1998) described the bioenergy situation in Sweden, and explained that 70% of the biomass comes from final felling. Davner (2001) reported that 80% of harvest residue is chipped at roadside or on landings, 10% in the cutover and 10% is transported whole to the conversion plants.

Keville (1982) discussed the equipment necessary to harvest, transport, and process harvesting biomass in a short-rotation stand. He described a machine concept to cut the biomass and convey it into a chipper. This unit would be towed behind an agricultural tractor.

LeDoux (1984) examined the recovery of forest residues from old-growth clearcuts using cable yarding with three configurations. Turn size was important to the productivity of the systems.

Alexandersson (1985) presented proceedings of a conference entitled "Comminution of Wood and Bark" where papers that discussed both roadside and off-road chipping economics were presented.

Kipping and Stiasny (1987) reported on seven whole-tree chipping operations in New Brunswick. They found two were viable: chainsaw/cable skidder systems, and feller-buncher/grapple skidder systems. Schneider (1987) summarizes biomass recovery and productivity for small-scale chipping operations in the Maritimes.

Morvan (1987) compared hand and mechanized systems of producing chips and fuelwood (billets). One mechanized system was tested.

Natalicchio and Zibetta (1989) described a trial of a machine capable of collecting and chipping felled stems. The results were promising for coppice woodland on steep slopes.

FERIC prepared a handbook for fuelwood chipping (Folkema 1989) that provides logging contractors with information on establishing and operating cost-effective fuelwood chipping enterprises. The handbook covered all operational aspects, including selecting appropriate equipment, product quality, and economic considerations. Although the handbook was targeted at small woodlot operators in eastern Canada, the content has universal application.

Hartsough et al. (1992, 2000) discussed short-rotation harvesting of poplar as a source of fuelwood. In both cases, chips were produced. In Hartsough et al. (1992), flail delimber/debarker/chippers were used to process stems. Hartsough et al. (2000) reported on both ground skidding and cable yarding to harvest the poplar stands. The skidder appeared viable, but the cable yarder required pre-bunching to improve production rates.

Laurier et al. (1990) conducted three harvesting trials aimed at increasing the yield of biomass. Pulp chips and fuelwood were both produced at the harvesting site.

Lisa (1987) investigated the drying of fuel chips to reduce moisture content. The less expensive storage in small heaps protects them from the rain and proved successful. Natural storage drying was improved by felling in autumn and by skidding and chipping in the spring.

Richardson (1986) reported on two short-term studies of two Bruks chippers operating both at roadside and at the stump. Both models performed well under the conditions tested. Hunt (1994) studied a Bruks mobile chipper working in roadside debris in west-central Alberta as an alternative to burning. Even though Hunt's study focused on slash reduction rather than biofuel recovery, the results are applicable to fuel chip production.

Desrochers et al. (1995) presented case study productivity results for five chipping operations in eastern Canada and the northeastern United States. The Bruks model 1001 CT, the Nicholson WFP 3A, and the Erjo 120 HM 903 were evaluated while processing roadside residues.

Mafrici and Zimbalatti (2001) studied a Bruks 803CT mobile chipper that used wood waste 30–35 cm in diameter from a timber yard. Productivity in the yard was one-third higher than at the harvesting site.

Spinelli and Hartsough (2001a) observed 100 chipping operations in Italy. The chipping business was the secondary domain of loggers rather than the primary domain of chipping contractors. Most loggers preferred self-propelled machines. Tractor-powered and towed chippers were used in a wide range of conditions. Disc chippers dominated the industry at the time of the study but drum chippers were increasing in use, especially in fuel supply operations. Chips were transported by farm tractors and powered trailers for distances of less than 4 km, by high speed tractors for intermediate distances, and by trucks for distances over 30 km. Verani (2001) also described chipping operations in Italy.

Transportation

Biomass transportation is defined as moving biomass from the forest site to a conversion facility. Transportation modes addressed in this report include truck and rail, and 11 reports are included. In most cases, the reports described trucking systems for other purposes, e.g., logs or chips, which can be simply adapted to transport biomass.

Johansson (2000) analyzed hauling fuel chips or bundles from young stands, using a timber truck, container truck, or fuel chip truck. Two moisture contents were compared as well. He identified one of the main constraints with transporting low bulk density materials: volume was the limiting factor at 25% moisture content, and truck capacity in terms of weight could not be achieved. At 50% moisture content, Johansson found weight was reached, and in fact became limiting. The least costly system was bundles, particularly when dried, and the most expensive was the container truck. Even though the truck configurations and highway regulations are different in Sweden compared to Canada, the relative costs should remain similar.

