Effects of Stem Inclination on Compression Wood Formation in Young Radiata Pine Trees

Barbara Lachenbruch
Department of Wood Science and Engineering
Oregon State University
Corvallis, OR 97331

Fernando Droppelmann
Instituto de Silvicultura
Universidad Austral de Chile
Valdivia, Chile

Many individuals of radiata pine (*Pinus radiata* D. Don) have crooked stems, which can hinder volume recovery and wood quality. We tested the hypotheses that 1) trees with straight stems have less compression wood (CW) than trees with crooked stems, 2) the amount of CW in samples from either straight or crooked trees is positively correlated with the sample's inclination, and 3) straight trees produce more CW at a given inclination angle than crooked trees. The study was undertaken for 142 days in 5-year old trees in a plantation in Chile. Trees were tethered just below the last whorl of the previous year's growth to either 15º or 30º, or they were left untethered. On the 15º trees, we also marked and sampled the zone at which the stem inclination was 7.5º, and on the 30º trees, we marked and sampled the zones at which the stem inclination was 7.5º and 15º.

1) There was no significant difference in the amount of CW in straight vs. crooked trees, as shown by the wood that had been produced before the experiment began. 2) For the older positions, there about 25% CW in vertical stems and a weak positive correlation between stem angle and the amount of CW. In younger positions, there was a two-phase response. Below the threshold inclination of 10º, young stems had CW from 0-50% of the circumference. At stem inclinations >10º, these stems never had the low values of CW, but instead produced CW from 30-60% of their circumferences. 3) Trees with straight stems tended to produce more CW for a given original inclination angle than did trees with crooked stems in the older wood that was studied. In some cases this difference was statistically significant. Younger wood showed no such tendency.

Keywords: Compression wood, radiata pine, wood quality, wood development, sinuosity

Introduction

Many coniferous tree species have poor stem form that can hinder both volume recovery and value. Value can be lost because of elevated incidence of compression wood (CW) and increased slope of grain, both of which can increase longitudinal shrinkage and warp (Harris 1977), decrease strength values, and decrease appearance values. Compression wood is also bad for production of pulp (da Silva Perez and Fauchon 2003). Radiata pine (*Pinus radiata* D. Don) is a commercial species that is notorious for its often poor form. Here we compared straight trees, to crooked trees, whose main stem had a significant level of sweep and/or sinuosity.

These trees were growing intermingled with one another within an operational plantation, suggesting that the causes of stem form differences were genetic, and not strictly environmental. Previous studies have shown many environmental correlates with poor stem form in radiata pine, such as nutrient availability (Turvey et al. 1992, 1993), previous land use (Carlyle et al. 1989), wind environment (Burdon 1975, Turvey et al. 1993), and potentially other factors as well that have not been identified but that differ from site to site (Burdon 1975, Burdon and Low 1992). Other studies have given abundant evidence that many stem form differences are genetic (e.g., Pederick 1984, Burdon and Low 1992). However, stating that the causes are 'genetic' still leaves open the actual causality for one genotype to differ from another. Possibilities include that compared to crooked trees, the straight trees have a better-aligned apical bud that can then grow vertically with little deviation, that the straight trees have stiffer stems, and/or that the straight trees have a tighter regulation of apex angle, reacting more rapidly than crooked trees to become straight once again. In this research, we tested only the latter possibility, related to overcompensation (reviewed in Timmell 1986, and suggested explicitly by Harris 1977, Downes et al. 1994, and Gartner and Johnson 2006). If the tree leans to a large angle before compression wood (CW) is formed, the apex may adjust to vertical before the slightly lower region of the leader adjusts toward vertical. When the lower part has fully adjusted, the former apex (no longer at the apex because of continued growth) is pushed away from vertical, requiring the production of more compression wood to right the stem, and so on.

We tested the following hypotheses. 1) Trees with straight stems have less CW than trees with crooked stems, 2) the amount of CW in samples from either straight or crooked trees is positively correlated with the sample's stem inclination, and 3) straight trees produce more CW at a given angle of stem inclination than do crooked trees.

Materials and Methods

Site, Plant Material, and Treatments

Trees were sampled from San Alejandro, a 4-year old operational plantation near Valdivia, Chile. The half-sib trees were planted as 1-year old seedlings in 2002. We initiated studies on 11 Jan. 2006, at which time trees were part-way through their fifth year.

