Satchell & Moore *New Zealand Journal of Forestry Science* (2023) 53:1
https://doi.org/10.33494/nzjfs532023x238x
E-ISSN: 1179-5395
published on-line: 16/11/2022

Research Article **Open Access**

New Zealand Journal of Forestry Science

Sawn timber and structural products from 'Kawa' poplar (*Populus deltoides* Marshall *x P. yunnanensis* Dode) grown in Northland, New Zealand

Dean Satchell[1]* and John Moore[2]

[1] *Northland Regional Council, Private Bag 9021, Whangarei 0148, New Zealand*
[2] *Timberlands Limited, P.O. Box 1284, Rotorua 3046, New Zealand*

*Corresponding author: deans@nrc.govt.nz

(Received for publication 23 May 2022; accepted in revised form 26 October 2022)

Abstract

Background: While poplar (*Populus* spp.) is an important source of raw materials for the wood processing sector in many regions of the world, in New Zealand it has a reputation for producing poor grade recoveries of sawn timber that is unsuitable for structural applications. However, the 'Kawa' poplar clone (*Populus deltoides* Marshall *x P. yunnanensis* Dode), which has relatively high wood density, could yield structural timber. This, along with evidence demonstrating building code compliance, would improve utilisation options for this species in New Zealand.

Methods: Sawn timber conversion and grade recovery were quantified for a 28-year-old pruned stand of 'Kawa' poplar grown in Northland, New Zealand. A sample of 90 mm x 45 mm structural boards were tested to determine their mechanical properties and the resulting strength class. Boron preservative retention and penetration were measured to determine whether timber could be treated to the level required under New Zealand's building standards. Density, modulus of elasticity and modulus of rupture were assessed on small defect-free specimens taken from different radial and vertical positions within trees to determine intra-stem and inter-stem variation in these properties.

Results: The overall conversion of logs to sawn timber was 53%, with approximately 94% of this recovery consisting of graded timber. The most common sources of downgrade were knots, pruning wounds, and end-splits. Approximately 70% of the sawn boards were graded as clears, with smaller recoveries of cladding and structural boards. The average length of clear section was approximately 2.5 m. Mechanical testing of structural boards demonstrated that they have characteristic values sufficient to meet the requirements for the SG10 strength class. Preservative treatment achieved the H1.2 specification. Density, modulus of elasticity and modulus of rupture were all higher in specimens cut from the outside of the log compared with those taken from near the pith at all heights up the stem.

Conclusions: Mechanical properties and boron treatment results indicate suitability for structural applications in accordance with New Zealand's building code. 'Kawa' poplar also produced high grade recoveries suggesting potential for commercial sawn timber production, especially for structural appearance products.

Keywords: hybrid poplar; structural timber; timber preservation; mechanical properties; building code; end-splitting; timber grading; pruning wounds; knots; stiffness; strength

Introduction

Globally, poplar (*Populus* spp.) is increasingly being used to provide a fast-growing source of raw material to different parts of the forest products sector (Ball et al. 2005; Truax et al. 2014). There has been considerable focus on hybrids of fast growing poplar species to provide feedstocks for biomass energy and the pulp and paper sector (Stanton et al. 2002). Despite its relatively low density and mechanical properties, hybrid poplar timber has been used in structural applications in North America, although generally at a disadvantage compared with softwood species (Balatinecz & Kretschmann 2001). Poplar is a light-coloured timber with an attractive appearance and lustre, so can also be used for

© The Author(s). 2023 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.

other solid wood applications such as furniture and a range of engineered wood products including plywood, laminated veneer lumber and cross-laminated timber (Hematabadi et al. 2021).

‘Kawa’ (*Populus deltoides* Marshall *x P. yunnanensis* Dode) is the first hybrid poplar bred in New Zealand and was released in 1986 (Wilkinson 2000). ‘Kawa’ has been the primary poplar cultivar supplied by Northland’s only commercial poplar nursery, Stix, from 1990 to 2010 for pastoral soil conservation, (Murray Hunter, pers. comm) and from the Northland Regional Council nursery since 2016. Despite this information on nursery sales, unfortunately there is no detailed information on the overall extent of the resource. The National Exotic Forest Description groups poplars together with other hardwood species, excluding *Eucalyptus* species. The total area of “other hardwoods” in New Zealand is roughly 12,500 ha with the Northland resource being 2300 ha in size (Ministry for Primary Industries 2020). While these statistics are only approximate, they do indicate that most of the Northland resource is 16-30 years old, and therefore potentially able to be harvested and processed.

Wilkinson (2000) recommended ‘Kawa’ poplar as suitable for sawn timber production because it produces a relatively high-density wood. However, the same author also reported that poplar has a lower sawn timber recovery than radiata pine (*Pinus radiata* D.Don), which is the main commercial timber species grown in New Zealand, and knots constitute a considerable defect in the sawn timber. Distortion resulting from the presence of tension wood also occurs in drying of poplar, earning the genus a reputation for a high reject rate after drying (Williams et al. 1986). No data on sawn timber and grade recovery data from New Zealand-grown ‘Kawa’ poplar have been available from which to determine its suitability as a source of sawn timber, however ‘Kawa’ has good form and monopodial architecture typical of most commercial conifer species, suggesting opportunity for sawlog production. Because much of the Northland ‘Kawa’ resource comprises straight trees that are maturing with appropriate diameters for sawing, it is of interest to both existing and prospective growers to determine whether the timber may have value and what applications it is most suitable for. Furthermore, the relatively small size of the resource and its distributed nature means that it is likely to be processed using portable sawmilling equipment. Therefore, there is interest in determining the timber grade recovery when processing ‘Kawa’ logs using this type of equipment.

Low wood density is associated with low strength properties in poplar (Wilkinson 2000). Wood density also varies significantly among poplar clones, with basic density varying between 300-400 kg m^{-3} for the most common hybrid clones, with little density variation among individual trees of a specific clone (Wilkinson 2000). For example, ‘Kawa’ had an individual tree density range of only 9 kg m^{-3}, compared to an individual tree density range of over 100 kg m^{-3} for radiata pine (Wilkinson, 2000). An earlier study using material from 8-year-old ‘Kawa’ trees reported a mean basic density of 365 kg m^{-3} with a mean stiffness of 5.4 GPa at 12% moisture content (Wilkinson, 2000). ‘Kawa’ poplar also showed no marked radial density change. While these values are higher than many of the other New Zealand-grown poplar species tested, they are still significantly lower than those reported for 25-year-old radiata pine which had a mean basic density of 415 kg m^{-3} and a mean stiffness of 8.2 GPa at 12% moisture content, suggesting that stiffness of ‘Kawa’ may not be adequate for structural applications. This result agrees with the conclusions of Williams et al. (1986) that poplar generally has “moderate to low strength properties”. A more recent study by Jones (2016) based on a single ramet of the ‘Kawa’ poplar clone grown in the North Island found that while density at breast height was over 400 kg m^{-3}, dynamic modulus of elasticity was less than 6 GPa. Despite these results, anecdotes from end users of ‘Kawa’ timber are that it is sufficiently stiff and strong to be used in structural applications (Peter Davies-Colley, pers. comm).