Davner (2001) identified another problem associated with low density materials. During transport, loads settle, and methods of adequately compensating hauling contractors need to be determined.

Angus-Hankin et al. (1995) identified secondary transportation as being responsible for 20 to 40% of delivered cost. Truck transportation systems often do not reach full payload because woody biomass frequently has a low bulk density. For this reason, compacting or comminuting biomass prior to transportation may be a feasible option. Once comminuted, transportation systems are similar to those used for pulp chips.

The references include several studies of vans used to transport chips from either whole-tree chipping operations, or delimber/debarker/chipper operations (Duncan et al. 1984; Williams and Markham 1991; Blair 1998). Constraints were associated with low ground clearance for chip vans on non-paved forest roads, and reducing non-productive time for both the chipper and truck at the landing. Webb (2002) describes an alternative means of improving chip/log truck utilization by alternating transportation of logs and comminuted material on two-way hauls. While Webb addresses pulp chips, the concept could be used for any loose material.

Silversides and Moodie (1985) described the latest equipment used for full-tree transportation. These are generally conventional trucks, in some cases with confining structures to prevent excessive load width. As with chips, hog fuel, and branch/top/small-tree bundles, low bulk densities result in load volume being the constraining factor.

Three reports presented different perspectives from the conventional trucking options. Provencher (1997) reported on an analysis of using existing rail tracks to transport forest products including chips and potentially woody biomass. Sinclair (1984, 1985) looked at container system to recover biomass from mountainous terrain (Figure 7). Sinclair found that this system showed good potential as a means to haul chunks and short logs from landings and roadside debris accumulations in mountainous areas.

Figure 7. Waste bins used to transport low-grade harvesting material (Sinclair 1984).

Processing

Processing is defined as the primary comminution of biomass into particles suitable for transportation, or in some cases, after transportation but before secondary processing (e.g., pelletizing or conversion to energy). Activities include chipping, hogging, or chunking into either lengths between 15 and 100 cm, or fist-sized material. Twenty reports and articles that specifically address processing equipment and systems were found in the literature.

Pottie and Guimier (1985) presented an overview of equipment used for primary processing of biomass. This report was comprehensive and contained a good description of techniques and equipment available. The authors made several recommendations, including developing: an industrial-sized chunking machine; drying techniques other than thermal; and equipment to improve transportation, handling, and storage after primary processing. The authors also suggested investigating the feasibility of tailoring conversion systems to suit the product available rather than converting the product to suit the conversion systems. Some of these recommendations have been implemented, e.g., the chunking developments described below, and baling as described in some Sweden reports discussed in the Recovery section of this report.

Mattson et al. (1985), Arola et al. (1988), Danielsson (1988), Nurmi (1988), and Sturos (1988) all described chunking—fist-sized or 5–10 cm long—as a method of producing fuelwood. Energy consumption is less than for chipping. Although prototypes and some production models have been produced, recent literature does not mention this equipment.

Laurier (1997) and Ilavsky and Oravec (2000) describe how chipping is used for the production of biofuels in France and Slovakia, respectively.

Hogging is another common method of comminuting woody biomass, and this technique is described in Cobb (1985). Tub grinders produce a similar product, and Young (1992) describes a portable tub grinder in Newfoundland used to convert harvesting debris to smaller-sized material. More operations are described in the Recovery section of this report.

Guimier (1985) described compaction concepts, experiments, and equipment. Although some equipment has become available since the time of his report, the information he presented is still current.

Du Sault (1985a, b) reported on a dual roll splitter. The objective of the equipment was to dewater the material mechanically, and splinter and crush the biomass.

Refined fuelwood products, e.g., pellets, wood flour, and wood briquettes, are produced primarily from sawmill waste (Alriksson 1996), and these products form an important part of the biofuel supply in Sweden, especially for small heating plants and private houses (Davner 1994a, b, 1996a, b, 1999).

Finally, Eriksson and Westerberg (1998) emphasized the importance of providing quality fuels to the conversion plant. Material that is poorly comminuted, too dry, or too wet can result in problems in handling and conversion. Inorganic contaminants can also be a problem.

Economics

The reports and articles in this section describe studies of the economics of forest biomass utilization for energy. Forty-two reports were identified.