Two observers walked between rows of trees, searching for extremes of form that were either very straight or very crooked. Straight trees had main stems (excluding the current year's leader growth) that were within 2-3° of vertical and that appeared straight, both within interwhorls and in the mutual alignment of subsequent interwhorls. Crooked trees had main stems with either marked sweep and/or marked sinuosity.

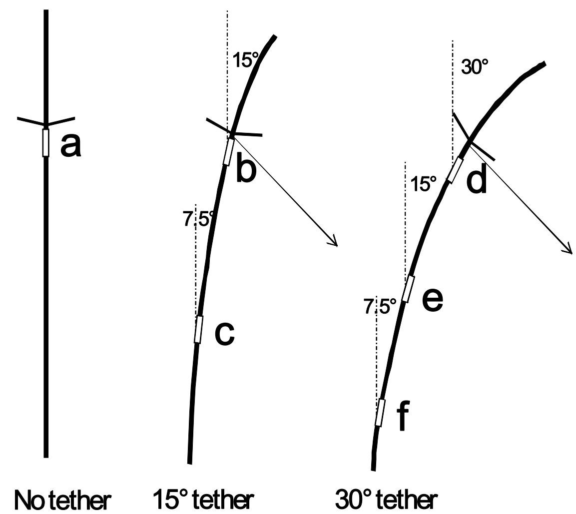

Fig. 1. Diagram of the three inclination treatments: no tether, 15° tether, and 30° tether showing sample locations (white rectangles).

After a sufficient number of trees had been found, we divided them into three treatments for each stem type: no tether, 15° tether, and 30° tether (Fig. 1). For trees in the 15° and 30° tether treatments we attached a hose-covered wire just below the final branch whorl that had been formed in the previous growing season.

Tethered trees were pulled in the direction of the prevailing wind, and the wire was attached to a stake such that the stem in the 20-cm zone basal to the tether was either 15° or 30° from vertical. The same zone was marked on the no-tether trees, but no tether was attached.

We marked the center of these zones, and designated them as position *a, b, and c* in the no-tether, 15°, and 30° trees, respectively (Fig. 1). For trees in the 15° tether treatment, we also marked the point where the stem was 7.5° (position *c*). For trees in the 30° tether treatment, we also marked the points where the stem was 15° and 7.5° (positions *e* and *f*, respectively). At harvest, wood age averaged 1.5 years in the upper positions (*a*, *b*, and *d*), 2 years in position *c*, 2.3 years in position *e*, and 2.7 years in position *f* (Table 1).

Sample position	Straight	Crooked	p
Growth rings (no.)			
a	1.5 ± 0.2	1.6 ± 0.2	0.6420
b	1.4 ± 0.2	1.4 ± 0.2	1.0000
c	2.0 ± 0.0	2.0 ± 0.0	no variance
d	1.4 ± 0.2	1.6 ± 0.2	0.9661
e	2.0 ± 0.0	2.5 ± 0.2	no variance
f	2.9 ± 0.1	2.6 ± 0.2	0.2782
Compression wood score in pre-treatment wood in stem			
a	2.6 ± 0.6	3.3 ± 0.5	ns
b	1.8 ± 0.3	2.6 ± 0.5	ns
c	3.1 ± 0.6	3.9 ± 0.6	ns
d	1.8 ± 0.4	2.0 ± 0.3	ns
e	3.6 ± 0.7	3.5 ± 0.5	ns
f	4.1 ± 0.5	3.8 ± 0.7	ns

Table 1. Number of growth rings and compression wood score in the pre-treatment wood (1 is low, 6 is high) at the different positions sampled (see Fig. 1). Mean ± s.e., n=8 trees per tree type and treatment combination.

Angle Measurements and Harvest

Angles were measured at all positions (*a-f*) six times throughout the 142-day period. The same observer stood several meters from the tree at 90° from the tether, and held a protractor with a plumb bob such that the protractor aligned visually with the 20-cm long zone of the stem surrounding the position. The plumb indicated the stem angle.

On 22 May 2006, 142 days after treatment had started, we measured the angles of all the positions for a final time. The 20-cm long stem segment from each position was labeled and harvested.