In addition to having the required mechanical properties, structural timber products are required to hold sufficient durability for a minimum 50-year building life under New Zealand’s building code (Clause B2 Durability, 2nd edition amendment 12). Two New Zealand Standards, NZS 3602:2003 (Standards New Zealand 2003a) and NZS 3640:2003 (Standards New Zealand 2003b) provide the Acceptable Solutions for achieving building code compliance for durability performance. NZS 3640:2003 provides definitions of the Hazard classes and their preservative treatment requirements and NZS 3602:2003 lists species and level of treatment (as Hazard class per NZS 3640:2003) required for specific structural applications. The Hazard class for interior structural applications is H1.2 for “service conditions protected from the weather but with a risk of moisture content conducive to decay” (NZS 3640:2003).

The preservative treatment for radiata pine is prescribed in NZS 3640:2003 for H1.2 Hazard class service conditions. Like radiata pine, poplar wood is non-durable (Williams et al. 1986). Sawn softwood timber requires complete sapwood penetration along with a retention level in the sapwood cross section of 0.4% Boric Acid Equivalent (BAE). Because poplar is a hardwood and is not listed in NZS 3602:2003 for H1.2 service conditions, the route to compliance is via a Similar Materials test as per Building Code Verification Method B2/VM1 (1.0 Durability Evaluation, Building Code clause B2). This test compares the relative durability performance of the test material (e.g., boron-treated poplar) with a reference softwood (e.g., radiata pine boron-treated to H1.2).

There is little published information on preservative treatment of poplar timber. One study in the United States using 100 mm x 50 mm sawn boards from yellow poplar (*Liriodendron tulipifera* L) found that wrapped diffusion storage for at least eight weeks after dipping was required to achieve adequate borate penetration (Chen et al. 1997). In New Zealand, pressure treatment of poplar with boron has yielded unsatisfactory penetration results (Tripti Singh pers. comm), but Williams et al. (1986) tested the boron diffusion method, demonstrating that 50-mm-thick poplar boards could be effectively treated to above the 0.2% BAE required at that time by the Timber Preservation Authority (1980) for preservation of wood against borer attack. However, Hazard class H1.2 now requires 0.4% BAE (NZS 3640:2003) to protect against decay and no research data are available demonstrating that the boron diffusion method consistently achieves this.

For 'Kawa' poplar to be used in structural applications, more information is needed on its physical and mechanical properties, and the ability of preservative treatment to improve its durability so that it can meet the requirements of the New Zealand building code for structural applications. Therefore, the objective of this study was to assess the sawn timber recoveries and performance of structural products cut from a plantation of 28-year-old pruned 'Kawa' poplar grown in Northland. The specific questions that this research project sought to answer were:

(1) Can 'Kawa' poplar be processed with minimal degrade using best practice portable sawmilling followed by air-drying, to enable on-farm production of structural timber?

(2) To what degree does log diameter and log position within the stem from which it was cut affect sawn timber and grade recoveries?

(3) What levels of defect and knot defect can be expected in Northland plantation 'Kawa' poplar at 28 years of age?

(4) To what degree does radial position and vertical position in tree affect mechanical properties and density?

(5) What relationships exist between density, stiffness, and strength, among trees and within trees?

(6) Can the boron diffusion method be used on 'Kawa' poplar to meet the preservative penetration and retention requirements under NZS 3640:2003 for the H1.2 hazard class?

Methods

Tree harvesting and log preparation

Seventeen pruned 'Kawa' poplar trees were harvested from a small 28-year-old stand growing near Titoki, Northland, New Zealand (latitude 35°44'08''S, longitude 174°01'37''E). The trees were growing on a reasonably sheltered pastoral hill country site, on a moderately fertile clay loam soil. Trees were harvested mechanically, and 71 logs were cut to length on site, with the bark and limbs removed mechanically.

Diameter under bark and the diameter of visible heartwood were measured on both the large end and the small end of all logs. Sawlog lengths were measured, and logs were marked to identify tree and log position in each sawn board. Only those logs with a small-end diameter (SED) greater than 18 cm were milled into boards.

Timber processing and sawn timber preparation

A total of 43 logs from 15 trees were milled two weeks after harvest. This period was deemed as commercially appropriate for minimising end-splitting of logs, which increases as the interval between cross-cutting logs and sawmilling increases. Forty sawlogs were 3.7 m long, one was 4.0 m long, one was 3.6 m and one was 3.5 m long, and their small end diameters ranged from 18 cm up to 44.5 cm, with a mean small end diameter of 30.6 cm. Heartwood diameters ranged from 7.0 cm up to 40 cm, with a mean of 20.2 cm. Corresponding values of heartwood percentage (on an area basis) ranged from 9.7% up to 76.3%, with a mean of 32.8%. There was no evidence of discoloured heartwood or "biological blackheart" which can occur in poplar (Johansson & Hjelm 2013). Sawlogs were sawn on a Wood-Mizer 3 mm kerf horizontal bandsaw into 25 mm and 50 mm slabs; slabs were then edged using a Wood-Mizer twin-blade edger (Wood-Mizer, Indianapolis, USA). Wider central slabs were ripped through the centre of their width into two slabs, before edging into straight boards, avoiding inclusion of pith. Edging included visual judgment calls that focused on grade recoveries in preference to volume recoveries. Resulting nominal board widths were 75 mm, 100 mm, 150 mm, 200 mm, 250 mm and 300 mm. Nominal board thicknesses were 25 mm and 50 mm. Boards were oversized during sawing to allow for shrinkage during drying. Sawn recoveries were calculated from nominal board dimensions but excluded those sections containing taper and wane. After air drying outdoors under cover for eight months, boards were visually graded as either "clears", "cladding" or "structural". Two grading methods were used. The first targeted clearwood lengths ("best grade") and the second targeted longest graded lengths in preference to shorter lengths of a higher grade ("long length grade"). Criteria for the three grades are described in Table 1 (criteria for higher grades always exceeds those for lower grades).

The lengths of defect were marked as if docked and allocated to the following categories: knots; pruning wounds; end-splits; pith; excessive crook and excessive bow. Lengths of end splits were measured from the end of the board to where the visible crack ended. Knots were further categorised as follows: (1) knot (only classified as defect according to the grade allocated); (2) large knot defect; (3) spike knot (only classified as defect according to the grade allocated); (4) large spike knot defect; (5) pruning wound (only classified as defect according to the grade allocated); and (6) large pruning wound defect. The presence of pith was recorded as a defect. Crook and bow were also recorded as defects where these exceeded the limits given in NZS 3631:1988 (Standards New Zealand 1988).

Bending strength and stiffness testing of structural grade boards

Air dry 100 mm x 50 mm boards were machined to 90 mm x 45mm and a sample of 31 structural-grade boards was randomly selected for bending tests to

TABLE 1: Criteria used to allocate boards to specific grades.

Grade	Criteria
Clears	Clearwood on the front face and edges, with the board also meeting the requirements of Cladding grade.
Cladding	Dressing grade as per NZS 3631:1988 (Standards New Zealand 1988) with two additional requirements for cladding from NZS 3602:2003 (Standards New Zealand 2003a): 1. All holes, resin and bark pockets shall be excluded; 2. Knot size shall not exceed 50 mm, or 25 mm width for spike knots.
Structural	No. 1 framing grade as per NZS 3631:1988.

determine modulus of elasticity and modulus of rupture. Testing was undertaken at the New Zealand Forest Research Institute Limited (Scion) in Rotorua using a Baldwin universal testing machine. Specimens were tested as a joist (on edge) in accordance with AS/NZS4063.1:2010 (Standards New Zealand 2010a) and AS/NZS4063.2:2010 (Standards New Zealand 2010b) over a span to depth ratio of 18:1 (i.e. 1620 mm). A short cross section was then cut from an undamaged clearwood section close to the failure point of each test specimen for determining density and moisture content. Moisture content was measured using the oven drying method. Nominal density was calculated for each section from the oven dry weight and the volume at the time of testing. Density at the time of testing was calculated for each section from the test weight and volume at time of testing.

