TRANSPIRATIONAL DRYING AND COSTS FOR TRANSPORTING WOODY BIOMASS A PRELIMINARY REVIEW

Bryce J. Stokes, Project Leader
Timothy P. McDonald, Research Engineer
Tyrone Kelley, Support Engineer

USDA Forest Service
Southern Forest Experiment Station
Auburn, AL 36849

ABSTRACT

High transport costs arc a factor to consider in the use of forest residues for fuel. Costs can be reduced by increasing haul capacities, reducing high moisture contents, and improving trucking efficiency. The literature for transpirational drying and the economics of hauling woody biomass is summarised here. Some additional, unpublished roundwood and chipdrying test results are also included.

INTRODUCTION

Transportation costs are a significant cost in utilising logging residues and unmerchantable timber for energywood. Major reasons for the high costs are the high moisture content, the low bulk density, and non uniformity of biomass material used for energy.

A study, partially supported by IEA/BA Task IX, Activity 6, was undertaken to: (1) review and summarise the literature concerning biomass transpirational drying, drying and handling of biomass, increasing bulk density, and methods .of transportation; (2) summarise current methods of biomass transportation with emphasis on highway trucking alternatives; and (3) develop more information on drying and increasing bulk densities for alternative wood products. A summary of the work-to-date, which has been primarily a literature review of biomass hauling costs and economics, transpirational drying, and chip handling is given in this paper. Some additional field testing of dryii roundwood and chips has been completed and is also included. A more complete assessment of hauling alternatives and increasing bulk density will be published at a later date.

LITERATURE REVIEW

Costs/Economics

In a high-volume/low-unit-value operation such as energywood production, optimisation of the transport system, as well as harvesting, is crucial for its economic success (Bradley, 1989). Decisions must be made concerning the product form to transport, the mode of transport, and how the transport system will interact with harvesting operations. These factors are further complicated by customer requirements, such as seasonal fluctuations in demand, fuel storage capacity, or restrictions on moisture content of boiler feedstock.

Several studies have examined or developed hauling-cost estimates as part of harvesting costs (Ames, 1980; Bradley and Biltonen, 1972; Watson et *al*, 1991). Transportation of products generally contributes a significant portion of overall harvest cost variability (Curtin *et* al, 1980), mainly because of large fluctuations in haul distance, which has the largest effect on transport costs (Adler, 1985). In most cases, nothing can be done about this since haul distance normally cannot be controlled and the cost of transport per ton-mile is generally assumed to be uniform over any distance (Puttock, 1987). Adler (1985), however, found that costs per mile decrease with increasing distance up to about 100 miles, after which they level off. The decrease was about 40 percent for an increase in distance of 20 to 100 miles. The decrease may reflect a more efficient utilisation of trucking capacity in relation to the overall harvest system. Beyond a certain distance, transport becomes limiting and its costs become directly proportional to haul lengths.

The form in which fuelwood is transported can significantly influence transport costs. Several methods of increasing bulk density, which presumably increases per trip capacity, have been investigated. Larsson and Carlsson (1982) showed compaction of logging residues in trailers using a heavy loader could reduce hauling costs by 30 to 35 %. The decrease in cost was related to the moisture content of the residues - less savings for wetter wood. Fractioning of wood (chipping) was found to reduce costs an additional 25%. The authors concluded that fractioning should occur in as central a location as possible.

From a survey of loggers in the North-eastern United States, Adler (1985) reported that there were no cost differences in hauling chips or roundwood. Average load sizes, however, were at or near legal limits, indicating that for the cases studied, average log sizes were such that a full load was made before exceeding height limits. This might not pertain to residues or logs from thinnings.

Increasing bulk density of roundwood loads from thinnings was also studied by Larsson and Carlsson (1982). They examined two experimental trailers with specialised load-compression fixtures. In most cases, the load compression increased the total load solid biomass over the uncompacted trailers by 50 to 100% for softwoods and somewhat less for hardwoods. Best results for compaction were achieved for lower moisture contents (30%). Costs, however, tended to be higher for the compacted loads, probably due to higher equipment costs, slightly lower productivity, and smaller load capacity of the specialised trailers.

Mode of transport is generally not an issue in the United States, but some studies have looked at alternatives to trucks. Adler (1985) reported that rates for rail transport of fuelwood were about 35% lower than trucks for haul lengths averaging 80 miles. Rail haul rates tend to decrease fairly uniformly with increasing haul distance (Hyde and Corder, 1971). Perhaps economic haul-distance limits could be extended using satellite fuelwood centres located on rail lines, much like chipping facilities are used for pulp furnish.

Drying

There are several problems associated with high moisture content in woody material used for fuel including: (1) reduced fuel value; (2) degradation; (3) freezing; (4) poor handling/transportation economics; and (5) pricing and trade values. If wood chips are to become a substantial source of energy for residential, institutional, and commercial users, these problems have to be resolved (Smith and Riley, 1985). The benefits of drying woody biomass fuels are evident, but the economics require careful assessment and continued development of alternative methods. The extent and techniques of drying are myriad; they range from simple, transpirational drying to elaborate, high-temperature precombustion drying. While natural drying occurs, it can be enhanced at one or several points along the supply chain. Some of the wood-drying options are reviewed in this paper, but primary concentration is placed on the use of transpirational drying of whole trees and airdrying of chips. High and low-temperature drying and storage are briefly reviewed.

Transpirational drying: A primary method of drying wood is to allow transpiration of felled trees to occur. Transpirational drying, also known as "sour felling," "leaf seasoning," "leaf felling," "biological drying," and "delayed bucking", takes place when felled trees are left for several weeks with the crowns intact (McMinn and Taras, 1982). This method of drying has been studied in oak and birch by Patterson and Post (1980), in pine and hardwoods by Rogers (1981), in a species mixture by Lawrence (1981), in pine in New Zealand by Wells and Booker (1981), in eucalyptus and pine by McMinn and Taras (1982) and McMinn and Stubbs (1985), in softwoods and hardwoods by Garrett (1985), in Piedmont hardwoods by McMinn (1986a), in pine and hardwoods by Stokes *et al* (1987), and in pine and hardwoods by Sirois *et al* (1991). McMinn (1986b) reviewed and summarised several studies in the Southern United States.

