Jones et al. *New Zealand Journal of Forestry Science* (2022) 52:14
https://doi.org/10.33494/nzjfs522022x196x
E-ISSN: 1179-5395
published on-line: 3/05/2022

Research Article **Open Access**

New Zealand Journal of Forestry Science

Predicting resin pockets and blemishes in radiata pine lumber from log properties

Trevor G. Jones[1*], Jun Li Yang[2], Don L. McConchie[3] and Geoffrey M. Downes[4]

[1] *The New Zealand Institute for Plant & Food Research Ltd, Private Bag 11600, Palmerston North 4442, New Zealand.*
[2] *Melbourne University, PO Box 4399, Victoria 3052, Australia.*
[3] *Wood Quality Focus, PO Box 176, Lake Tekapo 7945, New Zealand*
[4] *Forest Quality, PO Box 293 Huonville, Tasmania 7109, Australia*

*Corresponding author: trevor.jones@plantandfood.co.nz

(Received for publication 26 October 2021; accepted in revised form 11 April 2022)

Abstract

Background: Resin pockets and blemishes in pruned logs of radiata pine (*Pinus radiata* D.Don) can reduce the value of clear and moulding grades of lumber. External resin features (ERF) on the bark of the logs have proved an effective method of predicting the incidence of resin pockets in the lumber. Resin canals have been associated with resin blemishes in radiata pine, and could prove useful in improving the prediction of the grade recovery of lumber.

Methods: Pruned butt logs of radiata pine trees from two forests in the North Island, New Zealand, were selected for low, moderate, and severe levels of external resin features (ERF) on the bark, and for low, average, and high resin canal diameter, frequency and brightness from breast height increment cores. The relationships were evaluated between these properties, and the lumber resin features and grade recovery of the logs.

Results: The number of resin pockets, the blemish rating, and the percentage of boards with resin streaks and resinous heartwood increased, and the recovery of clears and moulding grade boards and the lumber value declined, with the severity of the ERF class of the logs. Multiple regression models gave good predictions of the grade recovery and loss of lumber value, using the log ERF class, volume, heartwood content, and number of Type 1 resin pockets on the ends of the logs, as independent variables. The resin canal properties did not improve the regression models. Resin blemishes were associated with Type 2 resin pockets, and were more frequent in the forest where false growth rings were present. This suggests the constitutive resin flow from resin canals, rather than the resin canal size and frequency, is more important in determining the incidence of resin blemishes.

Conclusions: The prediction of the grade recovery of lumber using the ERFs of radiata pine logs, was supplemented by the log volume, heartwood content and number of Type 1 resin pockets on the ends of the logs. The environmental factors that drive the constitutive resin enrichment of resin canals, such as drought conditions that give rise to false growth rings, could be useful in improving the prediction of grade recovery for forest stands.

Keywords: resin pockets, blemishes, radiata pine, resin canals, lumber

Introduction

Resin pockets are found in radiata pine (*Pinus radiata* D.Don) plantations in all regions of New Zealand, with a higher prevalence in Northland, Hawkes Bay, Nelson, Marlborough, and Canterbury (Clifton 1969; Cown 1973; Park 2004, Woollons et al. 2008). The incidence of resin pockets in lumber produced from pruned logs from the forests in these regions can vary from 0 to 3 resin pockets per square metre (m^2) of sawn surface area. The recovery of clears and moulding grades of lumber is reduced as the incidence of resin pockets increases in the pruned logs, with a loss in value as the boards are downgraded to shop and commons grades of lumber.

The lumber from pruned logs of radiata pine with low to severe levels of resin pockets can be reduced in

© The Author(s). 2022 Open Access This article is distributed under the terms of the Creative Commons Attribution 4.0 International License (https://creativecommons.org/licenses/by/4.0/), *which permits unrestricted use, distribution, and reproduction in any medium, provided you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made.*

value by 20 to 68%, due to the presence of resin pockets and other resinous defects on the surface of the boards (Hughes 2007). The presence in lumber of 0.7 to 2.0 resin pockets/m^2 of sawn surface area was found to reduce the value of the lumber from pruned logs of radiata pine by 7 to 34% (McConchie 2003). The loss in lumber value has led to the development of methods for the visual grading of pruned logs for resin pockets and blemishes.

The resin pockets and blemishes that occur on the ends of the logs have been evaluated as a method for predicting the incidence of resin pockets in the lumber (Ridoutt et al. 1999). The predictive models that were developed for radiata pine logs were limited by the low incidence of resin pockets on the ends of the logs. This prevented the establishment of consistent relationships between the log end assessments and the grade recovery of lumber.

The external resin features (ERF) on the bark of the logs have been a more effective method of predicting the incidence of resin pockets in the lumber (McConchie, 2003). The presence of external resin bleeding, lesions, and galls on the surface of the logs, can be used to segregate the radiata pine logs for the grade recovery of lumber. The volume of mouldings and better grades of lumber declined by 12, 26, and 55% for pruned logs of radiata pine with low, moderate, and severe classifications of ERF on the bark of the logs (McConchie, 2003).

Resin blemishes have been associated with the frequency of resin canals in the logs of radiata pine, with a higher incidence of resin blemishes on the ends of logs, among forest sites with higher resin canal frequency (Yang et al. 2007). Resin canal frequency appears to be weakly linked to the external resin features (ERF) on the bark of radiata pine trees (Yang et al. 2007; Ananais et al. 2010), and the resin pockets and resinous patches on the ends of radiata pine logs (Yang et al. 2007), which suggests it may be useful in predicting the incidence of blemishes in the lumber.