Mechanical testing of small defect-free specimens

Small defect-free specimens were prepared from sections with 25 mm x 25 mm cross-sectional dimensions that were ripped from two radial positions (inner/outer) at up to five height positions from seven trees. Inner specimens were cut as close as possible to the pith, but no closer than 1 cm from the pith line. Outer specimens were cut no closer than 2 cm from the outside of the log to avoid physical damage caused by machine debarking. The first vertical height position was at 1.85 m +/- 1 m and then at 3.7 m increments +/- 1 m up the stem.

Sections containing only clearwood were selected. Wood with incipient decay or discolouration was excluded. Growth ring orientation was marked on sample ends and only specimens with growth rings parallel to a face were used for testing. Specimens were machined to their final cross-sectional dimensions of 20 mm x 20 mm and crosscut into 500 mm lengths, resulting in 140 small clear specimens (two or three replicates for each radial position and height position within each tree). Specimens were conditioned at 20°C and 65% RH until they achieved constant mass (approximate equilibrium moisture content of 12%). Bending tests were conducted using an Instron universal testing machine at Scion, Rotorua. The growth rings were aligned as much as possible with the direction of loading, in accordance with ASTM D143-94 (American Society for Testing and Materials 2000). The test span was 280 mm with a centre point load. From the load-deflection data the fibre stress at the proportional limit (FSPL), fibre stress at maximum load (modulus of rupture) and modulus of elasticity were calculated. Following testing, each entire specimen was used for determination of density and moisture content. Moisture content was measured using the oven drying method. Oven-dry density (a proxy for basic density) was calculated for each test specimen from the oven dry weight and volume measured at the time of testing. Density at the time of testing was calculated for each test specimen from the weight and volume at the time of testing.

Boron treatment retention and penetration

A boron solution was prepared by adding 2.3 kg of granular boric acid (Inkabor Orthoboric acid 99.99% H_3BO_3 min, CAS No:10043-35-3 EC No:233-1239-2) and 3 kg of borax pentahydrate (disodium tetraborate pentahydrate $Na_2B_4O_7.5H_2O$ ETiMADEN Etibor-48 CAS No:12179-04-3 EC No:215-540-4) per 10 litres of water used. The solution was gently heated and stirred until the salts dissolved and no visible solids remained. The solution was used within 12 hours of dissolving the boron salts and before any crystallisation occurred in the solution.

Rough-sawn freshly milled boards with cross-sectional dimensions of 100 mm x 50 mm and 150 mm x 50 mm were immersed in the solution for five seconds, then block stacked and fully wrapped with a black polythene cover and stored outdoors for 41 days to allow the boron to diffuse into the wood. Boards were then filleted and allowed to air dry for eight months. Sixteen samples representative of the batch of treated timber were selected and prepared for analysis by machining to 90 mm x 45 mm and then cross-cutting a single 20 cm length that contained defect-free wood, no closer than 50 cm from board ends.

Boron retention and penetration tests were conducted by Independent Verification Services Ltd in Hamilton. Variamine blue RT (VBRT) salt solution with ammonia buffer was used as a staining test to determine the heartwood sapwood boundary following AS/NZS 1605.1:2018 (Standards New Zealand 2018a). However, this test was unsuccessful for determining the boundary between heartwood and sapwood, so two other staining tests (Methyl Orange and Ferric Chloride) were trialled for heartwood/sapwood differentiation. These tests also proved unsuccessful, so it was decided that analysis would be based on total cross section retention and penetration. Boron penetration was analysed using the Turmeric Acid test as per AS/NZS 1605.2:2018

(Standards New Zealand 2018b). Boron retention samples were prepared using nitric acid micro digestion at 100°C for 60 minutes as per AWPA A7-12 (American Wood Protection Association 2012). Boron content was measured using Inductively Coupled Plasma - Optical Emission Spectrometry (ICP-OES), with correction for moisture as per AWPA A21-08 (American Wood Protection Association 2008). Boric Acid Equivalent (BAE) was calculated as elemental boron x 5.717.

Data analysis

Individual log volumes were calculated from data on their large and small-end diameters and length using Smalian's formula (Avery & Burkhart 2015). The nominal volumes of the individual boards cut from each log were summed to give the total sawn timber recovery per log. These values were divided by log volume to give the proportional recovery. Because these data are bounded by zero and one, beta regression was used to model sawn timber recovery as a function of log characteristics (e.g., log diameter and taper). The recovery of different grades was calculated from the grade assigned to a board (based on the two different grading methods) and its overall nominal dimensions. The volume downgraded due to defects such as knots and end splits was calculated from the nominal cross-sectional dimensions of the board and the length affected by the particular defect. Beta regression was used to model the relative proportion of volume with these defects and log characteristics.

Data from the bending tests on structural boards were used to calculate the characteristic strength, stiffness and density values using the procedures set out in AS/NZS4063.2:2010 (Standards New Zealand 2010b). These, in turn, were used to assign the timber to a strength class according to NZS3603:1993 (Standards New Zealand 1993). Ordinary least squares regression was used to explore inter-relationships among density, stiffness and bending strength.

A linear mixed effects model was fitted to examine the effects of radial and longitudinal position on density, bending strength and stiffness measured on the small defect-free specimens. Fixed effects were included for radial position (inner and outer) and log height class. Because the data had a hierarchical structure with multiple specimens collected from the same log within a tree, a term was included in the model to account for the random effect of the different trees. The model had the following form:

$$y_{ijk} = \mu + \alpha POS_i + \beta LOG_j + \gamma POS_i \times LOG_j + a_k + \varepsilon_{ijk} \quad (1)$$

where y_{ijk} is the density, bending stiffness or bending strength of a small defect-free specimen cut from the i^{th} radial position in the j^{th} log cut from the k^{th} tree and ε_{ijk} represents the within-group error. The random effect of the k^{th} tree is assumed to be normally distributed ($a_k \sim N(0, \psi)$) where ψ is the variance-covariance matrix.

Results

Sawn timber

The 43 logs that were processed had a total volume of 14.2 m^3. These logs were processed into 7.6 m^3 of nominal sized (i.e., dry) sawn boards, giving an overall conversion of 53%. The most common section size produced by piece count was 150 mm x 50 mm (26% of boards), while the most common section size by volume was 200 mm x 50 mm (34% of volume; Table 2). Sawn timber recovery for individual logs ranged from 32% up to 62% and increased with increased log diameter (p=0.01; Figure 1). It also decreased with increasing log taper (p=0.009). Log taper was highest in the butt logs (on average around 2 cm/m), and lowest in the second and third logs cut from the stem (approximately 0.7 cm/m). Overall, the beta regression model that included terms for log diameter and log taper explained 47% of the variation in sawn timber recovery. The fitted model had the following form:

$$CONV = -1.598 + 0.08845 DIAM - 0.0009543 DIAM^2 - 0.118 TAPER \quad (2)$$

where *CONV* is the proportion of log volume converted into timber, *DIAM* is the average log diameter (cm), and *TAPER* is the change in log diameter per unit length (cm/m).

