Minimizing the Impact of Mountain Pine Beetle Veneer on Plywood Glue Dry-Out and Delamination

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Mountain Pine Beetle Working Paper 2008-12

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MPBI Project #: 8.62

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2008

Library and Archives Canada Cataloguing in Publication

Xu, Heng
Minimizing the impact of mountain pine beetle veneer on plywood glue dryout and delamination / Heng Xu, Guangbo He and Chunping Dai.

(Mountain Pine Beetle Initiative working paper 2008-12)
"MPBI Project # 8.62".
Includes bibliographical references: p.
Includes abstract in French.
ISBN 978-1-100-10638-0
Cat. no.: Fo143-3/2008-12E

1. Veneer industry--British Columbia--Quality control. 2. Plywood industry--British Columbia--Quality control. 3. Laminated wood--Drying. 4. Mountain pine beetle--Economic aspects. 5. Trees--Diseases and pests --Economic aspects. 6. Blue stain. I. Dai, Chunping, 1963- II. He, Guangbo, 1965- III. Pacific Forestry Centre IV. Title. V. Series.

SB945.M78H46 2008 674'.83 C2008-980325-6

Abstract

Delamination currently accounts for approximately 85% of customer complaints about plywood as a sub-flooring product. It has become a critical issue for many plywood mills. The dryness of mountain pine beetle (MPB) veneer coupled with an inability to sort MPB-killed material from a mill's regular species mix can result in problems in over-drying and high veneer temperature, further exasperating glue dry-out and subsequent panel delamination. With potentially as much as 50% of a mill's future log supply being derived from MPB-killed material, a manufacturing strategy that reflects the impact of the change in raw material is needed.

This project quantified the impact of key parameters during plywood manufacturing on glue dry-out and bond quality using mountain pine beetle veneers. A multi-step pressing method was applied to MPB plywood manufacturing for minimizing the impact of glue dry-out on plywood bonding properties. The following conclusions and recommendations were drawn from this study based on laboratory tests:

1. Mountain pine beetle plywood produced from bluestained and non-bluestained veneers did not show significant differences in glue dry-out and bond quality. Mountain pine beetle veneers could be used for plywood manufacturing without being further sorted into bluestained and non-bluestained veneers.
2. Among all key factors, the assembly time gave the most significant impact on glue dry-out and bond quality. A long assembly time (i.e., 25 min) should be avoided in the lay-up process for minimizing glue dry-out.
3. Veneer characteristics, including veneer moisture and temperature, also showed significant impact on glue dry-out and bond quality. Appropriate veneer moisture contents (3-5%) and low veneer temperature (about 21ºC) distinctly reduced glue dry-out compared to dry veneer and high veneer temperature.
4. Glue spread rate generally gave a positive impact on glue dry-out and bond quality, but this impact was not significant in the experimental range compared to other key parameters.
5. Hot pressing factors, including press pressure, temperature and time, had less significant impact on glue dry-out compared to veneer characteristics and lay-up parameters. However, increasing press temperature, pressure and time could help minimize the impact of glue dry-out induced by inappropriate veneer conditions and long assembly time.
6. The multi-step pressing method compared to the conventional one-step pressing method produced better bond quality resulting in higher percentage wood failure without significant thickness loss of MPB plywood. It is recommended that the plywood industry look into modifying their existing presses to adopt this new pressing method.

Keywords: MPB-killed veneer, glue dry-out, bond quality, multi-step pressing

Résumé

Le délaminage représente à l'heure actuelle 85 % des plaintes des clients au sujet du contreplaqué en tant que produit pour faux-planchers. Cela constitue un problème grave pour de nombreuses usines de fabrication de contreplaqué. La siccité du placage attaqué par le DPP, conjuguée à l'incapacité de séparer le bois tué par le DPP des autres essences traitées dans une usine, peut donner lieu à des problèmes de surséchage et de température élevée du placage, ce qui exacerbe davantage le séchage de la colle et le délaminage ultérieur des panneaux. Étant donné qu'à l'avenir, jusqu'à 50 % de l'approvisionnement en billes des usines pourrait provenir de bois tué par le DPP, une stratégie de fabrication qui reflète ce changement de la matière brute s'impose.

Le présent projet d'observation quantifie l'incidence des principaux paramètres de la fabrication du contreplaqué avec des placages attaqués par le DPP sur l'assèchement de la colle et la qualité de liaison. Une méthode de pressage en plusieurs étapes est utilisée dans la fabrication du contreplaqué avec des placages attaqués par le DPP afin de limiter les conséquences de l'assèchement de la colle sur les propriétés de liaison du contreplaqué. Les conclusions et recommandations qui suivent sont tirées de cette étude fondée sur des analyses en laboratoire :

1. Le contreplaqué fabriqué avec des placages bleuis et non bleuis par le DPP ne montrait pas de différence importante d'assèchement de la colle ou de qualité de liaison. Il n'est donc pas nécessaire de trier les placages bleuis et les placages non bleuis.
2. De tous les principaux facteurs, le temps d'assemblage est celui qui a la plus grande incidence sur l'assèchement de la colle et la qualité de liaison. Il faut éviter un temps d'assemblage trop long (25 min) pour minimiser l'assèchement de la colle.
3. Les caractéristiques du placage, y compris l'humidité et la température, ont aussi une grande incidence sur l'assèchement de la colle et la qualité de liaison. Un pourcentage d'humidité approprié (3 à 5 %) et une température adéquate (environ 21 °C) réduisent considérablement l'assèchement de la colle, comparativement à des placages plus secs et à température plus élevée.
4. La vitesse à laquelle la colle est appliquée est aussi un facteur ayant une incidence positive sur l'assèchement de la colle et la qualité de liaison, mais ce facteur n'a pas eu une grande incidence pendant ce projet d'observation.
5. Les facteurs de pressage à chaud, comme la pression, la température et le temps de pressage ont eu moins d'incidence sur l'assèchement de la colle comparativement aux caractéristiques de placage et aux paramètres d'assemblage. Toutefois, le fait d'augmenter la température, la pression et le temps de pressage pourrait aider à réduire l'assèchement de la colle découlant du mauvais état du placage et de la lenteur de l'assemblage.
6. Comparativement à la méthode de pressage classique en une étape, la méthode de pressage en plusieurs étapes a produit une plus grande qualité de liaison, ce qui signifie que le contreplaqué attaqué par le DPP est plus résistant à l'épreuve de ruptures sans perte d'épaisseur. Nous recommandons à l'industrie du contreplaqué de modifier ses presses afin de les adapter à cette nouvelle méthode de pressage.

