Jones et al. New Zealand Journal of Forestry Science 2013, 43:10
http://www.nzjforestryscience.com/content/43/1/10

New Zealand Journal of Forestry Science
a SpringerOpen Journal

RESEARCH ARTICLE Open Access

Effect of stem bending and soil moisture on the incidence of resin pockets in radiata pine

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Abstract

Background: Mechanical bending stress due to tree sway in strong winds and water stress during drought are thought to contribute to the formation of resin pockets, but it is unclear if these are linked and whether the initiation of resin pockets is influenced by the water status of the trees at the time of stem bending.

Methods: The effect of stem bending on the formation of resin pockets was evaluated under various soil moisture conditions. The stems of 12-year-old radiata pine (*Pinus radiata* D.Don) trees were bent mechanically in spring or summer when the soil was water deficient, and in summer after rehydration. After the completion of the growth season, a selected sample of trees was felled and stem discs were assessed for the presence of resin pockets, using disc photos and image analysis. All stem bending treatments were compared with control trees.

Results: Stem bending in spring or summer was found to increase the number of Type 1 resin pockets, but had no effect on the number of Type 2 resin pockets. The soil moisture conditions at the time of stem bending had no effect on the number of Type 1 or 2 resin pockets.

Conclusions: The Type 1 resin pockets occurred in the inner part of the early wood, adjacent to the growth ring boundary. This suggests the Type 1 resin pockets were initiated in the mature wood, behind the cambium and zone of differentiation, and were not influenced by the water status of the tree stems at the time of stem bending.

Keywords: Resin pockets; *Pinus radiata*; Stem bending; Water stress; Winching

Background

Resin pockets are a major cause of degrade in the appearance grade timber of radiata pine (*Pinus radiata* D. Don). When present at moderate to severe levels in the logs of radiata pine, they can lead to significant reductions in the value of the timber (McConchie & Turner, 2002; Cown et al., 2011). Resin pockets occur as Type 1 and 2 forms in the logs of radiata pine (Sommerville, 1980; McConchie et al., 2008; Ottenschlaeger et al., 2012). Type 1 resin pockets are described as lens-shaped accumulations of resin and callus tissue within a growth-ring that cause no damage to the cambium, while Type 2 resin pockets are similar except the cambium is ruptured and healing results in an occlusion scar that can occur over several growth rings. Resin pockets occur at some level in all stands of radiata pine in New Zealand (Park, 2004), but reach epidemic levels in regions that are windy and/or dry. The formation of resin pockets in trees is thought to occur as a result of the stress associated with wind exposure. Frey-Wyssling (1938; 1942) suggested that resin pockets in European larch (*Larix decidua* Mill.) and Norway spruce (*Picea abies* (L.) Karst.) were formed as checks in the cambium due to wind forces. The swaying of trees in strong winds was believed to induce sufficient shear stress in the cambium to cause tearing of the cells in the tangential direction, which formed into resin pockets. Wind exposure was proposed by Clifton (1969) as the cause of the high incidence of resin pockets in radiata pine grown in Canterbury, New Zealand. The distribution of resin pockets in the trees suggested a mechanically induced cause - in the vertical direction the resin pockets were predominant in an area representing the zone of maximum wind sway, and in the radial direction the incidence of resin pockets decreased when the trees

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reached a size where they were able to resist wind sway (Clifton, 1969). The exposure to wind has been implicated in the increase in the number of resin pockets observed after storm events in central Europe. Survivor trees of European larch and Norway spruce have been shown to produce resin pockets more intensively in the years following severe storms (Wernsdörfer et al., 2002; Zielonka & Malcher, 2009). The increase in the number of resin pockets is thought to occur as the result of wind sway in the remaining stems of the storm thinned stands. Heavy thinning of managed plantation forests to low final stockings has produced similar increases in the number of resin pockets in Norway spruce in central Europe (Schumacher et al., 1997) and radiata pine in New Zealand (Barker & Tombleson, 1999; Dean & Barker, 1999). However, Watt et al. (2011) found no relationship between the incidence of resin pockets and wind speed at a given site.

The role of stem movement on resin pocket formation has been evaluated in controlled experiments involving stem bending, and restraints on wind sway. Temnerud et al. (1999) found the application of mechanical bending stress during growth to the stems of 5-year-old Scots pine (*Pinus sylvestris* L.) trees increased the formation of xylem wounds that resembled resin pockets by 30% over the controls. Watt et al. (2009) found that restraints on 14-year-old radiata pine trees to limit wind sway reduced the number of resin pockets, compared with unrestrained control trees on the Canterbury Plains in New Zealand. The effects were most marked on the incidence of Type 1 resin pockets. Ottenschlaeger et al. (2012) proposed a common cause triggering the occurrence of Type 1 and Type 2 resin pockets.

Water stress due to drought has been proposed as a cause of resi pockets of radiata pine in New Zealand and Norway spruce in Europe. Cown (1973) showed that resin pockets in radiata pine on the Canterbury Plains in New Zealand were often associated with false rings, which are an indirect effect of soil moisture deficit on xylem formation. More recently, the availability of water was found to be a factor in the formation of resin pockets in radiata pine in the central North Island of New Zealand (Woollons et al., 2009). This analysis was based on observations of resin pocket occurrence. The authors found that high vapour pressure deficit in October (which is a measure of water demand), low soil water availability, stem top-outs (which are a highly localised measure of maximum wind gusts), and fast diameter growth (which is indicative of early heavy thinning) were positively related to the number of resin pockets. Seifert et al. (2010) found that stress due to lack of water appeared to play a role in the presence of resin pockets in Norway spruce, with increased numbers of resin pockets associated with lower precipitation during the growth season, wider growth rings, and longer crown lengths. Watt et al. (2011) reported the incidence of resin pockets in radiata pine showed regular peaking in the latter part of the growth rings on sites where the water stress would be expected to peak late in the growing season.

The way in which water stress leads to resin pocket formation, and how it interacts with stem movement is not understood. The association of resin pockets with false rings suggests that soil water deficits lead to zones of weakness in the growth rings (Cown, 1973), which predisposes the trees to resin pocket formation during wind events. However, it could be that changes in cell turgor pressure in the cambium following the release of water stress, lead to conditions that predispose the cambium to damage and the formation of resin pockets. The cells in a severely water-stressed cambium tend to load their vacuoles with minerals that will help the cell retain enough water to prevent death (Sudachkova et al., 1994). Over the surface of the cambium, there will be gradients of cells with lower or higher osmotic potential. When a heavy rainfall event occurs, the sudden influx of water will be drawn into the vacuole of some cells more rapidly than others. Those with a very high osmotic potential will be better competitors, than cells with lower osmotic potential, and the influx of water and high cell turgor pressure could make the cambium more susceptible to mechanical damage.