In this study, the use of external resin features (ERF) on the bark of the logs was evaluated in combination with the resin canals from increment cores, and log end properties, to determine if these measurements could improve the prediction of the grade recovery of lumber. The pruned butt logs of radiata pine trees selected for low, moderate, and severe ERF classes, and a range of resin canal properties, were sawn into random-width boards and graded for appearance lumber. The relationships were evaluated between the log ERF classes, the resin canal, and log end properties, and the lumber resin features and grade recovery.

Methods

External resin features

Trees of 26-year-old radiata pine trees were selected for low, moderate, and severe levels of external resin features (ERF) on the bark of pruned butt logs, from plantation stands in Northland and coastal Hawke's Bay (Figure 1, Tables 1 and 2). Ninety trees in Parengarenga Forest, Northland, and eighty-seven trees in Tangoio Forest, coastal Hawke's Bay, were selected based on the presence of external resin bleeding, lesions, and galls on the bark of the pruned butt logs, using the ERF classification in the WQI Field Guide (McConchie, 2003).

FIGURE 1: Radiata pine trees of: (a) low; (b) moderate; and (c) severe external resin feature (ERF) classes on the bark of the pruned butt logs, at Parengarenga Forest in Northland.

Resin canals

The vertical resin canal properties of all the selected trees were measured using breast height (1.4 m) increment cores, taken from the outer ten growth rings from the bark. One 12 mm diameter increment core was sampled from each tree, and air-dried at room temperature. A SilviScan strip (Evans, 1994), was cut from each core, and one transverse surface was polished with 240, 320 and 1200 grit abrasive paper, and scanned at 600 DPI using a flat-bed scanner. The scanning parameters were kept the same for all the strips (image brightness = 140, image contrast = 170) to ensure the resin canal brightness could be compared between the strips.

TABLE 1: Description of the Parengarenga and Tangoio Forest sites

Descriptor	Parengarenga forest	Tangoio forest
Latitude	34° 36' 29'' S	39° 20' 31'' S
Longitude	172° 54' 05'' E	176° 53' 45'' E
Elevation, m	60	80
Slope, °	3	23
Average annual temperature, °C	15.6	13.8
Average annual rainfall, mm	1296	1284
Soil series and type	Pinaki sand	Tokeawa silt loam

TABLE 2: Stand history of the Parengarenga and Tangoio Forest stands

Descriptor	Parengarenga forest	Tangoio forest
Compartment/ stand	259/1, 261/1	280/1, 281/1
Planted	1982	1982
Planted stocking, s/ha	1794	
1st prune	1988 to 2.2 m	1988 to 2.2 m
2nd prune	1988 to 4.2 m	1990 to 4.2 m
3rd prune*	1991, 1990 to 6.3 m	1993 to 6.7 m
Waste thinning		1988 to 538 s/ha
Production thinning*	1995 to 229 s/ha, 1994 to 293 s/ha	1997 to 296, 256 s/ha

* Information given in consecutive order for compartment/stand.

The diameter, frequency, and brightness of the resin canals were measured using the IDL imaging routine developed at CSIRO (Chen et al. 2008, Figure 2). Resin canal size was estimated by drawing a circle over each canal and calculating the circle area using the software. Resin canal diameter was derived from circle area. The average greyscale intensity of the pixels within the boundary of each resin canal was used to represent the brightness of the resin canal.

Log selection

The butt logs of thirty trees were selected for sawmilling from each of Parengarenga and Tangoio Forest, based on the ERF classes of the logs and the resin canal properties of the breast height increment cores. Ten trees were selected from each of the low, moderate and severe ERF classes, and for each ERF class the trees were selected for combinations of low, average, and high resin canal diameter, frequency and brightness.

Log measurements

The trees were felled in April 2009 and the pruned butt logs for sawmilling were assessed for small and large end diameter, length, acoustic velocity, heartwood content, resin pockets, and blemishes. Log volume, excluding bark, was calculated using Smalian's formula (Ellis, 1995). Acoustic velocity was measured using a Director HM200 (Fibre-gen, New Zealand) connected to a laptop computer and operated in supervisor mode, to ensure the correct resonance peak was used in calculating the log acoustic velocity. Heartwood content, resin pockets, and blemishes were measured using 50 mm thick discs, cut from both ends of the logs. One transverse surface of the discs was cut smooth using a disc-surfacing saw, then wetted with water, mounted in a camera booth on a back board with calibration pins, and photographed using a digital camera (Lee and Brownlie, 2009).

Resin pockets and blemishes in the disc photos were classified by type, and the dimensions, location, and ring position were measured using an IDL imaging routine developed at CSIRO (Ottenschlaeger et al. 2012). Disc photos were corrected to a constant scale, using the back board calibration pins, and the resin pockets classified as Type 1 or 2 (Figure 3). XY positions of the resin pockets were recorded, the annual rings identified, and the within-ring position of the resin pockets estimated as a percentage of the ring width.

Sawing and grading of boards

The pruned butt logs were sawn into 40 mm thick random-width boards, using a sawing-for-grade cutting pattern (Figure 4). Boards were visually graded in the green rough-sawn condition, using the WWPA Factory grading rules (WWPA 1991), and assigned to the grades: clears, mouldings, No. 1 shop, No. 2 shop, No. 3 shop, and commons. Boards were assessed for: width, length, actual grade (including resin features), adjusted grade (excluding resin features), number of Type 1 and Type 2 resin pockets, blemish rating (0 – 3), presence of resin streaks, resinous latewood, and galls on the worst long-grain face and edge combined.