TABLE 2: Number and volume of boards produced with different nominal dimensions

Nominal width (mm)	Nominal thickness (mm)	Number of boards	Total volume of boards (m^3)
75	25	6	0.04
100	25	55	0.49
100	50	50	0.90
150	25	50	0.64
150	50	92	2.48
200	25	23	0.42
200	50	71	2.56
250	25	1	0.02
300	50	1	0.06
Total		349	7.59

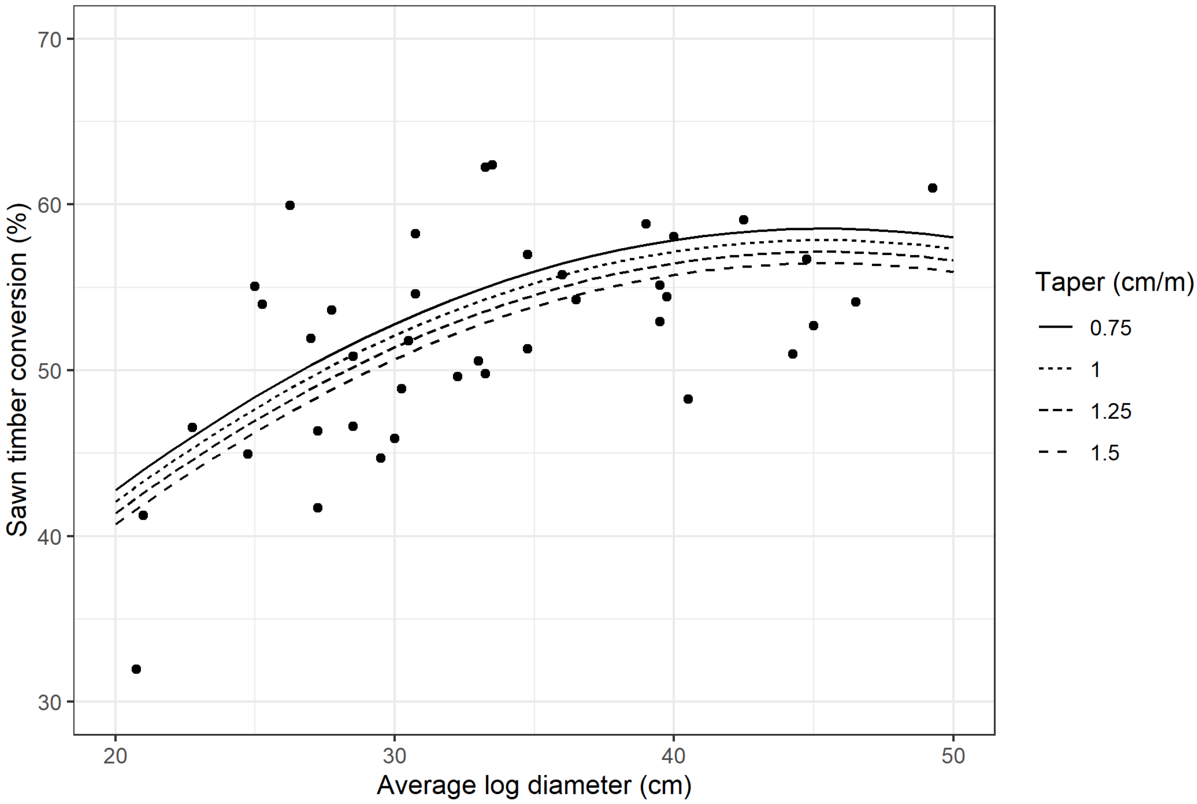

FIGURE 1: Relationship between sawn timber conversion and log diameter and taper.

Sawn timber grade recovery

Of the total volume of timber produced, there was a 94% recovery of graded timber based on the "best grade" method (Table 3), with an average graded board length of 2.6 m. Most of the downgraded volume was due to end splits, knots and pruning wounds. End splits are of similar importance as knot/pruning defects as being the most significant cause of degrade. The volume docked due to knots and pruning wounds was broken down into different categories, which showed that the most common downgrade was due to large spike knots, followed by large knots and then pruning wounds (Table 4). Recovery of graded timber was slightly higher (circa 95%) under the "long length" grading method due to a reduction in degrade due to knots and pruning wounds (Table 3). The average length of "long length" graded boards was slightly longer at 2.8 m.

Most of the recovered timber volume was assigned to the "clears" grade (Table 5). Under the "best grade" method, 74% of the recovered volume was assigned to the "clears" grade with the average length of clear sections being 2.5 m (range 0.7-4.0 m). Under the "long-lengths" method, the proportion of recovered volume assigned to the clears grade decreased to 64%, but the average length of clear sections increased to 2.6 m (range 0.7-4.0 m). This method resulted in greater proportions of recovered volume being assigned to the cladding and structural grades, and the average board lengths for these grades being 0.3 m and 0.5 m longer, respectively, than under the "best" grading method.

TABLE 3: Recoveries of graded timber and defects as percentages of sawn timber volume for the two grading methods.

Outturn category	**Percentage of sawn timber in category by grading method**	
	"Best"	**"Long length"**
Graded timber	93.9	94.7
Defect - End splits	2.4	2.4
Defect - Knots and pruning wounds	3.2	2.4
Defect - Crook and bow	0.5	0.5
Defect - Pith	<0.1	<0.01
Total	**100**	**100**

TABLE 4: Frequency of different categories of knot and pruning wound defect/degrade.

Knot/pruning wound defect category	Percentage of total volume
Large knot defect	20
Large spike knot defect	33
Knot degrade	12
Spike knot degrade	3
Large pruning wound defect	12
Pruning wound degrade	19
Total	**100**

Relationships between timber defects and log characteristics

There was a significant relationship between the incidence of knot and pruning wound defects and both log position (p<0.001) and log taper (p=0.001). There was no relationship with log diameter (p=0.781). The incidence of knot and pruning wound defects increased with increasing log position up the stem (Figure 2) and with increasing log taper. Boards cut from the butt log had approximately 0.5% of their volume downgraded due to these defects, while boards cut from the upper logs had more than 2% of their volume downgraded.

No relationship was established between end-splits and log position (p=0.5). However, there was a weak positive relationship with log diameter (p=0.02) and suggestive but inconclusive evidence of a negative relationship with taper (p=0.08). These two variables were only able to explain approximately 13% of the variation in the volume downgraded due to end-splitting.

Bending strength and stiffness of structural grade boards

The moisture content of the structural timber specimens at the time of testing ranged from 8.7% up to 12.1% with a mean of 10.8% (Table 6). Values of modulus of elasticity (unadjusted for moisture content) ranged from 6.88 GPa up to 13.04 GPa, with a mean value of 10.76 GPa. Modulus of elasticity exhibited a moderate liner relationship with modulus of rupture (R^2=0.47) and nominal density (R^2=0.36). The characteristic values of modulus of elasticity and modulus of rupture were 10.58 GPa mm^{-2} and 45.90 MPa, respectively, which were sufficient for the timber to be assigned to the SG10 strength class. The bending strength exceeded the requirement for higher strength classes, with the assignment to SG10 determined by bending stiffness (modulus of elasticity).

