# ASSESSMENT OF WHITE SPRUCE AND JACK PINE STEM CURVATURE FROM A NELDER SPACING EXPERIMENT

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**Abstract.** This study presents a method for calculating stem curvature for trees with multiple deviations. Generally, tree curvature is assessed using the maximum deflection method. It consists of measuring the farthest point from a straight line drawn between the large and small ends of a stem. It works fairly well for a single deviation but gives poorer results for stems with several deviations. The stems used for developing this method were harvested from a 32-yr-old Nelder spacing experiment established near Woodstock, New Brunswick, Canada. A total of 96 trees were selected for this study from the white spruce (*Picea glauca* [Moench] Voss) and jack pine (*Pinus banksiana* Lamb.) that were planted on the same Nelder circle. This particular plantation design offered a gradient of initial spacings ranging from 640 to 12,000 stems/ha. Results of analysis revealed that initial spacing had an impact on tree curvature. Stem curvature increased with wider initial spacing. However, this influence varied between species and differed according to the method used to calculate curvature. The vector length calculation method showed that stem curvature in jack pine was more pronounced and more often encountered at lower densities than in white spruce. It was also observed that tree shape was influenced by the cardinal points with white spruce growing more in westerly and southerly directions.

***Keywords:*** Curvature assessment methods, stem quality, Optitek, stem shape, jack pine, white spruce, Nelder plantation.

## INTRODUCTION

Curvature is an important element in assessing stem or log quality. This variable can significantly affect the wood amount or quality extracted from a tree. Tree curvature is a measurement that can be used to qualify a tree because it generally tends to lower the amount and quality of sawn timber. The sawmill industry has developed standards to assess the value of a log according to its curvature. These methods can be found in several forest guides (Fig 1) (Rast et al 1973; Petro and Calvert 1976).

For the same diameter, a crooked stem gives less lumber than a completely straight one. However, stem curvature may have other impacts on wood quality. Indeed, significant correlations were found between stem deformation and percentage of compression wood (Krause and Plourde 2008). Ivkovic et al (2007) estimated that a 10% improvement in radiata pine (*Pinus radiata* D. Don) stem straightness decreased sawlog downgrade caused by sweep by 17.1% and increased green timber recovery by about 0.5%. Decreasing the presence of tree deviations by adequate thinning should therefore be a priority for any forest manager, silviculturist, forester, or wood scientist. Some research has been done on sinuous stem growth (Spicer et al 2000; Temel and Adams 2000). Sinuosity is defined as stem crookedness that occurs entirely within an internode or interwhorl (Campbell 1965). There are no studies relating sinuous growth to amount and location of slope of grain or pith deviations, both of

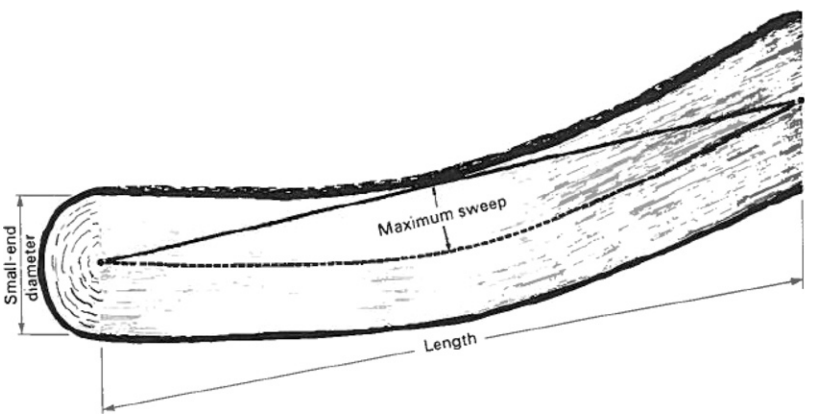


Figure 1. General method of determining maximum sweep (Petro and Calvert 1976).

which could strongly impact strength properties (Spicer et al 2000). Although our visual observations of the Nelder plot trees suggest a more sinuous stem growth in jack pine than in white spruce, the aim of this study was not to understand the fundamental behavior of sinuous stem growth between internodes, but to develop a method to rapidly and more accurately calculate tree sweep based on true shape scanner data.

Many studies indicate that stem shape is also influenced by site quality, stand density (Gray 1956; Larson 1963; Ballard and Long 1988; Birk 1991; Sharma and Zhang 2004), and initial spacing (Tong and Zhang 2005). Curvature is an important component of tree shape, but taper is also a major factor. Sharma and Zhang (2004) found that taper significantly differed for jack pine, black spruce (*Picea mariana* [Mill.] BSP), and balsam fir (*Abies balsamea* [L.] Mill.) growing in a natural forest. Hence, stem shape varied among species even when the trees grew and developed in similar conditions.

Measuring tree external form using a true shape scanner usually involves drawing a virtual line through the center of the large and small end sections of the stem. Measurement of maximum deflection with the farthest point to this straight line is then easily obtained (Fig 2a). This value is usually divided by the length of the stem and provides an average curvature across a given length usually expressed in cm/m. When it is not possible to use a true shape scanner, the maximum deflection measurement can be obtained manually with a string using the same principle. Sweep is an important characteristic in assessing tree quality, but it might be possible to measure it with greater precision.