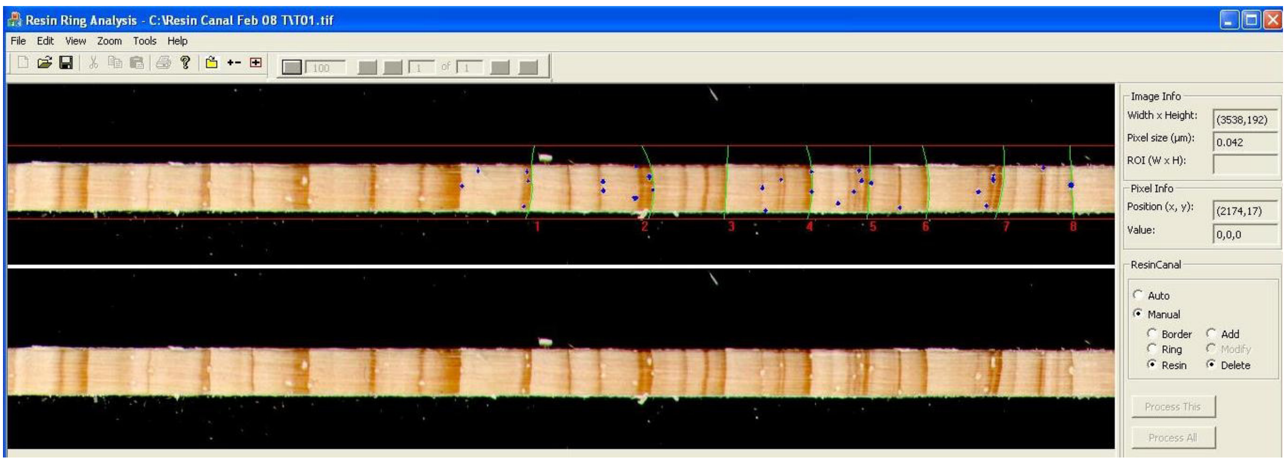

FIGURE 2: A view of the IDL imaging routine used to obtain resin canal information on the 2 mm wide polished transverse surface of a strip from Tangoio Forest. Annual growth rings are marked on the top strip, and show the frequent occurrence of false growth rings at Tangoio Forest. Resin canals are identified and their area and brightness measured.

FIGURE 3: The presence of Type 1 and 2 resin pockets in radiata pine logs. Left: Type 1 resin pocket, a narrow lens shaped cavity filled with resin and callus, occurring within a single growth ring. Right: Type 2 resin pocket, showing cambial damage and an occlusion scar, and centripetal resin bleeding towards the pith.

The frequencies of Type 1 and 2 resin pockets in the boards were calculated per square metre (m^2) of surface area, for the boards in each log, forest and ERF class. Volume-weighted average blemish rating of the boards was calculated for each log, forest and ERF class.
The number of boards with blemish ratings (0 – 3), resin streaks, resinous latewood, and galls were calculated as a percentage of the total volume of boards in each log, forest and ERF class.

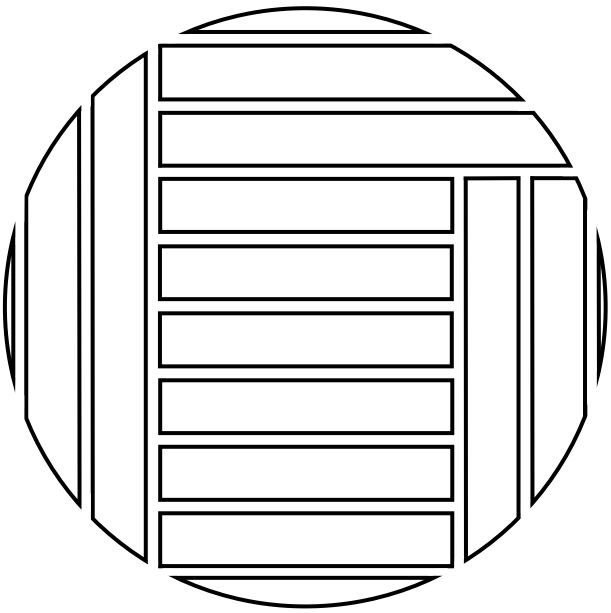

FIGURE 4: The sawing-for-grade cutting pattern used to saw the pruned butt logs into 40-mm thick random-width boards.

Grade recovery

Actual and adjusted grade recoveries of clears, mouldings, No. 1 shop, No. 2 shop, No. 3 shop, and commons, were calculated as a percentage of the total volume of boards in each log, forest and ERF class.

Lumber value

Lumber value of the actual grade and adjusted grade was calculated for each board, based on its volume and grade using the prices (NZ$): clears and moulding $780/m^3, No. 1 shop $490/m^3, No. 2 shop $380/m^3, No. 3 shop $290/m^3, commons $155/m^3. Lumber value was summed for all the boards in each log, forest and ERF class. Value per cubic metre ($/m^3) was calculated by dividing the total value of the lumber by the volume. Value loss of the resin pockets and blemishes was the difference between the value of actual and adjusted grades, expressed as a percentage of adjusted grade. Average 2001 prices for 5/4 random width lumber at the mill door in New Zealand were used to provide a comparison with McConchie and Turner (2002).