Patterson and Post (1980) conducted a study in which paper birch (*Betula papyrifera* Marsh) and red oak (*Quercus rubra* L.) trees were felled, then left to dry with their tops intact for 3 weeks. The moisture content of these frees, which measured 20 to 30 cm dbh, was compared to the moisture content of other similar trees that were immediately bucked and stacked as bolts for drying. The results revealed no significant change in red oak moisture content, but a significant loss from the birch was reported. The authors noted an increasing gradient of moisture content from bole to crown. They concluded that transpirational drying may reduce the moisture content of some species, mainly those that contain less high-moisture heartwood.

Maximum fuel energies need to be recovered during utilisation of logging residues to make the recovery process economical. This can be done by allowing these residues to dry in the field before recovery (Rogers, 198 1). The author evaluated drying of loblolly pine (*Pinus taeda* L.), white oak (*Q. alba* L.), and sweetgum (*Liquidambar styraciflua* L.). The whole trees were left to dry for 3 months in eastern Texas during winter. Climate conditions were monitored, and wood samples were taken weekly or bi-weekly at the tree butt and at diameters of 30, 20, and 10 cm. Moisture content of the heartwood decreased about 50, 12, and 7%t for the pine, sweetgum, and oak respectively. The net fuel value increased about 72, 24, and 14% for the sapwood and 33, 9, and 4% for the heartwood, respectively, for the pine, sweetgum, and oak. There appeared to be an effect from rainfall on wood-drying rates. The authors recommended allowing residues to lie in the woods during the winter for 10 to 12 weeks to reduce moisture content. Possible drawbacks were pointed out, such as fibre loss from skidding brittle trees and increased chipper-knife wear.

Lawrence (1981) reported a detailed summary of the various practices of air-drying logging residues in the field after harvest for existing species mixtures in Virginia. He cited studies done in which species were felled, delimbed or left whole, and allowed to dry for up to 4 months. In all cases, the highest drying rate occurred immediately after felling. Minimum average moisture contents, after drying, were approximately 40 % (dry weight basis). The diffuse-porous species dried faster than the ring-porous species. The season of felling, species, and diameter were the variables that most influenced drying rates.

A 47day study was completed in New Zealand on 7 year old and 17 year old *P. radiata* D. Don (Wells and Booker, 1981). Some trees from both sets were left to dry with their branches and needles intact; others were delimbed. The Relative Moisture Content - the percentage of water-filled space in wood that is independent of age, tree position and season - was used as the drying indicator. It was concluded that the younger, 7 year old trees left to dry with their limbs intact, dried more quickly, and therefore, more economically than the older trees. It was also found that the older trees showed no real moisture change when they were left to dry with their limbs intact.

McMinn and Taras (1982) evaluated eucalyptus (*Eucalyptus grandis)* and slash pine (*P. elliottii* Engehn) for transpirational drying in Florida. These species were expected to have a near maximum drying potential because of high initial moisture content, evergreen foliage, and south Florida's weather conditions. The eucalyptus was 7 years old and averaged 15 cm dbh; the pine was 13 to 23 cm dbh and from a 19 year old plantation. The eucalyptus was felled in November and dried for 1 month, the pine was felled in both winter and summer and allowed to dry 'for 2 weeks in each season. The moisture content was reduced by 50 percentage points for the eucalyptus, 1 to 18 percentage points for the pine in winter, and 14 to 41 percentage points for the pine in summer. The season of felling significantly influenced the drying rate of the pines. At least 4 weeks of drying may be needed for optimal drying as indicated by the data.

Another study was completed in south Florida for transpirational drying of 7 year old, 15 cm dbh ***E.*** *grandis* (McMinn and Stubbs, 1985). Initial average moisture contents ranged from 131% (oven dry-basis) for the first 2.5 m bolt to 122% for the fourth bolt of the tree After a 4 week drying period, these moisture contents were reduced to 114 and 94% in stacked bolts and 78 and 63% in trees left with stems and crowns intact after felling. The moisture reductions resulted in recoverable heat energy gains of about 6 **to** 9 % for the stacked bolts and 14% for the intact trees. These reductions represent gains in energy yield per unit weight of fuel of 15 to 24 % for the stacked bolts and about 50% for the intact trees.

Garrett (1985) evaluated the drying of felled hardwood and softwood trees in three diameter classes from 15 to 51 cm dbh in New England. From July to September, 120 trees were systematically felled in 4 replications, and their moisture contents were monitored over a 14 day period. It was found that the average moisture loss was 4%. The loss varied with each species and occurred within 36 hours of felling. Subsequent losses over the 14 day drying period were less significant.

Garrett (1985) also monitored soil and climatic conditions during the drying period. There was no significant association between weather and moisture content of the felled trees. It was suggested that wood removal be delayed for 7 to 10 days after felling for significant moisture reduction, for lowering of transport and handling costs for the dried wood.

A study of three Piedmont Plateau hardwood species - red oaks (*Quercus* spp.), sweetgum, and yellow-poplar (*Liriodendron tulipifera* L.) - was completed by McMinn (1986a). The 13 to 30 cm trees, once felled, were left to dry at the stump for up to 8 weeks with the bole and crown intact. Sets of trees were then destructively sampled at weekly intervals to estimate moisture loss. The mean moisture content for the whole-tree samples was reduced from 74 to 60% in red oaks, 109 to 67% in sweetgum, and 104 to 64% in yellow-poplar. Most drying was achieved within 1 week. McMinn concluded that de greatest gains in transpirational drying tie in species with the least desirable characteristics. Diffuse-porous species, such as the sweetgum and poplar, have several outer rings with active vascular tissue. This 'characteristic results in high initial moisture content' and facilitates moisture loss. Ring-porous species, such as red oaks, have active vascular tissue in only the outer rings, resulting in low initial moisture content and low moisture loss after felling.

