

Effect of Plantation Density on Kraft Pulp Production from Red Pine (*Pinus resinosa* Ait.)

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Red pine (Pinus resinosa Ait.) butt logs from 38 year old research plots were used to study the effect of plantation stand density on kraft pulp production. Results indicate that plantation stand density can affect pulp yield, unrefined pulp mean fibre length, and the response of pulp fibre length to pulp refining. However, the effect of plantation stand density on physical and optical properties of paper was not significant and within the measurement errors of data obtained from testing handsheets. Therefore, we conclude that pulp and paper properties should not be a factor affecting forest management for the plantation density range studied.

Nous avons utilisé des billes de souches de pin rouge (Pinus resinosa Ait.) de parcelles expérimentales de 38 ans afin d'étudier l'effet de la densité du peuplement sur la production de la pâte kraft. Les résultats indiquent que la densité du peuplement peut avoir une incidence sur le rendement de la pâte, la longueur moyenne des fibres de pâte non raffinée, et la réponse de la fibre de pâte au raffinage de la pâte. Toutefois, l'effet de la densité de peuplement sur les propriétés optiques et physiques du papier n'était pas marqué et se situait dans les limites des erreurs de mesure obtenues à partir des essais avec les formettes. Nous pouvons donc en conclure que les propriétés de la pâte ne devraient pas être un facteur à considérer lors de l'aménagement forestier si l'on reste dans l'échelle de densité du peuplement étudiée.

INTRODUCTION

Tree stand density is a very important silviculture treatment tool and is used widely to improve forest productivity [1]. In commercial production forest land, it is common practice to alter tree stand density through forest thinning. This type of thinning operation produces a large amount of juvenile wood while improving the growth of the remaining trees. Much work has been conducted also on understanding the effect of juvenile wood, especially that from forest thinning, on pulp production [2–10].

In the United States, forest thinning has been adopted recently to manage national forests overpopulated with trees under suppressed-growth conditions resulting from

decades of passive forest management. Materials from this type of forest thinning are very different from those of commercial thinning operations in fast-growing plantation forestry, as reviewed in our previous study [11]. The main characteristic of these materials is a very narrow growth-ring width because of natural overpopulation (high stand density). Stand density is a measure of tree growth environment; therefore, it can be used to study overpopulated trees in nonplantation national forests in the United States. Our research studied the effects of stand density in plantation research plots on wood and tracheid properties and pulp production. One objective is to understand the effect of suppressed-growth conditions on wood and tracheid properties for fibre production in nonplantation forests.

Much research has been conducted on tree growth compared with stand density [12–14]. However, limited studies have been conducted on the effect of stand density on wood and tracheid properties and pulp production. Kang et al. [15] studied the effect of plantation stand density on wood and fibre properties of

jack pine (*Pinus banksiana* Lamb.). They found that wood density increased as plantation stand density increased, because of increased latewood content. Kang et al. [15] also reported that pulp yield increased and mean fibre length decreased with an increase in plantation stand density. Yang and Hazenberg [16], Hatton et al. [17] and Watson et al. [18] studied the effect of plantation spacing on relative wood density and fibre properties in *Picea mariana*, western red cedar and western hemlock, respectively.

Because of its value for lumber and pulp production, red pine (*Pinus resinosa* Ait.) is one of the important plantation species in the northeastern and Great Lakes areas of the United States and parts of Canada. Red pine is planted commonly on clear-cut sites and requires maximum sun for healthy growth. Therefore, tree stand density is a particularly important silviculture tool in the management of red pine plantation plots. In this study, we evaluate the effect of plantation stand density on kraft pulp production. The goals of the present study are to provide knowledge for effective forest management that maximizes the

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value of plantation forest land, and to understand the effect of suppressed growth caused by overpopulation on the quality of wood pulp produced from nonplantation forests. Unfortunately, the effect of plantation density on fibre properties is most likely species specific [18].

EXPERIMENTAL

Raw Material and Chip Production

Red pine logs used for chipping and pulping were from 38 year old research plots in the Lake Superior State Forest in northern Michigan of the United States. Logs were obtained from five 38 year old research plots with initial plantation densities of 220, 320, 420, 620 and 820 stems/acre. The plots were never thinned. Ten trees were harvested from each plot. Diameter at breast height of the sampled trees ranged from 119 to 292 mm. After the tree samples were harvested, a 4.9 m long butt log was bucked from each tree onsite and shipped to the USDA Forest Products Laboratory (FPL) in Madison, Wisconsin, USA.

