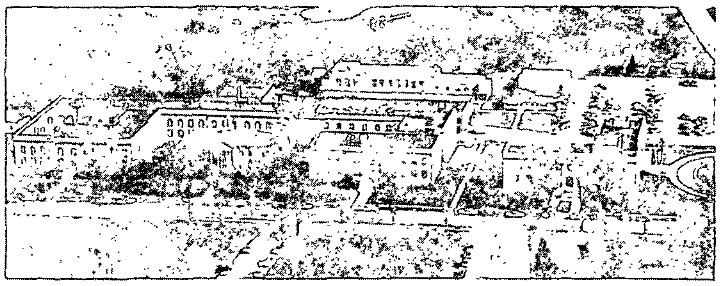

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THE INFLUENCE OF SHORT-ROTATION FORESTRY ON PULP AND PAPER QUALITY.
I. SHORT-ROTATION CONIFERS.
II. SHORT-ROTATION HARDWOODS.

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Dean W. Einspahr

SUMMARY

Short-rotation forestry (SRF) is expected to involve utilization of young rapidly-growing trees and full-tree harvesting. The wood produced is expected to have a higher level of bark, shorter fiber length, and for some species lower specific gravity. Cellulose content, extractive levels, fiber width and cell wall thickness are also expected to differ. The magnitude of the differences and the impact on pulp and paper quality will vary with the species, growth rates and the rotation ages selected. Conifer pulp yields and pulp strength properties are expected to be reduced to a greater degree than for short-rotation hardwoods. With rotation ages of 6 to 20 years and bark removal procedures that remove 50-75% of the bark, both SR conifers and SR hardwoods are expected to produce pulps satisfactory for a variety of uses. Pulp strength values, with the exception of modestly reduced tearing strength, will be comparable to pulps from mature trees. Beating energy requirements and cooking times are expected to be less and pulping chemical requirements are expected to be higher for SR conifers and about equal for SR hardwoods.

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The influence of short-rotation forestry on pulp and paper quality: Part I. Short-rotation conifers

Dean W. Einspahr

Abstract

Future world fiber demands will require increased use of short-rotation forestry (SRF). Harvesting is expected to involve utilization of young rapidly-growing trees and full-tree harvesting. The wood produced is expected to have a higher level of bark, shorter fiber length and, for some species, lower specific gravity. Cellulose content, extractive levels, fiber width and cell wall thickness are also expected to differ. The magnitude of the differences and the impact on pulp and paper quality will vary with the species, growth rates and the rotation ages selected. Conifer pulp yields and pulp strength properties are expected to be reduced to a greater degree than for short-rotation hardwoods. With rotation ages of 6 to 20 years and bark removal procedures that remove 50-75% of the bark, SR conifers are expected to produce pulps satisfactory for a variety of uses. Pulp strength values, with the exception of modestly reduced tearing strength, will be comparable to pulps from mature trees. Beating energy requirements and cooking times are expected to be less and pulping chemical requirements are expected to be higher for SR conifers.

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Projected increases in the world population and in the per capita consumption of wood, paper, and board production, along with recent land use trends, have resulted in considerable concern regarding the ability of industrially developed nations to meet their future fiber requirements (1,2). Production of wood fiber using SRF management techniques is one approach being considered by many industrial and governmental forestry organizations as a way of increasing future fiber supplies.

Short-rotation forestry (SRF) involves not only the harvesting and utilization of young trees (ages twenty years or less) but implies the use of complete tree harvesting, the employment of intensive management techniques, and the use of genetically improved trees to maximize fiber production. Wood produced via SRF is expected to have a higher percentage of bark, shorter fiber length and, in certain instances, lower specific gravity than wood produced by conventional forest management. Levels of extractives and such fiber dimensions as fiber width and cell wall thickness may also be affected. Pulp and paper quality and the economics of pulping and papermaking are also expected to be influenced by increased use of wood produced by SRF. Conifers and hardwoods, because they differ in the way wood quality is influenced by age and rapid growth, are considered separately.

Despite the fact that the use of conifers in SRF is relatively new, there have been a number of papers published that provide appropriate insight into the impact that increased use of such materials will have on pulp and paper quality. Most advocates of SRF indicate that the trees involved will be younger, rapid growing and smaller in size than trees employed under our present conventional pulpwood rotations.