Stokes *et* al (1987) evaluated transpirational drying for different species of both hardwood and softwood trees being used for energy. They segregated the whole trees into 5 cm classes ranging from 2.5 to 43.0 cm. There were seasonal variations, and the climatic conditions of temperature and rainfall were monitored. Drying time lasted up to 8 weeks. Reduction in tree weight was modelled. Days since felling (drying period), temperature, and rainfall were significant in models and dependent on species and season. Weight loss in pine stems began to stabilise after about 50 days. Hardwood drying was influenced by rainfall, season, and tree size; the hardwood species dried in about 40 days during the summer.

Previous studies have linked the processing of small-diameter whole trees to the reduction of transportation costs and the valuable and more efficient recovery of energy fuels. This is due to lowered stem-moisture content. Sirois *et al* (1991) reported the results of tests done in both winter and summer months using a roller crusher/splitter test bench machine to crush small stems. The crushed stems and an uncrushed control group were then allowed to field dry.

The species evaluated were loblolly pine, sweetgum, and oak (*Quercus* spp.) for diameters of 2.5 to 12.7 cm dbh.

All the stems were weighed over a 21 day period. Crushing whole trees has conditional drying benefits and can be detrimental under heavy rainfall conditions. Rainfall is readily absorbed and lost by exposed wood fibers. As drying time increased, moisture fluctuations from rainfall diminished.

Transpirational drying, in general, can be used to reduce moisture content Transpirational drying is most economical when trees are felled and allowed to dry at the stump whole. Most drying takes place in the first 2 weeks. The procedure is dependent on species and climate.

Air and chip drying: Koch (1985) gave a detailed analysis of various drying practices, mostly for lumber, but for some fuel products also. He covered all types of drying methods including m-woods, transpirational drying, accelerated-air drying, humidifying, low-temperature drying, and kiln drying.

Low-temperature, long-term drying of chips in deep beds is attractive from energywood production and economic viewpoints, but logistic problems may need to be solved with rapid, high-temperature dryiig systems (Smith and Riley, 1985). High-temperature dryers were discussed as an economical, labour-saving alternative to the less efficient deep-bed drying with ambient air. Drucker (1980) reviewed several options for wood-fuel drying. He reviewed the drawbacks and benefits with several options including retrofits and adoptions from other industries.

These authors reported that deep-bed drying with forced ambient air: (1.) is best done in summer, but is feasible year-round; (2)' needs pre-storage chemical treatment to reduce fimgal growth and allow air circulation; (3) has a drymg rate proportional to airflow; (4) has a final moisture content as a function of relative humidity; (5) is relatively worthless at night; (6) can increase icing; and (7) should be Completed in 21 days during the summer. If solar heating is used for deep-bed drying with warm air, then: (1) drying improves during summer and the winter drying season can be extended;. (2) the ice problem is aggravated; and (3) fungal growth increases. When heated air is used in deep-bed drying: (1) chips can be significantly over-dried; (2) ice is not a problem; and (3) fungal growth is faster due to the high temperatures. High-temperature, high-speed dryers for wood chips can be economical if an on-line, labour saving input mode of operation is used. Heated-air drying is much less efficient than ambient-air drying.

Because whole-tree chips deteriorate more rapidly than do clean, debarked chips they present a greater hazard for spontaneous ignition in outdoor piles (Springer,' 1979). Whole-tree chips can only be stored for short periods of time and must be frequently rotated. This results in high handling costs. Springer reported that pre-storage drying and covered storage without rotation were the least expensive methods for maintaining whole-tree chip inventory. In many instances, drying costs can be entirely recovered when whole-tree chips are burned for fuel.

The effect of pile depth on the tune needed to dry whole-tree chips under cover was reported by Koch (1983). He evaluated whole-tree chips from 13 to 18 cm dbh southern red oak and hickory (*Carya* spp.) trees at depths of 10, 20, and 30 cm. The shallow piles dried more quickly than the deep pile chips. Hickory dried more rapidly than the southern red oak because it had a lower initial moisture content. There were no seasonal differences in drying rates. In 30 cm depths, chips dried considerably faster if turned; unroofed chips increased in moisture with time, but turning lessened the amount. At the end of 151 days, the moisture contents of turned and unturned chips based on dry weight were 29 and 41%, respectively.

A study by Nurmi (1987) was done by the Finnish Forest Research Institute on small-scale drying of whole-tree fuel chips and chunks. The effects of particle size, season, bin type, and tree species under protected and improved conditions were evaluated. The drying rates of chunks were faster than the chips. Summer drying was best. Drying was enhanced by using chips made from transpirational-dried trees. The chunks had a higher net gain in heat values than the chips, but energy values per unit volume were about the same because of the higher density of the chips.

Reisinger and Kluender (1982) reported on the need for increased research because industrial, wood-fired energy systems require extensive planning in the areas of long-term availability of fuel supplies, efficient combustion techniques, and m-plant handling and storage of fuel material. They discussed the importance of research in the storing and handling of large quantities of whole-tree fuel chips. They concluded that whole-tree chips, when left outside and uncovered, begin to lose heat value as soon as harvested and continue for approximately 120 days until further losses are negligible. At that time, approximately 25% of the potential heat value has been lost.

The effects of exposed bulk piling on the fuel potential of green hardwood residues stored at various sites were tested by White and Green (1978). Although outside bulk piling is the most common method for maintaining large inventories of green, woody material, it was expected that storage procedures would affect fuel character. White, *et al* (1983a; 1983b; 1986) built a 6.4 m high, 136 tonne pile of green, hardwood, whole-tree fuel chips outdoors. The effect of such storage on the rate of fibre loss, the level of noncombustibles in the pile, and the pH of water-soluble matter were evaluated. Samples were taken periodically from the pile and tested for ash content.