Upon arrival at the FPL, a 61 cm long section from each end of each butt log (two sections) was retained for the pulping study. Logs were hand peeled to remove bark and chipped to 19 mm length in a four-knife commercial-size chipper. The chips were screened to remove all particles greater than 38 mm and less than 6 mm in length. The thickness of the accepted chips ranged from 1 to 5 mm. Screened chips were mixed thoroughly in a large V-mixer, weighed into 4 or 5 kg samples, placed in polyethylene bags, and stored at 4°C until used for pulping. After mixing and bagging, chip

solids content was determined by oven drying three chip samples from each log to remove all moisture. Then we recorded the average of three samples for each log.

Kraft Pulping

Kraft pulping experiments were conducted in a 23 L stainless steel batch digester. The cooking liquor had a sulphidity of 25%, liquor-to-wood ratio of 5 to 1, and an active alkali range of 16–18% to produce pulp of kappa numbers 90, 60 and 30. Two kg of oven-dry (o.d.) wood chips were used in each cook. A screen basket that allows for free circulation of cooking liquor was filled with 100 g of o.d. wood chips and put in the middle of the digester for pulp yield measurement. After putting chips in the digester, a vacuum of ~82 kPa was created in the digester and held for at least 5 min before adding cooking liquor. This was to create better penetration of the cooking liquor into the chips. The cooking liquor was heated indirectly by steam in an external heat exchanger. Liquor passed through the heat exchanger while being pumped from the bottom to the top of the digester. Circulation of liquor continued at a rate of ~17 L/min. The temperature of the digester was raised to 80°C in 10–15 min. Then the temperature was ramped to the cooking temperature of 170°C in 60 min. Cooking time at 170°C was varied to obtain the desired pulp kappa number ~30, 60 and 90. The kappa numbers of most of the 53 cooks were within the ranges of 26–33, 57–63 and 88–96. The liquor was blown and the chips were washed in situ with water at a temperature above 80°C for 15 min. Then the washed chips

were fiberized while still hot.

Kraft Pulp Refining

Pulps were refined in a Sprout-Waldron (Andritz Group, Graz, Austria) 300 mm (12 inch) atmospheric laboratory refiner equipped with an auger feed. Plates were a C2976C pattern: 440-C alloy, no dams, closed periphery. Pulp at 150 g/min (o.d.) was fed to the auger by a constant-speed conveyor belt. Refining consistency was 15%. Pulps of 30 kappa were refined in one pass using a plate clearance sufficiently tight to achieve the desired freeness. Pulps of 60 and 90 kappa received a two-pass treatment, each at 15% consistency. Plate clearance for the first pass was adjusted to give a Canadian standard freeness [19] of 600–650 mL depending on the desired final freeness. The second-pass clearance was adjusted to achieve the desired freeness. Target freenesses were 500 ± 25 mL to 400 ± 25 mL. The refining temperature was targeted at 100°C by preheating, then maintaining the refiner with boiling dilution water. Refined pulps were allowed to seep hot at a consistency of ~0.25% for a minimum of 1–1.5 h to remove latency before dewatering.

Pulp and Paper Property Measurements

Measurements of handsheet physical and optical properties were conducted by the Paper Test Laboratory (PTL) of FPL according to TAPPI Test Methods T 220 [20], T 425 [21], T 494 [22], T 403 [23] and T 414 [24]. Pulp fibre length measurements also were carried out by the PTL using a fibre quality analyzer.

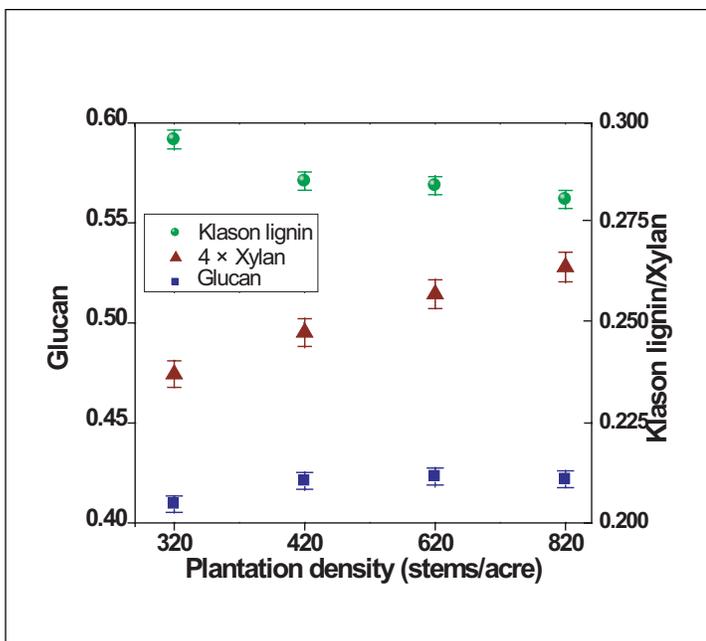


Fig. 1. Effects of plantation density on glucan, Klason lignin and xylan contents in wood.