Statistical analyses

Log variables of Parengarenga and Tangoio Forest were compared using one-way analysis of variance (ANOVA) with Tukey's multiple comparison test, using Genstat statistical software (VSN International Ltd, Hemel Hempstead, UK) and the model:

$$y_{ij} = \mu + f_i + t_{j(i)} + e_{ij}$$

where: y_{ij} denotes the log variable measured on the butt log of tree j in forest i; μ is the overall population mean; f_i represents the effect of forest (fixed), $t_{j(i)}$ the effect of trees (random), and e_{ij} represents the error term for the log measurements.

Correlations between log and board variables were calculated using SAS statistical software (SAS Institute, Inc., Cary, NC, USA) and the procedure PROC CORR.

Stepwise regression equations for the actual grade recovery of clears + mouldings, actual grade value, and lumber value loss, were fitted using log variables as potential independent variables. SAS procedure PROC REG was used for this analysis. A p-level of 0.05 was used for selecting variables to enter the regression, or for removing variables.

Results

Resin canal properties

The size and frequency of the resin canals in the outer ten growth-rings at breast height (1.4 m) differed for Parengarenga Forest, Northland, and Tangoio Forest, Hawke's Bay (Table 3). Resin canals of trees in Parengarenga Forest were on average larger in diameter, of higher frequency per unit area, and of slightly lower brightness, compared with trees in Tangoio Forest.

Log properties

Volume of the logs, and numbers of Type 1 and 2 resin pockets on ends of the logs were similar at Parengarenga and Tangoio Forest. Acoustic velocity of the logs was higher at Parengarenga Forest, and number of resin blemishes on ends of the logs was higher at Tangoio Forest (Table 4).

Acoustic velocity was higher on average for low ERF class logs, compared with moderate and severe ERF class logs (Table 4). The trend was more evident for the logs at Parengarenga Forest, but there was a weak but significant correlation between acoustic velocity and ERF class for logs from both forests (Table 5).

Number of Type 2 resin pockets and blemishes on the ends of the logs increased with the severity of the ERF class of the logs (Table 4). There were moderate correlations between the number of Type 2 resin pockets and blemishes on ends of the logs, and ERF class of the logs (Table 5).

TABLE 3: Resin canal properties for the log ERF classes of Parengarenga and Tangoio Forest. Average breast height increment core values followed by the same letter do not differ significantly ($p > 0.05$).

ERF class	Diameter (mm)	Frequency (canals/cm²)	Brightness (greyscale, 0 – 255)
Parengarenga forest			
Low	0.22 b	27 ab	204 bc
Moderate	0.24 a	31 a	205 abc
Severe	0.22 b	31 a	202 c
Tangoio forest			
Low	0.20 c	17 c	208 abc
Moderate	0.20 c	17 c	208 ab
Severe	0.20 c	22 bc	211 a

TABLE 4: Log properties for the log ERF classes of Parengarenga and Tangoio Forest. Average log values followed by the same letter do not differ significantly ($p > 0.05$).

ERF class	Volume (m^3)	Acoustic velocity (km/s)	Heartwood (%)
Parengarenga forest			
Low	1.0a	3.5a	34a
Moderate	1.1a	3.2 bc	33a
Severe	1.2a	3.3 b	30a
Tangoio forest			
Low	0.9a	3.2 bcd	21a
Moderate	0.9a	3.0 d	22a
Severe	0.9a	3.1 cd	22a
	Type 1 resin pockets (number/ log*)	**Type 2 resin pockets (number/ log*)**	**Resin blemishes (number/ log*)**
Parengarenga forest			
Low	0 b	1 c	5 c
Moderate	2ab	2 bc	5 c
Severe	2ab	5ab	11 bc
Tangoio forest			
Low	1ab	1 bc	3 c
Moderate	2ab	5abc	15ab
Severe	4a	8a	20a

* Average number of resin pockets and blemishes on the large and small ends of the logs combined.

Board properties

Presence of resin features on the sawn surface of the random-width boards was strongly influenced by the ERF class of the logs (Table 6). Numbers of Type 1 and 2 resin pockets, blemish rating, and percentage of boards with resin streaks, and galls, increased with severity of the ERF class of logs. There were weak to moderate correlations between these resin features on the surfaces of boards, and ERF classes of the logs (Table 7).

The number of Type 2 resin pockets and blemishes on the ends of the logs showed weaker correlations with resin features on the surface of the boards, compared with ERF class of the logs (Table 7). The number of Type 1 resin pockets on the ends of the logs, showed a stronger correlation with number of Type 1 resin pockets on the surfaces of boards, compared with ERF class of the logs. Resin canal properties of breast height increment cores was only very weakly correlated with resin features on surfaces of the boards (Table 7).

Grade recovery

Actual grade recoveries of random-width boards showed a substantial reduction in the volume of clears and moulding grades, and a corresponding increase in

TABLE 5: Correlation coefficients (r) of the log properties, for the combined Parengarenga and Tangoio Forest logs (n = 60).