Mots-clés : placage attaqué par le DPP, assèchement de la colle, qualité de liaison, pressage en plusieurs étapes

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1 Introduction

Delamination currently accounts for approximately 85% of customer complaints about plywood as a sub-flooring product. It has become the most important issue to many plywood mills. Among other variables, veneer temperature and over-drying cause glue to dry out, which in turn results in delamination of plywood in service. Surface inactivation of veneers may also occur due to high temperatures during drying, resulting in poor bondability and delamination (Chow, 1975).

Glue dry-out could be overcome by modification of wood adhesives to improve the dry-out resistance. An effective method was to modify phenolic resins with alkylated phenols (Chen and Rice, 1976). An investigation (Troughton and Chow, 1972) found that the bond quality could be improved by improving the wetting capacity of the resin with the addition of polyethylene glycol. However, these chemical modifications are not widely practical in the manufacturing of plywood. Most plywood mills can only make adjustments empirically on the process variables to avoid glue dry-out and delamination during the production.

A much greater proportion of plywood veneer is now being produced in B.C. from post mountain pine beetle (MPB) wood. The MPB wood can be considered a new type of wood material due to its dryness and brittleness, blue stain, high permeability, and high resin acid content. The dryness of MPB veneer coupled with an inability to sort MPB-killed material from the regular species mix can result in additional problems associated with over-drying and high veneer temperature, and the subsequent increase in glue dry-out and delamination.

The Forintek plywood research program is currently focused on finding solutions to delamination problems associated with a limited number of species - Douglas-fir (commonly used in B.C. plywood) and aspen (commonly used in eastern Canada). As stated above, beetle-killed lodgepole pine presents additional problems when dealing with bond quality. This project applied the methodology and testing facility developed for testing other species for the study of MPB wood. The goal of this project was to investigate the means of maximizing the value of MPB-killed wood for plywood production. Therefore, the impact of key manufacturing parameters on glue dry-out and delamination of MPB plywood was first investigated. Also, the non-bluestained pine was studied for the purpose of comparison. Based on the results of glue dry-out for MPB plywood, a new hot pressing strategy was developed to minimize glue dry-out and delamination in MPB plywood production.

2 Objectives

The goal of this project is to investigate the means of maximizing the value of MPB killed wood for plywood production.

Targeted objectives are as follows:

1. To investigate the effect of key manufacturing parameters on glue dry-out and delamination of MPB plywood;
2. To develop a manufacturing strategy to minimize glue dry-out and delamination in MPB plywood production.

3 Material and Methods

3.1 Veneer preparation

All dry 4'x 8' x 1/8" MPB pine veneers were obtained from a Forintek member mill. The average moisture content (MC) was 3-5%. The veneers were cut into 15" x 15" or 24" x 34" size for plywood manufacturing. Part of the MPB pine veneers was sorted into bluestained and non-bluestained veneers for producing corresponding plywood. The selection criteria were set as follows:

- Non-bluestained veneers (Heartwood veneers): <5% bluestained area on veneer surface.
- Bluestained veneers (Sapwood veneers): >80% bluestained area on veneer surface.

3.2 Glue mix preparation

Phenol-formaldehyde (PF) resin (Prefere 14A480) was obtained from Dynea. Glue mix used in this study was made in our laboratory using the following formulation:

- PF resin 3660 (first) + 3050 (second) parts
- Water 1400 (first) + 250 (second) parts
- Flour 440 parts
- Cocob 550 parts
- Soda ash 200 parts

The glue mix was mixed for 25 – 30 minutes.

3.3 Plywood production

All plywood panels were produced in Forintek's pilot plant. The plywood production was divided into three parts.

3.3.1 Part one

In this part, bluestained and non-bluestained veneers were used to produce blustained and non-bluestained plywood, respectively. The veneers from the mill were used without further drying. The veneers were coated with PF resin mix using a hand roller, and the assembled veneers were pressed in the small hot press. The plywood was manufactured with the production parameters listed as follows:

- Panel size 15" x 15", 5-ply
- Glue spread rate 30 lbs and 35 lbs/1000 ft^2SGL
- Assembly time 10 min
- Press temperature 145°C
- Press pressure 175 psi
- Press time 5 min
- Repetition 5 panels for each condition

3.3.2 Part two

The plywood panels were produced with different veneer and pressing parameters that affected glue dry-out and bond quality. The key factors (parameters) and levels used in the experiment are given in Table 1.

Table 1. Key factors and levels in the experiment

	Factor	Level 1	Level 2	Level 3
A	Moisture content of veneer (%)	0-2	3-5	
B	Amount of glue (lb/1000ft^{2}SGL)	28	31	34
C	Press temperature (ºC)	140	149	160
D	Press time (min)			
	At 140ºC	5	5.5	6
	At 149ºC	4.5	5	5.5
	At 160ºC	4	4.5	5
E	Assembly time (min)	10	25	
F	Press pressure (psi)	175	200	
G	Temperature of veneer (ºC)	21	32	43

Table 2. Plywood production key parameters

Test	A	B	C	D	E	F	G
No	Veneer MC (%)	Glue spread rate (lb/1000ft^2)	Press temperature (ºC)	Press time (min)	Assembly time (min)	Press pressure (psi)	Veneer temperature (ºC)
1	0-2	28	140	5	10	175	21
2	0-2	28	149	5	25	175	32
3	0-2	28	160	5	10	200	43
4	0-2	31	140	5	25	175	32
5	0-2	31	149	5	10	200	43
6	0-2	31	160	5	10	175	21
7	0-2	34	140	5.5	10	175	43
8	0-2	34	149	5.5	25	175	21
9	0-2	34	160	4	10	200	32
10	3-5	28	140	6	10	200	32
11	3-5	28	149	4.5	10	175	43
12	3-5	28	160	4.5	25	175	21
13	3-5	31	140	5.5	10	200	21
14	3-5	31	149	5.5	10	175	32
15	3-5	31	160	4	25	175	43
16	3-5	34	140	6	25	175	43
17	3-5	34	149	4.5	10	200	21
18	3-5	34	160	4.5	10	175	32