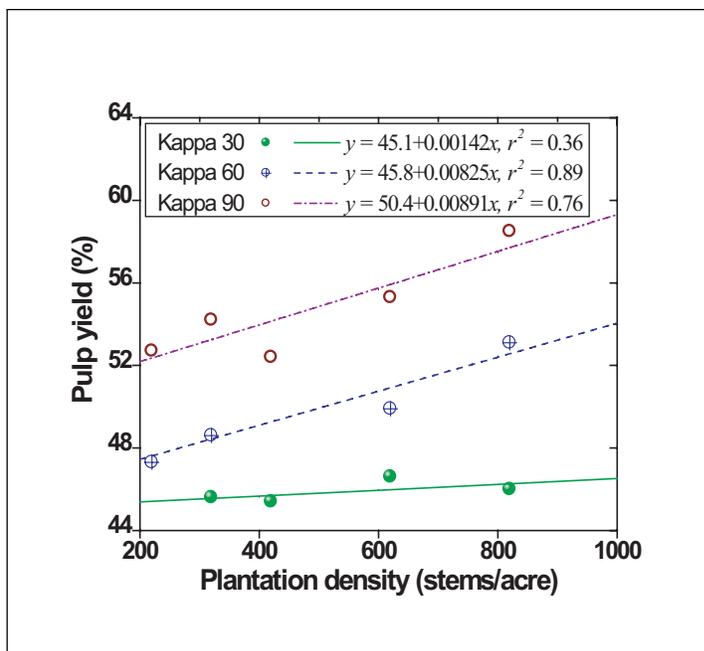


Fig. 2. Effect of plantation stand density on pulp yields of three grades of pulp.

RESULTS AND DISCUSSIONS

Pulp Yield and Pulping Chemical Consumption

Chemical composition analyses of wood from various plantation stand density plots were conducted by the Analytical Chemistry and Microscopy Laboratory of FPL following the method developed by Davis [25]. Figure 1 shows the effect of plantation density on three major components. Results indicated that Klason lignin content in wood was reduced by ~1.5% with a relative standard deviation of 0.8%, whereas glucan and xylan content was increased by 2% with standard deviations of 1.0 and 1.4%, respectively, when plantation stand density increased from 320 to 820 stems/acre.

The effect of plantation stand density on pulp yield caused by variations in wood chemical composition can be seen clearly in Fig. 2. Pulp yield increases linearly with plantation stand density for pulp kappa numbers 30, 60 and 90. Yield increased more than 4% in producing pulp with a kappa number 90 (liner-board grade) when the plantation stand density was increased from 320 to 820 stems/acre. The 4% increase was double the difference in xylan and glucan content between two plantation stand density plots of 320 and 820 stems/acre. The difference in pulp yield may indicate less cellulose and hemicellulose degradation through interactions between pulping chemicals and wood when pulping trees from higher density plantation plots, or it may be due to the difference in reactivity of the residual lignin in pulp with potassium permanganate (measure of kappa number), or possibly a combination of the two. The yield results agree with the yield

results of jack pine reported by Kang et al. [15]; that is, pulp yield increased with the increase in plantation density. Yield increase diminishes in producing bleachable-grade pulp with kappa numbers ~30.

Figure 3 shows the variation in the amount of active alkali consumed during the pulping of wood chips from various plantation density plots. The active alkali consumed was reduced by ~7% for pulping wood chips from the 820 stems/acre plot compared with that of 320 stems/acre. The yield difference in pulping wood from high-density plantation plots is possibly due to the increased content of latewood with a smaller lumen than earlywood lumen, which decreases pulping chemical diffusion and therefore causes less disintegration of wood tracheids. This reduction in pulping chemical diffusion diminishes as pulping proceeds to a longer reaction time (to pulp kappa number below 60).

Pulp Fibre Length

We measured fibres obtained from macerated wood blocks based on the method of Brisson, Gardner, and Peterson [26]. The description of the maceration experiments can be found in a separate study [27]. These unpulped fibres were considered to be virtually the length of the original wood tracheid. We found that the mean (length-weighted) tracheid length of a wood block from a tree harvested in high-density plantation plots is lower than that of an equivalent tree (in terms of average age) from low-density plantation plots. It is important to know whether a high mean tracheid length translates to a high mean pulp fibre length. All mean pulp fibre lengths discussed here are length-weighted.