Wood and Data Analyses

All CW measurements were undertaken on wetted cross-sections to enhance the color contrast between CW and normal wood. The CW did not vary much in its color and so we used the presence of this brown coloration as an indicator of CW.

To learn whether there were differences in the amount of CW in straight vs. crooked stems we examined the pre-treatment wood, which was the wood that had formed before the stems were manipulated. Samples were categorized visually from 1-6 on the basis of the proportion of the pre-treatment transverse area that was CW: 1, 0% CW; 2, <5% CW; 3, 5-15% CW; 4,

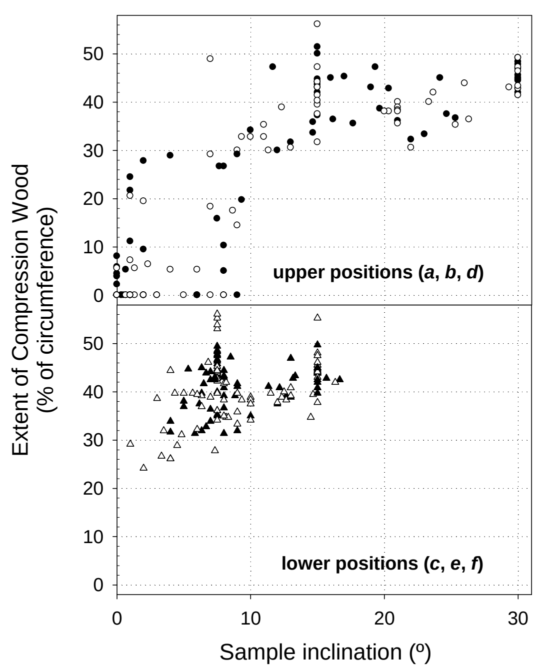

Fig. 2. Extent of compression wood vs. the inferred angle of the stem at the time of wood formation for samples on the leader and samples that are not on the leader, separately. There are three points per sample representing three dates and thus positions along the stem radius. Closed symbols are straight trees, open symbols are crooked trees.

5-25% CW; 5, 25-40% CW; and 6, 40-60% CW. All 96 samples were examined together and with their labels hidden, to ensure a consistent designation of categories.

Extent of CW in the post-treatment wood was estimated as the proportion of the circumference in which the new wood was brown. This extent was measured for three radial locations within the new growth: at the beginning, middle, and end of the new growth. We also determined stem ages for each sample.
Stem age, CW score of pre-treatment wood, CW extent, and stem angle were analyzed with a two-factor analysis of variance with the factors of tree type (straight, crooked) and position (a, b, c, d, e, f) using SAS v. 6.11. Regression analysis was calculated with SigmaPlot 2002 for Windows v. 8.

Results

Samples from straight trees had no significant differences in compression wood (CW) score for pre-treatment wood from samples from crooked trees at any position (Table 1). There was no apparent difference in the amount of CW made at a given stem inclination for straight trees (filled symbols) vs. crooked trees (open symbols, Fig. 2).

For the youngest wood studied (positions *a*, *c*, and *d*), there appeared to be a two-phase response: at stem inclination angles of 0-10º samples had from 0-50% of their circumference in CW, but at angles >10º samples had 30-60% of their circumference in CW (Fig. 2). Within either phase, there was no strong relationship of angle with CW extent.

For the older wood (positions *b*, *e*, and *f*), there was always at least 25% CW, even at very low inclinations (1-3º), and the samples all had from 25-60% of their circumference in CW (Fig. 2). Linear regression analysis showed a weak but significant adjusted r^2 of 0.13 for inclination angle vs. CW extent when data from straight and crooked trees were pooled. Straight trees alone had an adjusted r^2 of 0.08, and crooked trees had an adjusted r^2 of 0.15.

In the first days of the experiment, there were no significant differences in the extent of CW produced in straight vs. crooked trees for any of the positions (Fig. 3).