The key factors were placed in an orthogonal array, which was a balanced matrix that described how the experiment would be running. The outline of the experimental panels with combined factors is listed in Table 2. Five-ply plywood with a dimension of 15”x15” was produced using random MPB veneers without sorting into bluestained or non-bluestained ones. Veneers with 3-5% MC were used directly from the mill, and dry veneers with 0-2% MC were obtained by re-drying the mill veneers in the oven at 90°C for 4 h. The veneers with different veneer temperatures (except 21°C veneers, which were used as room temperature) were obtained by conditioning the veneers in the oven until the target temperature was reached using a non-contact thermometer. The veneers were coated with PF mix using a hand roller, and the assembled veneers were pressed in the small hot press. Six replicates were produced for each condition, and a total of 108 panels were made. During pressing, the core glueline temperature of the panel was monitored and the final temperature was recorded using a thermocouple.

3.3.3 Part three

A multi-step pressing strategy was applied to manufacture plywood compared to the conventional pressing method in this part. The veneers were coated with PF mix using a glue spreader. The assembled veneers were pressed in the 36”x36” hot press controlled by “Pressman” software and the pressing data were monitored and recorded by computer. The pressing parameters are shown as follows:

- Panel size 24” x 34”, 5-ply
- Glue spread rate 32 lbs/1000 ft^2 SGL
- Open assembly time 15 min
- Press temperature 150°C
- Repetition 3 panels for each condition

For the conventional pressing,

- Press pressure 200 psi
- Press time 340 s

For multi-step pressing,

- Pressure & time 250 psi for 85 s
  200 psi for 85 s
  150 psi for 85 s
  100 psi for 85 s

3.4 Plywood tests

Shear tests were conducted according to CSA Standard O151-04 for Canadian Softwood Plywood under wet conditions. From each panel, 24 shear specimens were cut at open lathe check and close lathe check directions (12 specimens for each direction) for testing. For wet shear tests, the specimens were subjected to vacuum pressure cycle in cold tap water under vacuum (85 kPa) for 30 min and then under pressure (480 kPa) for 30 min. Both wood failure percentage and shear strength were used to evaluate the bond quality of the plywood panels.

4 Results and Discussion

4.1 Impact of veneer bluestain on bonding properties of mountain pine beetle plywood

Mountain pine beetle wood is subsequently divided into bluestained and non-bluestained parts. After killed by the mountain pine beetle, the sapwood of dead trees gradually becomes bluestained, but the heartwood does not. The MPB veneers can then be sorted into bluestained (>80% bluestained area on veneer surface) and non-bluestained (<5% bluestained area on veneer surface) veneers. To evaluate the bonding properties of MPB wood, the shear testing results of plywood produced from bluestained and non-bluestained veneers were compared.

Table 3. Plywood shear test results for bluestained and non-bluestained veneers

MPB Veneer	Shear Strength (psi)				Wood Failure (%)			
	Average	Std	Max	Min	Average	Std	Max	Min
Heavy glue spread (35 lbs/1000ft^{2}SGL)								
Non-bluestained	183.9	42.1	263.8	121.3	85.5	12.1	97.5	56.3
Bluestained	153.9	30.4	205.0	105.0	88.9	10.2	100.0	61.0
Light glue spread (30 lbs/1000ft^{2}SGL)								
Non-bluestained	151.9	51.6	247.5	82.5	83.8	10.2	100.0	65.0
Bluestained	160.0	44.8	235.0	80.0	84.6	18.1	100.0	35.0

Table 3 lists the average results of shear tests for plywood produced from bluestained and non-bluestained veneers respectively. No significant differences in both wood failure and shear strength were found between bluestained plywood and non-bluestained plywood at both glue spread rates. In a previous study (Wang et al. 2005), MPB wood required a little more resin because of the higher permeability of bluestained veneers. The results in this study indicated that wood failure for the bluestained veneer plywood was slightly higher than for the non-bluestained veneer plywood, particularly at the heavy glue spread rate. This confirmed that bluestained veneers had a slightly higher permeability to resin. However, the shear strength of the non-bluestained veneer plywood appeared higher than that of the bluestained veneer plywood at the heavy glue spread rate, indicating that non-bluestained veneers were slightly higher in wood strength than bluestained veneers.

In summary, the results showed that wood failure was over 80% with high shear strength for both bluestained and non-bluestained veneer plywood at both glue spread rates. The difference in bond quality between these two types of plywood was insignificant. This suggested that MPB veneers could be used for plywood manufacturing without further sorting into bluestained and non-bluestained veneers.

Table 4. Bond quality of MPB plywood at various conditions

Sample No	Wood failure (%)	Strength (psi)	Core temperature (°C)
1	52 (30.4)	111.59 (35.17)	113
2	3 (8.4)	14.60 (16.30)	119
3	40 (27.5)	89.12 (35.66)	126
4	8 (9.8)	25.45 (12.46)	116
5	80 (26.7)	116.50 (44.11)	120
6	88 (18.1)	158.16 (38.60)	120
7	54 (32.8)	129.51 (46.69)	118
8	59 (23.8)	97.60 (47.63)	119
9	61 (31.7)	111.04 (36.52)	115
10	81 (21.1)	137.30 (38.60)	116
11	55 (31.4)	130.61 (37.92)	110
12	64 (27.6)	179.30 (50.50)	112
13	94 (24.3)	162.64 (40.32)	112
14	68 (28.6)	173.01 (54.57)	118
15	69 (29.6)	147.61 (45.31)	110
16	34 (29.6)	163.26 (47.03)	115
17	68 (19.8)	135.33 (44.30)	108
18	77 (27.2)	148.97 (44.36)	116

** The numbers in parentheses are the standard deviations.*

4.2 Impact of key parameters on bonding properties of MPB plywood

In this study, several key parameters, including veneer moisture content, veneer temperature, glue spread rate, assembly time, press temperature and time, and press pressure, have been evaluated for their impact on the glue dry-out and bond quality of plywood (see Table 1).