Figure 4 shows the measured mean fibre length of unrefined kraft pulps produced from trees from various plantation stand density plots. Results indicate that the mean fibre length of unrefined pulp from higher density plantation plots is higher than pulp from lower density plantation plots. The maximum difference in mean fibre length is ~6% (or 0.15 mm) at kappa number 90 between pulps from the 220 and 820 stems/acre plots, whereas the measurement error in terms of standard deviation was less than 2%. Perhaps the increase in mean pulp fibre length with plantation stand density is due to the difference in the disintegration and destruction of tracheids between kraft pulping of low-density and high-density wood. High stand density produced high-density wood with a large latewood fraction based on our separate study of red pine. Kraft pulping is a much stronger and faster chemical reaction process than wood maceration (a slow and gentle reaction). Therefore, mass diffusion is the rate-limiting process in kraft pulping. Reduced chemical diffusion into and consumption by (Fig. 3) high-density wood from high-density plantation plots as discussed above may have reduced the destruction of tracheids, which resulted in a higher mean pulp fibre length. This explanation of chemical diffusion and consumption can also be verified indirectly by examining the effect of pulp kappa number on mean pulp fibre length (Fig. 4). A less-delignified pulp (higher pulp kappa number) has a high fibre length. Figure 4 also indicates that the effect of plantation stand density on the mean fibre length of unrefined pulp diminished with the increase in plantation stand density.

Figure 5 shows the effect of pulp refining, measured by Canadian standard freeness

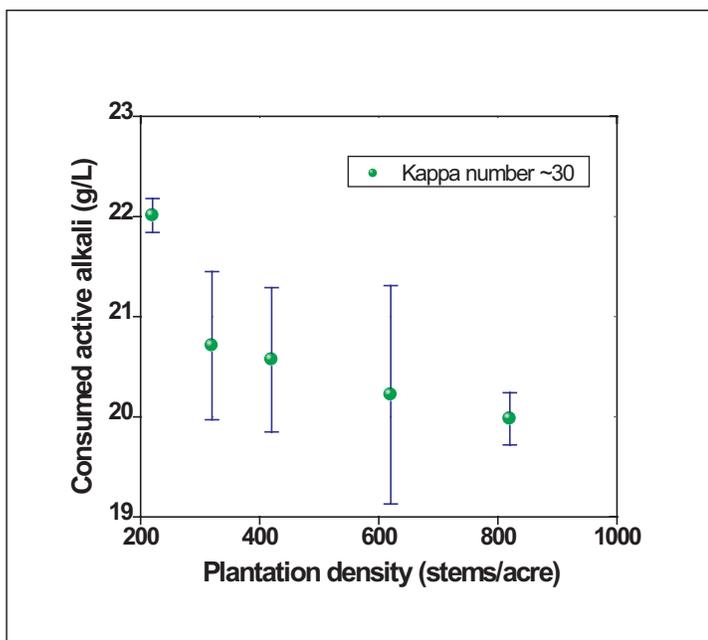


Fig. 3. Effect of plantation density on the amount of active alkali consumed during kraft pulping.

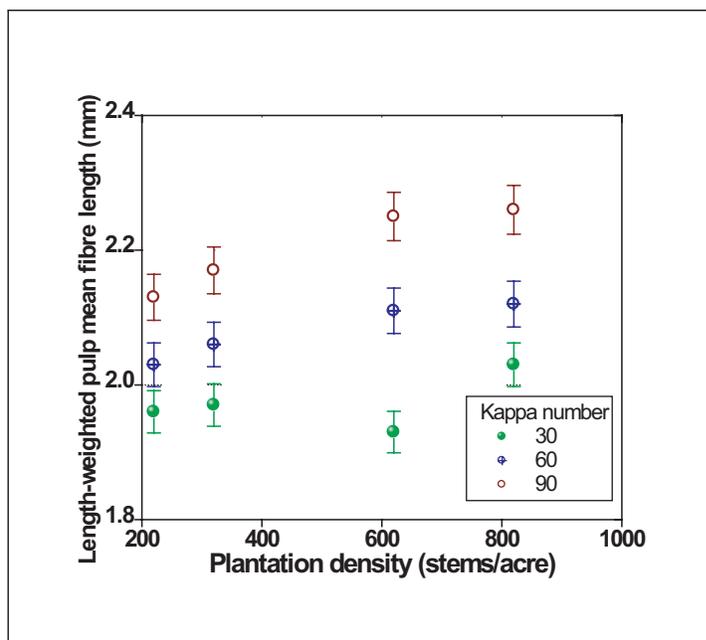


Fig. 4. Effect of plantation stand density on length-weighted mean fibre length of three grades of unrefined pulps.

(fibre-length data of unrefined pulp with the highest freeness were reported in Fig. 4.), on the reduction of mean fibre length of two kappa number pulps from low- (220 stems/acre) and high-density (620 stems/acre) plantation plots. For clarity, data from other plots were not presented in Fig. 5, and data were normalized by the mean length of unrefined pulp (Fig. 4). Results show clearly the pronounced reduction through refining in the mean fibre length of linerboard-grade pulp (kappa number 90) produced from the high-density plantation plot: 15% for pulp from the low-density plot (220

stems/acre) compared with 25% for pulp from the high-density plot (620 stems/acre). For bleachable-grade pulp (kappa number 30), the difference in the fibre-length reduction through refining between the pulps from the two plantation stand density plots is insignificant.