There also is increasing evidence that, because of tree size, "whole tree" chipping in the woods will be required in order to meet the economic harvesting restrictions involved. "Whole tree" chips can be expected to have higher levels of bark than normal and contain large amounts of wood from the unmerchantable top, branches, stump and, in some instances, the roots. Chip uniformity will be less and greater amounts of embedded soil will require greater pulp mill expenditure for chip washing, screening and pulp cleaning (3-5).

JUVENILE WOOD, REACTION WOOD AND RAPID GROWTH

Several interrelated factors are involved in the use of "short-rotation" wood. Briefly, it appears the wood involved will have high levels of juvenile wood, higher-than-normal amounts of reaction wood and the wood will have been formed under conditions of rapid growth. Table I summarizes the interrelationships involved. An additional important item not considered in detail by this review involves the influence of increased levels of bark on pulp quality. Of the factors considered (Table I), high levels of juvenile wood are expected to have the greatest impact on pulp quality. The existence and properties of juvenile wood in conifers have been well documented (6-9) and, although exceptions can be cited, juvenile wood in conifers, when compared to mature wood, has been found to have: (1) lower specific gravity, (2) lower levels of summerwood (latewood) and a greater proportion of thin-walled fiber elements, (3) shorter fiber length, (4) higher levels of compression wood, and (5) higher levels of lignin, extractives, and moisture. When reaction wood in conifers is considered, reaction wood (compression wood) is similar in many ways to juvenile wood although in a number of instances less desirable than juvenile wood for use in papermaking.

[Table I here]

The influence of growth rate in conifers on wood and fiber quality has been investigated by a number of researchers. Generalized statements regarding the influence of growth rate cannot be made because the type of response obtained is influenced by the species involved, the condition of the trees prior to treatment, the reasons for the response (increased light, soil fertility, moisture, temperature, etc.) and the part of the tree being considered (bole, top, branches, etc.).

Klem (10) presents an excellent review on the effect of forest fertilization on growth rate and wood quality of conifers. He concludes that the type of results obtained will depend upon the condition of the trees prior to treatment. For most pine and spruce forests, fertilization and the accompanying increased growth will change the springwood/summerwood ratio and the greater number of springwood tracheids will result in an estimated overall decrease of 5% in specific gravity. This reduction in specific gravity is expected to be more than compensated for by growth increases and the greater proportion of springwood fibers can be expected to result in modest increases in tensile and bursting strength and slight decreases in tear factor. Klem also concludes that, under most normal growth conditions, reported reductions in tracheid length and cell wall thickness due to fertilization would be too small to noticeably influence paper quality.

PULP QUALITY

The pulp and paper industry is expected to be a major user of SRF techniques. The impact of this source of wood can best be demonstrated through pulping studies and this procedure has been employed by a number of investigators. Considering first the southern pines, McKee (11), in one of the earlier studies on kraft pulping of small-diameter southern pines, reported pulp yields and pulp quality comparable to that from conventional pulpwood-sized trees. Kirk, Breeman, and Zobel (12) compared the pulp properties of selected low, medium, and high specific gravity 12-year-old loblolly pine trees with normal mill chips. They found the young trees were high in juvenile wood and had short thin-walled tracheids that produced pulps high in tensile strength, bursting strength, fold endurance, apparent density, and sheet smoothness and lower than normal in tearing strength. Pulp yield was lower for the younger trees except in the case of the trees selected for high specific gravity. Table II compares the magnitude of the differences involved.

[Table II here]

Semke and Corbi (13), in studies investigating sources of less coarse pine fibers, presented data that indicated pulp from young loblolly pine had lower machine direction tensile strength, better formation and similar opacity when compared to sawmill and conventional roundwood chips. Bole topwood chips tended to be intermediate in strength properties. Palmer and Gibbs (14-16), in comprehensive studies on several nine and ten-year-old sources of slash pine growing in Fiji, and in a similar study comparing fast- and slow-growing sources of twelve- to sixteen-year-old Pinus patula and Pinus elliottii, found no major differences associated with growth rate and concluded that the physical strength properties were comparable to commercial southern pine pulps having moderate to good tensile and good but not exceptional tearing strength.