The maximum deflection method is presumably adequate when stems have a single curve as shown in Fig 2a. In a stem bent in several places as in Fig 2b, the approach may not be adequate. It is therefore important to quantify all deviations to improve method precision, understand its impact on product recovery, and compare and model this distinctive feature to compare different forest tree assortments.

The objectives of the study were to 1) investigate the influence of initial spacing on tree curvature; 2) develop a new method of measuring stem sweep taking into account all deviations; and 3) examine the influence of the cardinal points on tree shape.

## MATERIALS AND METHODS

### Selection and Geometry Scanning of Sample Trees

The stems used in this study were harvested from a Nelder spacing experiment, Type 1a design, (Nelder 1962) of jack pine and white spruce that was established in 1977 near Woodstock, New Brunswick, Canada (latitude 46.16° N, longitude 67.58° W). The study site offered various initial spacings that suited the objectives of this study. No silvicultural treatments were performed on this site. Table 1 shows the change in stand density as a function of position in the plantation.

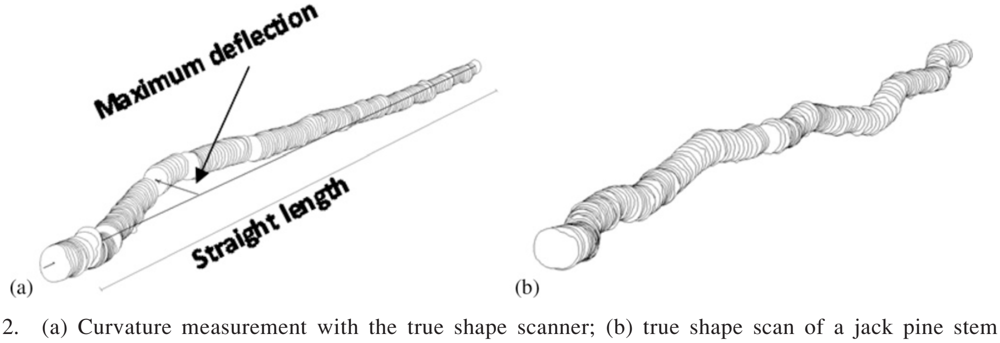


Figure 2. (a) Curvature measurement with the true shape scanner; (b) true shape scan of a jack pine stem with multiple deviations.

Table 1. Layout of tree spacing in the Nelder spacing experiment used in this study.

| Row no. | Radius (m) | Spacing (m) | Distance between rows (m) |
|---|---|---|---|
| 0 | 9 | | Guard tree |
| 1 | 9.87 | 0.87 | 0.91 |
| 2 | 10.83 | 0.96 | 1.00 |
| 3 | 11.88 | 1.05 | 1.10 |
| 4 | 13.03 | 1.15 | 1.21 |
| 5 | 14.29 | 1.26 | 1.32 |
| 6 | 15.68 | 1.39 | 1.45 |
| 7 | 17.20 | 1.52 | 1.59 |
| 8 | 18.86 | 1.66 | 1.75 |
| 9 | 20.69 | 1.83 | 1.92 |
| 10 | 22.70 | 2.01 | 2.10 |
| 11 | 24.90 | 2.20 | 2.31 |
| 12 | 27.32 | 2.42 | 2.53 |
| 13 | 29.96 | 2.64 | 2.77 |
| 14 | 32.87 | 2.91 | 3.04 |
| 15 | 36.06 | 3.19 | 3.34 |
| 16 | 39.56 | 3.50 | 3.66 |
| 17 | 43.40 | 3.84 | 4.02 |

Source: Project notes on file at Natural Resources Canada, Atlantic Forestry Center, Fredericton, NB, Canada.

The plot had 68 radial spokes and 17 circles, representing 17 different initial spacings ranging from about 12,000 stems/ha in the center of the Nelder plot to about 600 stems/ha in the circle periphery (Fig 3). Distance between trees increased from the center to the periphery of the plot. Thus, trees grown near the center had strong competition, whereas those on the periphery grew almost without competition. The circle was divided into two species, white spruce on one side and jack pine on the other, which is a rare experiment in the literature. This experimental design provided similar growth and site conditions for both species. A total of 96 trees were collected from the study site: 46 jack pine and 50 white spruce. Dead trees or trees with defects such as forks were removed from the sample. Outer guard trees in row 17 were also included in the sample for analysis in this study, which reflected open growth conditions.