The authors reported that woody fuels accumulate moisture when stored in large, outside piles, thereby lowering the heat values. Also, at ambient temperatures above 20°C, wood-substance loss occurred at a uniform rate of 1.5% per month. The adverse effects of wood loss and ash content can be virtually eliminated when the chips are frozen during winter months.

Various wood-particle forms can be achieved through different methods of comminution. One such particle form is chunkwood. Sturos *et al* (1983) reported on two drying experiments that were conducted to determine whether chunks dry more readily than chips. In one experiment, the authors used natural convective ambient air and found that chunks dried faster than chips. When forced ambient air was used, the chips dried faster than the chunks, but the chunks required less fan energy.

TRANSPIRATIONAL DRYING SCHEDULES

Schedules for transpirational drying are important to determine when to recover woody biomass at optimal moisture content without causing unnecessary degradation. Drying curves or weight reduction models have been developed for various species, seasons, regions, degrees of protection from weather, products, pile sizes, etc, (see References). To establish some general trends, three studies from the Southern United States are summarised in this section. They include dry curves for whole trees, chips, and bolewood.

Stokes et *al* (1987) reported a study of a fuelwood harvesting firm that used transpirational drying operations. Under-story and small diameter trees were felled in the first pass of a two pass operation. After air-drying, the trees were skidded and chipped.

A study was conducted to determine optimal drying schedules for loblolly pine, soft hardwoods (sweetgum, blackgum [*Nyssa sylvatica* Marsh], and red maple [*Acer rubrum* L.]), and hard hardwoods (dogwood [*Cornus florida* L.], southern red oak [*Q. falcate* Michx.], and water' oak [*Q. nigra* L.]). Stems were felled and segregated by 5 cm diameter classes into bundles and weighed each week for 8 weeks. Daily rainfall and temperatures were recorded for the drying period. Samples were taken to determine dry weight for each tree from a laboratory analysis.

The analysis used reduction in weight on a percentage scale as the drying rate indicator. Prediction equations were developed for the three species groups using drying days, temperature, season, and rainfall in the models. Figure 1 shows the drying rate for southern pine for two seasons, winter and summer. Note that the pine stems were only beginning to stabilise in weight loss after 50 days of drying. The drying days and seasons were significant prediction variables.

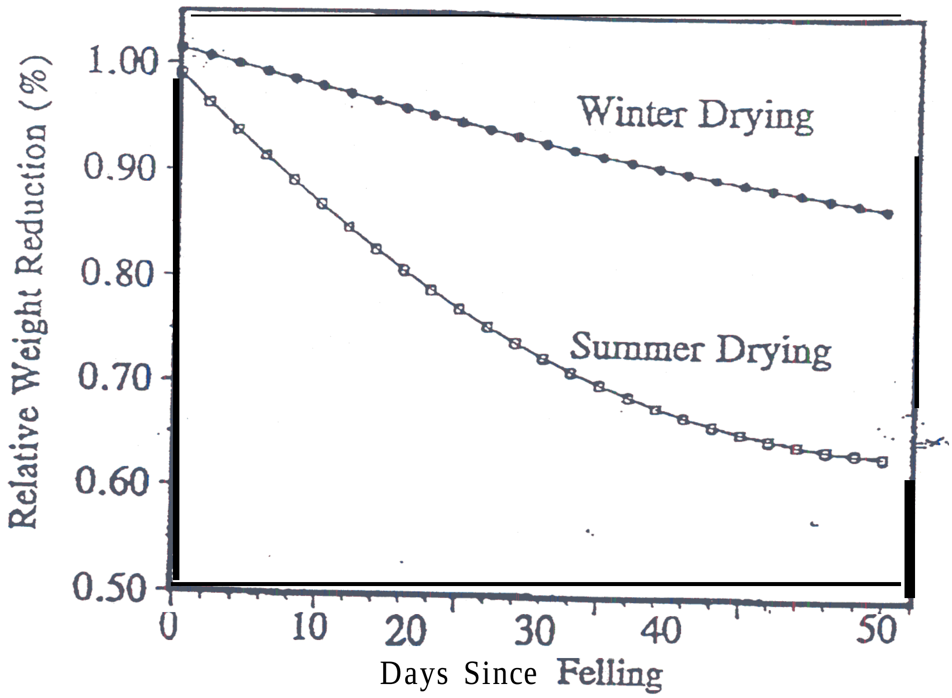


Figure 1. Drying Rate for Southern Pine.

Figures 2 and 3 are weight-reduction curves for hardwood species in the Southern United States. In the case of the soft hardwoods, total rainfall is significant in predicting weight loss. Tree size (on a weight basis) was significant in the hard hardwood species. The weight reduction begins to stabilise after 30 to 40 drying days. During the summer, with little rain, hardwood species can be dried in about 40 days to 45 to 60% moisture content (dry weight basis).