The testing results of shear strength, wood failure and final core glueline temperature of MPB plywood at various conditions are given in Table 4. The results in Table 4 showed that the final core temperatures during pressing reached 110 ºC except for sample 17. Achieving this core temperature ensures that the PF glue is fully cured to produce good bond quality. The main cause for poor bonding quality was glue dry-out induced by changing the key production parameters.

The shear strength and wood failure for each individual sample in Table 4 did not clearly show the impact of each factor. To better characterize this impact of each factor on bond quality of MPB plywood, the response of percentage wood failure of plywood for each factor was calculated with a statistical method and graphed as shown in Figs. 1-7, respectively. The response of percentage wood failure for a factor was calculated by averaging all percentage wood failure values under the same level of this factor (see Tables 2 and 4). For example, the response of percentage wood failure for the factor of veneer moisture content at 0-2% level was the average percentage of wood failure from samples 1 to 9. It is much easier to analyze how each factor affects the bond quality using the response of percentage wood failure as an index.

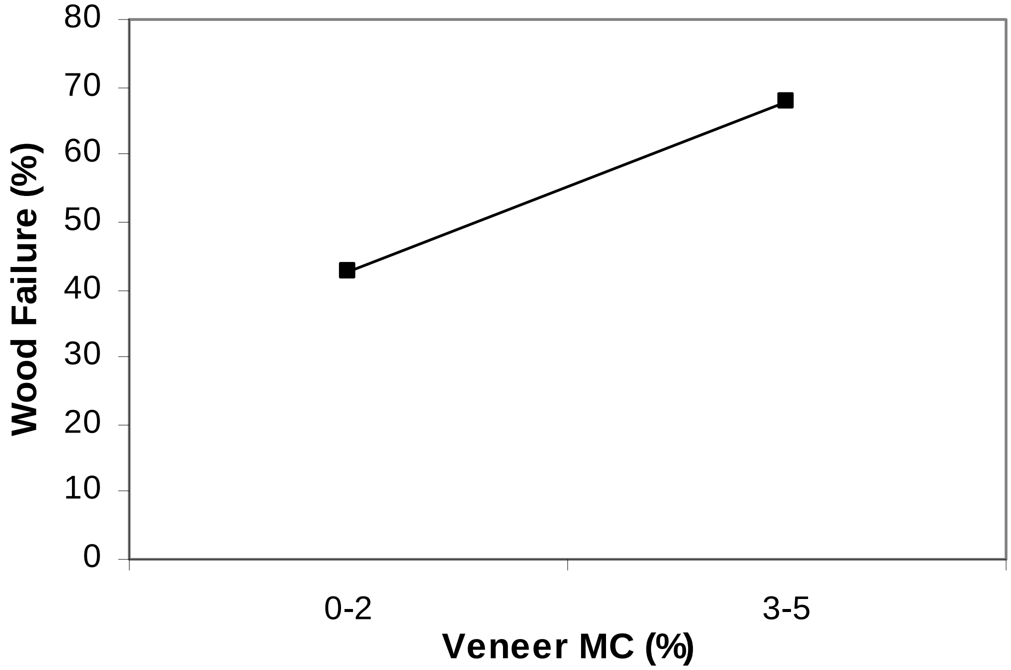

Figure 1. Response of percentage wood failure to veneer moisture content

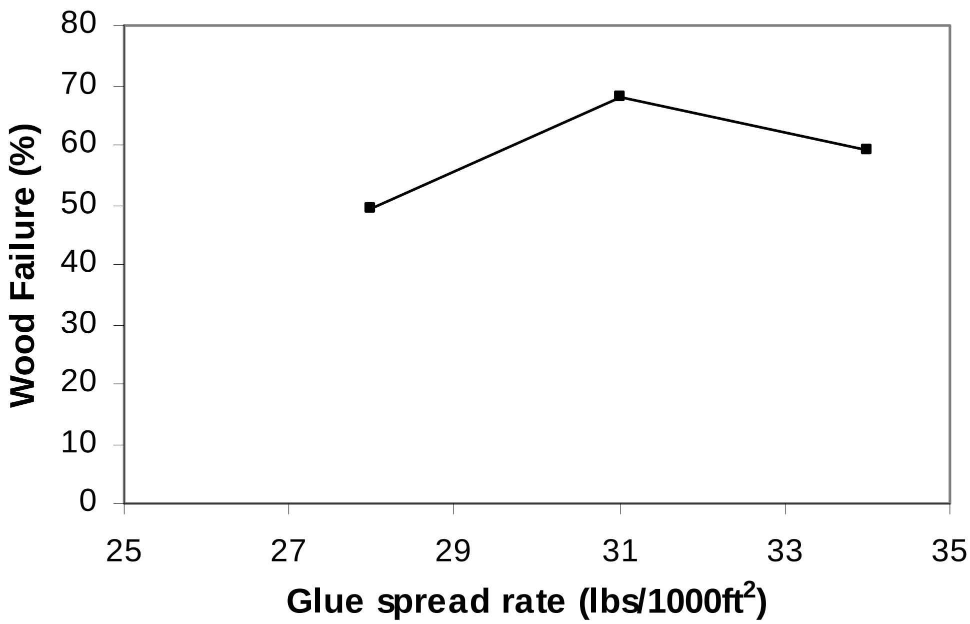

Figure 2. Response of percentage wood failure to glue spread rate

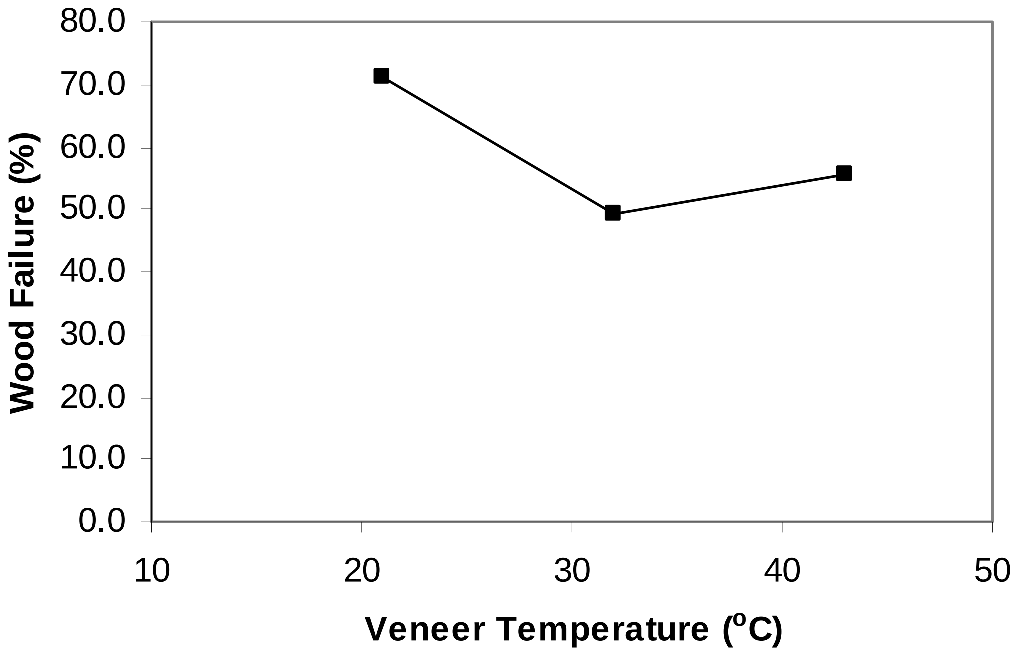

Figure 3. Response of percentage wood failure to veneer temperature

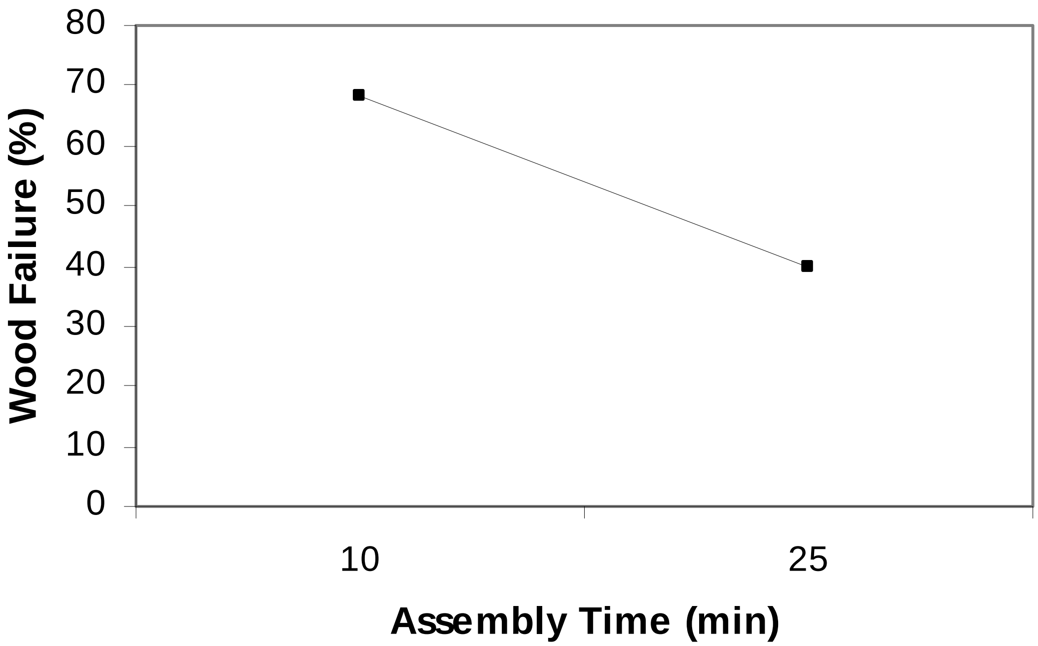