In this study, a field experiment was undertaken to determine the interactive effects of stem movement and water stress on resin pocket formation in a 12-year-old radiata pine stand. The stems of the radiata pine trees were mechanically bent at two different times during the 2007/2008 growing season, over a range of naturally occurring and artificially induced soil moisture conditions. Following the completion of this growth season, the incidence of resin pockets was assessed and compared with unbent control trees. Type 1 and Type 2 resin pockets were assessed.

Methods

Site selection

A stand of 12 year-old radiata pine trees in Balmoral forest, Canterbury, New Zealand (latitude 42° 49’ 56”, longitude 172° 47’ 20”, altitude 190 m, slope 0°) was selected as the trees had high levels of external resin bleeding, a trait that has been found to be positively related to resin pocket incidence (McConchie & Turner, 2002). The long-term annual rainfall at the site is 624 mm year^{-1}, which is considered low. The soils are Balmoral stony and shallow silt loams (Soil Bureau, 1968). The low water storage capacity (47% soil fractional root-zone water storage, Palmer et al., 2009) of the soil, in combination with the low rainfall and high evaporative demand over spring and summer, typically results in severe seasonal soil water deficits in summer. The stand was planted in 1995 at a stocking rate of 868 stems ha^{-1}, and was thinned to waste in 2003 to 600 stems ha^{-1}.

Stem bending treatments

The trees for the stem bending and control treatments were selected for moderate to severe external resin bleeding and the absence of dead-tops. The stem bending treatments were applied during the growing season in spring, and in summer when the trees were water-stressed and after the trees had been released from water stress by the application of water (Table 1). The trees were allocated to treatment groups to provide a balanced distribution of diameter at breast height, height, and external resin feature score (McConchie, 2003) for each of the stem bending treatments and control (Table 2).

The spring stem bending treatment was applied in late September 2007, after the commencement of new shoot growth. Soil conditions at the Balmoral forest site were dry at the time of the spring stem bending treatment (Table 2), with little rainfall having occurred during the preceding winter and early spring. The ten trees were bent using a winch to 30% of the predicted failure load of the trees (Table 1), to simulate strong winds, while staying within the elastic limits of the stem. This was done to prevent structural damage to the stem and roots that might affect the tree diameter growth during the subsequent growth season.

The summer water-stressed stem bending treatments were applied in early February 2008, when the Balmoral forest site was experiencing extreme soil water deficit (Table 2). Stem bending commenced on the first day under these dry soil conditions, with three of the ten trees winched. Then overnight the site experienced 78 mm of rainfall, and the stem bending of the remaining seven water-stressed trees was completed over a period of two days under conditions of partial rehydration, as it takes 24 to 48 hours for trees to rehydrate from soil water deficits (Rook et al., 1976). The ten trees were bent using a winch to 30 or 40% of the predicted failure load of the trees (Table 1). The 40% of the failure load was applied to achieve the same range of tree stem deflection and bending moment that was obtained with the application of 30% of the failure load in the spring stem bending treatment.

Table 1 Description of the stem bending and control treatments

Treatment	% of failure load	Number of trees
Control		10
Stem bending, Spring	30	10
Stem bending, Summer – water stressed	30	5
Stem bending, Summer – water stressed	40	5
Stem bending, Summer – released from water stress	30	5
Stem bending, Summer – released from water stress	40	5

The summer released-from-water-stress stem bending treatments were also applied in early February 2008. The water-stressed trees were rehydrated by applying water to the trees 48 hours prior to stem bending. Approximately 300 litres of water was applied to each tree, to a distance of 1.5 metres from the tree stem (the distance to the tree canopy drip line), using hoses run out from a fire truck. The soil wetting agent Breakthru® Gold (SST Products, New Zealand) was added to the water (2.5 litres to 3600 litres of water) to improve the water penetration into the extremely dry soil. The stem bending of the summer released-from-water-stress trees was completed over a period of two days, from 48 to 76 hours following the application of water. The ten trees were bent using a winch to 30 or 40% of the predicted failure load of the trees (Table 1).

Soil moisture content

The water content of the soil was measured at the time of the spring and summer stem bending treatments. Four soil samples (2 kg weight minimum) were collected to a depth of 30 cm at the time of the spring stem bending, at the start of summer stem bending when the trees were water-stressed, and 48 hours after the trees had been released from water stress. The soil available volumetric water content was determined gravimetrically by drying the soil samples at 105°C for 48 hours.

Stem bending method

The stem bending was applied using an electric vehicle winch (EP9.0, Superwinch, Inc., USA) with the tension force on the winch rope measured using a load cell (EMC 1000 kg S type tension load cell) that was graduated in 1 kg increments. The nominal height of the winch rope attachment on the tree stem was 75% of tree height. Each stem was bent four times, twice in the direction of the prevailing wind (magnetic bearing 158°), and then twice at 90 degrees to the prevailing wind (magnetic bearing 68°). On each occasion, stems were bent to 30 or 40% of the calculated stem failure load, held for five minutes, then slowly released. The stem bending was immediately repeated in the same direction.

The tension force on the winch cable was a percentage of the maximum force, $F_{\max}$ that could be applied. For each tree, $F_{\max}$ was calculated using the equation:

$$F_{\max} = \frac{cM_b}{h\cos\theta} \quad (1)$$

where $F_{\max}$ is the maximum tension force, M_b is the maximum resistive bending moment of the tree, c = 0.3 or 0.4

Table 2 Tree diameter at breast height, tree height, and tree external resin feature score, for the ten trees of each treatment in August 2007, and soil water content at the time of the spring and summer stem bending treatments in September 2007 and February 2008

Treatment	Diameter at breast height (cm)	Tree height (m)	External resin feature score	Soil available volumetric water content (%)
Control	20.2 (17.0-23.4)	11.9 (9.6-14.3)	2.2	
Spring	20.5 (16.1-23.7)	12.6 (11.0 -14.7)	2.0	33
Summer – water stressed	20.4 (16.7-25.5)	11.9 (9.2 -13.3)	2.1	20
Summer – released from water stress	20.2 (16.3-24.3)	12.1 (11.0 -13.2)	2.1	75

Average and range in brackets.

corresponding to 30% or 40% of the maximum respectively, h is the height of the rope attachment, and $\ominus$ is the angle of the rope from the horizontal in degrees. The maximum resistive bending moment (M_b) was calculated for each tree using the regression equation from Moore (2000) for radiata pine trees:

$$\ln(M_b) = 1.740 + 2.655\ln(DBH) \quad (2)$$

where DBH is the tree diameter at breast height.