Blair, Zobel and Barker (17), in a study dealing with the pulping properties of young loblolly pine, reported pulping strength values for a ten-year-old progeny group had similar yields, slightly lower tear and higher bursting strength than the values reported for slash pine by Palmer and Gibbs. Fahey and Laundrie (18), in investigating the potential of using southern pine thinnings for paper and paperboard, found kraft pulps from slash and loblolly pine thinnings and corewood were comparable and had burst and tensile strengths equal to the pulps from mature pulpwood logs but tearing resistance and pulp yields were lower. Outerwood pulps were comparable in burst and tensile strengths to mature pulpwood and had greater tearing resistance. Papers and linerboard made from thinnings of loblolly pine were better formed, smoother and stronger, except for tear, than pulps made from mature wood.

Chidester, *et al*. (19) reported pulp yields of jack pine decreased from the stump to the top and sulfide and kraft pulps from the unmerchantable tops compared favorably with pulps from the merchantable bole. Johnstone and Keays (20), in investigating kraft pulps of lodgepole pine, reported the yields and pulp strength differences summarized in Table III. The reduced yield and low strength of branch pulps confirm the results of other researchers and are believed to be due to high levels of compression wood.

[Table III here]

Early pulping studies involving Douglas-fir revealed that, like other conifers, bursting strength increased and tearing strength decreased from the stump to the top of the tree. Similarly, younger trees were found to have lower alpha cellulose, lower tear and higher burst (21). Hatton and Keays (22), in a comprehensive study dealing with yield and kraft pulp quality of the tree components of Douglas-fir, reported lower yields and, in many instances, significant differences in pulp strength properties for the several tree components when compared to the merchantable bole (full bole). Pulp yield and strength properties of branches were found to be substantially lower than that of the merchantable bole. Burst factors and breaking lengths of pulps from unmerchantable tops and full boles are equivalent, but pulps from the roots and stumps are, respectively, 10 and 25% lower. Pulps from the unmerchantable tops, roots and stumps are 30, 25, and 10% lower, respectively, in tear factor than full-bole pulps.

Keays and Hatton (23,24), in studies similar to that described for Douglas-fir above, found yield differences for western hemlock and white spruce to be comparable to that described for Douglas-fir. Pulp strength also differed from the merchantable bole in a manner similar to that of Douglas-fir with branchwood pulp having the lowest strength and pulp from the unmerchantable top being comparable in burst and breaking length and about 15% lower in tear factor. Eskilsson (25), in a similar kraft pulping study, compared pulps of white spruce and Scotch pine made from the bark, branches, roots and bole. Pulps from stumps and roots deviated insignificantly from the pulp from the bole concerning beatability, drainage behavior and optical properties. Pulp strength was slightly lower. Tops and branches gave easy beating pulps and branchwood pulps high elongation to break and rather low strength. Twigs, needles and bark gave pulps that were more or less easily beaten, slow draining, dark and mechanically weak.

Alestalo and Hentola (26) compared kraft pulps from pine and spruce logging waste with pulps from partially barked pine stemwood. The pulp strength of the tops were comparable to good stemwood and branchwood pulps were comparable to low-quality stemwood. Nacu and Constantinescu (27), in comparing the pulping characteristics of coniferous branchwood, found branchwood contained higher levels of lignin, ash, and extractives; screened yield was lower and for most pulp properties, the strength values were inferior to roundwood pulps. Stairs, *et al.* (28), in a study comparing fast- and slow-growing Norway spruce, found that fast-grown trees gave higher pulp yields and slightly higher paper strength properties than was obtained from the slow-grown trees.

CONCLUSIONS

Conifer pulps produced from SR forestry operations are expected to produce pulps that are derived from wood that is lower in specific gravity and has shorter fiber length. Branchwood pulps, although present in minor quantities (± 8%), are inferior in strength properties to the other tree components. Table IV summarizes the pulp quality interrelationships that are involved. Based upon the widely accepted specific gravity/paper property relationships, it appears that SRF conifer pulps will have lower tear factor, higher burst factor, tensile strength and fold endurance and will require less beating than pulps prepared from older, slower-growing trees. Pulp yields are expected to be lower, cooking time less and chemical requirements higher. The magnitude of difference will depend upon the levels of juvenile wood, reaction wood and, to a lesser degree, on growth rate.