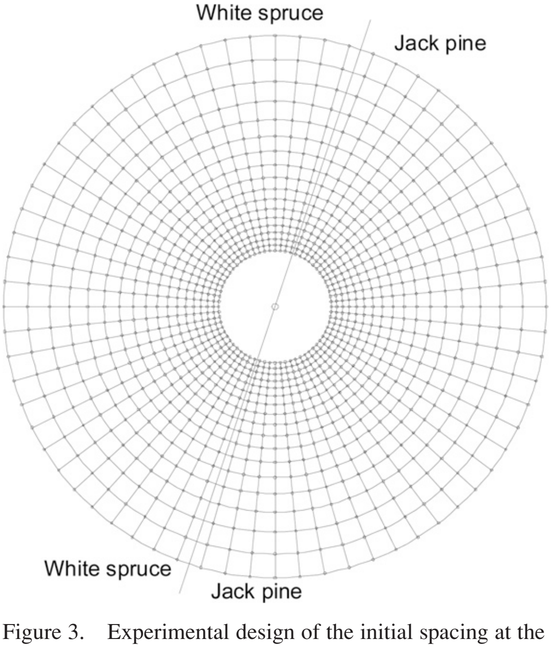


Figure 3. Experimental design of the initial spacing at the Nelder plot used in this study.

After cutting and limbing the trees and topping them at 7 cm diameter, each stem was scanned using FPInnovations' (Québec, QC, Canada) Comact true shape scanner to obtain its form in 3D. The stems were placed horizontally on a series of brackets, and then the scanner moved along the stem extracting the external shape with laser technology at 5 cm intervals. This produced a series of cross-sections along the length of the stem. Each cross-section was defined by a diameter and a geometric center in the 3D Cartesian coordinate system with X and Y coordinates indicating the position on the X–Y plane and the Z coordinate indicating the distance to the large end of the stem. Subsequently, Optitek, a sawing simulation software developed by FPInnovations, made it possible to visualize the stems and provides data such as the large end diameter, small end diameter, taper, curvature, and volume of the stem. The sweep provided by Optitek was the maximum perpendicular deflection from a straight line drawn between the large and small ends of the stem (Fig 2a). Taper was calculated as the difference between the large and small end diameters across the full length of the stem and was expressed in cm/m.

## Assessment of Stem Curvature

To accurately express curvature, it is necessary to consider multiple deviations instead of only the maximum deviation across the whole stem length. Multiple tests were conducted to better express stem curvature. The approach proposed here refers to X, Y, and Z coordinates. The true shape scanner provided X and Y center coordinates for each disk every 50 mm along the stem length. To accurately express curvature, one must consider the impact of multiple deviations across the entire stem, not just one section. By having coordinates X, Y, and Z every 50 mm, it is possible to calculate the length of the vectors $\vec{V}$ (L) from the center of one cross-section to another (Fig 4). The smaller the Z coordinate is, the more accurate the estimate of curvature will be. Therefore, total length of all vectors in the stem should reflect overall deviation of the stem. The more pronounced tree curvature is, the higher the sum of the vectors will be, and the smaller the scanning intervals are, the more accurately the sum of the vectors will represent the true sweep of the stem. By comparing stem length with total length of all vectors (the sum of all vectors), it was possible to estimate stem curvature (Eq 1). To avoid bias, the sweep was expressed as the difference between total length of all vectors and stem length across the stem length:

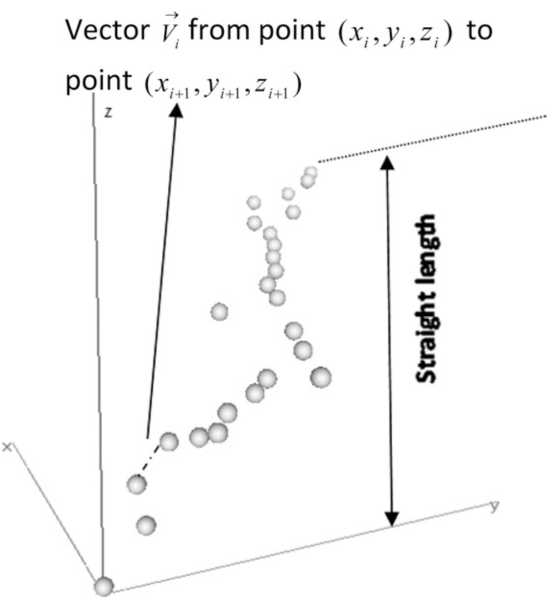


Figure 4. Example of coordinates X, Y, and Z of a log section.

$$L = \sum_{i=1}^{n-1} \left\| \vec{V}_i \right\| = \sum_{i=1}^{n-1} \sqrt{(X_{i+1}-X_i)^2 + (Y_{i+1}-Y_i)^2 + (Z_{i+1}-Z_i)^2} \quad (1)$$

where $\vec{V}_i$ is the $i^{th}$ vector from the $i^{th}$ point to the $(i + 1)^{th}$ point, $x_i$, $y_i$, $z_i$ are the 3D coordinates of the center point of the $i^{th}$ cross-section, $i = 1,2,3,\ldots,n$, and $n$ is the total number of cross-sections in the stem.

Subsequently, the measurement was compared with the full straight length on the Z axis. Because there are no perfectly straight stems, the sum of the vectors will always be higher than the completely straight distance taken on the Z axis. The equation used to calculate curvature is

$$CurvatureVectorMethod = \frac{(L - StraightLength)}{StraightLength} \times 100 \quad (2)$$

where L is the total length of all vectors, calculated using Eq 1.