The actual height of the winch rope attachment on the tree stem, the magnetic bearing and distance between the vehicle winch and the tree, and the tension force on the load cell, were measured and used to calculate the horizontal force and bending moment acting on the tree during the stem bending. The bending moment due to the self-weight of the off-set stem and crown was not calculated in this study, due to the relatively small deflection angles of the tree from vertical.

Stem bending deflections

The deflection of the tree stems during stem bending was measured using photographs taken at 90 degrees to the direction of stem bending (Figure 1). The tree stem profiles were digitised using the Surfer® Surface Mapping System (Golden Software, Inc., USA) and scaled using the measured distance between the base of the stem and the height of the winch rope attachment. The angle of stem deflection during stem bending was measured at the height of the winch rope attachment, as the difference between the stem angle before and during winching.

Tree harvest

The stem bending and control treatment trees were left to grow for the remainder of the 2007–2008 growth season, to allow for the expression of the resin pockets, and then felled and sampled for resin pockets in November

Figure 1 Stem profile photographs, before (left) and during stem bending (right), taken at 90 degrees to the direction of stem bending.

2008. The trees selected for felling from the spring and summer stem bending treatments were chosen to cover a wide range of stem deflection and bending moment during the stem bending. Five trees were selected from the spring stem bending treatment, but for the summer water-stressed and released-from-water-stress stem bending treatments, the trees were pooled for the 30 and 40% of failure loads to obtain an equivalent range of stem deflection and bending moment. Five trees were selected from the summer water-stressed treatments, and included three trees of 30% and two trees of 40% of failure load. The three summer water-stressed trees winched before the rain, and two of the trees winched the following day were felled. Five trees were selected from the summer released-from-water-stress treatments, and included two trees of 30% and three trees of 40% of failure load. The five trees from the control treatment were selected for a range of tree size and distribution in the stand.

After felling, the following variables were measured on all trees sampled: tree height, internode length, branch whorl depth, and diameter of the largest branch in each branch whorl. Stem discs were cut at 50 mm intervals from the butt to 5 metres height, as described in Watt et al. (2009), and then at 100 mm intervals to 80% of tree height. The top surface of each disc was cleaned, and the disc mounted on a back board with calibration pins and photographed with a digital camera.

Disc image analysis

The resin pockets in the disc photographs were classified by type, and the dimensions, location and ring position were measured using an IDL imaging routine developed at CSIRO. The disc photographs were corrected to a constant scale, using the back board calibration pins, and the resin pockets were classified as Type 1 or 2 (McConchie et al., 2008; Ottenschlaeger et al., 2012). The XY coordinates of the resin pockets were recorded, the annual rings identified, and the within-ring positions of the resin pockets were estimated as a percentage of the ring width.

Disc acoustic velocity measurements

Acoustic velocity (which is a surrogate for wood stiffness) was measured in the breast height air-dried discs cut from the felled trees. Ultrasonic transducers (500 MHz) mounted on pneumatic rams coupled with digital callipers and interfacing hardware and software (Emms & Hosking, 2006) were used to measure the acoustic velocity at 10 mm intervals from pith-to-bark on eight equidistant radii for each disc. The area-weighted average acoustic velocity was calculated for each of the breast height discs.

Statistical analyses

The stem bending force, bending moment and deflection, and the physical properties of the tree stems, were compared for the stem bending and control treatments using one-way analysis of variance (ANOVA) with the SAS procedure PROC GLM (SAS Institute, 2000) and the model:

$$Y_{ij} = \mu + Treatment_i + tree_{j(i)} + e_{ij} \qquad (3)$$

where: Y_{ij} denotes the stem variable measured on tree j in treatment i; μ is the overall population mean; $Treatment_i$ represents the effect of the stem bending and control treatments (fixed), $tree_{j(i)}$ the effect of trees within treatments (random), and e_{ij} represents the error term for the stem measurements.

The SAS Proc GLM (SAS Institute 2000) MEANS statement and LSD option, which performs pairwise t-tests, equivalent to Fisher's least-significant-difference LSD test in the case of equal cell sizes, was used to provide multiple comparisons of the stem bending and control treatment means.

The Type 1 and 2 resin pocket raw data were summarised for the stem bending and control treatments prior to analysis. Growth rings prior to 2003, and heights above 6 metres from the ground, were not used in the analysis. The exclusion of this data is unlikely to affect the results, as the vast majority of the resin pockets occurred from 2003, and at heights below 6 metres above the ground. Within each combination of ring and height class, the presence or absence of resin pockets of each type, and the number of resin pockets were obtained. Presence/absence of resin pockets was then analysed using the PROC GLIMMIX procedure in SAS Version 9.2 with a logistic link function and binary distribution function. The number of resin pockets was also analysed with PROC GLIMMIX using a Poisson link function but this analysis gave similar results to the presence/absence analysis and is not presented here. The distribution of resin pocket numbers was extremely skewed with some trees having large numbers and others having only a few resin pockets. This meant that a simple measure of presence/absence within each combination of height class and ring gave comparable results to complete counts.

The following model was firstly fitted to the presence/absence data for the ring formed in the 2007–2008 year (i.e., during the treatment period):

$$E(Y_{ij}) = g^{-1}(\mu + tree_i + height_j + trt_h) \qquad (4)$$

where, $E(.)$ is the expectation operator, $g^{-1}(.)$ is the inverse of the logistic link function, Y_{ij} is a binary variable indicating the presence/absence of resin pockets within the j^{th} height class in the i^{th} tree, μ is the mean, $height_j$ is a fixed effect for the j^{th} height class, and trt_h is a fixed effect for the h^{th} treatment where h is determined by the