[Table IV here]

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Table I. Summary of Interrelated Factors Influencing Wood Quality of Short-Rotation Conifers[a]

Wood or Paper Property	Juvenile wood *vs*. mature wood	Reaction wood *vs*. normal wood	Rapid *vs*. normal growth
Specific gravity	lower	higher	equal or lower
Fiber length	shorter	shorter	equal
Cell wall thickness	thinner	thicker	thinner
Lignin	higher	higher	lower
Cellulose	lower	lower	higher
Extractives	higher	higher	equal

[a]Based upon rotation ages 8-20 years and 50-75% of bark removed.

Table II. Pulp Yield, Wood Properties, and Pulp Properties from Normal Mill Chips and Juvenile Wood of Three Specific Gravity Levels[a]

Property	Normal mill chips	Loblolly pine juvenile wood		
Specific gravity	0.44	0.37	0.42	0.48
Moisture, % of dry wood	119	142	119	112
Pulp yield, % of dry wood	47.5	44.2	45.7	47.1
Kappa number	27.5	26.5	28.3	28.4
Physical tests at 750 ml SR freeness				
Tensile, kg/inch	15.0	16.9	16.8	15.9
Burst factor (Mullen)	60	73	69	70
Tear factor, g	120	88	96	109
Fold endurance (MIT)	1540	2390	2150	1970

[a]Adapted from data by Kirk, Breeman and Zobel (12).

Table III. Yield and Quality of Kraft Pulp from 100-Year-old Lodgepole Pine[a]

Component	Permanganate number	Adjusted unscreened yield, %	Unbleached pulp quality[b]		
			Burst factor	Tear factor	Breaking length, m
Full bole	20.3	47.0	97.2	115	12,648
Root-stump	19.8	46.1	74.3	120	9,952
Branches	20.5	38.6	53.2	103	7,002

[a] From paper by Johnstone and Keays (20).

[b] Unbleached pulp quality at 300 ml Canadian standard freeness.

Table IV. Summary of Interrelated Factors Influencing Paper Quality of Short-rotation Conifers[a]

Wood or paper property	Juvenile wood *vs*. mature wood	Reaction wood *vs*. normal wood	Rapid *vs*. normal growth
Pulp yield	lower	lower	equal or lower
Tear factor	lower	lower	lower
Burst factor	higher	lower	higher
Tensile strength	higher	lower	higher
Fold endurance	higher	lower	higher
Beating energy	lower	higher	lower
Cooking time	shorter	longer	equal
Chemical requirements	higher	higher	equal

[a]Based upon rotation ages 8-20 years and 50-75% of bark removed.

The influence of short-rotation forestry on pulp and paper quality:
Part II. Short-rotation hardwoods

Dean W. Einspahr

Abstract

Short-rotation forestry (SRF) will be needed to meet future fiber requirements. Rapid growth and the coppicing ability of certain hardwoods has resulted in considerable interest in their use in fiber production. Use of SR hardwoods is expected to involve wood produced under conditions of rapid growth, consist primarily of juvenile wood and be higher than normal in levels of reaction wood. Specific gravity and pulp yields are expected to be equal to that of mature wood if rotation ages are not less than eight years. Tearing strength is expected to be lower and, unless tension wood is excessive, burst, tensile and fold endurance will be higher for SR hardwoods. Beating energy requirements and cooking times are expected to be less and chemical requirements about equal. Higher than normal levels of bark, if not reduced to about 5%, can be expected to result in lower pulp yields, increased extractive levels, lower pulp strength and cause a number of mill operating problems. SR hardwoods, if bark levels are not excessive, are expected to produce pulps useful for a variety of purposes that with the exception of tearing strength will be comparable to pulps from mature trees.

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Increasing world wood and fiber requirements have resulted in considerable concern regarding the ability of industrially developed nations to meet their future needs. Production of wood fiber using SRF management techniques is one approach being considered by many industrial and governmental forestry organizations as a way of increasing future fiber supplies. Interest in using hardwoods in short-rotation management has increased greatly in the last five years. Although not as much is known about the pulp and paper quality of young hardwoods, several recent investigations suggest the use of this major source of fiber has considerable promise. The sprouting and/or suckering ability of many hardwoods is one important reason for the increased interest in using them in SRF programs.

Essential to hardwood utilization are the recent "full tree" harvesting innovations which allow the more efficient use of small-sized trees and the unmerchantable crown and branches of larger trees. With "full tree" chipping come higher levels of juvenile wood, reaction wood and the complicating influence of bark.