Recall that wood maceration experiments showed that the measured tracheid length of wood from the high-density plantation plot (620 stems/acre) was ~20% lower than that of wood from the low-density plantation plot (220 stems/acre), whereas the measured mean fibre length of pulp produced from

high-density plots is actually 6% greater than that of pulp from a low-density plot of 220 stems/acre. Therefore, the pronounced reduction in mean fibre length of linerboard-grade pulp (kappa number 90) from high-density plots perhaps is due to pronounced tracheid disintegration and destruction through refining. We also observed a pronounced reduction in mean pulp fibre length (Fig. 5) when examining two different grades of pulp produced from the same plantation stand density plot. Linerboard-grade pulp (kappa number 90) has a greater reduction in mean fibre length than

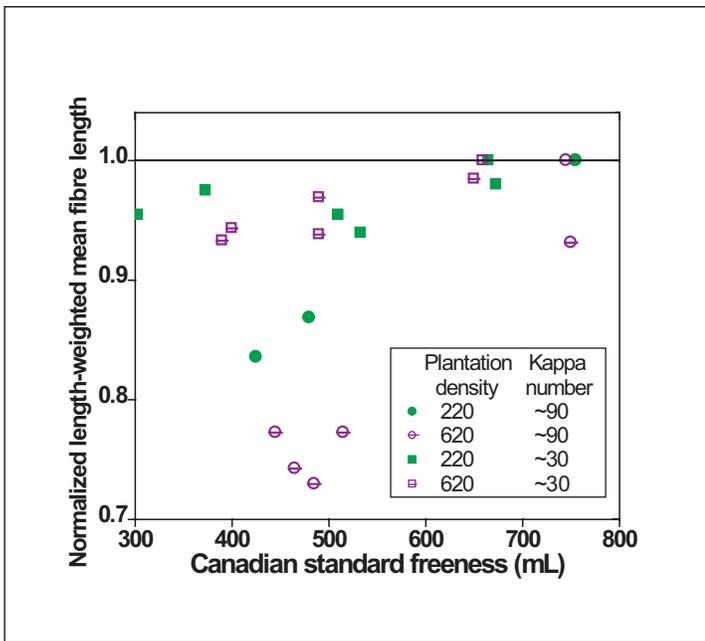


Fig. 5. Effect of refining on the reduction of mean fibre length of pulps produced from two plantation stand density plots.

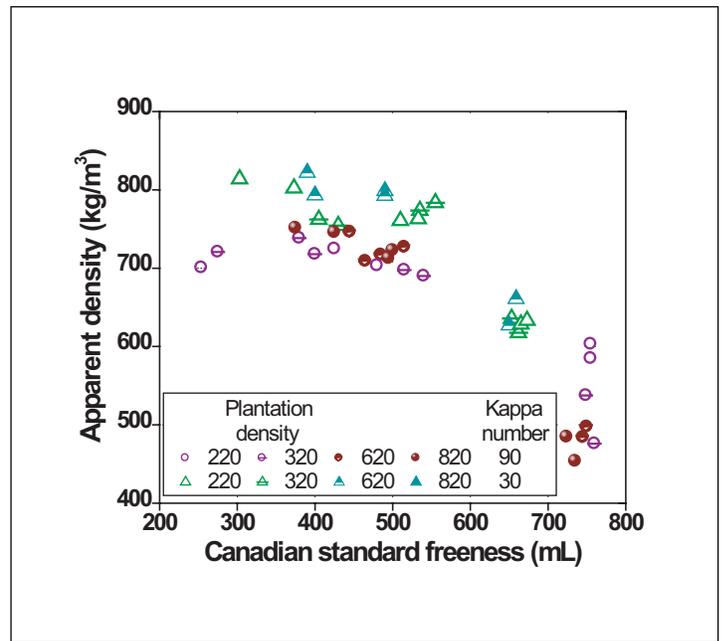


Fig. 6. Effect of refining on the apparent density of handsheets made of pulps of two grades from various plantation stand density plots.