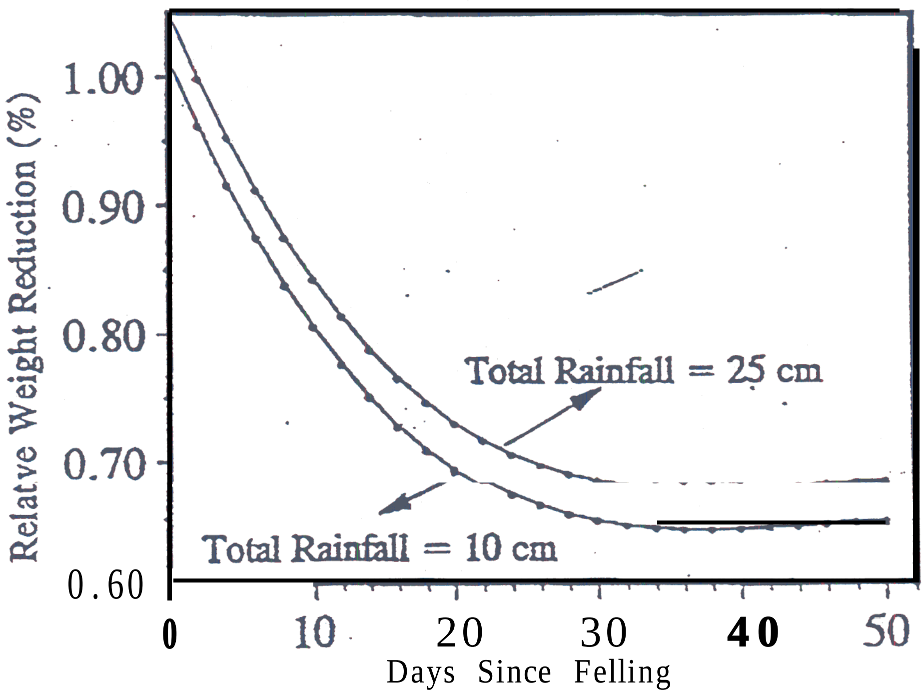
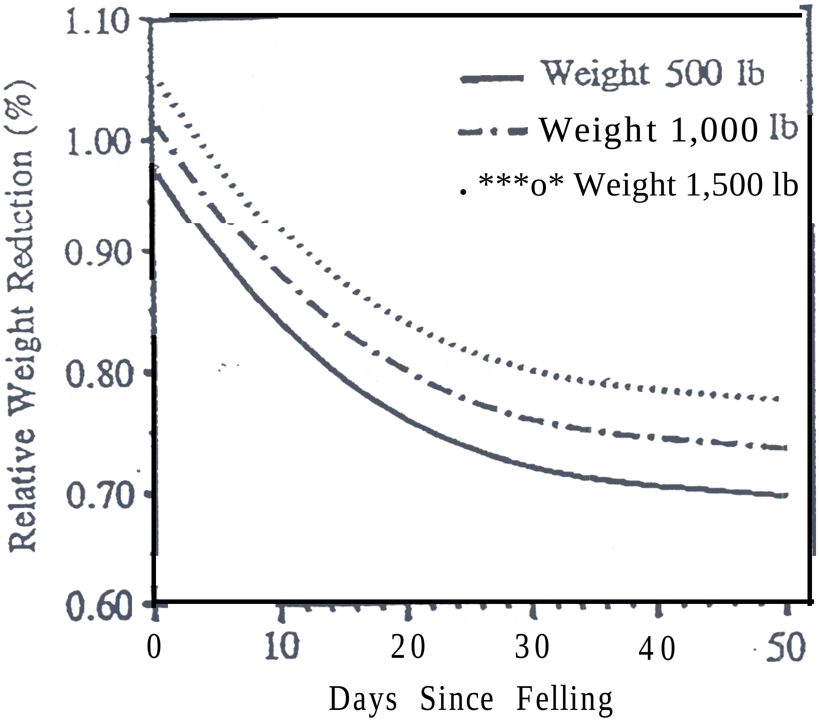


Figure 2. Weight Reduction Curve for Hardwood Species.



Fiie 3. Weight Reduction/Weight for Hardwood Species.

. Past studies have suggested that processing small trees, using methods such as crushing, can reduce transport costs and increase energy value **by reducing moisture** content when combined with transpirational drying. Sirois et *al* (1991) evaluated drying rates for crushed and uncrushed trees. Figures 4 and 5 summarise the treatments as a function of drying time and amount of rainfall for winter and summer drying. Most benefits of crushing were realised in the first 5 weeks of, drying (especially in the summer). However, crushed trees were very susceptible. to **moisture** recovery from rah3fal.l. Under field conditions, there is no guaranteed. benefit associated with crushing trees to increase the rate of moisture loss over long drying periods or in times of heavy rainfall.

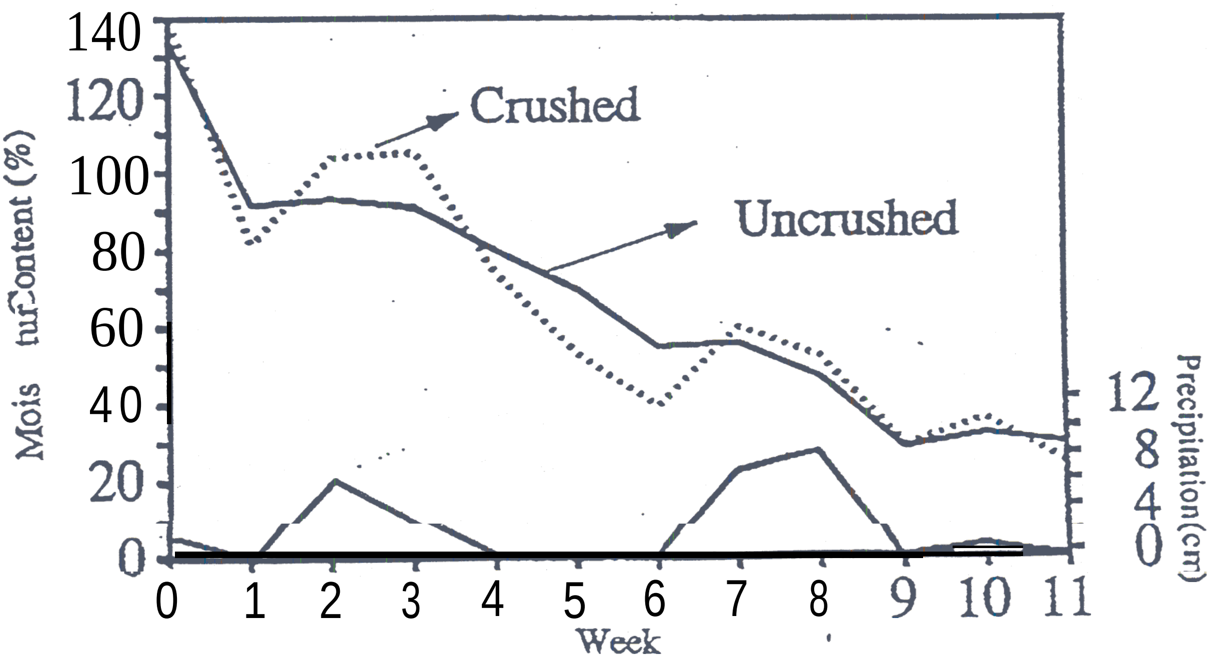


Figure 4. Moisture Content Change with Tie - Winter Drying.