JUVENILE WOOD, REACTION WOOD AND RAPID GROWTH

As with conifers, the use of SR hardwoods is expected to not only involve the use of wood that is primarily juvenile wood with higher-than-normal levels of reaction wood but, in most instances, will be wood that has been formed under conditions of rapid growth. Table I summarizes the interrelationships involved and is based upon an extensive review of the literature.

[Table I here]

Generally, it appears that the use of young hardwoods and the tops of large mature trees, depending somewhat upon the species, will have similar or slightly lower specific gravity and shorter fibers than wood from mature trees. Contrasting juvenile wood in hardwoods with juvenile wood in conifers, hardwoods suffer less of a reduction in fiber length and very little reduction in specific gravity. Also, reaction wood in hardwoods has higher specific gravity, higher cellulose content and often comparable or nearly comparable pulp strength properties, whereas exactly the opposite is true for conifers (1-3).

The influence of growth rate on the wood quality of hardwoods has been widely investigated and, because of the great diversity of types of hardwoods, considerable variation in results has been reported. Fielding (4), in discussing specific gravity, indicates hardwood specific gravity is much more affected by growth rate than in conifers and, because of the nature of hardwoods, the relationship between growth rate and specific gravity is not a simple one. Slow growth rates, particularly in ring-porous hardwoods, are generally associated with reduced specific gravity. Diffuse-porous hardwoods, on the other hand, have a less consistent specific gravity pattern and normally, except under conditions of extremely rapid growth, are little affected by growth rate. Rapid growth rates in diffuse-porous hardwoods appear to be most often accompanied by slightly reduced specific gravity and longer fiber length.

PULP QUALITY

Considering specific gravity and fiber length and the previously reviewed influence of growth rate on these properties in juvenile wood leads to the conclusion that the wood of SR hardwoods will produce pulps not greatly different from mature wood. The impact of this source of wood on pulp quality can best be demonstrated through pulping studies and this approach has been employed by a number of researchers.

The pulping of Populus species, because of their rapid growth, has received the attention of a number of researchers. Hunt and Keays (5,6), in studies dealing with the pulping of SR quaking aspen (P. tremuloides Michx.) and the pulping of aspen tops and branches, reported that average unscreened kraft pulp yields were 55.3, 59.8, and 57.4% for 6, 16, and 53-year-old bark-free wood. Breaking length and burst factors were similar for pulps from all three age groups at CF 300 and tear factor was lower for the pulps from the six-year-old trees (Table II). Lignin levels were lower and holocellulose levels highest for the 16-year-old trees. These yield results agree with those of Jayme and Reh (7) for Populus monilifera where studies demonstrated the 17-year-old trees gave the highest yield and poplar wood in the age range of 9-17 years had the highest cellulose yield. Hunt and Keays (5) in their work with the tops and branches of quaking aspen found that pulp yields for bark-free samples for the larger branches were 85-95% of that from the boles and the inclusion of the bark decreased the yield an additional 6-10%. Pulp strengths for the bark-free unmerchantable tops and larger branches was modestly lower in breaking length and tear factor and considerably lower in burst. Inclusion of bark was reported to further decrease the pulp strength values.

[Table II here]

The wood and pulp quality of young sycamore (Platanus occidentalis L.) has also been the subject of a number of investigations. Laundrie and Fahey (12), in a kraft pulping study, and Steinbeck, et al. (13), in a neutral sulfite semichemical (NSSC) pulping study, reported results indicating that four-year-old coppice materials produce pulps comparable, with the exception of tear, to pulps in commercial use. Tear factor for the kraft pulps was about 20% lower while for the NSSC pulp tear was 46% lower (77 vs. 144). The four-year-old sycamore NSSC pulp, which had a yield of 76%, was evaluated for use in corrugating medium and compared favorably in Mullen (burst), breaking length, ring crush, and concora but, as indicated, was lower in tear. The kraft pulp from short-rotation sycamore, when compared to 33-year-old trees, was about equal in bursting and tensile strength, 10% lower in apparent handsheet density and 20% lower in tear factor.

Steinbeck and Gleaton (14,15) also examined the use of young sycamore for producing fine kraft papers and NSSC papers. They reported yields of 44-57% for kraft pulping and 68-75% for NSSC. They concluded the pulp was suitable for use in a variety of products. Tear, however, for the NSSC pulp was lower than desirable and runnability was lower than for commercial corrugating medium, suggesting the need to mix the SR fibers with high-tear fibers from conventional sources.