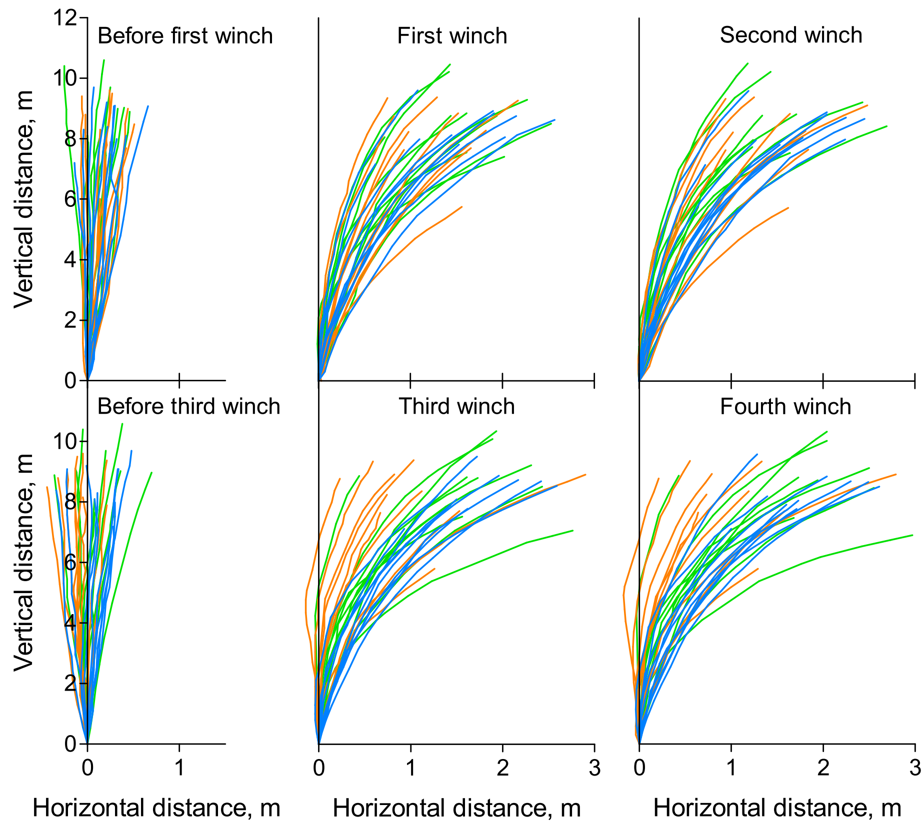

Figure 2 Tree stem profiles before and during the first and second winches in the direction of the prevailing wind, and before and during the third and fourth winches in the direction 90° to the prevailing wind. Lines: Green line Spring, Orange line Summer - water stressed, Blue line Summer - released from water stress. Note the differences in the horizontal and vertical scales.

Table 3 Stem bending force and deflection at the rope attachment for the trees in the spring and summer stem bending treatments

Properties	Spring	Summer – water stressed	Summer – released from water stress
30% of failure load applied			
Horizontal force, kN	0.6 a (0.3-0.8)	0.6 a (0.4-1.0)	0.6 a (0.4-0.9)
Bending moment, kNm	5.3 a (2.7-7.7)	5.5 a (3.3-9.3)	5.5 a (3.0-8.1)
First winch stem deflection, °	26 a (14–38)	13 b (10–18)	21 ab (11–27)
Second winch stem deflection, °	26 a (13–38)	13 b (10–19)	23 ab (11–30)
Third winch stem deflection, °	29 a (11–51)	11 b (9–16)	23 a (14–31)
Fourth winch stem deflection, °	31 a (12–56)	13 b (9–20)	23 ab (12–32)
40% of failure load applied			
Horizontal force, kN		0.8 a (0.5-1.0)	0.7 a (0.4-1.1)
Bending moment, kNm		6.7 a (3.8-9.6)	6.5 a (3.7-10.4)
First winch stem deflection, °		23 a (17–35)	23 a (15–35)
Second winch stem deflection, °		25 a (16–38)	23 a (17–33)
Third winch stem deflection, °		24 a (18–41)	25 a (20–35)
Fourth winch stem deflection, °		25 a (14–45)	27 a (21–37)

Average and range in brackets. Average values for the treatments followed by the same letter do no differ significantly (least significant difference test, α=0.05).

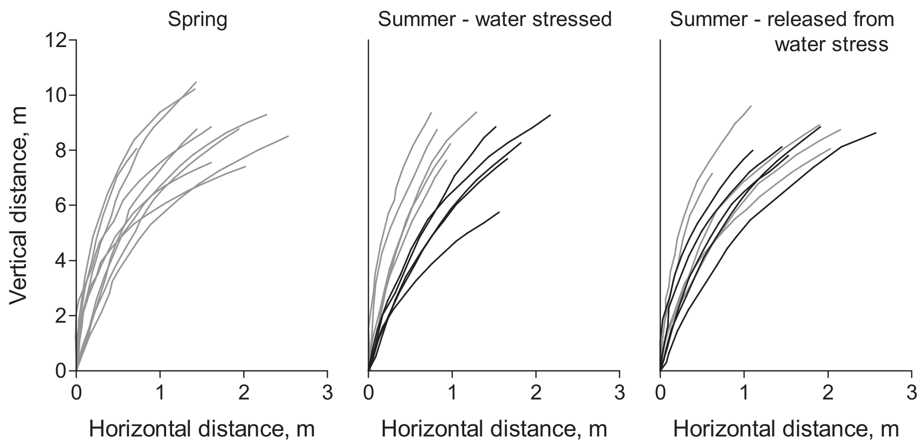

Figure 3 Tree stem profiles of the first winches in the prevailing wind direction to 30% and 40% of the failure loading (Fmax). Lines: Gray line 30% of Fmax, Black line 40% of Fmax. Note the differences in the horizontal and vertical scales.

tree number. This model was fitted separately for Type 1 and Type 2 resin pockets.

Secondly, a more complex model adapted from a standard model used for analysing cross-over trials was fitted. This model utilised all data, including those from rings formed in the pre-treatment period (2003–2007). It was potentially more sensitive than Model (4) because it uses the pre-treatment data to improve the precision of treatment estimates. The model includes subscripts for group (i) and period (k). The two periods are the pre-treatment (k=1) and treatment (k=2) periods, while the groups are the 4 selections, each of 5 trees, which were assigned different treatments during the treatment period. The model is as follows:

$$E\left(Y_{ijklm}\right) = g^{-1}\left(\mu + group_i + tree_{j(i)} + tree.p_{kj(i)} + year_l + height_m + trt_h\right) \quad (5)$$

where Y_{ijklm} is a binary variable indicating presence/absence of resin pockets within the l^{th} ring of the m^{th} height class for the j^{th} tree of the i^{th} group. The fixed effects in the model are the mean, and effects for group ($group_i$), ring formation year ($year_l$), and height class ($height_m$). The fixed effect trt_h represents the h^{th} treatment where h is determined by the group and period (i and k). The model includes a random effect for each tree ($tree_{j(i)}$) and for the pre-treatment and treatment periods within each tree ($tree.p_{kj(i)}$). This model was fitted separately for Type 1 and Type 2 resin pockets. To aid the interpretation of the treatment effects, in both Models (4) and (5) the 3 degree of freedom (d.f.) test for treatment was split into a 1 d.f. contrast between the control and the combined stem bending treatments, and a 2 d.f. contrast testing for differences between the three stem bending treatments.