Log properties	Volume	Acoustic velocity	Heartwood	ERF class	Type 1 resin pockets	Type 2 resin pockets	Resin blemish	Resin canal diameter	Resin canal freq.
Acoustic velocity	-0.05								
Heartwood	0.16	0.13							
ERF Class	0.12	-0.30*	-0.05						
Type 1 resin pockets	0.07	-0.25	-0.20	0.42**					
Type 2 resin pockets	0.12	-0.28*	-0.21	0.54**	0.50**				
Resin blemishes	-0.02	-0.36**	-0.24	0.54**	0.40**	0.87**			
Resin canal diameter	0.48**	0.25	0.11	0.10	0.02	-0.13	-0.22		
Resin canal frequency	0.31*	0.24	0.07	0.18	0.04	-0.10	-0.15	0.39**	
Resin canal brightness	0.20	-0.26*	-0.15	0.05	0.18	0.17	0.14	-0.05	-0.02

* P < 0.05, ** P < 0.01

No.3 shop and commons grades, with an increase in severity of the ERF class of the logs (Table 8). Recoveries of clears + moulding grades for the low, moderate, and severe ERF class logs were: 55, 19, and 7 percent of the total board volume at Parengarenga Forest, and 38, 19, and 5 percent at Tangoio Forest. Moderate ERF class logs produced very few boards of clears grade, and there were no boards of clears grade from severe ERF class logs.

Adjusted grade recovery of the random-width boards showed that if resin features on the surfaces of boards were excluded, the low, moderate, and severe ERF class logs had similar board grade recoveries (Table 8). Recovery of clears grade boards was however, much higher for logs from Parengarenga Forest, compared with those from Tangoio Forest. This was explained by larger defect cores and pruned branches in logs from Tangoio Forest, which had the effect of downgrading many boards from Tangoio Forest to No. 3 shop grade.

TABLE 6: Board resin pockets and blemishes for the log ERF classes of Parengarenga and Tangoio Forest. Average board values followed by the same letter do not differ significantly (p > 0.05).

ERF class	Type 1 resin pockets (number/m²)	Type 2 resin pockets (number/m²)	Blemish rating (grade, 0 – 3)
Parengarenga forest			
Low	0.1 b	0.1 c	0.8 cd
Moderate	0.4 b	0.3 c	1.5 ab
Severe	0.6 ab	1.0 ab	2.0 a
Tangoio forest			
Low	0.4 b	0.1 c	0.6 d
Moderate	0.8 ab	0.6 bc	1.2 bc
Severe	1.4 a	1.2 a	2.0 a
	Resin streaks (% of boards)	**Resinous latewood (% of boards)**	**Galls (% of boards)**
Parengarenga forest			
Low	53 b	6 a	0 b
Moderate	79 a	23 a	5 ab
Severe	92 a	34 a	7 ab
Tangoio forest			
Low	52 b	7 a	1 b
Moderate	94 a	23 a	3 b
Severe	98 a	13 a	13 a

TABLE 7: Correlation coefficients (r) of the board resin features and log properties, for the combined Parengarenga and Tangoio Forest logs (n = 60).

Log properties	Type 1 resin pockets[2]	Type 2 resin pockets[2]	Resin blemish rating	Resin streaks	Resinous latewood	Galls
Volume	-0.17	-0.13	0.15	0.10	0.02	0.19
Acoustic velocity	-0.23	-0.20	-0.17	-0.34**	-0.04	-0.13
Heartwood	-0.16	-0.14	0.25	0.16	0.02	-0.11
ERF Class	0.38**	0.68**	0.80**	0.65**	0.28*	0.47**
Type 1 resin pockets[1]	0.59**	0.50**	0.20	0.12	-0.13	0.26*
Type 2 resin pockets[1]	0.34*	0.64**	0.50**	0.43**	0.05	0.34*
Resin blemishes	0.27*	0.59**	0.50**	0.43**	0.10	0.33*
Resin canal diameter	-0.17	-0.09	0.08	-0.05	0.07	0.10
Resin canal frequency	-0.20	0.04	0.09	-0.05	0.23	0.27*
Resin canal brightness	0.17	0.23	-0.02	0.02	-0.15	0.03

* $P < 0.05$, ** $P < 0.01$

[1] Number of resin pockets on the large and small ends of the logs combined.

[2] Number of resin pockets per m^2 of board surface, worst face and edge.

Comparison of actual and adjusted grade recoveries for the low ERF class logs, showed that when resin features were excluded the recovery of clears grade boards doubled, recovery of mouldings grade boards decreased, and overall, recovery of clears + mouldings grade boards increased by 10 and 6 percent of total board volume for Parengarenga and Tangoio Forest, respectively. For moderate ERF class logs recoveries of clears + mouldings grade boards increased by 44 and 21 percent of the total board volume for Parengarenga and Tangoio Forest, with the increase occurring in clears grade boards. For severe ERF class logs the recoveries of clears + mouldings grade boards increased by 66 and 56 percent of the total board volume for Parengarenga and Tangoio Forest, with increases in both the clears and moulding grade boards.

Lumber value

Resin features on the surface of the random-width boards reduced total lumber values by 38 percent for Parengarenga Forest logs, and 31 percent for Tangoio Forest logs. Actual grade values of the lumber were similar for Parengarenga and Tangoio Forest, but adjusted grade values (resin features excluded) were lower for Tangoio Forest, due to the larger defect cores and pruned branches in the Tangoio Forest logs (Table 9).

Moderate and severe ERF class logs were effective in segregating for lumber value (Table 9). There was greater loss of lumber value with increased severity of the log ERF class. Losses of lumber value for the low, moderate, and severe ERF class logs were 9, 42, and 57 percent at Parengarenga Forest, and 6, 28 and 57 percent at Tangoio Forest.

TABLE 8: Actual and adjusted board grade recoveries for the log ERF classes of Parengarenga and Tangoio Forest. The average board grade values are a percentage of the total board volume.