Eq 2 gives a percentage of extra length caused by the curvature present in the stems. This allows for direct comparison of total curvature between stems on the same basis.

The straight vector between two sets of coordinate sections will always be equal to or shorter than the real length of the segment. The greater the distance between the Z coordinates, the larger the underestimation of the curvature will be. Thus, the distance between the Z coordinates should be adjusted to the precision needed.

## Effect of Cardinal Points on Stem Shape

In the Cartesian coordinate system, a point with nonzero X or Y coordinates means an offset in X and/or Y directions from the origin. The sign of the X or Y coordinates can thus be used to detect the deviation of a cross-section in the cardinal directions. For example, a positive sign of the Y coordinate implies a shift to the north, whereas with a negative sign, it would be a shift to the

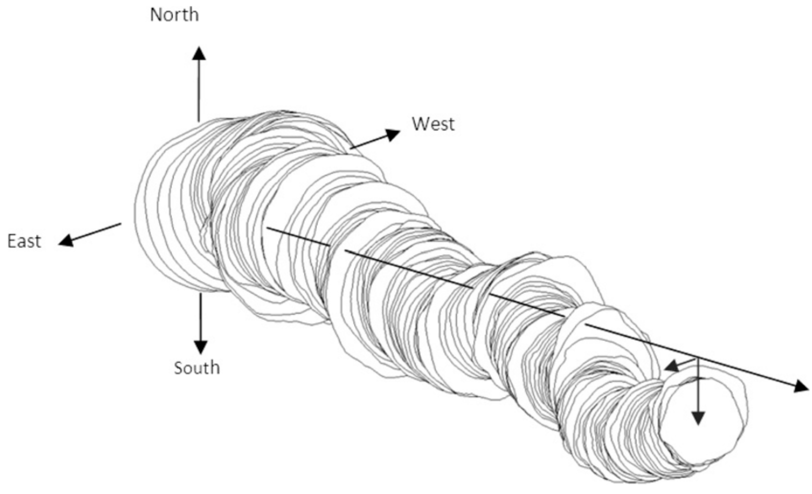


Figure 5. Example of calculated volume in the north direction.

south (Fig 5). All vectors were reorganized into four groups corresponding to the four cardinal directions (north, south, east, and west) according to the sign of the X and Y coordinates. Each group contained the vectors starting with the point of the same sign of the X or Y coordinates. For example, the north group contained the vectors starting with the points with positive Y coordinates, and the east group consisted of the vectors starting with the points with positive X coordinates, etc. The absolute difference in each coordinate of corresponding sign and group, eg $|y_i - y_{i-1}|$ for the north and south groups and $|x_i - x_{i-1}|$ for the east and west groups, was then determined for each vector in each group. The absolute differences were weighted using the scanning intervals $|z_i - z_{i-1}|$ and then summed. The weighted sum divided by the stem length gives the average displacement in each cardinal direction as shown in Eqs 3-6. These equations give an average of displacement in centimeters for each cardinal point.

It is also possible to proceed with another method to evaluate the effect of cardinal points.

$$VectorMethod(North) = \sum_{i=1}^{n} \left\{ \frac{|y_i - y_{i-1}||z_i - z_{i-1}|}{StraightLength}, \right. \text{if } y_i > 0, \text{ otherwise } 0 \quad (3)$$

$$VectorMethod(South) = \sum_{i=1}^{n} \left\{ \frac{|y_i - y_{i-1}||z_i - z_{i-1}|}{StraightLength}, \right. \text{if } y_i < 0, \text{ otherwise } 0 \quad (4)$$

$$VectorMethod(East) = \sum_{i=1}^{n} \left\{ \frac{|x_i - x_{i-1}||z_i - z_{i-1}|}{StraightLength}, \right. \text{if } x_i > 0, \text{ otherwise } 0 \quad (5)$$

$$VectorMethod(West) = \sum_{i=1}^{n} \left\{ \frac{|x_i - x_{i-1}||z_i - z_{i-1}|}{StraightLength}, \right. \text{if } x_i < 0, \text{ otherwise } 0 \quad (6)$$

The second approach to detect the deviation in each cardinal direction was based on stem volume in each quadrant of the stem. Each stem was divided into four quadrants along the Z axis with east from 45° to 135° (northeast to southeast), south from 135° to 225° (southeast to southwest), west from 225° to 315° (southwest to northwest), and north from 315° to 45° (northwest to southeast) (Fig 6).

The volume for each quadrant of the stem was the sum of the volume in each quadrant of

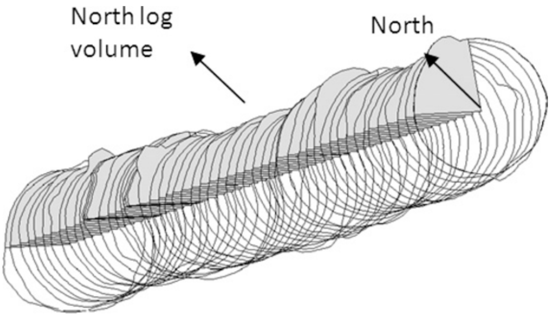


Figure 6. Example of calculated volume in the north direction.

stem segment between neighboring cross-sections. To simplify the calculation, stem segments were treated as cylinders. This may have compromised the precision of the volume estimate. Nevertheless, this should not have a considerable impact on the results because the sweep was expressed on a percentage basis (Eq 7) and all the volumes were calculated in the same manner:

$$Volume_D = \frac{SumVolume_D}{TotalVolume} \quad (7)$$

where D = north, south, east, or west.