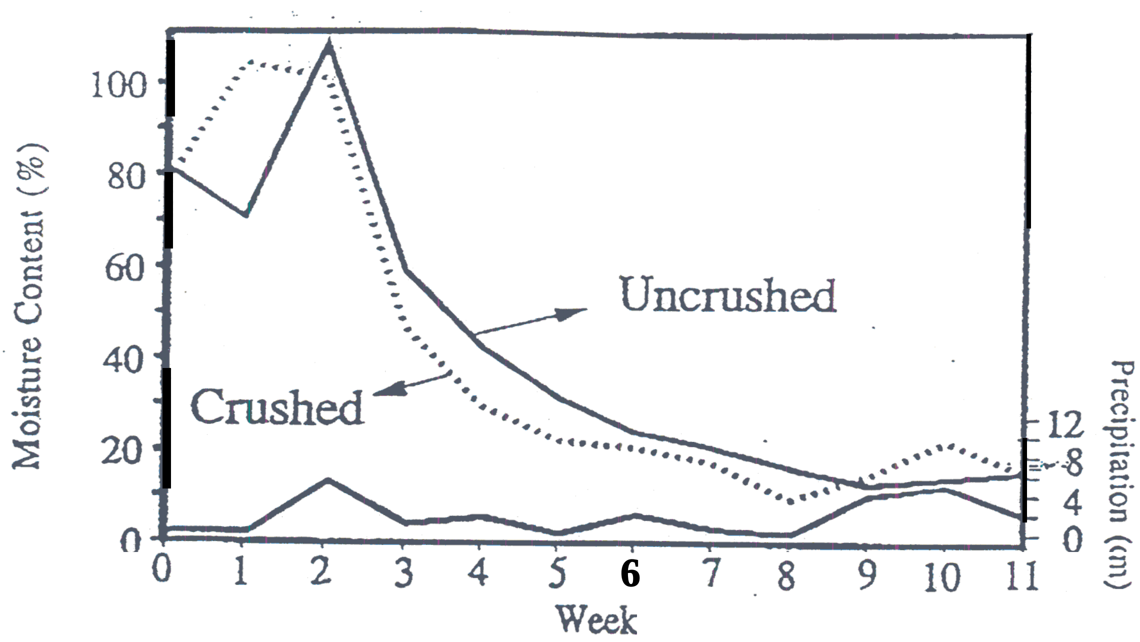


Figure 5. Moisture Content Change with Time - Summer Drying.

A field study has been evaluating drying rates for bolewood and chips for short rotation intensive culture sycamore (*Platanis occidentalis* L.) plantations. The sycamore trees used in the test averaged about 7 cm dbh. The stems were either delimbed and left as tree-length material, or whole-tree chips (with no foliage because they were harvested during the dormant season). The chips were placed on a woven geotextile to facilitate weighing of the approximate 70 to 230 kg piles. The drying tests were initiated in March 1993.

Figure 6 shows the moisture content for the tree-length sycamore. At the end of 100 days, the stems were still drying, but the moisture content was less than 40% (dry basis) for all diameter classes. The tree-length material was not too sensitive to tree diameter.

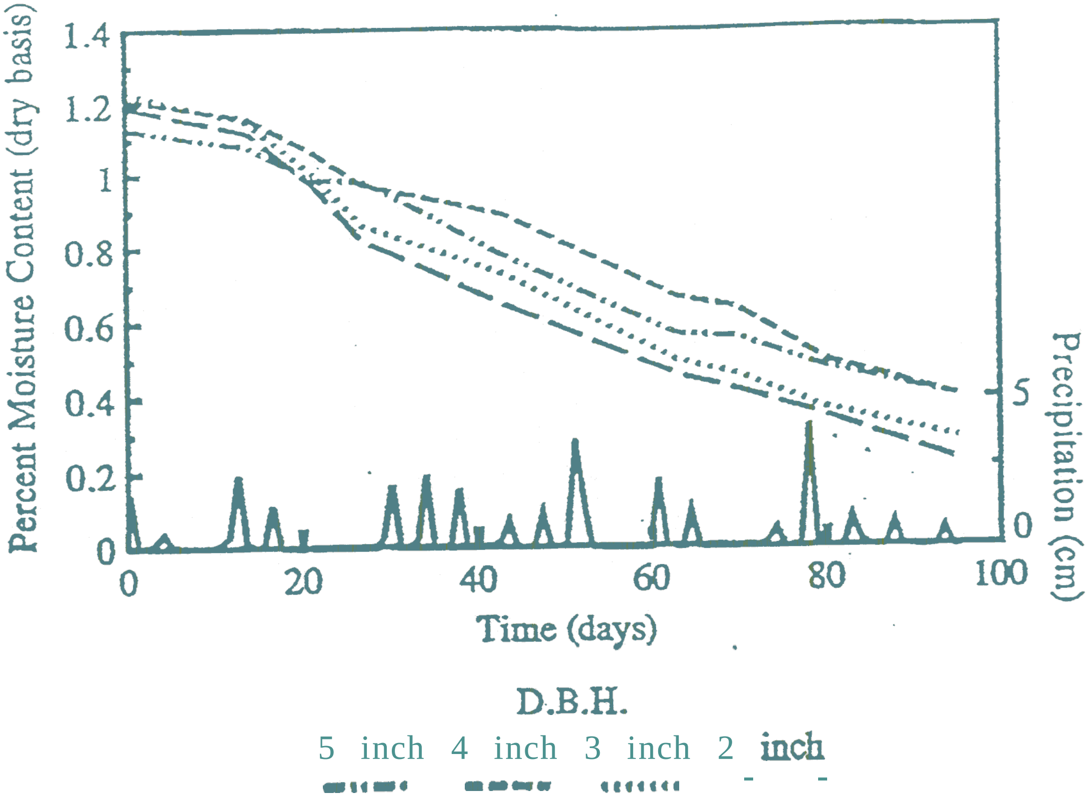


Figure 6. Moisture Content Change with Tie - Tree Length Sycamore.