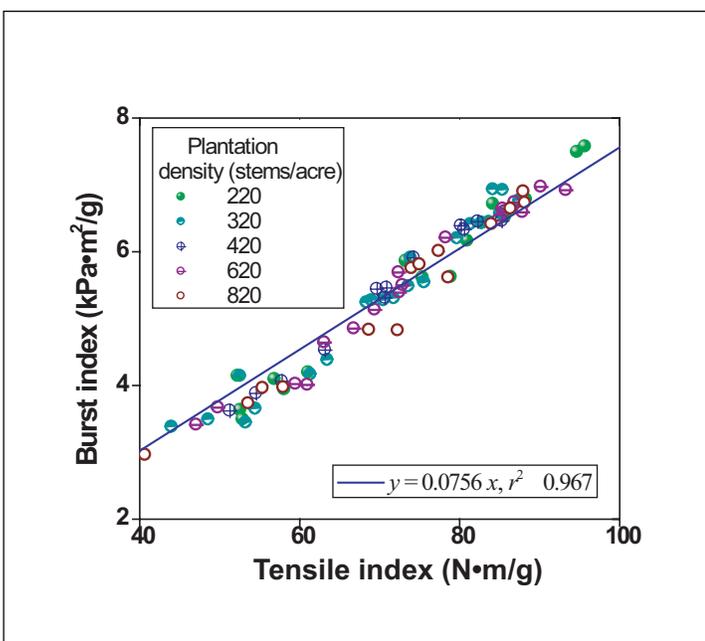


Fig. 7. Correlation of burst and tensile indices of handsheets made of pulps from various plantation stand density plots.

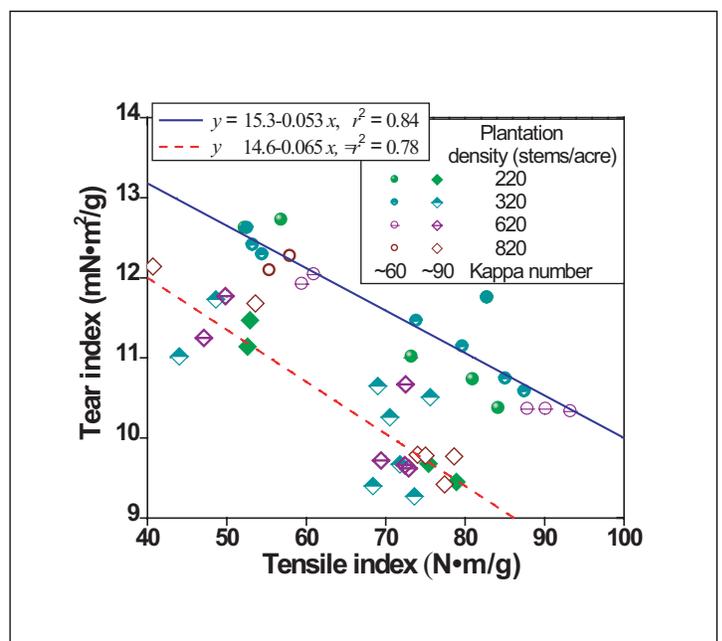


Fig. 8. Correlation of tear and tensile indices of handsheets made of bag grade pulps from various plantation stand density plots.

bleachable-grade pulp (kappa number 30). Results in Fig. 5 indicate that incomplete tracheid disintegration or destruction during the pulping process will continue through refining. A pronounced reduction in pulp fibre length will result for pulp that went through a low degree of disintegration or destruction. For example, producing nonbleachable-grade pulp resulted in mild delignification and limited chemical diffusion in pulping wood of high density and high latewood content. Because of incomplete tracheid disintegration and destruction, the

mean fibre lengths of refined pulps from the high-density plot are only ~5, 7 and 10% lower than those of pulps from the low-density plot for linerboard, bag and bleachable grade, respectively. These differences in mean fibre lengths are also smaller than the 20% difference in tracheid length between the two plantation stand density plots.

Paper Physical Properties

The mechanical properties of pulps were determined by testing handsheets made of refined pulps. Figure 6

shows that the correlation of pulp freeness (as measured by Canadian standard freeness) and the corresponding handsheet density follows a universal curve independent of tree plantation stand density, indicating that plantation density has no effect on conformability of the refined pulps. However, Fig. 6 shows that the relationship is slightly dependent on kappa number. At a given freeness, pulp with a low kappa number produces a denser sheet than a pulp with a high kappa number. Data in Fig. 6 include two grades of liner-

board and bleachable-grade pulp with kappa numbers 90 and 30, respectively.

Figure 7 shows the relationship between the burst and tensile indexes of handsheets. We found that correlations between burst and tensile fall on a universal line, independent of plantation density and the kappa number of the pulps. Figure 8 shows the relationship between the tear and tensile indexes of handsheets. Only data from handsheets made of bag-grade pulps (kappa number ~60) and linerboard-grade (kappa number ~90) were presented in Fig. 8, as the tear strength is more important to bag-grade papers. Despite the data scattering in the tear index data (typical standard deviation in tear testing is ~7.5%, compared with 3% for tensile and 4% for burst), results show that the tear index decreases as tensile increases during pulp refining because of the shortening of the fibres. An effect of tree plantation density on tear and tensile correlation is not visible from the data (Fig. 8). Pulp kappa number has an effect on the handsheet tear-tensile relationship. Apparently, tear strength decreases at high pulp kappa numbers; furthermore, the tear-tensile correlation of sheets made of linerboard-grade pulps has a larger negative slope than the correlation for sheets made of bag-grade pulps.