## Statistical Analysis

The SAS system (SAS Institute, Inc., Cary, NC) was used for statistical analysis. Regression analysis was performed (PROC MIXED of SAS system) with stem curvature as the dependent variable and stand density and species as the indicator variables. Because of the nature of the Nelder plot, spatial coordinates of each sample should normally be included in the statistical models. In this study, statistical tests showed that spatial coordinates had no effect on the results. Thus, these were not included in the models. Data transformations were necessary to ensure that the assumption of homogeneity of variance and normality were met. Variables were natural logarithm-transformed before analysis.

# RESULTS

Tree diameter at breast height (DBH) for white spruce ranged from 9.9 to 27.0 cm, whereas that for jack pine ranged from 11.5 to 33.8 cm (Table 2). The total length of the white spruce trees ranged from 7.5 to 17.5 m, whereas that for jack pine ranged from 10.6 to 19.5 m.

## Stem Curvature

First, results revealed that initial spacing affected several variables such as DBH, taper, live crown length, width of live crown, and volume and diameter of live knots. Stem curvature (maximum deflection) and taper were highly correlated with stand density and species at the 95% confidence level. Tree taper decreased with an increase in stand density (Fig 7), which is consistent with the theory (Jozsa and Middleton 1997). The principal change in stem form from the open-grown to the stand-grown condition was the decrease in taper associated with the decrease in live crown length caused by branch mortality. A smaller live crown decreases radial growth in the lower part of the tree (compared with radial growth in the live crown), which

Table 2. Stem summary data for jack pine (JP) and white spruce (WS).

| Species | No. of stem | | Curvature max. deflection (cm/m) | Taper (cm/m) | DBH (cm) | Total length (m) | Live crown length (m) | Live crown dimension (m) | Stem volume ($dm^3$) |
|---|---|---|---|---|---|---|---|---|---|
| JP | 46 | Average | 0.894 | 1.071 | 18.5 | 17.1 | 6.3 | 3.4 | 238.7 |
| | | Maximum | 3.650 | 2.871 | 33.8 | 19.5 | 10.5 | 9.0 | 597.6 |
| | | Minimum | 0.402 | 0.627 | 11.5 | 10.6 | 1.6 | 0.7 | 70.1 |
| | | Standard | 0.532 | 0.407 | 4.9 | 1.9 | 2.1 | 1.8 | 115.0 |
| WS | 50 | Average | 0.666 | 1.497 | 18.0 | 12.7 | 5.5 | 3.7 | 175.4 |
| | | Maximum | 1.736 | 2.232 | 27.0 | 17.5 | 12.5 | 6.7 | 408.0 |
| | | Minimum | 0.226 | 0.581 | 9.9 | 7.5 | 1.6 | 1.2 | 38.7 |
| | | Standard | 0.295 | 0.413 | 4.8 | 1.8 | 2.2 | 1.4 | 97.9 |

DBH, diameter at breast height.

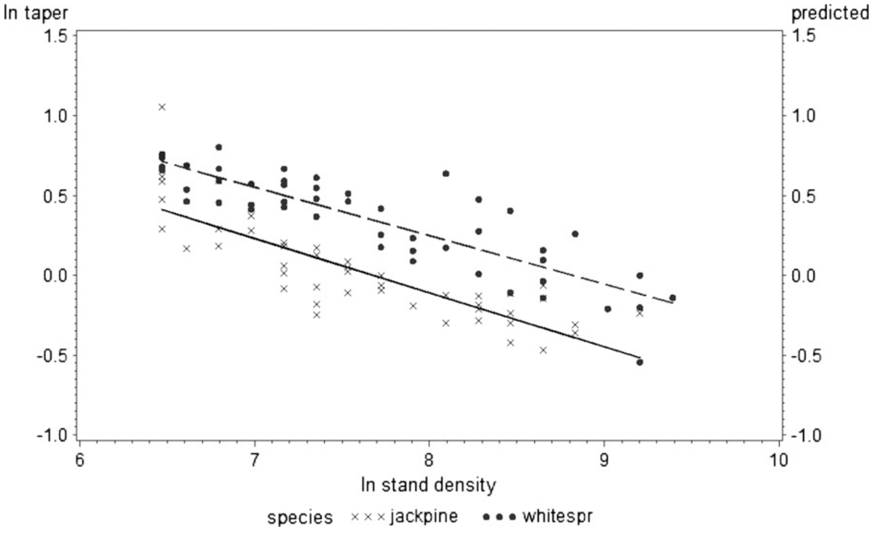


Figure 7. Natural logarithm of taper as a function of natural logarithm of stand density for jack pine (x) and white spruce (dots). (The stand density values are transformed into logarithmic values. For example, ln[640 stems/ha] corresponds to 6.5, whereas ln[12,000 stems/ha] corresponds to 9.4 on the logarithmic scale.)

decreases the overall taper of the stem (Panshin and de Zeeuw 1980; Jozsa and Middleton 1997). The fluctuation of height growth of trees in stands of dissimilar density has been ascribed to a number of causal factors; among these are wind and light in addition to the well-known effects of soil moisture (Larson 1963). On average, white spruce taper was significantly larger than jack pine taper (Table 3; Figure 7).