Grassi et al. (1989) edited the proceedings of a European conference on biomass research. This report included presentations that addressed a variety of biomass sources and technologies.

Asikainen and Kuitto (2000) provided a good overview, including a complete description of the cost factors related to procuring forest biomass. Site-based variables such as volume of wood to be harvested, site conditions, available equipment, transportation distance, transportation method, quality of biomass, and type of storage all affect the harvesting cost. The authors also point out issues related to ecological sustainability and seasonal variation in energy consumption as important considerations. They discuss the influence of scale of operation. Because equipment is expensive, annual throughput is important to the final cost. However, increasing throughput requires more sites and more volume, which often require harvesting from more distant or poorer quality sites.

Hall et al. (2001) presented the New Zealand situation, and described the cost of delivery systems (including harvesting through processing) for arisings—residues produced during the harvesting of logs. As in the previous report, the authors identified site characteristics, delivery systems, and transportation distance as the primary factors influencing costs. Residues accumulated at the landing were somewhat less expensive than those collected from the cutover. The simpler system tended to be the cheapest option because increased handling added extra cost. Product characteristics and machine data were the most sensitive model parameters and therefore must be estimated accurately when doing analyses.

Most recently, Richardson et al. (2002) is a comprehensive document that describes various aspects of developing bioenergy using sustainable forestry systems. This book describes the rationale for forest fuel production; the science of wood, combustion, and energy production; silvicultural and forest management considerations, including recovery; economic considerations and competitive position compared to other energy sources; environmental sustainability; social implications; policy; and framework for evaluating the applicability of fuelwood systems.

Gullberg (2000) conducted a cost analysis of simulated treatments in young stands 3–10.5 cm in diameter. Motor-manual felling and manual bunching of material were least expensive at the lower diameter ranges, while machine concepts for combined felling/chipping/extracting and felling/bunching plus forwarding showed promise in the larger stands.

Natt and Ryynanen (1999) described a computer-based model that can be used to calculate the cost of fuelwood in Finland, and to test the sensitivity of cost to specific variables. Another model described by Gunnarsson et al. (2001) can be used to improve the efficiency of planning for large fuelwood enterprises. The authors suggested that a 10–15% reduction in costs could be achieved with improved logistics.

Borjesson and Gustavsson (1996a) analyzed regional production and utilization of biomass in Sweden. They concluded that an average distance for biomass transportation to a large-scale production facility would be 30–42 km if the facility was in the centre of a biomass production area. This would result in a total energy efficiency of production and transportation of 95–97%; some emission of air pollutants would be expected. Borjesson and Gustavsson (1996b) estimated transportation costs were 20–25% of delivered cost.

Koch (1982) presented an economic analysis of the utilization of southern pine residues and forecast a return of 40% on a

$50 million investment. Perlack et al. (1996) suggested an alternate approach that utilized high intensity forest farming and genetic improvements to maximize fibre production and minimize costs.

Golob (1986), Smith and Riley (1985), and Hummel and Hall (1985) discussed short-rotation silvicultural crops as a source of biomass for energy. Golob (1986) recommended 10-year rotations for these crops to give a better return than shorter rotations.

Several papers described the harvesting of biomass concurrently with sawlogs and pulp logs. Adams (1983) reported on a study in Oregon that used skyline logging in old-growth forests, with three levels of utilization. The author stated that costs increased with a reduction in piece size. Adams also gave an interesting comparison that the ratio of potential energy content of the residue material if used as fuel compared to the energy used in harvesting was 24 to 1. Zundel (1986) presented the results of a study delivering full-tree conifer stems to a central area, where conventional products as well as biomass for energy were recovered. The economics could be positive because the centralized equipment was highly productive, provided that hauling costs could be kept low.

Despite Scandinavia's history as one of the leaders in large-scale use of fuelwood, two articles on Scandinavia's energy industry (Davner 2001a, b) point out the sensitivity of biomass economics not only to the cost of petrofuels and other bioenergy, but also to additional costs such as disposal of ash. When diesel is expensive, the costs for the harvesting and comminution of woody material also increase, and off-shore construction debris becomes more competitive. Establishing a biofuels industry is subject to the volatility of alternate fuel costs.

The disposal of the ash generated from burning woody material is the topic of a number of studies and articles from Sweden (Davner 1994, 1997; Jacobson 1997). Returning ash to the forest site as a fertilizer is recommended in some cases, but it appears to be effective only on fertile sites (Jacobson 1997). Growth reductions, however, following whole-tree thinning were 7 and 12% for Scots pine and Norway spruce, respectively, after ten years (Jacobson and Kukkola 1999). Fertilization was successful in recovering growth rates.