The circumferential direction effects of winching on the distribution of Type 1 resin pockets, was assessed using the number of resin pockets formed per winched tree in 4 equal sized azimuth classes, and two-way ANOVA with factors for tree and azimuth class. The models were fitted separately for the pre-treatment period (2003–2007), and the treatment period (2007–2008). The azimuth classes were orientated such that the

Table 4 Harvested tree measurements for the stem bending and control treatments in October 2008

Properties	Control	Stem bending, Spring	Stem bending, Summer – water stressed	Stem bending, Summer – released from water stress
% of failure load		30	30-40	30-40
Diameter at breast height, cm	21.3 (18.9-24.6)	22.4 (17.9-25.8)	23.6 (21.4-25.3)	22.6 (18.4-26.2)
Tree height, m	13.5 (12.6-15.0)	14.0 (12.8-16.3)	14.2 (13.0-15.1)	13.6 (12.7-14.0)
Mean internode length, cm	29 (23–35)	25 (22–31)	29 (24–34)	30 (27–33)
Mean whorl depth, cm	8 (6–10)	8 (7–10)	9 (8–11)	9 (7–10)
Max branch diameter per whorl, mm	21 (16–24)	20 (15–25)	23 (21–27)	22 (18–24)
Max branch diameter, mm	52 (29–73)	57 (33–105)	54 (42–64)	53 (38–88)
Acoustic velocity, km/s	4.0 (3.6-4.4)	4.0 (3.3-4.5)	4.0 (3.7-4.3)	3.9 (3.5-4.2)

Average and range in brackets. No significant differences occurred between the treatments (least significant difference test, α=0.05).

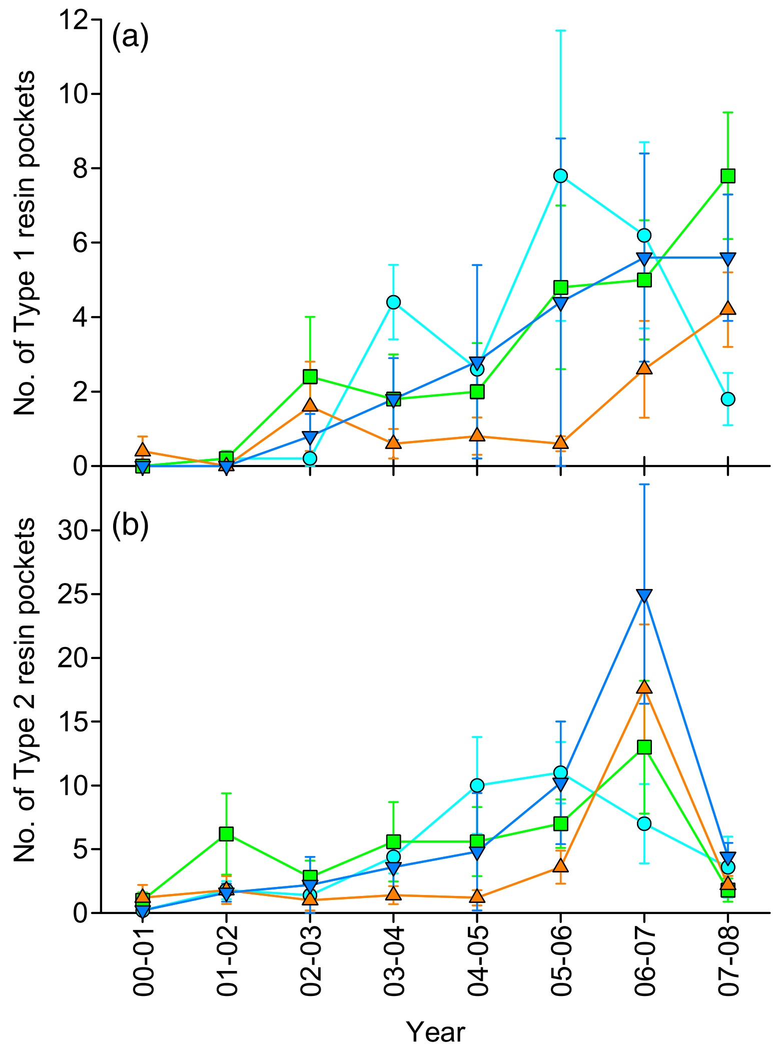

Figure 4 The number of (a) Type 1 resin pockets and (b) Type 2 resin pockets formed per tree in each growth season, for the stem bending and control treatments. Symbols: Light blue circle with line Control, Green Square with line Spring, Orange triangle with line Summer - water stressed, Dark blue down triangle with line Summer - released from water stress. Note the different y-axis scales. The error bars are the standard errors.

Table 5 Analyses of variance for Model (5) showing the significance of the main and interactive effects of treatment, year (2003–2008) and height (0–6 m) on the incidence of Type 1 and 2 resin pockets

Source of variation	Degrees of freedom	Type 1		Type 2	
		F-value	*P*-value	*F*-value	*P*-value
Treatment	3, 16	4.87	0.014	1.00	0.42
Control versus stem bending	1, 16	14.15	0.0017	0.55	0.47
Test among the stem bending treatments	2, 16	0.26	0.78	1.20	0.33
Group	3, 16	1.94	0.16	0.67	0.58
Year	4, 552	8.88	<.0001	10.62	<.0001
Height class	5, 552	18.12	<.0001	23.85	<.0001

Table 6 Mean presence of Type 1 and Type 2 resin pockets in each growth ring × 1 m height class combination, in the lower 6 m of the stem, in the 2007–08 year

Treatment	Mean presence of Type 1 resin pockets (%)	Mean presence of Type 2 resin pockets (%)
Control	10 a (3)	26 a (6)
Stem bending, Spring	72 b (21)	21 a (20)
Stem bending, Summer – water stressed	84 b (14)	47 a (30)
Stem bending, Summer – released from water stress	82 b (16)	65 a (26)

Estimates are least squares means obtained using Model (5). Standard errors are given in parentheses. Values within a column followed by the same letter do not differ significantly (least significant difference test, α=0.05).

classes were separated along the lines of the directions of winching.

Results

Stem bending treatments

The tree stem profiles prior to stem bending showed many of the trees were leaning slightly in the direction of the prevailing wind, while at 90° to the prevailing wind there was a more balanced distribution of stem lean (Figure 2).