With the method of maximum deflection for curvature evaluation, there was a statistically significant difference between species. Indeed, jack pine curvature was significantly higher than white spruce curvature at 99.9% confidence level (Table 3). As shown in Fig 8 for both species, the curvature (maximum deflection) decreased with increasing stand density. With respect to the slope of the relationship between the logarithms of curvature and the logarithm of stand density, Fig 8 shows that the slope for jack pine is almost the same as that for white spruce.

Table 3. Statistical results using an indicator variable for taper.

| | Source | F value | Pr > F |
|---|---|---|---|
| Taper | Species | 101.89 | <0.0001 |
| | Log_density | 228.24 | <0.0001 |
| | Log_density*species | 0.72 | 0.3984 |

However, when the curvature calculation was evaluated with the length of the vector, we obtained an interaction between stand density and species, indicating that the slope of the curves between the two species significantly differed (Table 4). The results suggest that the method of calculating curvature commonly used may not be appropriate in all situations. When characterizing the curves, it is important to consider the smallest deviations because no matter how small they are, they may have an impact on the quality of the wood or lumber produced.

In addition to this interaction between species and stand density, it was possible to detect a breaking point for jack pine, which suggests that the relationship between curvature and stand density is not linear. Indeed, performing the Bacon and Watts (1971) test, the piecewise model, showed that stem curvature of jack pine changed significantly below 1600 stems/ha. For a stand density lower than 1600, curvature increased considerably for jack pine. Above 1600 stems/ha, curvature varied little. White spruce also appeared to have a breaking point around 3000 stems/ha, but this was not statistically significant (Fig 9). For white spruce, curvature decreased in a similar way. That is, it decreased steadily with

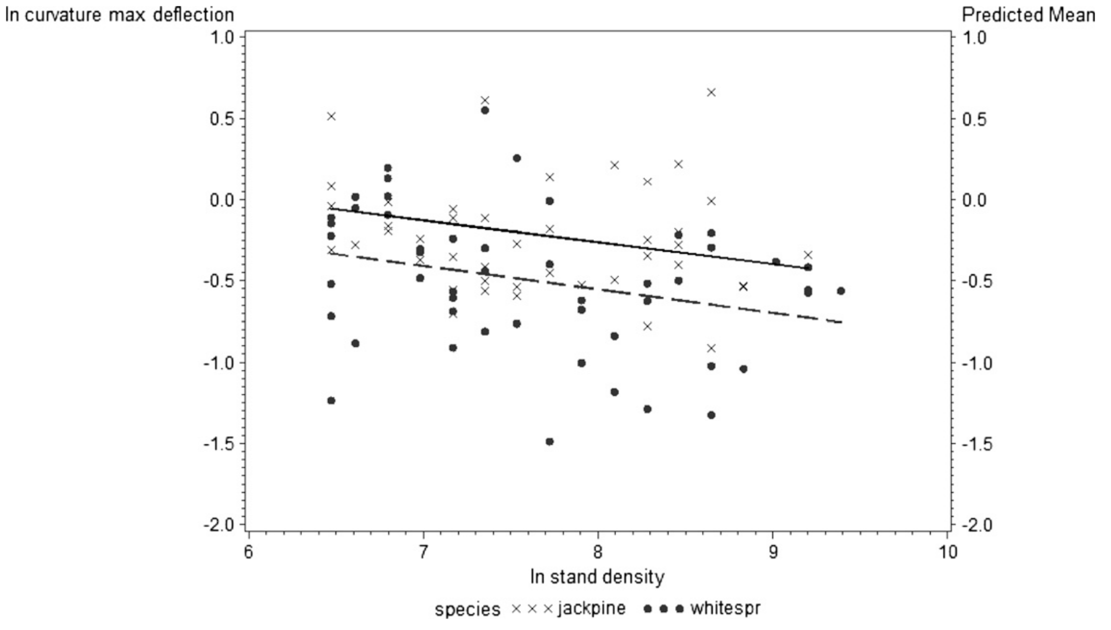


Figure 8. Natural logarithm of curvature as a function of natural logarithm of stand density (maximum deflection method) for jack pine (x) and white spruce (dots).

increasing stand density for the site sampled. The Bacon and Watts test was also used to determine if there was a breaking point with the maximum deflection curvature maximum method. This test has not proved to be significant. It is therefore not possible to observe a breaking point with the method of maximum deflection that results in a linear relationship with stand density for both jack pine and white spruce. However, when the general relationship of the two species was compared, there was a statistical difference between the curves. Jack pine was significantly more crooked than white spruce, regardless of stand density.