However, chips are very sensitive to rainfall as shown in Figure 7. In addition to the sycamore chips discussed, drying tests were also completed on some mill-run mixed-hardwood and pine chips for comparison. In all cases, the chips dried to about 40 to 45 % moisture (dry basis), and were very sensitive to rainfall.

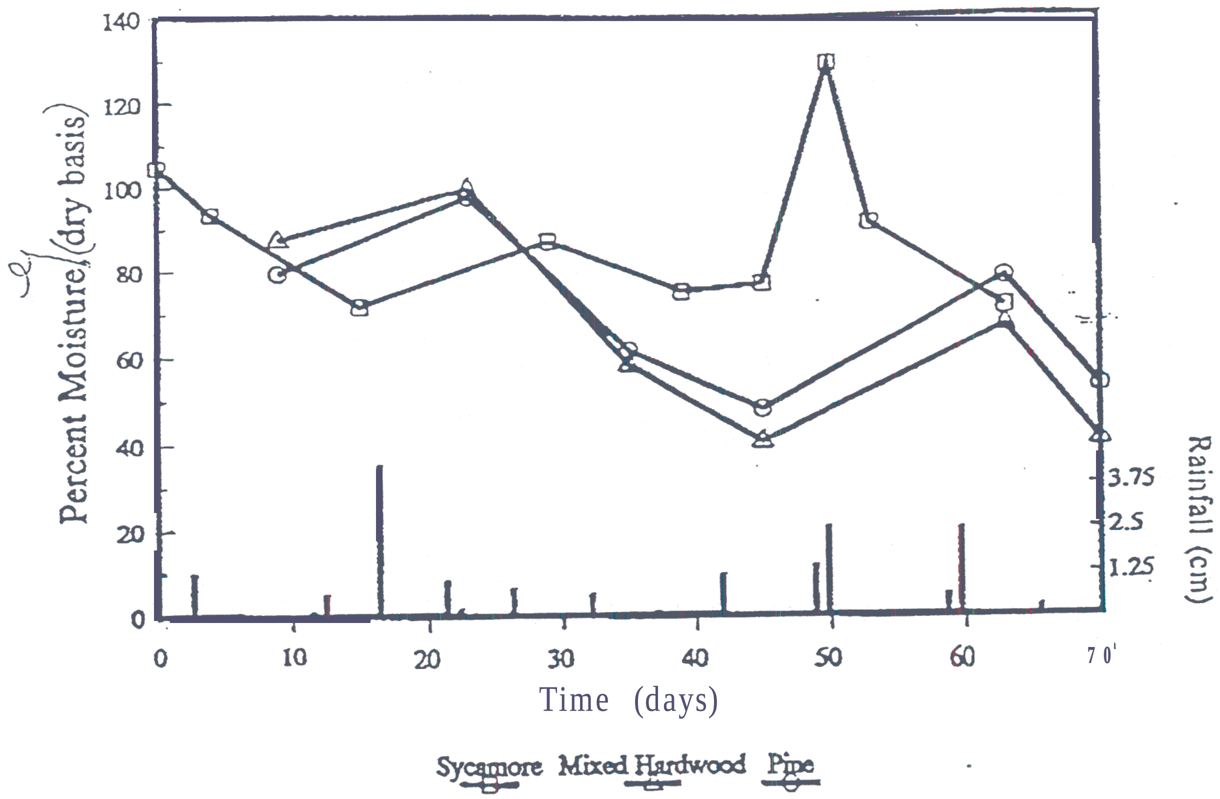


Figure 7. Moisture Content Change with Time - Sycamore, Mixed Hardwood and Pine Chips.

SUMMARY

Generally, there is little specific information available from the literature concerning alternative methods and the costs associated with biomass transportation. Most of the information concerns conventional hauling, mostly trucking, and is mostly limited to transporting whole-tree chips. As expected, biomass transportation costs, ie costs of hauling units of heat value, are a function of haul distance, material-moisture content, and vehicle capacity and utiliiation.

Transpirational drying has been proven as a satisfactory method of reducing high moisture contents for certain species and specific applications. Climatic conditions, especially rainfall, affect transpirational drying for some species. Drying techniques such as crushing, covering, etc and drying season also affect drying. Chip drying is more difficult, requiring special handling procedures; otherwise, moisture increases when the chips are subjected to heavy rainfall. Auxiliary heat drying processes may be needed for chip and other comminuted biomass material for sufficient drying.

ACKNOWLEDGEMENTS

The authors express their appreciation to the offices of International Energy Agency/Biomass Agreement, Task IX, Activity 6, “Transport and Handling,” for their financial contribution to this study.

REFERENCES

Adler, T. J., 1985. An analysis of wood transport systems: costs and external impacts. In co-operation with: North-eastern For. Exp. Sta., US. Department of Agriculture, Forest Service, Burlington, VT. Hanover, NH: Thayer School of Engineering, Dartmouth College: 39 p.

Ames, G., 1980. Wood fuel costs. In: Wood Energy Economics; 1980 April 30; Georgia Office of Energy Resources. Atlanta, GA: 44-66.

Bradley, D. P., 1989. When you say harvest and transport cost, you've said it all (or nearly all)! In: Ek, A. R.; Hoganson, H. M., eds. Minnesota's timber supply: perspectives and analysis: proceedings of the conference; 1988 September 21-22; [Grand Rapids, MN]. St. Paul, MN: University of Minnesota, College of Natural Resources and Agricultural Experiment Station: 145-152.