ERF class	Clears	Moulding	No.1 shop	No.2 shop	No.3 shop	Commons
Actual grade recovery, %						
Parengarenga forest						
Low	22	33	1	0	30	14
Moderate	3	16	0	0	50	31
Severe	0	7	0	2	54	37
Tangoio forest						
Low	14	24	9	2	43	8
Moderate	1	18	3	2	52	24
Severe	0	5	0	1	42	52
Adjusted grade recovery, %						
Parengarenga forest						
Low	47	18	3	0	22	10
Moderate	46	17	3	0	25	9
Severe	54	19	1	0	19	7
Tangoio forest						
Low	28	16	8	1	40	7
Moderate	25	15	9	2	41	8
Severe	32	29	2	0	27	10

TABLE 9: Actual and adjusted board grade values for the log ERF classes of Parengarenga and Tangoio Forest.

ERF class	Actual grade value ($/m^3)	Adjusted grade value ($/m^3)	Lumber value loss (%)
Parengarenga forest			
Low	545	601	9
Moderate	341	593	42
Severe	275	642	57
Tangoio forest			
Low	482	511	6
Moderate	358	498	28
Severe	246	579	57

Prediction of grade recovery and lumber value

Linear regression models gave good predictions of actual grade recoveries of clears + moulding grade boards, actual grade value, and loss of lumber value (Table 10). Predictions of actual grade recovery, and loss of lumber value, were weaker using numbers of resin pockets and blemishes on the ends of the logs, compared with ERF classes of logs. Resin canal properties of the logs showed no significant correlations with actual grade recovery, or loss of lumber value.

Multiple regression models gave improved grade recovery and value predictions using log ERF class, volume, heartwood content, and number of Type 1 resin pockets on ends of logs as independent variables (Table 11). ERF class of log was the main contributor to the models, with the other log variables providing only small reductions in residual sums of squares. The exclusion of ERF class of log from the models resulted in poor predictions, with the number of Type 1 and 2 resin pockets and blemishes on the ends of the logs proving to be relatively ineffective predictive variables in the absence of ERF class.

Discussion

Weaker relationships between resin features on the surface of the boards and those on ends of the logs could be attributed to the small number of the resin pockets and blemishes that were sampled on the log ends. Type 1 resin pockets rarely extend more than 50-100 mm longitudinally, and while Type 2 resin pockets can extend for more than 200-250 mm (Ottenschlaeger et al. 2012), the distances are short compared with 5 m lengths of pruned butt logs. Resin bleeding and occlusion scars of Type 2 resin pockets, and lesions and galls that accumulate on the surface of the bark during the life of a tree, provide good indications of the severity of the internal resin defects that are present in the wood (McConchie 2003; McConchie et al. 2007; Ottenschlaeger et al. 2012).

Losses of lumber value for the moderate and severe ERF class logs from Parengarenga and Tangoio Forest (Table 9) were greater than the 14 and 34 percent losses for the moderate and severe ERF class logs from Tikitere Forest in the Bay of Plenty (McConchie 2003). Logs from Tikitere Forest had a lower number of resin pockets on log ends, compared with logs from Parengarenga and Tangoio Forests. Hughes (2007) found an increase in loss of lumber value with increasing numbers of resin pockets on log ends, with logs from Nelson forests having similar value losses to those of logs from Parengarenga and Tangoio Forests, when compared with the same numbers of resin pockets on the log ends. This suggests that resin pockets on the log ends could be useful indicators of the relative loss of lumber value among radiata pine plantation forests and stands.

TABLE 10: Coefficients of determination (r^2) for prediction of the board grade recovery from the log properties, using the combined Parengarenga and Tangoio Forest logs (n = 60).

Log properties	Actual grade recovery of clears + mouldings	Actual grade value	Adjusted grade value	Lumber value loss
Volume	0.00	0.00	0.39**	0.00
Acoustic velocity	0.10**	0.08*	0.04	0.03
Heartwood	0.02	0.03	0.00	0.04
ERF class	0.44**	0.54**	0.02	0.71**
Type 1 resin pockets[1]	0.14**	0.14**	0.00	0.18**
Type 2 resin pockets[1]	0.14**	0.17**	0.02	0.24**
Resin blemishes[1]	0.13**	0.18**	0.00	0.21**
Resin canal diameter	0.01	0.01	0.28**	0.00
Resin canal frequency	0.00	0.00	0.21**	0.00
Resin canal brightness	0.00	0.00	0.00	0.00

* P < 0.05, ** P < 0.01

1 Number of resin pockets and blemishes on the large and small ends of the logs combined.

TABLE 11: Coefficients of determination (R^2) for the regression models, using log properties for the prediction of log grade recovery. Partial R^2 values given for the log variables.

Log properties	Actual grade recovery of clears + mouldings	Actual grade value	Adjusted grade value	Lumber value loss
ERF class included				
Model	0.49	0.71	0.53	0.82
Acoustic velocity			0.07	
Volume		0.07	0.41	
Heartwood	0.04	0.06		0.08
ERF class	0.45	0.55	0.05	0.72
Type 1 resin pockets[1]		0.03		0.02
ERF class excluded				
Model	0.29	0.44	0.53	0.47
Acoustic velocity	0.07		0.07	
Volume		0.05	0.41	
Heartwood	0.07	0.11		0.13
Type 1 resin pockets[1]		0.07	0.05	0.06
Type 2 resin pockets[1]	0.15			0.28
Resin blemishes[1]		0.21		

[1] Number of resin pockets and blemishes on the large and small ends of the logs combined.