The horizontal force and bending moments applied to the trees during stem bending were similar for the stem bending treatments, but the stem deflections of the trees were different for the spring and summer treatments (Table 3). The spring stem bending treatment showed larger stem deflections, compared with the summer

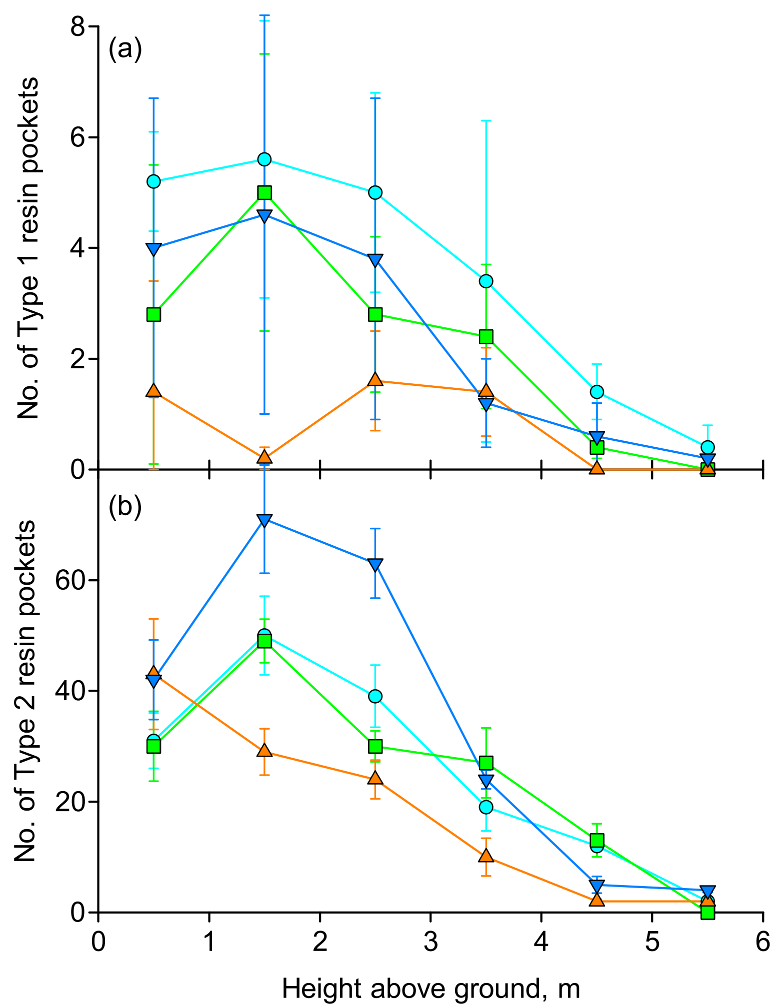

Figure 5 The number of (a) Type 1 resin pockets and (b) Type 2 resin pockets formed per tree in each 1 m height interval, during the pre-treatment years (2003–2007), for the stem bending and control treatments. Symbols: Light blue circle with line Control, Green Square with line Spring, Orange triangle with line Summer - water stressed, Dark blue down triangle with line Summer - released from water stress. Note the different y-axis scales. The error bars are the standard errors.

water-stressed treatment, at the 30% failure loading. The application of 40% failure loading to the summer stem bending treatments gave stem deflections that were similar to the spring stem bending treatment at the 30% failure loading (Table 3, Figure 3).

Harvested trees

The harvested trees from the stem bending and control treatments had similar distributions of diameter at breast height, tree height, internode length, whorl depth, maximum branch size, and acoustic velocity at breast height (Table 4). There were no significant differences between the treatments, which suggests the differences in the stem deflections of the spring and summer stem bending treatments were due to factors other than tree size and branching properties, and the acoustic velocity of the wood.

Resin pockets

Inspection of the number of Type 1 resin pockets formed in the 2007–2008 year suggests that more resin pockets were formed in the trees subjected to stem bending than the control trees (Figure 4), especially when compared with the number of resin pockets that formed during the pre-treatment period (2003–2007). In many cases, the number of Type 2 resin pockets observed was much lower in the 2007–2008 year, compared with preceding years, making treatment effects difficult to detect (Figure 4).

The number of trees studied was small and a direct test of the effect of treatment on resin pocket occurrence in the 2007–2008 year using Model (4) detected no significant treatment effect for either Type 1 ($F_{3,16}$=2.04, p=0.15) or Type 2 ($F_{3,16}$=0.87, p=0.48) resin pockets. However, the contrast between the control

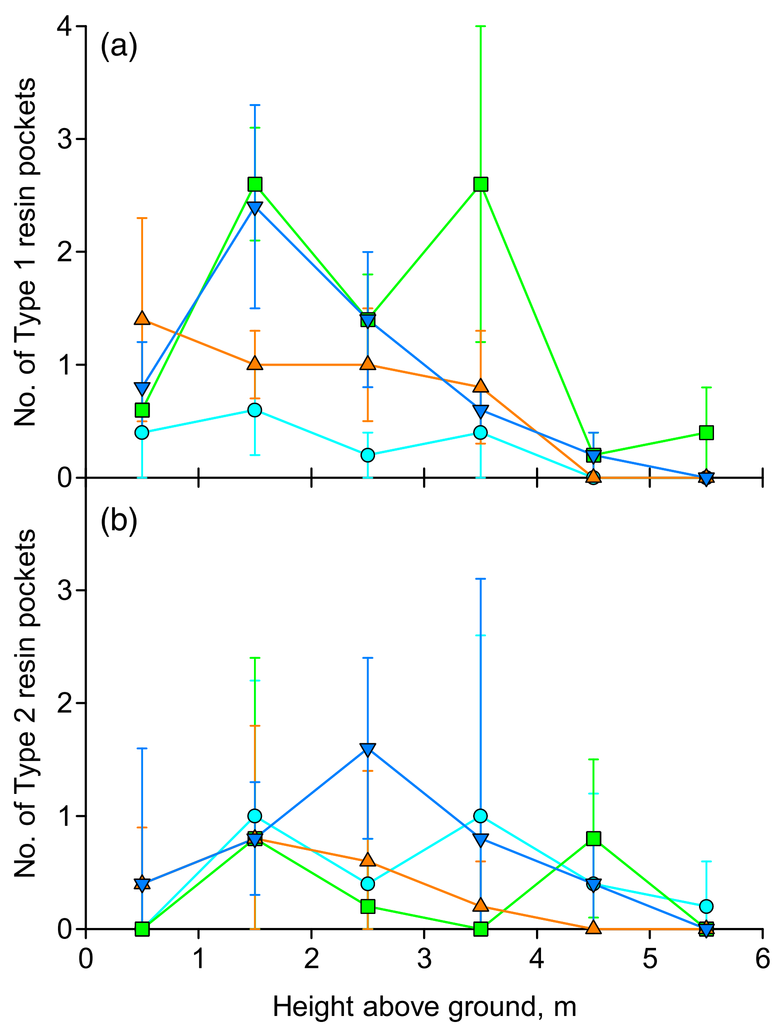

Figure 6 The number of (a) Type 1 resin pockets and (b) Type 2 resin pockets formed per tree in each 1 m height interval, during the treatment year (2007–2008), for the stem bending and control treatments. Symbols: Light blue circle with line Control, Green square with line Spring, Orange triangle with line Summer - water stressed, Dark blue down triangle with line Summer - released from water stress. The error bars are the standard errors.