Figure 4. Response of percentage wood failure to assembly time

Figure 1 shows the response of percentage wood failure for veneer moisture content. Obviously in the two veneer moisture contents, the dry veneer resulted in lower wood failure which was induced by more frequent glue dry-out. Therefore, an appropriate moisture content of veneer is needed to avoid glue dry-out and improve bond quality.

The response of percentage wood failure for glue spread rate is shown in Figure 2. It is intuitive that high glue spread rates can reduce glue dry-out and improve bond quality, but also increase production costs. In this study, the glue spread rate did not show significant impact on the percentage wood failure for the glue spread range of 28 to 34 lb/1000ft^2 SGL.

The veneer temperature also affected the percentage wood failure, as shown in Figure 3. The higher the veneer temperature, the lower was the percentage wood failure. Higher veneer temperature resulted in faster water evaporation from the glue on veneer surface, leading to glue dry-out and low bond quality.

A similar trend as above was found for the response of percentage wood failure for assembly time (Figure 4). Longer assembly time resulted in more water evaporation, and then more frequent glue dry-out.

From the analysis on the above four factors that affected glue dry-out, it was concluded that the factors resulting in water loss from the glue on the veneer surface increased the risk of glue dry-out and decreased bond quality. Any variation of factor level that decreased water evaporation in the glue from veneer surface also decreased glue dry-out and improved bond quality.