Barker (16) and Jett and Zobel (17) also have investigated the pulping properties of young sycamore and compared the results with mature wood and juvenile wood from several additional hardwood species. Barker, in comparisons involving 9 to 13-year-old sycamore, sweetgum, willow oak, and green ash, concluded the pulp yields for young hardwoods were at least comparable to those of mature woods (Table III) and the chemical demand was not greatly increased. Young gum and young oak were comparable to mature gum and mature oak (Table IV) in pulp yield and pulp strength properties, making the use of such material in SRF highly attractive. Jett and Zobel (17), in comparisons between juvenile sycamore (2-6 years) and mature sycamore, demonstrated that pulp yield was less

(40.8 vs. 44.5%), tear factor less (100 vs. 122), and breaking length and burst were comparable to pulp derived from mature sycamore.

[Tables III and IV here]

Knowledge of the chemical and pulping characteristics of tension wood helps to clarify the reasons hardwoods are less adversely affected by reductions in age than conifers. Reviews by Hughes (2) and Timell (3) point out that tension wood has lower lignin, higher cellulose, and produces higher pulp yields than normal wood. Tension wood fibers have thicker walls because of their characteristic gelatinous cell wall layer. Chemical pulps containing tension wood fibers are often inferior in strength properties, particularly where fiber bonding is involved because the thicker-walled fibers result in greater resistance to beating, less fiber collapse, and poor fiber-to-fiber bonding. Cleremont and Bender (1) reported longer beating time to reach the same degree of freeness and considerably higher tearing strength and slightly lower breaking length and fold endurance for NSSC quaking aspen pulps. NSSC tension wood pulps of Ulmus americana showed little difference in beating time or strength properties (1).

Summarizing, for hardwoods, there appears to be adequate evidence that young, short-rotation hardwoods can be used as a source of fiber for the pulp and paper industry. Table V illustrates the interrelated factors involved. Juvenile wood in hardwoods, unlike conifers, has comparable specific gravity and only modestly shorter fiber length than mature wood. Silvicultural treatments which result in modest growth acceleration can be expected to result in equal or slightly longer fiber lengths and equal or slightly lower specific gravity. Pulping research, which has included studies on both ring-porous and diffuse-porous woods, suggests, if rotation ages are not less than 8-10 years, pulp yield and strength properties will be comparable to those of mature trees. Cooking times will very likely be less, beating energy requirements less, and cooking chemicals required per ton of pulp about equal to that for mature wood. Inclusion of branches, as with conifers, reduces pulp yield and decreases pulp strength. Extremely short rotations (2-6 years) can be expected to produce wood that will have lower pulp yield, lower tearing strength, and equal or slightly higher burst and tensile strength. Chemical requirements per ton of pulp produced will be higher. Important to understanding the differences between young conifers and hardwoods as sources of short-rotation fiber is the knowledge of the juvenile wood differences and knowledge of differences between tension wood (hardwoods) and compression wood (conifers).

[Table V here]

DISCUSSION

The impact of pulping higher levels of bark as a result of complete tree harvesting has not been documented in this paper. Briefly this aspect of the problem, which is a research topic in itself, suggests increasing levels of bark will result in lower pulp yields, higher levels of extractives, lower pulp strength, greater equipment wear (screens, valves, beaters, etc.), greater pulp cleaning costs, higher recovery furnace operating costs, higher bleaching costs, reduced drainage and lower machine runnability.

A number of instances can be cited in which reducing the rotation age below 6 to 8 years has a serious influence on paper properties, particularly tearing strength. Because of reduced tearing strength and for a number of other interrelated reasons including reduced pulp yields, higher percent bark, greater harvesting costs, etc., the paper industry is expected to select rotation ages greater than 6 years and very likely less than 20 years. Assuming rotation ages from 8 to 20 years and bark removal procedures that will eliminate an equivalent of 50 to 75% of the bark (when the conditions require), data in Table VI summarize the expected impact that short-rotation forestry is expected to have on pulp and paper quality. Conifer pulp yields and pulp strength properties are expected to be reduced to a greater degree than for short-rotation hardwoods. However, by keeping rotation ages greater than 10 years, it appears that satisfactory conifer pulps can be produced, although overall pulping and papermaking costs are expected to be higher.