Tensile energy absorption (TEA) is derived from tensile strength and paper stretch. Figure 9 shows the correlation between tensile index and TEA. The effect of refining on paper stretch can be clearly seen from Fig. 9, where the top data set is from handsheets made of refined pulp and the bottom data set is from handsheets of unrefined pulp. The correlation coefficient between tensile index and TEA increased from 1.12 for unrefined pulps to ~2 (almost doubled) for refined pulps because paper

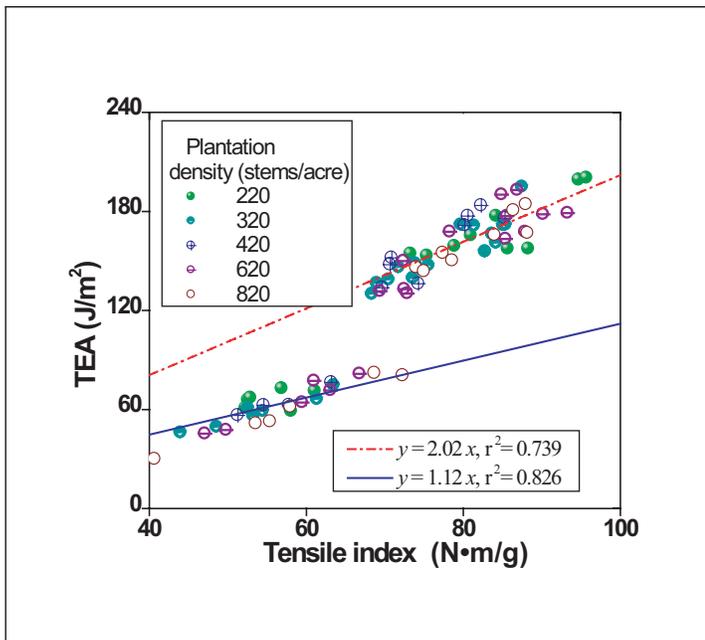


Fig. 9. Correlation of TEA and tensile index of handsheets made of pulps from various plantation stand density plots.

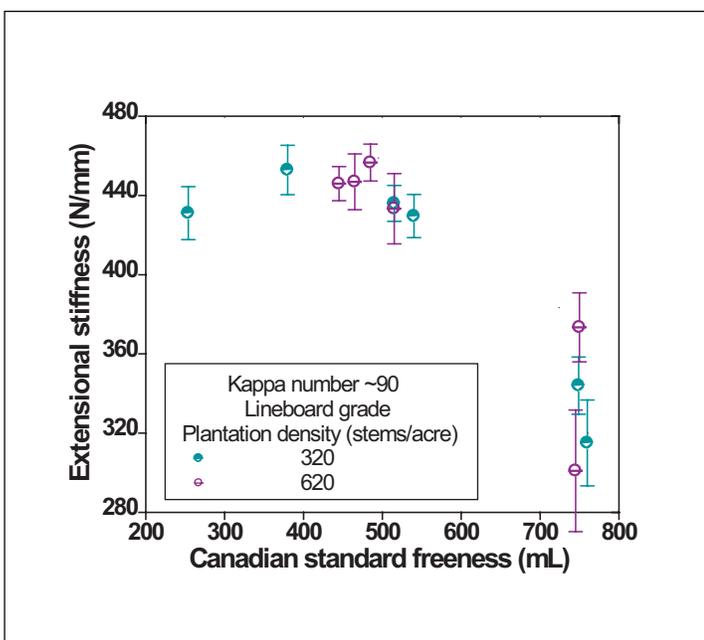


Fig. 10. Effect of refining on the paper stiffness of handsheets made of pulps from two stand density plots.