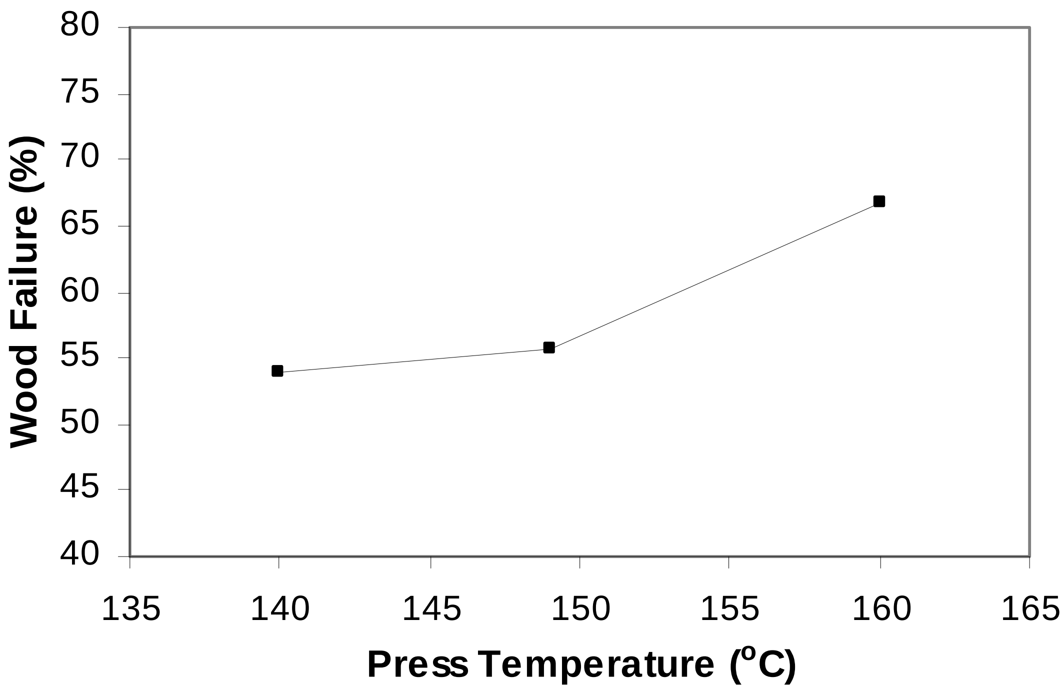

Figure 5. Response of percentage wood failure to press temperature

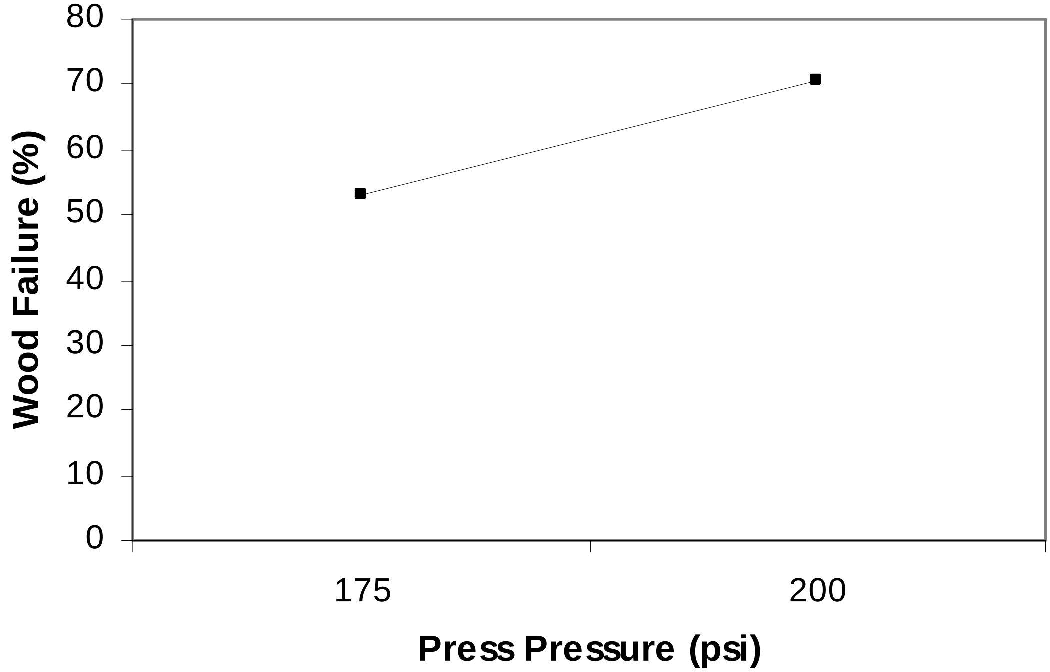

Figure 6. Response of percentage wood failure to press pressure

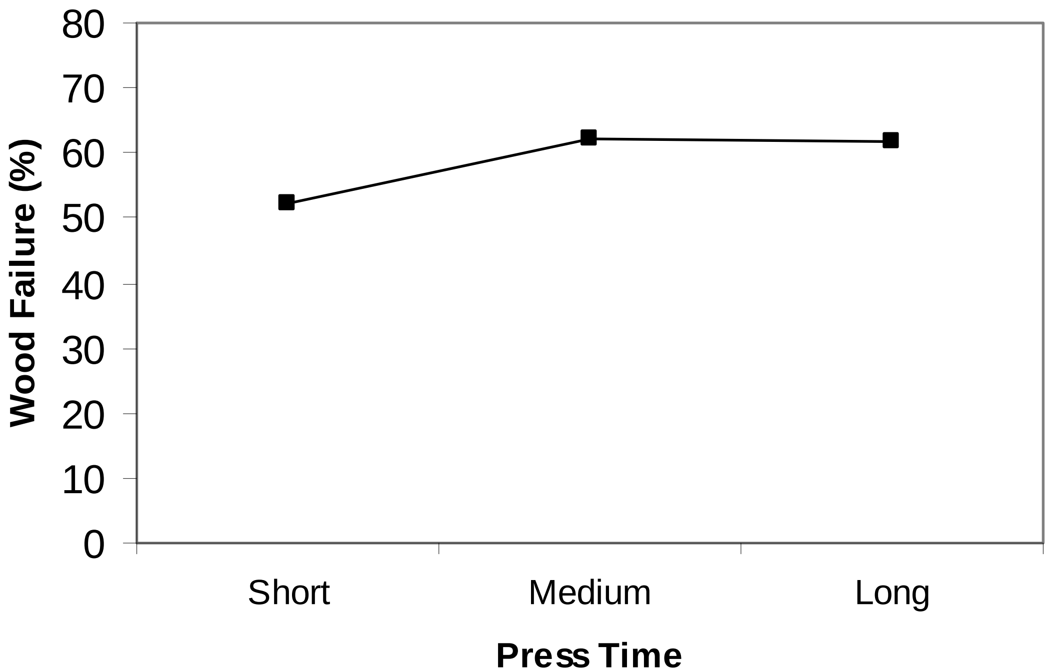

Figure 7. Response of percentage wood failure to press time

Figure 5 shows the response of percentage wood failure for press temperature. The percentage wood failure increased with an increase in press temperature, particularly from 149ºC to 160ºC. Higher press temperature could improve glue flow on wood surface and enhance glue transfer from one side to the opposite veneer side. This was probably the main cause for the higher percentage wood failure at the higher press temperature. On the other hand, it was possible that high temperature also enhanced resin cure for high bond quality, although the resin was considered well cured for all cases in this study.