Note, however, that the inclination had a large effect: position *a* had about 2-5% compression wood in

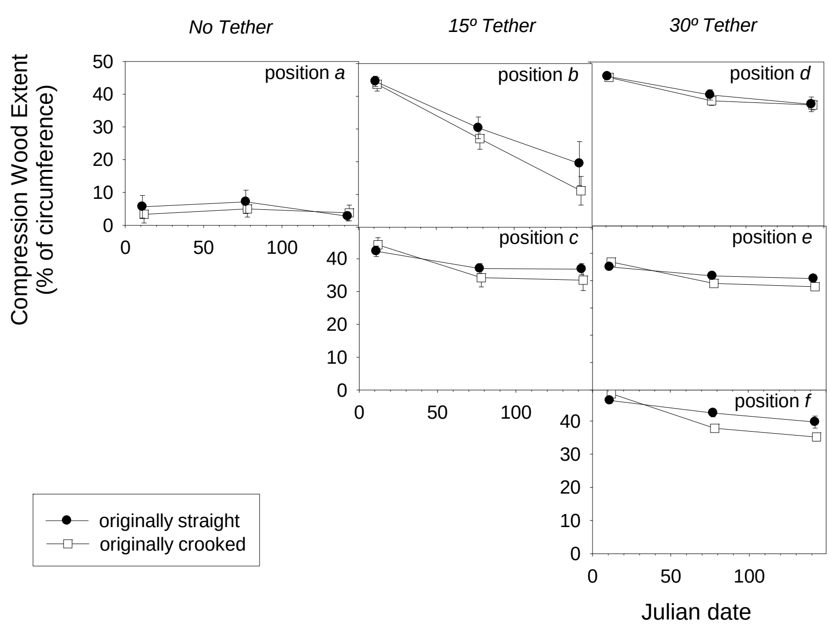

Fig. 3. Extent of compression wood formed throughout the experiment at each position. Mean ± s.e (n=8 values per point).

the newly produced wood, but the same-aged tethered positions, *b* and *d*, had about 45% CW. As the season progressed, there was a tendency for the straight trees (filled circles) to produce more CW than crooked trees (open squares) for all positions. These differences were significant ($p<0.05$) at positions *e* and *f* for both JD 77 and JD 142.

Discussion

Contrary to expectation, there was no significant difference in the amount of compression wood (CW) in straight vs. crooked trees. Also contrary to expectation, the relationship between stem angle and amount of CW was not strong, although it was positive. Lastly, there was little evidence that straight and crooked trees reacted differently to inclination in terms of production of CW: for a given angle there was no difference in the extent of CW produced by the different tree types, but by the end of the experiment the straight trees had slightly more compression wood than did the crooked trees at the lower positions.

One of the most interesting results of this study comes from the finding that there were only minor differences in CW production in straight and crooked trees. In the last two sampling dates, 9 of the 10 sets of samples that had been tethered had a higher CW extent in the straight than the crooked trees (although this difference was not always significant). The actual inclination of the stems for these same 10 sets of samples was actually higher in the originally straight trees than the originally crooked trees for 7 of these 10 samples (data not shown) because over time, the crooked trees straightened out more than did the straight trees. These data, therefore, suggest that the straight trees were slightly less effective than the crooked trees at straightening themselves when given the same inclination: a unit of CW appeared to be less effective at righting a stem in straight trees than in crooked trees. The differences may have been sufficient to cause overcompensation in crooked, although in a manner slightly different than our original hypothesis: crooked trees appeared to right themselves more than did the straight trees when they were placed at an angle, displacing the distal portions, which had already started to grow vertical so these apices then had to re-adjust, and so on, leaving crooks in the stem.

A second interesting result from this study was the looseness and shapes of the relationships between inclination and CW production. It is not remarkable that the upper stem parts and lower stem parts showed different relationships, but the lack of strong correlation between inclination angle and CW extent is more surprising. Numerous studies imply rather tight relationships of the two variables (e.g., as reviewed in Westing 1965, Timmell 1986) but other studies show a large amount of scatter (e.g., Barger and Ffolliott 1976) as seen here. These results underscore the dangers of modeling CW from inclination angle alone, and point to our incomplete understanding of where and when CW will form in stems.

Overall this study suggests that *Pinus radiata* individuals with crooked stems have a propensity to make compression wood that is more effective than individuals with straight stems, but that an enormous amount of compression wood is made by both crooked and straight stems of most individuals regardless of stem form in this Chilean plantation, in saplings in their first five years of life.

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Acknowledgments

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