Physical and mechanical properties of small defect-free specimens

Modulus of elasticity of the 140 small, defect-free specimens tested ranged from 5.65 GPa up to 11.17 GPa, with a mean of 9.02 GPa and a coefficient of variation of 13%. The mean moisture content of the specimens at the time of testing was 14.2%. There was a strong linear relationship between modulus of elasticity and modulus of rupture (R^2=0.87; Figure 3), and between nominal density and modulus of elasticity (R^2=0.76). Modulus of elasticity was significantly higher in specimens cut from the outer position in a log (p<0.001) and increased with log position up the stem (p<0.001; Figure 4). There was also a significant effect of the interaction between radial position and log position up the stem (p<0.001). Most notably, the difference in modulus of elasticity between specimens cut from the inner and outer positions was greatest in the butt log (i.e., log 1). Here the difference was approximately 2.2 GPa between specimens cut from the inner and outer radial positions. Overall, radial position, log number up the stem and their interaction explained approximately 70% of the variation in modulus of elasticity. Both modulus of rupture and nominal density also exhibited similar patterns of radial and longitudinal variation within a tree as the radial position, log number and interaction terms in the models for these properties were all highly significant (p<0.001). The model for modulus of rupture was able to explain approximately 75% of the variation in this property, while the model for nominal density explained approximately 60% of the variation.

TABLE 5: Overall recovery of different timber grades and the average board length from application of the two different grading methods.

Grade	"Best" grading method		"Long length" grading method	
	Grade recovery (%)	Average board length (m)	Grade recovery (%)	Average board length (m)
Clears	74	2.52	64	2.6
Cladding	17	2.96	23	3.3
Structural	9	2.71	13	3.2
Overall	100		100	

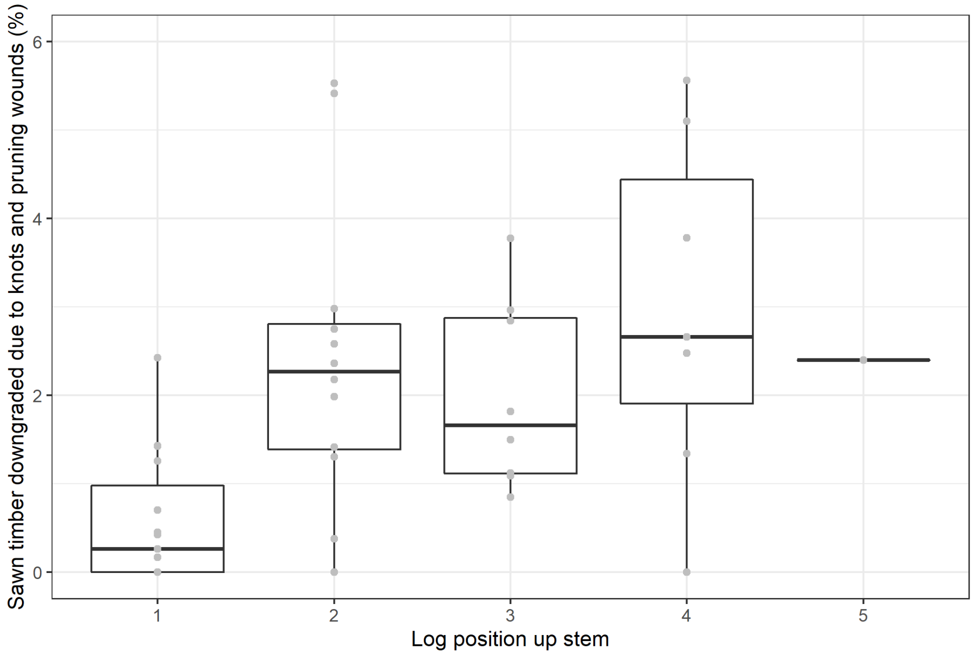

FIGURE 2: Incidence of knots and pruning wounds in timber as a function of log height up the stem.

Boron retention and penetration

Boric acid equivalent (BAE) ranged from 0.60% (m/m) up to 1.98%, with a mean of 1.03%. These values exceeded the threshold of 0.40%, which meant that all 16 samples passed the H1.2 boron retention and penetration requirements as per NZS 3640:2003. The samples tested also all achieved full cross section penetration of the preservation, not just penetration into the sapwood zone.

Discussion

The recovery of sawn boards was in line with sawing studies reported in the literature for a range of species (Cown et al. 2013; Lin et al. 2011). The positive relationship between log diameter and sawn timber conversion is well established in wood processing, as is the negative relationship with log taper (Moore & Cown 2015; Steele 1984). The same sawing pattern was used in earlier studies to process *Eucalyptus nitens* and *E. regnans* logs with a portable sawmill, and in these studies slightly lower recoveries were obtained, likely due to increased movement (distortion) of the boards as they were cut (Satchell & Turner 2011; Satchell 2015). Previous experience with processing poplar logs in the United States recommended using the saw-dry-rip method to help reduce timber distortion (Maeglin 1985), however downgrade due to excessive distortion did not occur in this study which means that timber could be cut to its final dimensions in the green state. In the current study, logs were sawn to visually target grade recoveries when edging the boards. This is assumed to be best practice, but involves a trade-off between grade recoveries and sawn recoveries. The intention was to maximise timber value recovered from the log and minimise levels of residual defects in sawn boards. Because the pruned logs had a large diameter over stubs (DOS), measured at 25 cm on boards cut through the centre of butt logs, and debarking caused deep (2 cm) mechanical cutting damage through the log surface, achieving high grade recoveries required significantly higher levels of wastage than would be necessary if mechanical debarking had not occurred and if pruning had controlled DOS to lower levels. Nevertheless, these recoveries do still provide a conservative benchmark for an economic analysis based on a return-to-log approach (Murphy & Moore 2018).

The modulus of elasticity of ‘Kawa’ poplar structural timber was considerably higher than observed in previous studies on the same clone (i.e., Jones 2016; Wilkinson 2000). Given the moderate positive relationship that was observed between modulus of elasticity and density in the current study, the modulus of elasticity reported

TABLE 6: Physical and mechanical properties determined from bending tests on full-size structural timber specimens.

	Moisture content (%)	Modulus of Elasticity (GPa)	Modulus of Rupture (MPa)	Density at test (kg m^{-3})	Nominal density (kg m^{-3})
Mean	10.8 ± 0.7	10.76 ± 1.33	59.13 ±11.25	476 ± 36	430 ± 32
Range	[8.7-12.1]	[6.88 – 13.04]	[33.37-74.34]	[395-567]	[358-511]
Characteristic value	-	10.58	45.09	471	426
Assigned grade	-	SG10	SG10	-	-