Figure 6 shows the response of percentage wood failure for press pressure. The high press pressure significantly improved the percentage wood failure compared to the regular press pressure (175 psi). Higher press pressure could generally increase the deformation of rough surface of veneer and resulted in more intimate contact between the two veneer surfaces. This intimate surface contact undoubtedly improved glue transfer from one side to the other side, and thereby reduced the impact of glue dry-out on bond quality.

Longer press time also improved the percentage wood failure, as shown in Figure 7, but this improvement was limited for the time range used in this study.

The analysis on pressing parameters that affected glue dry-out suggested that glue dry-out could also be reduced during hot pressing by increasing glue transfer. However, the change of hot pressing parameters during plywood manufacturing may introduce a negative impact on production and increase production costs.

Table 5. Response table of percentage wood failure

Factors		Level			
		1	2	3	Range
A	Moisture content	42.8	67.9		25.2
B	Glue amount	49.4	67.9	58.9	18.5
C	Press temperature	53.8	55.7	66.7	12.9
D	Press time	52.3	62.1	61.8	9.8
E	Assembly time	68.3	39.5		28.8
F	Press pressure	52.9	70.4		17.5
G	Veneer temperature	71.3	49.3	55.7	22.0

To analyze the significance of impact factors, a response table can be created with the statistical method for each output. Table 5 lists the response of percentage wood failure. It demonstrated the change level of the percentage wood failure as the key factor level changed in the designed levels shown in Table 1. The response gave the significance of impact factors in order as follows:

Assembly time (28.8%) — Moisture content (25.2%) — Veneer temperature (22.0%) — Glue amount (18.5%) — Press pressure (17.5%) — Press temperature (12.9%) — Press time (9.8%).

Among those factors, all lay-up factors, including veneer moisture content and temperature, assembly time, and glue spread rate, gave more significant impact on bond quality than hot pressing factors. The assembly time gave the strongest impact on the percentage wood failure, which decreased by 28.8% as the assembly time increased from 10 min to 25 min. The veneer moisture content and temperature also played important roles on glue dry-out. For hot pressing factors, the press pressure was the most significant factor that affected glue dry-out, followed by press temperature, and press time. The press time showed insignificant impact on wood failure within the experimental range.

4.3 Minimizing glue dry-out using multi-step pressing method

Mountain pine beetle logs usually produce higher rough veneer than regular pine wood because of its low moisture content. High roughness on the veneer surface contributes to glue dry-out by reducing glue flow and glue transfer from one veneer surface to the opposite surface. The impact of high roughness of veneer surface can be minimized through a high press pressure. Therefore, a multi-step pressing method was applied to produce 5-ply MPB plywood for minimizing glue dry-out in this study.