Higher incidences of Type 1 resin pockets on surfaces of boards of the moderate and severe ERF class logs from Tangoio Forest (Table 6), could be attributed to frequent occurrences of false growth rings at this site (Figure 1). False growth rings caused by drought conditions have been associated with presence of Type 1 resin pockets in Canterbury (Cown, 1973) and are considered zones of weakness that split tangentially along the false growth ring latewood/earlywood boundary. They are caused by axial compressive stresses (Bariska & Kučera, 1985), that occur with bending of tree stems, and this has been shown to increase the incidence of Type 1 resin pockets (Watt et al. 2009; Jones et al. 2013).

There was a relationship between Type 2 resin pockets on the log ends and blemish rating and resin streaks on the surface of the boards (Table 7). Ottenschlaeger et al. (2012) observed that the association between Type 2 resin pockets and blemishes, and resin streaks, occurs as a result of the centripetal transport of resin from the Type 2 resin pockets towards the pith, and is a wound response to cambial damage at the time of the resin pocket formation. The blemish rating and percentage of boards with resin streaks increased for the moderate and severe ERF logs from Parengarenga and Tangoio Forest, which suggests that the severity of the cambial damage by the Type 2 resin pockets increased in these logs.

Incidences of resin blemishes on the ends of the logs were strongly associated with Type 2 resin pockets (Table 4), with both occurring in larger numbers on the ends of the logs from Tangioio Forest (Table 5). This suggests there was greater resin flow in response to cambial damage at this site. Resin flow can increase with vertical resin canals of larger diameter and higher frequency (Blanche et al. 1992; Hood & Sala, 2015), and in response to drought conditions (Blanche et al. 1992; Lombardero et al. 2000; Zas et al. 2020; Rissanen et al. 2021). Constitutive resin enrichment of the resin canals and resin flow are greater when drought conditions limit growth (Lombardero et al. 2000; Rissanen et al. 2021), as occurred with the formation of false growth rings at Tangoio Forest. Resin enrichment of the resin canals appeared to be a stronger driver of resin blemish formation than the larger diameter and frequency of the resin canals at Parengarenga Forest. This suggests that the environmental and genetic factors which increase the size and frequency of the resin canals (Reid & Watson 1965; Rigling et al. 2003; Govina et al. 2021; Rissanen et al. 2021), may not increase the constitutive resin flow, and could explain the lack of relationships between the resin canal properties and resin pockets and blemishes.

Conclusions

External resin feature (ERF) class of the pruned butt logs provided an effective method of segregating logs for differences in the number of Type 1 and 2 resin pockets and blemishes on the surface of the boards, the actual grade recovery, and the loss of lumber value associated with the resin features.

Resin pockets and blemishes on the ends of the logs were less effective at predicting the actual grade recovery and lumber value, due to the small number of the resin features on the log ends, compared with the resin bleeding, lesions and galls assessed by ERF classes on the surface of the bark.

Resin canal properties of logs did not improve predictions of actual grade recoveries and the losses of lumber value associated with resin features, but inclusion of the log heartwood content, the number of Type 1 resin pockets on log ends, and log volume, improved predictions to a small extent when combined with the ERF classes of the logs.

Competing interests
The authors declare that they have no competing interests.

Acknowledgements
We thank Bob Shirley (PF Olsen Ltd) and Brian Garnett (Pan Pac Forest Products Ltd) for the selection of the radiata pine plantation stands and the logging at Parengarenga Forest, Northland, and Tangoio Forest, Hawke's Bay. Winston Liew and Maria Ottenschlaeger (CSIRO) for the resin canal measurements of the breast height increment cores. John Lee and Rod Brownlie (Scion) for the log end disc surfacing and photography, and Maria Ottenschlaeger (CSIRO) for the image analysis of the disc photos. The TITC sawmill at Waiariki Polytechnic for sawing the logs to random-width boards, and the assistance of Teresa McConchie, Walt Povey and Pat Hodgkiss in the grading of the boards. Graeme Young (Tenon Ltd) provided support and advice in the design of the study. The research was funded by the Wood Quality Initiative (WQI) Ltd.

Authors' contributions
GD and JY initiated the research and designed the study. DM organised the experimental work of tree selection, logging, sawmilling and lumber grading. TJ managed the study, assisted with the experimental work, carried out the data analysis, and wrote the manuscript. All authors read and approved the final manuscript.

References
Ananías, R.A., Lastra, J., Salvo, L., Contreras, H., Barría, C., & Peredo, M. (2010). Preliminary study of the resin canals in radiata pine. *Maderas. Ciencia y tecnología 12*(2), 135-142. https://doi.org/10.4067/S0718-221X2010000200008

Bariska, M., & Kučera, L.J. (1985). On the fracture morphology in wood. Part 2: Macroscopical deformations upon ultimate axial compression in wood. *Wood Science and Technology*, *19*(1), 19-34. https://doi.org/10.1007/BF00354750

Blanche, C.A., Lorio, P.L., Sommers, R.A., Hodges, J.D., & Nebeker, T.E. (1992). Seasonal cambial growth and development of loblolly pine: xylem formation, inner bark chemistry, resin ducts, and resin flow. *Forest Ecology and Management 49*, 151-165. https://doi.org/10.1016/0378-1127(92)90167-8

Chen, F., Yang, J.L., & Downes, G. (2008). A visual information assessment tool for resin canal identification and property measurement. *IAWA Journal 29*(4), 397-408. https://doi.org/10.1163/22941932-90000194

Clifton, N.C. (1969). Resin pockets in Canterbury radiata pine. *New Zealand Journal of Forestry 14*(1), 38-49.