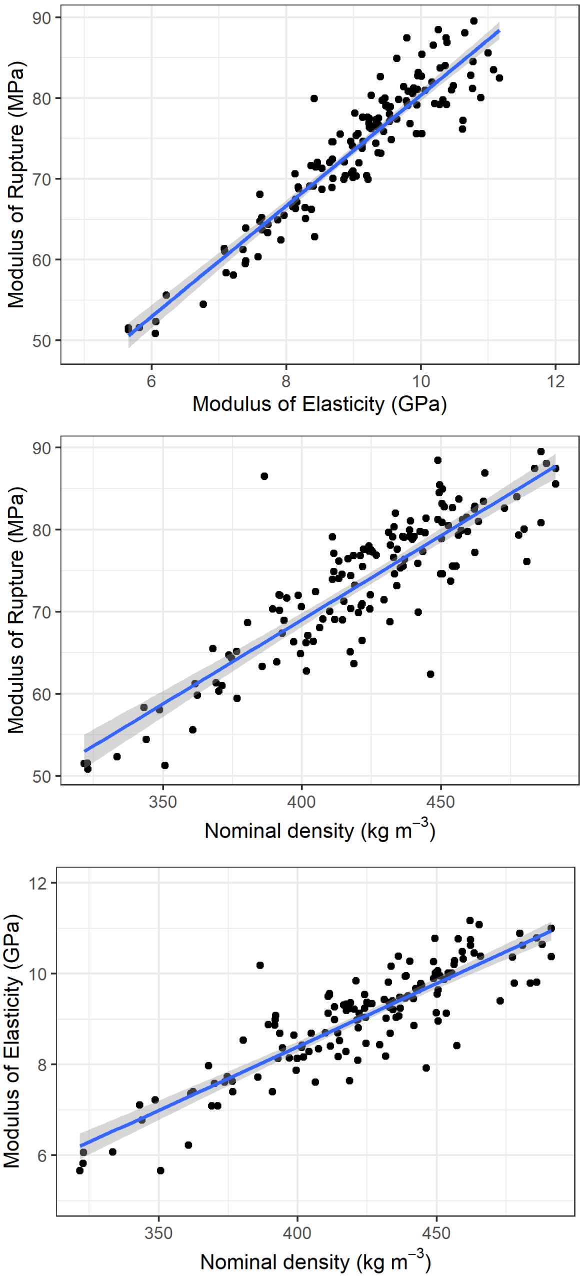

FIGURE 3: Pairwise relationships between nominal density, modulus of rupture and modulus of elasticity for small defect-free specimens. The blue lines represent ordinary least squares regressions fitted to the variables.

by Wilkinson (2000) appeared unusually low given the density value given in their publication, although results in this early paper were based on samples from much younger trees (*c.f.* 8 years old and 28 years old). The SG10 grade assigned to the structural timber in this study means that the timber is in a higher strength class than is typically achieved by the main structural timber species in New Zealand, radiata pine (Cown 1999). However, it should be noted that in warmer regions of New Zealand, such as Northland, trees typically have higher wood density than cooler regions such as the central North Island and central and southern parts of the South Island (Kimberley et al. 2017; Palmer et al. 2013). Given the positive relationship between density and modulus of elasticity, 'Kawa' poplar grown on cooler sites may not achieve the requirements for the SG10 strength class. Additional testing of material from a range of different regions would be required to confirm this. A larger dataset is required to provide more robust data on the characteristic strength properties for the species throughout New Zealand, although the sample tested in this study does provide evidence showing the potential of this clone as a structural timber species.

Results from testing the small defect-free specimens provided data to compare with other poplar species including *P. deltoides,* which is grown in many other regions of the world where it is also hybridised with other species. The modulus of elasticity of 'Kawa' in our study was higher than found in many other studies on poplar (Balatinecz & Kretschmann 2001; De Boever et al. 2007; Hernandez et al. 1998) but similar to the values found by Jia et al. (2021) for a *P. deltoides* clone grown in China. The results obtained from the tests also gave some insight into the radial and longitudinal variation in wood properties that exists within 'Kawa' poplar. The intention was to test the inner-most clearwood obtainable as 50 cm lengths, which tended to be very close to the pith, and to compare physical and mechanical properties with values obtained from specimens taken from the outer part of each log. While only two locations were sampled in the radial direction, the results were consistent with those from other studies which show that wood density, modulus of elasticity and modulus of rupture are higher in the outerwood than in the corewood (Lachenbruch et al. 2011; Zobel & Sprague 1998). If more locations in the radial direction had been sampled and the ring number from the pith recorded for each specimen, models such as those developed for Scots pine (*Pinus sylvestris* L.) by Auty et al. (2016) could have been developed. Such models could then be used to predict the impact of rotation age on wood properties, as numerous studies have demonstrated the impact that rotation age has on the mechanical properties of structural timber (Clark III et al. 1996; Cown & McConchie 1982; Duchesne 2006; Moore et al. 2012).

While much of the radial variation in modulus of elasticity and modulus of rupture is likely to be due to radial variation in density and microfibril angle, it was also observed that small defect-free specimens cut from the outer part of each log had straighter grain visible on the radial face than inner samples, which visually had more sloping grain caused by knots in the wood adjacent to the samples. In addition to this grain deviation caused by the presence of knots, spiral grain angle of many species is typically higher in the inner region of a tree and lower near the bark (Harris 1989). Regardless of its cause, grain deviations from the longitudinal axis of a board has a negative impact on timber mechanical properties (Harris 1989).

Although it is not known how far the weaker corewood zone extends radially out from the pith in poplar, our results show that provided pith is excluded, structural

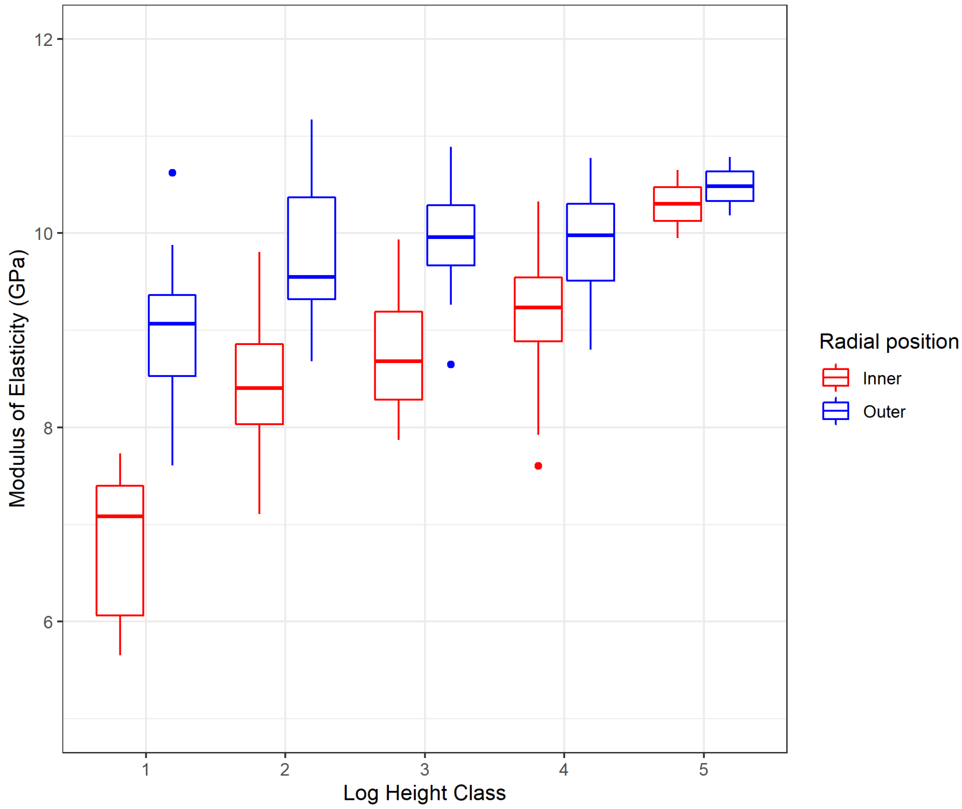

FIGURE 4: Variation in modulus of elasticity with radial position and log height class.

boards with acceptable strength characteristics can be produced. Further investigations to confirm this result could be undertaken by cutting structural boards from different locations within the log and comparing their mechanical properties and distortion.