[Table VI here]

Short-rotation hardwood pulp yields, if rotation ages are over 8 years, are anticipated to be approximately equal to that for mature wood. Tearing strength of SR hardwood pulps will very likely be lower while, unless tension wood is excessive, burst, tensile and fold endurance will be higher and beating energy requirements and cooking times will be less. Chemical requirements per ton of pulp produced, unless bark levels are high, are expected to be approximately equal. SR hardwoods (rotation ages 8 to 20 years), like conifers, are expected to produce satisfactory pulps for a variety of uses that will be comparable to pulps from mature trees, with the exception of modestly reduced tearing strength.

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Table I. Summary of Interrelated Factors Influencing Wood Quality of Short-rotation Hardwoods[a]

Wood or paper property	Juvenile wood *vs.* mature wood	Reaction wood *vs.* normal wood	Rapid *vs.* normal growth
Specific gravity	equal or lower	higher	equal or lower
Fiber length	shorter	equal	equal or longer
Cell wall thickness	equal or thinner	thicker	thinner
Lignin	lower	lower	lower
Cellulose	higher	higher	higher
Extractives	equal or higher	equal	equal

[a]Based upon rotation ages 8-20 years and 50-75% of bark removed.

Table II. Quaking Aspen Pulping Characteristics[a]

Sample	Screened yield, %	Permanganate no.	Beating time, min	Burst factor	Tear factor	Breaking length, m
53-year-old	56.6	17.0	23	51	87	11,000
16-year-old	59.4	14.3	30	55	73	10,100
6-year-old	55.2	15.9	21	57	68	11,600

[a]Strength values at 300 ml CF; data from Hunt and Keays (6).

Table III. Kraft Pulp Yields and Specific Gravity for Young Southern Hardwoods[a]

Wood Sample	Age, yr	Specific gravity	Unscreened yield, %	Kappa no.
Green ash	9	0.595	51.2	14.5
Sycamore	11	0.422	48.1	11.1
Young oak	13	0.57	49.5	13.7
Mature oak	--	0.58	47.9	12.4
Young gum	13	0.47	49.2	13.4
Mature gum	--	0.48	47.9	10.8

[a]Data from Barker (16).

Table IV. Handsheet Properties of Bleached Pulps for Young Southern Hardwoods[a]

Wood Sample	Fiber length, mm	CSF,[b] ml	Bulk, cm^3/g	Tear factor	Burst factor	Breaking length, km
Green ash	1.29	594	2.07	49.6	32.2	2.31
Sycamore	1.55	553	1.94	101	57.7	3.94
Young oak	1.25	587	2.06	61.9	36.8	2.58
Mature oak	1.48	560	1.89	60.0	32.0	2.60
Young gum	1.72	565	1.78	128	83.1	4.70
Mature gum	1.68	590	1.84	95.0	53.5	3.96

[a]Data from Barker (16).

[b]Canadian standard freeness at a refining time of 10 minutes.

Table V. Summary of Interrelated Factors Influencing Paper Quality of Short-rotation Hardwoods[a]

Wood or paper property	Juvenile wood *vs.* mature wood	Reaction wood *vs.* normal wood	Rapid *vs.* normal growth
Pulp yield	equal or higher	higher	equal or lower
Tear factor	lower	higher	lower
Burst factor	higher	lower	higher
Tensile strength	higher	lower	lower
Fold endurance	higher	lower	higher
Beating energy	lower	higher	lower
Cooking time	shorter	longer	equal
Chemical requirements	equal	equal	equal

[a] Based upon rotation ages 8-20 years and 50-75% of bark removed.

Table VI. Summary of the Impact of Short-rotation Forestry on Pulp and Paper Quality[a]

Wood or paper property	Short-rotation *vs.* conventional pulpwood	
	Hardwoods	Conifers
Specific gravity	equal	lower
Fiber length	shorter	shorter
Lignin	lower	higher
Extractives	equal	higher
Pulp yield	equal	lower
Tear factor	lower	lower
Burst factor	higher	higher
Tensile strength	higher	higher
Beating energy	lower	lower
Cooking time	shorter	shorter
Chemical requirements	equal	higher

[a]Based upon rotation ages 8-20 years and removal of 50-75% of bark.