Table 4. Regression with indicator variable (comparison of curvature calculation method).

| | Source | F value | Pr > F |
|---|---|---|---|
| Curvature | Species | 11.59 | 0.0010 |
| Maximum deflection | Log_density | 7.00 | 0.0096 |
| | Log_density*species | 0.01 | 0.9159 |
| Curvature | Species | 55.35 | <0.0001 |
| vector method | Log_density | 27.69 | <0.0001 |
| | Log_density*species | 4.71 | 0.0325 |

## Cardinal Points

Analysis of the effect of cardinal points on stem shape is shown in Table 5. Results showed an interaction between orientation and species. This relationship means that the positioning of jack pine as a function of the cardinal points did not occur in the same way as in white spruce (Fig 10).

As shown in Fig 10, the position of the center of the disks, ie the sum of all vectors in each of the cardinal points across the length of the tree, is different for the two species involved. In other words, the behavior of jack pine is different from white spruce with respect to the positioning of the disks on the Z axis. Jack pine moves randomly in all directions (north, south, east, and west), whereas white spruce tends to position itself significantly more often in the south and west directions (Fig 10). Several factors could affect the shape according to the cardinal points, such as shade tolerance, prevailing winds, the search for more light by height and crown development patterns, and branching present in the southern part of the stem. These

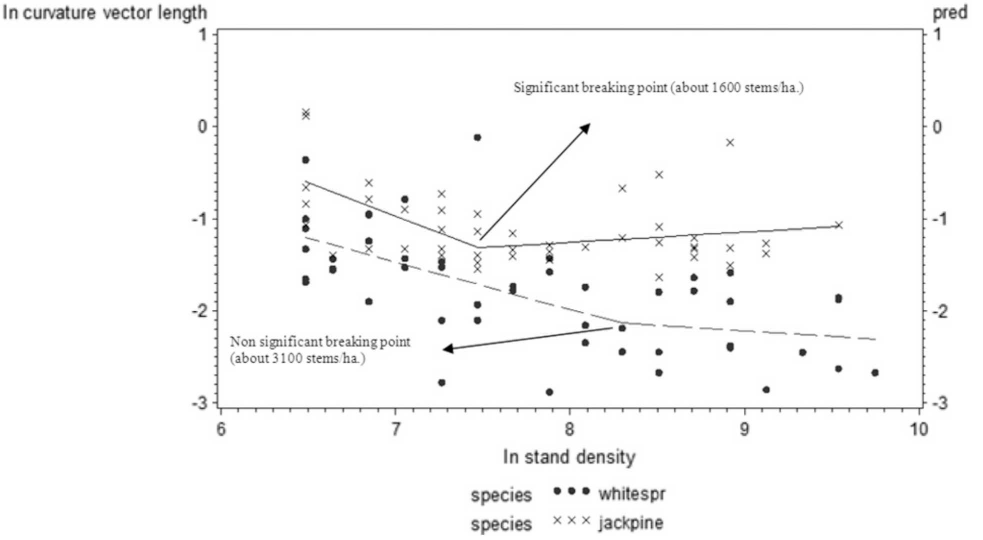


Figure 9. Natural logarithm of curvature as a function of natural logarithm of stand density calculated with piecewise test (using vector method) for jack pine (x) and white spruce (dots).

potential factors need to be examined in future studies. The fact that jack pine is prone to large branch and stem deformities at wide tree spacings may be the reason why there are no differences among cardinal points. The two species were statistically different in all directions except west. Moberg (1999) found that the azimuth direction in which branches grew had a highly significant effect on knot size. In general, the largest knots were found toward south, and the smallest knots were found toward north, whereas the other directions commonly resulted in intermediate knot sizes. Another external factor affecting stem form was the lateral incidence of light. Phototropism may play a relevant role in the determination of stem form (Sierra-de-Grado et al 1997). Different external factors may affect the main stem, inducing curvature. For instance, damage in the apex of the leader by frost, wind, or herbivores usually induces lateral branch dominance. Reorientation of a lateral branch to the vertical position is a typical origin of curvature in the bole (Loup 1990). The effect of wind in causing basal curvature of the bole has also been reported (Polge and Illy 1967; Radi and Castera 1992).

Table 5. Effect of orientation on tree positioning (repeated-measure analysis of variance).

| | Source | F value | Pr > F |
|---|---|---|---|
| Orientation | In-stand density | 0.10 | 0.7526 |
| Vector method | Species | 4.35 | 0.0400 |
| | Orientation | 10.70 | <0.0001 |
| | Species*orientation | 8.39 | <0.0001 |

The volume method (Fig 11) is also interesting for calculating the effect of cardinal points. To obtain the normality of the data, an arcsin transformation was done. In this study, as expected, the conclusions for the vector and volume methods are almost the same. There is also an interaction between orientation and species (Table 6). This observation means that the volume positioning of jack pine as a function of the cardinal points did not occur in the same way as in white spruce. Again, for white spruce, the volume was placed more in the west and south quadrants. For the volume method in the north and east directions, there was no difference between the two species, which differs from the vector method.