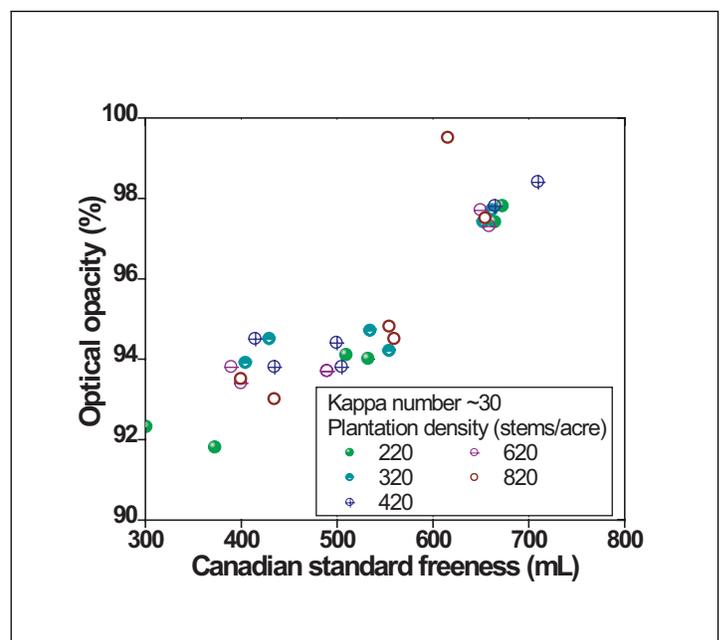


Fig. 11. Effect of refining on the optical opacity of handsheets made of bleachable-grade pulps from various stand density plots.

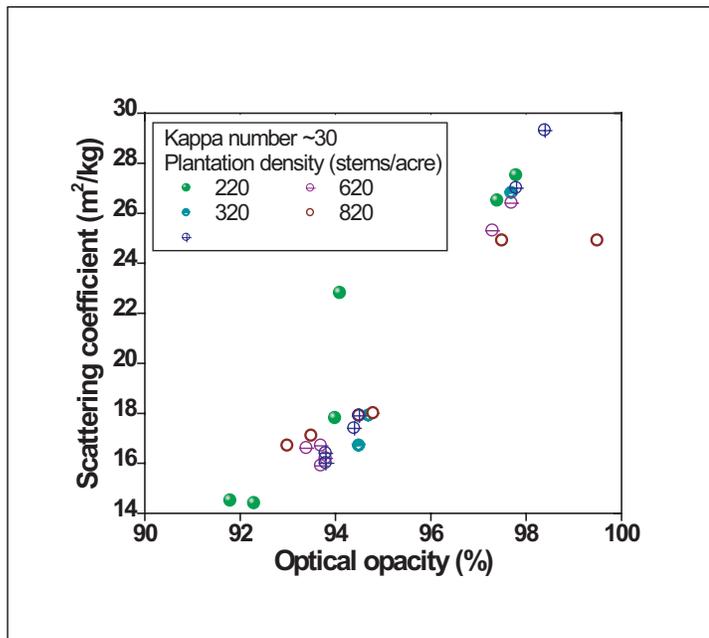


Fig. 12. Correlation of scattering coefficient and optical opacity of handsheets made of bleachable-grade pulps from various stand density plots.

stretch was almost doubled after the pulps were refined. The results in Fig. 9 show clearly that TEA is not affected by tree plantation stand density.

Stiffness is very important for linerboard-grade papers. Figure 10 shows the effect of refining and tree plantation density on stiffness of linerboard-grade paper. The results indicate that paper stiffness improves, reaches a maximum value at a freeness of ~450 mL, and then decreases slightly as refining proceeds. Tree plantation density has no effect on paper stiffness.

Paper Optical Properties

Optical properties are very important for bleachable-grade (kappa number 30) paper because they affect the quality of printing-grade paper. The results indicate that tree plantation density has no effect on paper opacity and scattering coefficient, as shown in Figs. 11 and 12, respectively. Relative standard deviations in opacity and scattering coefficient are 1 and 3%, respectively.

CONCLUSIONS

This study investigated the effect of tree plantation stand density on kraft pulp production from red pine by conducting laboratory pulping experiments using red pines harvested from 38 year old research plots with five plantation densities. The results indicated that logs from high-density plantation plots produced a higher pulp yield than logs from low-density plots because of differences in the chemical composition (lignin and xylan) of wood and perhaps in the degradation of hemicellulose through interactions between pulping chemi-

cal and wood. Yield differences diminished as pulping proceeded to bleachable-grade pulps of low kappa numbers (kappa number 30 for softwood). Logs from high-density plantation plots also produced pulp (unrefined) with greater mean fibre length than those from low-density plantation plots, despite the mean wood tracheid length from high-density plantation plots being higher than that from low-density plots. However, the reduction of mean pulp fibre length through refining was pronounced for pulp produced from high-

density plantation plots; for example, a 15% reduction for 220 stems/acre compared with a 25% reduction for 620 stems/acre for linerboard-grade pulp (kappa number 90). The pronounced effect diminished as delignification proceeded to bleachable-grade (kappa number 30). The pronounced effect may be due to the continued disintegration and destruction of wood tracheids through mechanical refining.

Despite differences in wood chemical composition, pulp yield and pulp fibre length, the results indicated that differences in the physical and optical properties of handsheets made of pulps obtained from logs of various plantation densities are insignificant and within measurement errors. For the plantation densities studied, we conclude that a high plantation density plot is beneficial for pulpwood production in that yield does not affect paper properties. Therefore, pulp and paper properties should not be a factor affecting forest management for the plantation density range studied.

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