Bradley, D. P., Biltonen, F. E., 1972. Economic operability factors affecting harvest and transport costs. Gen. Tech. Rep. NC-l. Duluth, MN: US Department of Agriculture, Forest Service, North Central Forest Experiment Station. 4 p.

Curtin, D. T., Brooks, R. T., Forrester, W. R., Paul, J. G., 1980. Biomass harvesting system test and demonstration. Tech. Note B-40. Norris, T. N.: Tennessee Valley Authority. 43 p.

Drucker, Steve, 1980. Wood fuel drying. Case studies in wood energy. Atlanta, GA: Georgia Institute of Technology, Engineering Experiment Station: 54-58.

Garret, L. D., 1985. Delayed processing of felled trees to reduce moisture content. Forest Products Journal. 35(3): 55-59.

Hyde, P. E., Corder, S. E., 1971. Transportation costs in Oregon for wood and bark residues. Forest Products Journal. 21(10): 17-25.

Koch, P., 1983. Moisture changes in oak and hickory fuel chips on roofed and unroofed Louisiana air-drying grounds as affected by pile depth and turning of chips. Forest Products Journal. 3(6): 59-61.

Koch, P., 1985. Utilisation of hardwoods growing on southern pine sites. Agric. Handb. 605. Washington, DC: US Department of Agriculture: 231 l-2463. Vol. 2.

Larsson, M., Carlsson, T., 1982. Trucking of logging residues and tree sections. In: Proceedings of the 6th international FPRS industrial wood energy forum '82, Vol. 1; 1982 March 8-10; [Washington, DC]. Madison, WI: Forest Products Research Society: 137-148.

Lawrence, W. E., 1981. Field drying logging residues as an industrial fuel. Blacksburg, VA: Virginia Polytechnic Institute and State University. 109 p. M.S. thesis.

McMinn, J, W., 1986a. Transpirational drying of red oaks, sweetgum, and yellow poplar in the upper Piedmont of Georgia. Forest Products Journal. 36(3): 25-35.

McMinn, J. W., 1986b. In-woods drying potential for woody biomass fuels in the Southeastern United States. In: Proceedings, program and abstracts of the 4th Southern biomass energy research conference; 1986 October 7-9; [Athens, GA]. Athens, GA: University of Georgia and TVA/SE Regional Biomass Energy Program: 32-33 .

McMinn, J. W., Stubbs, J., 1985. In-woods drying of eucalyptus in south Florida. Forest Products Journal. 35(1 1/12): 65-67.

McMinn, J. W., Taras M. A., 1982. Transpirational drying. In: Proceedings of the 6th annual FPRS industrial wood energy forum, Volume 1; 1982 March 8-l 1; [Washington, DC]. Madison, WI: Forest Products Research Society: 206-207.

Nurmi, J., 1987. Drying of fuel chips and chunks in wooden bins. Folia Forestalia. 687: 32-33.

Patterson, W. A., Post, I. L., 1980. Delayed bucking and bolewood moisture content. Journal of Forestry. 78(7): 407-408.

Puttock, G. D., 1987. The economics of collecting and processing whole-tree chips and logging residues for energy. Forest Products Journal. 37(6): 15-20.

Reisinger, T. W., Kluender, R. A.; 1982. Storage and handling of whole tree chips and residues for fuel. APA Paper No. 83-A-2. Washington, DC: American Pulpwood Association, Southwide Energy Committee. 5 p.

Rogers, K. E., 1981. Preharvest drying of logging residues. Forest -Products Journal. 3 1(12): 32-36.

Sirois, D. L., Rawlins, C. L., Stokes, B. J., 1991. Evaluation of moisture reduction in small diameter trees after crushing. Bioresource Technology. 37: 53-60.

Smith, N., Riley, J. G., 1985. Drying systems for woody biomass fuels. [Publisher unknown]: 175-178.

Springer, E. L., 1979. Should whole-tree chips for fuel be dried before storage? Res. Note FPL-0241. Madison, WI: US Department of Agriculture, Forest Service, Forest Products Laboratory. 5 p.

Stokes, B. J., Watson, W. F., Miller, D. E., 1987. Transpirational drying of energywood. ASAE Paper No. 87-1530. St. Joseph, MI: American Society of Agricultural Engineers. 13 p.

Sturos, J. B., Coyer, L. A., Arola, R. A., 1983. Air-drying of chunkwood and chips. Res. Note NC-293. St. Paul, MN: US Department of Agriculture, Forest Service, North Central Research Station. 4 p.

Watson, W. F., Stokes, B. J., Flanders, L. N., 1991. Cost comparison of the woodyard chip pile of clean wood chips and chips produced in the woodyard from roundwood. In: Proceeding of the 1991 Pulping Conference; 1991 November 3-7; [Orlando, FL]. Atlanta, GA; TAPPI. p. 183-187.

Wells, G. C., Booker, R. E., 1981. Drying logs in the forest. New Zealand: Logging Industry Research Association Report. 6(2). 4 p.

White, M. S., Green, D. W., 1978. The effects of fuel potential of green hardwood residues. Blacksburg, VA: Virginia Polytechnic Institute and State University, Department of Forestry and Forest Products. 10 p.

White, M. S., Curtis, M. L., Sarles, R. L., Greene, D. W., 1983a. Effects of outside storage on the energy potential of hardwood particulate fuels: Part I. Moisture content and temperature. Forest Products Journal. 33(6): 31-38.

White, M. S., Curtis, M. L., Sarles, R. L., Greene, D. W., 1983b. Effects of outside storage on the energy potential of hardwood particulate fuels: Part II. Higher and net heating values. Forest Products Journal. 33(11/12): 61-65.

White, M. S., Argent, R. M., Sarles, R. L., 1986. Effects of outside storage on the energy potential of hardwood particulate fuels: Part III. Specific gravity, ash content, and pH of water solubles. Forest Products Journal. 36(4): 69-73.