## CONCLUSIONS

This study highlights the impact of stand density on stem shape for a 32-yr-old jack pine and

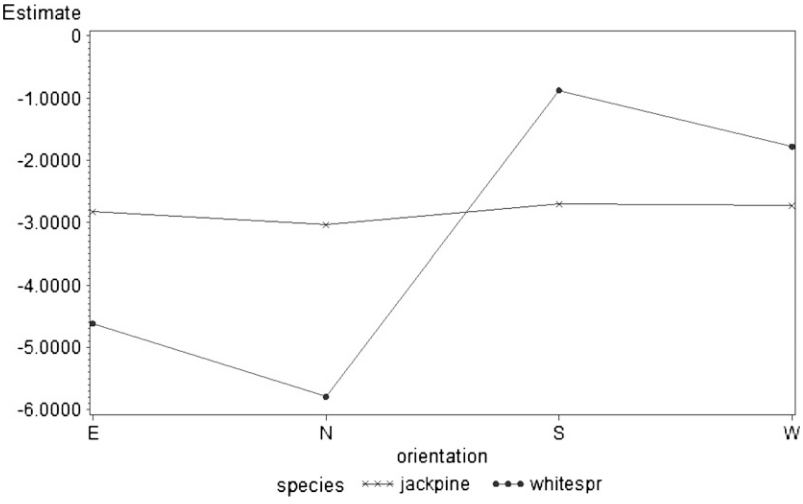


Figure 10. Tree positioning according to the cardinal points (vector method) for jack pine (x) and white spruce (dots).

white spruce Nelder plantation. The two species were not affected in the same way. There were statistical differences between jack pine and white spruce for factors such as stem taper and curvature at this study site. This study showed that the method used to calculate tree curvature is important for data analysis. This research has demonstrated that curvature using vectors clearly shows a significant interaction between species and stand density, whereas no interactions were seen with the maximum deflection method. The calculation method using the vector lengths shows that curvature of jack pine was more pronounced and more sensitive to low densities than that of white spruce. Also, the increase or decrease in curvature of jack pine was not constant according to stand density. Indeed, there was a change in the slope under 1600 stems/ha, indicating a significant increase in curvature. For white spruce, there was no statistical difference in the slope, suggesting that curvature increased steadily with a decrease in stand density.

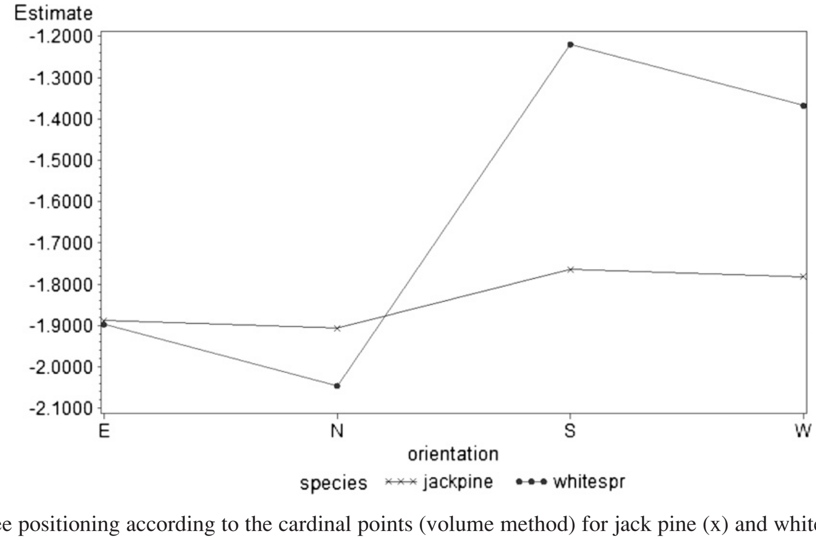


Figure 11. Tree positioning according to the cardinal points (volume method) for jack pine (x) and white spruce (dots).

Table 6. Effect of orientation on tree positioning using the volume method (repeated-measure analysis of variance).

| | Source | F value | Pr > F |
|---|---|---|---|
| Orientation | In-stand density | 6.98 | 0.0097 |
| Volume method | Species | 8.71 | 0.0094 |
| | Orientation | 7.30 | <0.0001 |
| | Species*orientation | 3.58 | 0.0144 |

These differences were not noted with the maximum deflection method. Therefore, results suggest that the method using vector lengths is better for diagnosing the impact of stand density on tree growth and could be used to optimize spacing selection in plantations. More research needs to be undertaken to determine this density threshold for white spruce and other commercially important planted tree species. Including a shade tolerant species such as black spruce would be of further value in exploring these relationships.

Results also showed that jack pine developed stem curves in all directions regardless of the cardinal points. Two methods were used: one with vectors and the other with volume. The two methods gave the same conclusions. Jack pine moves randomly in all directions with both methods (north, south, east, and west). White spruce tends to grow more south and west for both methods. Although several hypotheses may explain these results, such as quality and seasonal exposure to solar radiation, prevailing winds, or shade tolerance characteristics, the position of the rows used in this study may also be a factor. Hence, future research should examine this factor with seasonal and daily solar radiation patterns.

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