treatment and the combined stem bending treatments using Model (4) indicated that the occurrence of resin pockets was higher among the combined stem bending trees than the control trees for Type 1 resin pockets ($F_{1,16}$=5.79, p=0.029), but not for Type 2 resin pockets ($F_{1,16}$<0.01, p=0.95). A more sensitive test of treatment effects was provided by Model (5) which used the pre-treatment resin pocket occurrence in each tree to improve the precision of estimates obtained during the treatment period. Model (5) revealed a clearly significant treatment effect on the occurrence of Type 1 but not Type 2 resin pockets (Table 5). For Type 1 resin pockets, the 1 d.f. contrast between the control treatment and the combined stem bending treatments was highly significant, but there was no significant difference between the three stem bending treatments (Table 5). Estimates obtained using Model 5 showed the mean occurrence of Type 1 resin pockets for the control treatment was much lower than for the stem bending treatments (Table 6).

Significant differences were found in the numbers of Type 1 and 2 resin pockets with year, or height in the harvested trees (Table 5). There was an increase in the number of Type 1 and Type 2 resin pockets with successive years from 2000–2007 (Figure 4), and an increase with height to between 1 and 2 metres, and then a strong decrease with height from 2 to 5 metres, for the pre-treatment years (Figure 5), and treatment year (Figure 6). An interaction term for height class × treatment was added to Model (5) to test whether the effect of stem bending on Type 1 resin pocket formation varied with height in the treatment year (2007–2008). However, this term was not statistically significant indicating that compared with the controls, the increase in the number of Type 1 resin pockets caused by stem bending did not vary with height under the logistic transformation. However, both the stem bending and control treatments showed a marked reduction in the presence of Type 1 resin pockets at heights greater than 3 metres (Figure 7).

There were no significant circumferential direction effects in the number of Type 1 resin pockets found in stems subjected to bending events, either in the growth rings formed in the pre-treatment years (2003–2007), or in the growth ring formed during the treatment year (2007–2008) (Figure 8). The azimuth classes in the tree stems on the side of the trees that were subject to compressive stress during winching, and the azimuth class on the opposite side of the stems, that was subject to tensile stress, during the stem bending treatments, showed similar numbers of Type 1 resin pockets.

The location of the Type 1 resin pockets in the growth rings, were found mainly in the inner early wood, adjacent to the growth ring boundary. This applied to the Type 1 resin pockets formed in the pre-treatment years (2003–2007) and control trees, and to the Type 1 resin pockets formed during the spring and summer stem bending in the winching year 2007–2008 (Figure 9).

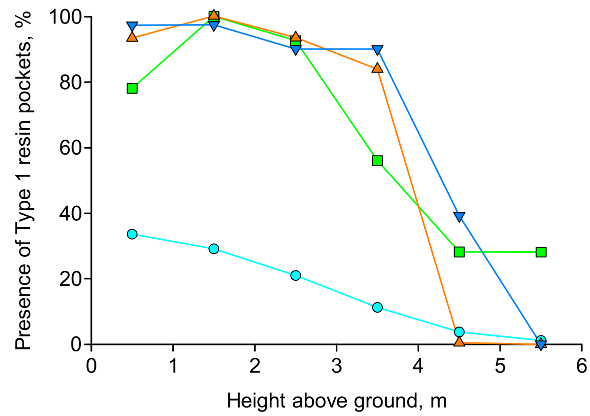

Figure 7 The mean presence of Type 1 resin pockets for each growth ring in 1 m height classes, in the lower 6 m of the stem, during the stem bending treatment year (2007–2008). The values plotted are least squares means from a treatment × height class interaction term added to Model (5). Symbols: Light blue circle with line Control, Green Square with line Spring, Orange triangle with line Summer - water stressed, Dark blue down triangle with line Summer - released from water stress.

Discussion

The number of Type 1 resin pockets in radiata pine trees increased with the application of stem bending treatments in this study. Although project resources did not permit the destructive sampling of all the trees to which bending treatments were applied, the numbers were sufficient to detect significant effects, despite the considerable variance among trees. The results were consistent with the formation of xylem wounds with stem bending in Scots pine trees (Temnerud et al.,

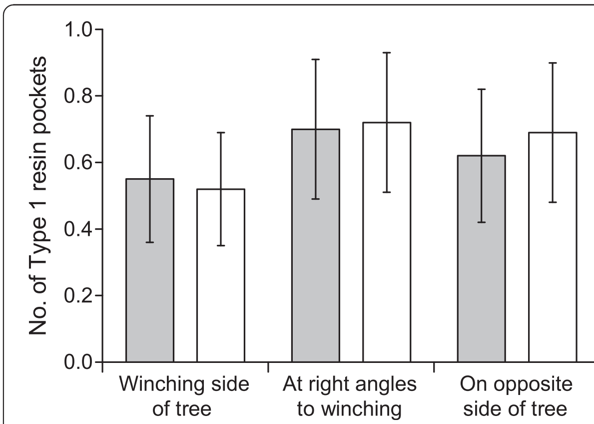

Figure 8 The number of Type 1 resin pockets formed per tree by stem azimuth class for: Gray rectangle the rings formed during the pre-treatment years (2003–2007), and White rectangle the ring formed during the stem bending treatment year (2007–2008). The error bars are the standard errors.