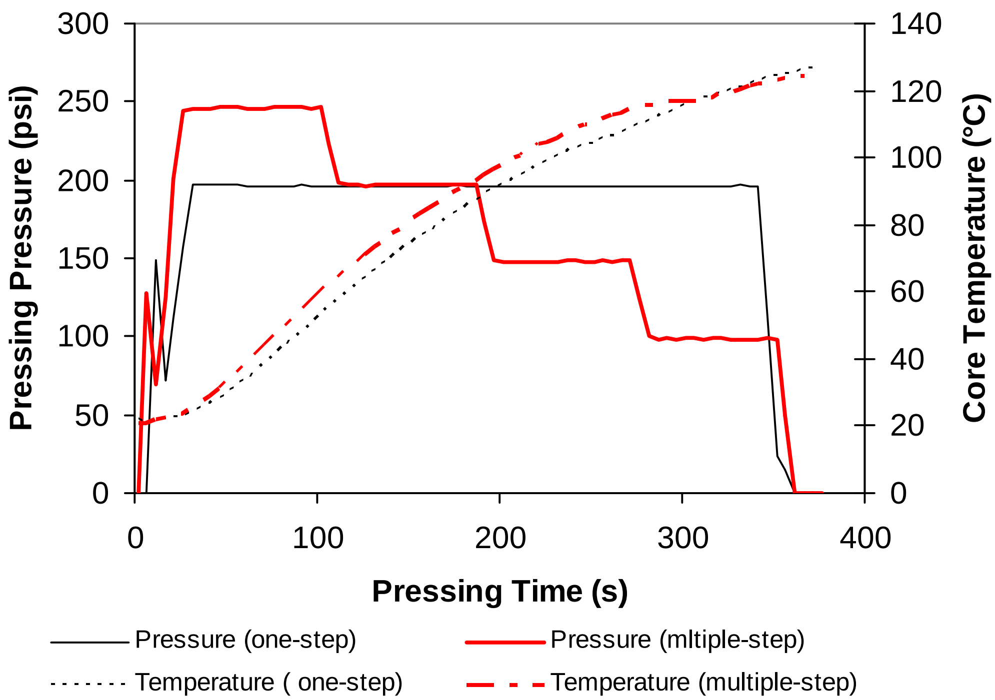

Figure 8. Press pressure schedule and core temperature during hot pressing

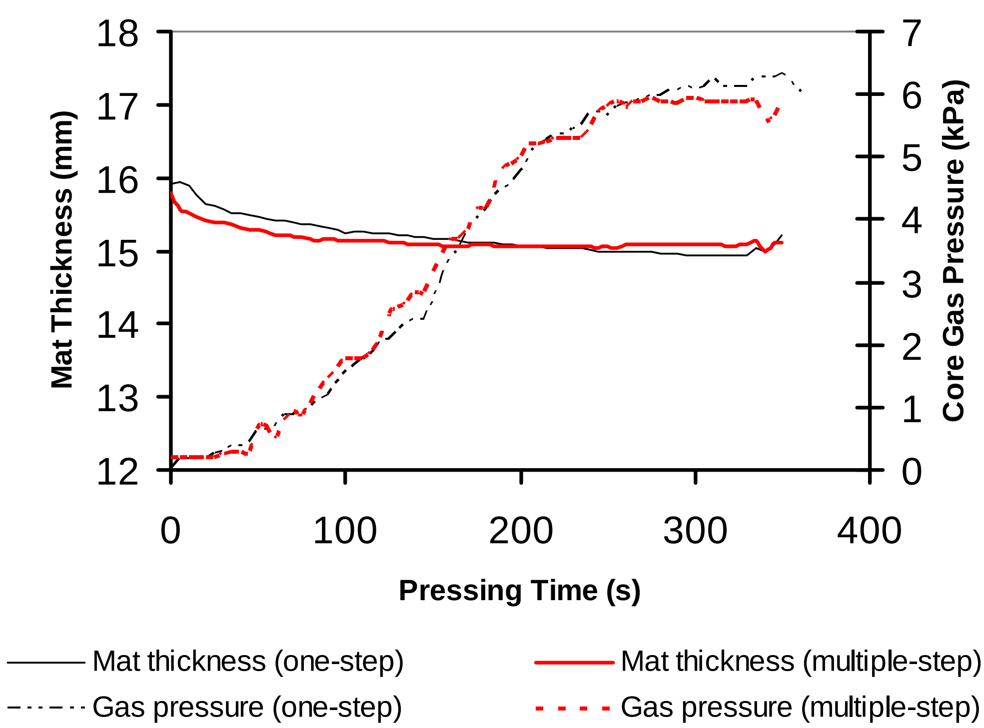

Figure 9. Mat thickness and core gas pressure during hot pressing

Figure 8 shows the press pressure schedule and core temperature between two different hot pressing methods during hot pressing. At the beginning of the multi-step pressing method, the press pressure was rapidly increased to a higher pressure. This initial high pressure benefited the glue flow and glue transfer by reducing the surface roughness of veneer and making intimate contact between the bonding veneers. The core temperature in multi-step pressing was higher than that in the one-step pressing for the press time between 60 s and 300 s. The higher temperature would be more favourable for glue flow, glue transfer and curing.

Figure 9 shows the mat thickness and core gas pressure during hot pressing. The mat thickness in multi-step pressing decreased faster than in one-step pressing during the first 100-second pressing because of the initial higher press pressure. However, the mat thickness became close to each other after a press time of 150 seconds. The two core gas pressure curves were similar for both pressing methods, even though the two press pressure curves were different (see Fig. 8).

The bond quality results of plywood produced with the two different pressing methods are listed in Table 6. The multi-step pressing method consistently gave better bond quality than the one-step pressing method. The average percentage wood failure in the three cases (face, back and core) for the multi-step pressing was close to 80%. In addition, higher percentage of good bond quality chips was obtained from the multi-step pressing than from the one-step pressing. It should be noted that the resinated veneers in part three plywood production suffered heavy glue dry-out when exposed in the air for 15 min before hot pressing. It is concluded that multi-step pressing would be a good method for minimizing the impact of glue dry-out on bond quality.

Table 6. Bond quality results of plywood with different pressing methods

Hot pressing method		One-step pressing			Multiple--step pressing		
Gluelines		Face	Back	Core	Face	Back	Core
Results of Glueline Shear Test							
Shear strength	psi	154 (44)	106(54)	103(62)	139(47)	149(53)	158(46)
Wood failure	%	76 (20)	69(22)	53(21)	80(16)	75(20)	76(12)
Classified Attribute Analysis of Bonding Quality							
Good	%	62	44	7	65	63	60
Fair	%	27	41	48	27	26	35
Bad	%	11	15	45	8	11	5

* *The categorization of bonding quality was done as follows:*
Good = Percentage wood failure in the 80-100%
Fair = Percentage wood failure in the 50-80%
Bad = Percentage wood failure lower than 50%

The compaction ratio of plywood panel was calculated based on the initial veneer thickness and final panel thickness, as given in Table 7. The results showed that the multi-step pressing improved bond quality, but it also resulted in higher panel thickness loss. However, the difference in panel thickness loss between these two methods was not significant.

Table 7. Compaction ratio of plywood panels

No	Veneer Thickness (mm)						Panel Thickness (mm)	Compaction Ratio (%)
	1	2	3	4	5	Total		
One-step hot-pressing								
1	3.24	3.40	3.32	3.22	3.45	16.62	15.62	6.01
2	3.35	3.35	3.43	3.31	3.36	16.81	15.89	5.47
3	3.29	3.25	3.34	3.26	3.26	16.4	15.69	4.30
Ave								5.26
Multiple-step hot-pressing								
1	3.34	3.42	3.34	3.19	3.40	16.69	15.56	6.77
2	3.28	3.30	3.26	3.30	3.36	16.50	15.60	5.45
3	3.33	3.27	3.33	3.32	3.35	16.60	15.68	5.54
Ave								5.92

5 Conclusions

1. Mountain pine beetle plywood produced from bluestained and non-bluestained veneers did not show significant differences in glue dry-out and bond quality. Mountain pine beetle veneers could be used for plywood manufacturing without further sorting into bluestained and non-bluestained veneers.
2. Among all key factors, the assembly time gave the most significant impact on glue dry-out and bond quality. The long assembly time (i.e., 25 min) should be avoided in lay-up process for minimizing glue dry-out.
3. Veneer characteristics, including veneer moisture and temperature, also had a significant impact on glue dry-out and bond quality. Appropriate veneer moisture contents (3-5%) and low veneer temperature (about 21ºC) distinctly reduced glue dry-out compared to dry veneer and high veneer temperature.
4. Glue spread rate generally gave positive impact on glue dry-out and bond quality, but this impact was not significant in the experimental range compared to other key parameters.
5. Hot pressing factors, including press pressure, temperature and time, gave less significant impact on glue dry-out compared to veneer characteristics and lay-up parameters. However, increasing press temperature, pressure and time could help minimize the impact of glue dry-out induced by inappropriate veneer conditions and long assembly time.
6. The multi-step pressing method compared to the conventional one-step pressing method produced better bond quality resulting in higher percentage wood failure without significant thickness loss of MPB plywood. It is recommended that the plywood industry look into modifying their existing presses to adopt this new pressing method.

6 Acknowledgements

This project was funded by the Government of Canada through the Mountain Pine Beetle Initiative, a Program administered by Natural Resources Canada, Canadian Forest Service. Publication does not necessarily signify that the contents of this report reflect the views or policies of Natural Resources Canada – Canadian Forest Service.

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