Cown, D.J. (1973). Resin pockets: their occurrence and formation in New Zealand forests. *New Zealand Journal of Forestry 18*(2), 233-251.

Ellis, J.C. (1995). Measuring Logs. In D. Hammond (Ed.), *Forestry Handbook*, 3rd ed (pp. 107-108). Wellington: New Zealand Institute of Forestry (Inc.).

Evans R. (1994). Rapid measurement of the transverse dimensions of tracheids in radial wood sections from *Pinus radiata*. *Holzforschung 48*(2), 168-172. https://doi.org/10.1515/hfsg.1994.48.2.168

Govina, J.K., Apiolaza, L.A., & Altaner, C.M. (2021). Variation and genetic parameters of axial resin canal features in clones and families of *Pinus radiata*. *New Forests 52*, 167-176. https://doi.org/10.1007/s11056-020-09780-8

Hood, S., & Sala, A. (2015). Ponderosa pine resin defences and growth: metrics matter. Tree Physiology *35*, 1223-1235. https://doi.org/10.1093/treephys/tpv098

Hughes, M. (2007). Resin assessment a valuable tool. New Zealand Tree Grower, August, 25-27.

Jones, T.G., Downes, G.M., Watt, M.S., Kimberley, M.O., Culvenor, D.S., Ottenschlaeger, M., Estcourt, G., & Xue, J. (2013). Effect of stem bending and soil moisture on the incidence of resin pockets in radiata pine. *New Zealand Journal of Forestry Science*, *43:* 10. https://www.scionresearch.com/__data/assets/pdf_file/0003/65127/1179-5395-43-10_Jones.pdf

Lee, J., & Brownlie, R. (2009). Assessment of the end grain of log ends and log discs. Wood Processing Newsletter No. 43. New Zealand Forest Research Institute, Rotorua.

Lombardero, M.J., Ayres, M.P., Lorio, P.L., & Ruel, J.J. (2000). Environmental effects on constitutive and inducible resin defences of *Pinus taeda*. *Ecology Letters 3*, 329-339. https://doi.org/10.1046/j.1461-0248.2000.00163.x

McConchie, D.L. (2003). *Field guide to assist recognition and classification of resinous defects on the bark of radiata pine.* WQI Report No. APP 12. Rotorua, New Zealand: Wood Quality Initiative.

McConchie, D.L., Cown, D., & Donaldson, L. (2007). *Resin and other features in logs and lumber. Field Guide.* Rotorua, New Zealand: Wood Quality Initiative.

McConchie, D.L, & Turner, J. (2002). How external resin on radiata pine logs relates to clearwood quality and value. *Wood Processing Newsletter* No. 32. Rotorua: New Zealand Forest Research Institute.

Ottenschlaeger, M., Downes, G.M., Bruce, J., & Jones, T.G. (2012). Type 1 and 2 resin pockets in New Zealand radiata pine: how do they differ? *New Zealand Journal of Forestry Science 42*, 39-46.

Park, J.C. (2004). The incidence of resin pockets. *New Zealand Journal of Forestry 49*, 32.

Reid, R.W., & Watson, J.A. (1965). Sizes, distributions, and numbers of vertical resin ducts in Lodgepole pine. *Canadian Journal of Botany 44*, 519-525. https://doi.org/10.1139/b66-062

Ridoutt, B.G., McConchie, D.L., & Ball, R.D. (1999). Predicting resin pockets in radiata pine logs from blemishes on log ends. *Wood and Fiber Science 31*(4), 434-440.

Rigling, A., Brühlhart, H., Bräker, O.U., Forster, T., & Schweingruber, F.H. (2003). Effects of irrigation on diameter growth and vertical resin duct production in *Pinus sylvestris* L. on dry sites in the central Alps, Switzerland. *Forest Ecology and Management 175*, 285-296. https://doi.org/10.1016/S0378-1127(02)00136-6

Rissanen, K., Hölttä, T., Bäck, J., Rigling, A., Wermelinger, B., & Gessler, A. (2021). Drought effects on carbon allocation to resin defences and on resin dynamics in old-grown Scots pine. *Environmental and Experimental Botany 185*. https://doi.org/10.1016/j.envexpbot.2021.104410

Watt, M.S., Downes, G., Jones, T., Ottenschlaeger, M., Leckie, A.C., Smaill, S.J., Kimberley, M.O., & Brownlie, R. (2009). Effect of stem guying on the incidence of resin pockets. *Forest Ecology and Management*, *258*(9), 1913-1917. https://doi.org/10.1016/j.foreco.2009.07.032

Woollons, R., Manley, B., Park, J. (2008). Factors influencing the formation of resin pockets in pruned radiata pine butt logs from New Zealand. *New Zealand Journal of Forestry Science*, *38*(2/3), 323-334.

WWPA (1991). *Western lumber grading rules*, Portland, OR, USA: Western Wood Products Association.

Yang, J.L., Downes, G.M., Chen, F., & Cown, D.J. (2007). Investigation of within-tree and between-site resin canal variation in radiata pine. In: *Proceedings of IUFRO All-Division 5 Conference, Forest Products and Environment: A Productive Symbiosis*, Taipei, Taiwan, October 2007, p. 179.

Zas, R., Touza, R., Sampedro, L., Lario, F.J., Bustingorri, G., & Lema, M. (2020). Variation in resin flow among Maritime pine populations: Relationship with growth potential and climatic responses. *Forest Ecology and Management, 474*: 118351. https://doi.org/10.1016/j.foreco.2020.118351