The wood properties in the butt logs were also different than at equivalent radial positions in upper logs. It is unlikely that pruning of butt logs has adversely influenced wood properties. In addition to removing branches and the associated knots, pruning can also lead to small increases in wood density and a more rapid transition from corewood to outerwood (Megraw 1996). It is more likely due to the zone of low wood density and high microfibril angle that is often found in the region near the pith at the bottom of the butt log in many tree species (e.g., Moore et al. 2014). This could be further tested by comparing inner wood from pruned and unpruned trees as well as measuring the radial variation in density and microfibril angle at different heights up the stem. Studies in other poplar species have shown that density and microfibril angle exhibit the typical radial pattern of variation that is observed in many tree species (Fang et al. 2006; Liu et al. 2022; Sheng-zuo et al. 2004). Regardless of the factors responsible for its occurrence, the lower stiffness clearwood produced from pruned butt logs could either be used for non-structural appearance applications, or it could be machine graded and allocated a stiffness class/grade.

The boron diffusion process was successful at achieving full cross section penetration and retention to greater than 0.4% BAE. Because NZS 3640:2003 only requires full sapwood penetration and retention to 0.4% BAE, if a method becomes available for determining the heartwood/sapwood boundary in ‘Kawa’ poplar then lower concentrations of boron could potentially meet the retention requirements for the standard. Further work may be required to prove that durability performance of ‘Kawa’ poplar (a perishable hardwood) treated with boron to the H1.2 specifications satisfies the Durability Evaluation section of Clause B2 of the New Zealand building code. A Similar Materials test, for example using the third-party test procedure described in the AWPC protocols (Australasian Wood Preservation Committee 2015), with H1.2 radiata pine as the reference preservative/material, would offer relative durability performance results within a short (1-2 years) time period.

Conclusions

Based on data from a 28-year-old ‘Kawa’ poplar stand we found that sawlogs can be processed into appearance and structural products with minimal degrade using best practice portable sawmilling methods described here, followed by air-drying. In the warmer climate of Northland, New Zealand ‘Kawa’ timber appears to be well suited to structural applications based on results for strength, stiffness and boron diffusion. There does not appear to be any significant differences between trees in terms of bending strength/stiffness and nominal density, suggesting that variation in mechanical properties may be negligible across the regional resource. However, it should be noted that wood immediately adjacent to the pith has lower density, strength and stiffness, especially in butt logs. Density, strength and stiffness all improve with height in the tree and processors could take advantage of this variation by selecting logs and cuts for production of higher-stiffness structural product.

The sawn timber properties and grades achieved in this study indicate that farm production of sawn 'Kawa' poplar timber from Northland can meet market quality and regulatory requirements for structural and appearance products in New Zealand. Applications such as exposed beams, rafters, and glue-laminated products where appearance achieves a market premium would be appropriate applications for 'Kawa' poplar sawn timber, however market studies to confirm this are required.

Competing interests

The authors declare that they have no competing interests.

Authors' contributions

DS initiated this study, oversaw the selection, felling and processing of trees and co-wrote the manuscript. JM analysed the data and co-wrote the manuscript. Both authors approved the final version of the manuscript.

Acknowledgements

Northland Regional Council funded this research through the Sustainable Hill Country and Regional Priorities (SHaRP) programme. The SHaRP programme was partly funded by the Ministry for Primary Industries (MPI). Many thanks to Duncan Kervell and John Ballinger (Northland Regional Council), who encouraged undertaking the research and understood its importance.

Special thanks to Peter Davies-Colley who provided the trees, harvested them and loaded the log truck at no cost. Without his enthusiastic approach and generous support this research would not have taken place. Thanks to Li Legler who patiently undertook the sawmilling to the required specifications and assisted with the boron treatment.

References

American Society for Testing and Materials. (2000). Standard Test Methods for Small Clear Specimens of Timber. *(ASTM D143-94)*.

American Wood Protection Association. (2008). Standard Method for the Analysis of Wood and Wood Treating Solutions by Inductively Coupled Plasma Emission Spectrometry. *(AWPA A21-08)*.

American Wood Protection Association. (2012). Standard for Wet Ashing Procedures for Preparing Wood for Chemical Analysis. *(AWPA A7-12)*.

Australasian Wood Preservation Committee. (2015). *Protocols for assessment of wood preservatives*.

Auty, D., Achim, A., Macdonald, E., Cameron, A.D., & Gardiner, B.A. (2016). Models for predicting clearwood mechanical properties of Scots pine. *Forest Science*, *62*(4), 403–413. https://doi.org/10.5849/forsci.15-092

Avery, T.E., & Burkhart, H.E. (2015). *Forest Measurements*. Long Grove, IL, USA: Waveland Press

Balatinecz, J.J., & Kretschmann, D.E. (2001). Properties and utilization of poplar wood. In D.I. Dickmann, J.G. Isebrands, J.E. Eckenwalder, & J. Richardson (Eds.), *Poplar Culture in North America* (pp. 277–291). Ottawa, ON, Canada: NRC Research Press, National Research Council of Canada.

Ball, J., Carle, J., & Del Lungo, A. (2005). Contribution of poplars and willows to sustainable forestry and rural development. *Unasylva*, *221*, 3–9.

Chen, P.Y.S., Puettmann, M.E., Williams, L.H., & Stokke, D.D. (1997). Treatment of 8/4 hardwood lumber with borate preservatives. *Forest Products Journal*, *47*(6), 63–68.

Clark III, A., McAlister, R.H., Saucier, J.R., & Reitter, K. (1996). Effect of rotation age on lumber grade, yield, and strength of unthinned loblolly pine. *Forest Products Journal*, *46*, 63–68.

Cown, D.J. (1999). *New Zealand pine and Douglas-fir: suitability for processing*. Rotorua: New Zealand Forest Research Institute.

Cown, D.J., Marshall, H., Silcock, P., & Meason, D. (2013). Sawn timber grade recovery from a planted coast redwood stand growing in New Zealand. *New Zealand Journal of Forestry Science*, *43*: 8. https://doi.org/10.1186/1179-5395-43-8

Cown, D.J., & McConchie, D.L. (1982). Rotation age and silvicultural effects on wood properties of four stands of *Pinus radiata*. *New Zealand Journal of Forestry Science*, *12*, 71–85.

De Boever, L., Vansteenkiste, D., Van Acker, J., & Stevens, M. (2007). End-use related physical and mechanical properties of selected fast-growing poplar hybrids (*Populus trichocarpa* × *P. deltoides*). *Annals of Forest Science*, *64*(6), 621–630. https://doi.org/10.1051/forest:2007040

Duchesne, I. (2006). Effect of rotation age on lumber grade yield, bending strength and stiffness in jack pine (*Pinus banksiana* Lamb.) natural stands. *Wood and Fiber Science*, *38*, 84–94.

Fang, S., Yang, W., & Tian, Y. (2006). Clonal and within-tree variation in microfibril angle in poplar clones. *New Forests*, *31*(3), 373–383. https://doi.org/10.1007/s11056-005-8679-7

Harris, J.M. (1989). *Spiral Grain and Wave Phenomena in Wood Formation*. Berlin, Heidelberg: Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-642-73779-4

Hematabadi, H., Madhoushi, M., Khazaeian, A., &

Ebrahimi, G. (2021). Structural performance of hybrid poplar-beech cross-laminated-timber (CLT). *Journal of Building Engineering*, *44*, 102959. https://doi.org/10.1016/j.jobe.2021.102959

Hernandez, R.E., Koubaa, A., Beaudoin, M., & Fortin, Y. (1998). Selected mechanical properties of fast growing hybrid poplar clones. *Wood and Fiber Science*, *30*(2), 138–147.