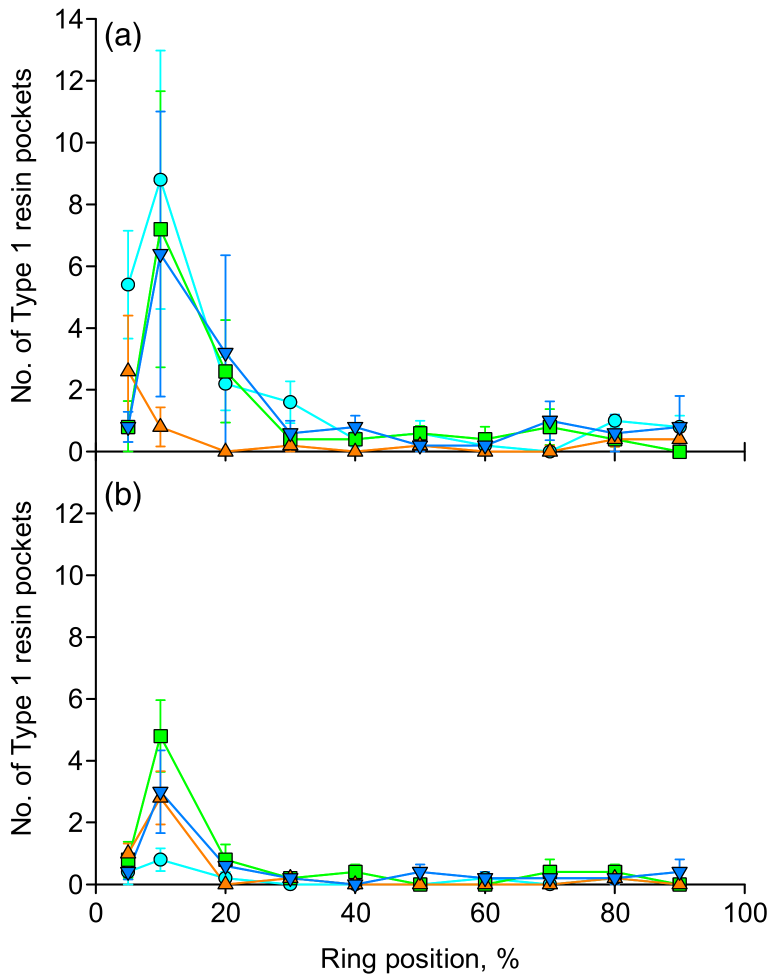

Figure 9 The number of Type 1 resin pockets formed per tree at radial positions within the growth rings (a) during the pre-treatment years (2003–2007) and (b) during the treatment year (2007–2008), for the stem bending and control treatments. Symbols: Light blue circle with line Control, Green Square with line Spring, Orange triangle with line Summer - water stressed, Dark Blue down triangle with line Summer - released from water stress. The error bars are the standard errors.

1999), and with the reduction in the number of Type 1 resin pockets that occurred with restraints on wind sway in radiata pine trees (Watt et al., 2009). This suggests the bending and axial stresses induced in the tree stems by wind sway, are an important factor in the formation of Type 1 resin pockets in radiata pine trees.

The greater incidence of Type 1 resin pockets in the lower part of the stems is consistent with the distribution of bending and axial stress in the stems. When stems bend in the wind, the maximum bending and axial stress occurs at the outer surface, close to the cambium, in the lower part of the stem (Mergen, 1954; Petty & Worrell, 1981; Morgan & Cannell, 1994; Chiba, 2000). The axial stress on the compression side of the bend, can lead to failure along the lamellate structures of the growth rings. In Norway spruce, tangential splits were produced by axial compressive stress, usually in the early wood along the growth ring boundary (Bariska & Kučera, 1985). The increase in the number of Type 1 resin pockets with stem bending in the radiata pine trees, occurred in the early wood of the outer growth-ring, and close to the growth-ring boundary.

The presence of Type 1 resin pockets in the early wood of trees subjected to the stem bending treatments applied here, suggests that Type 1 resin pockets were forming in the mature wood, behind the cambium and zone of differentiation, as observed by Donaldson (1983). The early wood that is close to the growth-ring boundary appears to have been a zone of weakness for the formation of Type 1 resin pockets, and will have contained fully differentiated mature wood at the time of the spring and summer stem bending treatments. The structural properties of the mature wood will not be affected by either the water status of the trees, or the timing of the stem bending during the growth season. This situation could explain the similar number of Type 1 resin pockets formed when the trees were water-stressed compared with trees that were water stressed then rehydrated.

The absence of increased numbers of Type 2 resin pockets suggests there was no cambial damage associated with the stem bending treatments. The influx of water and the high cell turgor pressure of the cambium cells, following the uptake of water by the water-stressed trees, did not appear to make the cambium cells susceptible to mechanical damage. Type 2 resin pockets are formed in response to damage to the cambium, as has been shown by Donaldson (1983). Either the bending and axial stresses produced by the stem bending treatments were not large enough to damage the cambium, or other factors are involved in the formation of Type 2 resin pockets.

The lack of circumferential differences in the number of Type 1 resin pockets, in any azimuth classes, is possibly an indication of the internal stresses that occurred in the tree stems during the swaying motion of the trees in wind gusts. Tree deflections are irregular in wind gusts and sways occur in complex looping patterns, as gusts constantly change in speed and direction (Mayer, 1987; Hassinen et al., 1998; James et al., 2006). As the swaying motion rotates the stems through the complex loops, all sides of the tree stems will be placed under internal stresses (Mergen, 1954). The horizontal displacement of the tree stems during the winching process may have contributed to internal stresses in other directions. Such stresses were observed with the vertical displacement of the branches of a Douglas-fir (*Pseudotsuga menziesii* Mirb. Franco) tree (Moore et al., 2005), and could help to explain the similar circumferential distribution of Type 1 resin pockets in the pre-treatment years and the stem bending year.

Conclusion

The application of stem bending to radiata pine trees in spring or summer of a single growth season increased the number of Type 1 resin pockets, but had no effect on the number of Type 2 resin pockets. The majority of Type 1 resin pockets were located in the lower part of the stems, in the early wood of the outer growth ring, and close to the growth ring boundary. This location appears to be a zone of weakness that is prone to the formation of Type 1 resin pockets compressive stresses in the stems during the application of stem bending.

The Type 1 resin pockets appeared to form in the fully differentiated mature wood behind the cambium and zone of differentiation. The number and location of Type 1 resin pockets produced was not correlated with either the timing of stem bending treatment or the water status of the trees.

Competing interests

The authors declare that they have no competing interests.

Authors' contributions

TJ organised the study, assisted in the analysis, and wrote the manuscript. GD initiated the study, and assisted with the technical design and revision of the manuscript. MW provided advice on the technical design, and the analysis. MK carried out the analysis of the resin pocket data. DC provided technical advice and assistance with the winching field work. MO carried out the image analysis of the disc images. GE provided technical advice and operated the winching equipment. JX carried out the selection of the trees, assisted with the field work, and the soil measurements.

Acknowledgements

We thank John Moore (Scion) for advice on the winching, Simeon Smaill (Scion) for assistance with the tree selection, Mark Miller and Kane Fleet (Scion) for their assistance with the tree winching operations, Rod Brownlie and David Henley (Scion) and David Menz (CSIRO) for their assistance with the tree harvesting, and Alistair Hayward and Siobhan Allen (Rayonier NZ Ltd) for providing access and use of the Balmoral forest site, and a fire truck during the summer winching operations. The research was funded by the Wood Quality Initiative (WQI) Ltd, Scion, and CSIRO.

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Received: 31 July 2013 Accepted: 31 July 2013
Published: 29 Aug 2013

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10.1186/1179-5395-43-10
Cite this article as: Jones *et al.*: Effect of stem bending and soil moisture on the incidence of resin pockets in radiata pine. *New Zealand Journal of Forestry Science* 2013, 43:10