In another study about growth losses, Mattson (1999) described work done in Sweden to identify the cost of future increment losses. The question is complex because, while there are increment losses, investment cost in the new crop can be reduced due to the removal of debris and potentially lower planting cost and higher seedling survival.

In Canada, the effects of biomass harvesting on tree growth and on forest soils and nutrients are reported in Maliondo (1988), Standish et al. (1988), Maliondo et al. (1990), and Commandeur and Walmsley (1993). This is not a comprehensive list of such studies, as this topic was not part of the literature review objectives. However, potential growth losses is an important aspect of biomass harvest, and must be considered.

Borjesson (1996) and Borjesson and Smith (1996) presented CO_2 emissions and energy analysis of biomass production and transportation. They found that CO_2 emissions from short-rotation forests, straw, and logging residues were lowest, compared to alternative agricultural crops, per unit energy delivered. The energy input for logging residues was 4–5% of energy output.

Two papers relate to the curing of biomass prior to processing (Jirjis and Nordén 2002; Nurmi 1998). Storage is done for several reasons: to reduce the moisture content of the biomass and to meet seasonal needs for energy. Two concerns were raised: the loss of biomass and subsequently energy during the storage period, and the concentration and release of fungal spores during chipping with attendant health concerns for workers. Needles were lost, but neither this nor the fungal content appeared to be problematic.

Graham (1998) presented a case study done in Tennessee using a GIS-based decision support system. The marginal cost of delivering wood chips varied with the specific locations or the short-rotation energy crops and the facility. The author emphasized the need to be geographically specific when projecting costs and supplies of biomass. Jensen et al. (2002) presented another analysis tool, a spreadsheet model to compare the cost of wood residues to other fuels.

Forsberg (2000) looked at bioenergy transport chains from Sweden to Holland, from a life cycle inventory perspective. The study concluded that biomass for energy could be transported without losing its environmental benefits.

Five Swedish articles from the 1990s (Alriksson 1997; Davner 1996a, b, 1999a, b) described the consumption of woody biomass by the energy sector in Sweden, and some of the constraints around the utilization of this material. Issues surrounding availability of biomass, cost of alternate fuels, employment, and environmental advantages and disadvantages all contribute to the utilization of biofuels.

In British Columbia, McDaniels (1982) and Nagle et al. (1987) presented a case for increased utilization of forest biomass for energy. Primary constraints, as valid today as at the time of the report, relate to institutional factors and low-cost alternative fuels.

McCallum (1997) described small-scale automated biomass energy heating systems that can be used in remote communities. This is a useful report for communities that are considering the use of heating systems independent of outside fuel sources.

Conclusions and implementation

This literature review identified that a substantial volume of applicable research on biomass recovery and processing has accrued over the past 20 years. However, research on biomass transportation is limited in comparison. If biomass is comminuted, transportation systems for pulp chips can be applied effectively, but if biomass is not compressed in some way, highway hauling combinations are inefficient. Nordic researchers have studied and refined biomass compression techniques, such as baling, as a means of achieving legal payloads on highways. Canada should study and adapt this technique because haul distances here are greater and the impacts of inefficiencies are much more significant.

In the past, Canada has had less incentive to promote bioenergy sources as our fossil fuel and hydro-electric energy supplies have been relatively cheap and abundant. Canada's recent commitment to the Kyoto Accord could change our philosophy to promoting energy sources with reduced CO_2 emissions, which include biofuels.

The implementation of new combustion technology could change the way we process biomass in the future. Common processing techniques today produce a fuel type (e.g., chips, hog fuel, or chunks) that can be used in boiler systems that were designed for fossil fuels. Evolving combustion systems will be designed for biomass fuels as the primary input. This could change how forest residues are recovered, transported, processed, and stored in the future.

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Acknowledgements

The authors express appreciation to Rubin Vineburg, Librarian at FERIC's Head Office in Pointe-Claire, for his assistance in the literature searches for relevant documents; Ernst Stjernberg, Group Supervisor, FERIC's Western Division, for his assistance in translating Swedish documents; and Peter Hall and Dave Winston of Canadian Forest Service, Ottawa for their support of the project. Funding was provided by Natural Resources Canada's POL 4.2.5 program.