Jia, R., Wang, Y., Wang, R., & Chen, X. (2021). Physical and mechanical properties of poplar clones and rapid prediction of the properties by near infrared spectroscopy. *Forests*, *12*(2), 206. https://doi.org/10.3390/f12020206

Johansson, T., & Hjelm, B. (2013). Frequency of false heartwood of stems of poplar growing on farmland in Sweden. *Forests*, *4*(1), 28–42. https://doi.org/10.3390/f4010028

Jones, T. (2016). Tree diameter growth and wood properties of poplar clones in New Zealand. In *Poplars and Other Fast-Growing Trees - Renewable Resources for Future Green Economies*. Berlin, Germany: International Poplar Commission (IPC).

Kimberley, M.O., McKinley, R.B., Cown, D.J., & Moore, J.R. (2017). Modelling the variation in wood density of New Zealand-grown Douglas-fir. *New Zealand Journal of Forestry Science*, *47*: 15. https://doi.org/10.1186/s40490-017-0096-0

Lachenbruch, B., Moore, J.R., & Evans, R. (2011). Radial variation in wood structure and function in woody plants, and hypotheses for its occurrence. In F.C. Meinzer, B. Lachenbruch, & T.E. Dawson (Eds.), *Size- and Age-Related Changes in Tree Structure and Function* (Vol. 4, pp. 121–164). Dordrecht: Springer Netherlands. Accessed 27 June 2020 https://doi.org/10.1007/978-94-007-1242-3_5

Lin, W., Wang, J., Wu, J., & DeVallance, D. (2011). Log Sawing Practices and Lumber Recovery of Small Hardwood Sawmills in West Virginia. *Forest Products Journal*, *61*(3), 216–224. https://doi.org/10.13073/0015-7473-61.3.216

Liu, Y., Zhou, L., Guan, Y., Hu, J., Zhao, Z., Gao, H., & Liu, S. (2022). Radial variation of wood anatomical and chemical properties in eight poplar clones. *Canadian Journal of Forest Research*, *52*(1), 19–26. https://doi.org/10.1139/cjfr-2020-0465

Maeglin, R.R. (1985). Using poplar wood for structural lumber: the SDR process. Presented at the 22nd Annual Meeting of the Poplar Council of the United States, Lawrence, KS.

Megraw, R.A. (1996). Effect of silvicultural practices on wood quality. Raleigh, CA: TAPPI.

Ministry for Primary Industries. (2020). *National Exotic Forest Description as at 1 April 2020* (p. 49). Wellington, New Zealand.

Moore, J.R., & Cown, D.J. (2015). Processing of wood for wood composites. In *Wood Composites* (pp. 27–45). Elsevier. Accessed 12 May 2022 https://doi.org/10.1016/B978-1-78242-454-3.00002-0

Moore, J.R., Cown, D.J., & McKinley, R.B. (2014). Modelling microfibril angle variation in New Zealand-grown radiata pine. *New Zealand Journal of Forestry Science*, *44*: 25. https://doi.org/10.1186/s40490-014-0025-4

Moore, J.R., Lyon, A.J., & Lehneke, S. (2012). Effects of rotation length on the grade recovery and wood properties of Sitka spruce structural timber grown in Great Britain. *Annals of Forest Science*, *69*(3), 353–362. https://doi.org/10.1007/s13595-011-0168-x

Murphy, G.E., & Moore, J.R. (2018). SEGMOD—a techno-economic model for evaluating the impact of segregation based on internal wood properties. *Annals of Forest Science*, *75*(3), 73. https://doi.org/10.1007/s13595-018-0755-1

Palmer, D.J., Kimberley, M.O., Cown, D.J., & McKinley, R.B. (2013). Assessing prediction accuracy in a regression kriging surface of *Pinus radiata* outerwood density across New Zealand. *Forest Ecology and Management*, *308*, 9–16. https://doi.org/10.1016/j.foreco.2013.07.024

Satchell, D., & Turner, J. (2011). Timber recovery and economics of short-rotation small-diameter eucalypt forestry. *Tree Grower* (February). https://www.nzffa.org.nz/members/special-interest-groups/eucalypt-action-group/eucalyptus-action-group-reports/eucalyptus-report-2010/

Satchell, D. (2015). *Evaluating profitability of solid timber production from 15-year-old pruned and thinned* Eucalyptus nitens *(Deane & Maiden) in Canterbury* (Master of Forestry Science Thesis). School of Forestry, University of Canterbury. http://dx.doi.org/10.13140/RG.2.1.4586.0563

Sheng-Zuo, F., Wen-Zhong, Y., & Xiang-Xiang, F. (2004). Variation of microfibril angle and its correlation to wood properties in poplars. *Journal of Forestry Research*, *15*(4), 261–267. https://doi.org/10.1007/BF02844949

Standards New Zealand. (1988). New Zealand Timber Grading Rules. *(NZS 3631:1988)*.

Standards New Zealand. (1993). Timber Structures Amendment 4 *(NZS3603:1993)*. Wellington, New Zealand.

Standards New Zealand. (2003a). Timber and Wood-based Products for use in Building. *(NZS 3602:2003)*.

Standards New Zealand. (2003b). Chemical Preservation of Round and Sawn Timber. *(NZS 3640:2003)*.

Standards New Zealand. (2010a). Characterization of structural timber Part 1: Test methods. *(NZS4063.1:2010)*.

Standards New Zealand. (2010b). Characterization of Structural Timber Part 2: Determination of characteristic values *(AS/NZS 4063.2:2010)*.

Standards New Zealand. (2018a). Methods for sampling and analysing timber preservatives and preservative-treated timber - Part 1: General requirements, sampling, and determination of sapwood and heartwood presence *(AS/NZS 1605.1:2018)*.

Standards New Zealand. (2018b). Methods for sampling and analysing timber preservatives and preservative-treated timber - Part 2: Determination of preservative penetration by spot test *(AS/NZS 1605.2:2018)*.

Stanton, B., Eaton, J., Johnson, J., Rice, D., Schuette, B., & Moser, B. (2002). Hybrid poplar in the Pacific Northwest: The effects of market-driven management. *Journal of Forestry*, *100*(4), 28–33.

Steele, P.H. (1984). *Factors determining lumber recovery in sawmilling. General Technical Report FPL-39*. Madison, WI: United States Department of Agriculture, Forest Products Laboratory. https://doi.org/10.2737/FPL-GTR-39

Timber Preservation Authority. (1980). *Timber preservation in New Zealand: specifications*. Wellington, New Zealand.

Truax, B., Gagnon, D., Fortier, J., & Lambert, F. (2014). Biomass and volume yield in mature hybrid poplar plantations on temperate abandoned farmland. *Forests*, *5*(12), 3107–3130. https://doi.org/10.3390/f5123107

Wilkinson, A.G. (2000). *Introduced forest trees in New Zealand recognition, role, and seed source 17. The poplars,* Populus *spp.* (No. FRI Bulletin 124) (p. 62). Rotorua, New Zealand: New Zealand Forest Research Institute.

Williams, D., Simpson, I., & Bier, H. (1986). *Properties of New Zealand-grown poplar* (No. FRI Bulletin 112). Rotorua, New Zealand: New Zealand Forest Service, Forest Research Institute.

Zobel, B.J., & Sprague, J.R. (1998). *Juvenile Wood in Forest Trees*. Berlin, Heidelberg: Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-642-72126-7