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Optimizing Surface Micro Grooving to Reduce the Checking and Cupping of Douglas Fir, Western Hemlock and White Spruce Decking Exposed to Natural Weathering

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Abstract: Machining grooves into the surface of pine and fir (*Abies* spp.) deckboards reduces undesirable checking that develops when "profiled" boards are exposed to the weather. We aim to develop improved profiles for Douglas fir, western hemlock and white spruce decking to reduce their susceptibility to checking, and understand how profile geometry influences the stresses that cause checking. We varied the width and depth of grooves in profiled deckboards, exposed deckboards to the weather, and measured checking and cupping of boards. A numerical model examined the effect of groove depth on the moisture-induced stresses in profiled spruce boards. Profiling significantly reduced checking, but increased cupping of deckboards made from all three species. Western hemlock checked more than the other two species. Profiles with narrow grooves (rib profiles) were better at restricting checking than profiles with wider grooves. A rib profile with deeper grooves developed smaller stresses than a rib profile with shallower grooves, and boards with the former profile checked less than boards with shallower grooves. We conclude that checking of profiled Douglas fir, western hemlock and white spruce decking is significantly reduced by changing profile geometry, and our results suggest the best profiles to reduce checking of all three species.

Keywords: wood; Douglas fir; western hemlock; white spruce; decking; micro-grooves; profiling; checking; cupping; finite element modeling; stress; weathering

1. Introduction

Wood exposed outside to the weather erodes, cracks and becomes grey in color [1]. These adverse effects of the weather on the surface properties of wood do not penetrate deeply into wood and are distinct from fungal decay, which under favorable conditions can penetrate into and affect the strength of large wooden structures [1,2]. Fungal decay can be prevented by pressure-treating wood with solutions of chemical preservatives [2]. Wood preservatives, however, are less effective at protecting wood surfaces from the adverse effects of the weather, and as a result, treated wood used outdoors is often finished with coatings to maintain its appearance and prevent the wood from cracking (checking) [3]. The checking of wood used outdoors can also be restricted by machining micro-grooves into the surface of wood [4–6]. Micro-grooving, hereafter referred to as profiling, is commonly applied to deckboards manufactured in Asia, Australia, Europe and New Zealand, but it is uncommon in North America [7,8]. The decking market in North America is valued at $US 7 billion per annum, and wood products command 84% of the market [9]. However, wood is rapidly losing market share to wood plastic composites that are less susceptible to checking and require less maintenance than wood decking [10]. For example, demand for wood plastic decking in North America is growing at 5% per annum compared to 3% per annum for wood decking [9]. The same trend is occurring in other countries [11]. As a result of the success of wood plastic decking, there has been significant interest in improving the resistance of wooden deckboards to weathering and in particular checking. This interest explains the recent attention in North America to optimizing profiling to make it better at reducing the checking of deckboards exposed to the weather [12–19]. It also accounts for increasing interest in Europe and elsewhere in deckboards made from tropical wood species or thermally or chemically modified woods that are less susceptible to checking and cupping than preservative-treated deckboards [20–22].

Research on optimizing surface profiling to reduce the checking of decking has focused on a limited number of wood species. The focus of research in Canada has been on the amabilis fir (*Abies amabilis*, (Dougl.) ex J. Forbe) because it is susceptible to checking and, as a result, is under-utilized for decking, even though it is easier to treat with wood preservatives than most other Canadian wood species [23,24]. The checking of amabilis fir can be reduced significantly by profiling, and profiles with narrow grooves (rib profile) are more effective at reducing checking than wavy profiles (ribble or ripple) with wider grooves [13,15]. In addition, rib profiles with deeper grooves appear to be more effective at reducing checking of amabilis fir than profiles with shallower grooves [19]. These findings on the greater effectiveness of rib profiles compared to wavy profiles at reducing the checking of wooden deckboards are only relevant to boards made from amabilis fir because two previous studies showed that wavy profiles were more effective than rib profiles at reducing the checking of southern pine (*Pinus* spp.) decking [13,15]. Hence, further research is needed to optimize profiling for commercially important North American wood species that are used to manufacture decking.

In this paper, we examine the effects of surface profiling on the checking and cupping of wood decking exposed outdoors to the weather. We selected three important commercial wood species for our research: Douglas fir (*Pseudotsuga menziesii* (Mirb.) Franco); western hemlock (*Tsuga heterophylla* (Raf.) Sarg.); and white spruce (*Picea glauca* (Moench) Voss). Douglas fir, hemlock and spruce comprise over 50% of the 27.5 billion cubic meters of wood growing in non-protected land in Canada [25]. Wood from these species is used to manufacture decking [23], and pre-commercial trials of profiled Douglas fir decking have commenced in North America [26]. This study was carried out to determine the profiles that are most effective at reducing the checking of decking made from the three different wood species. We hypothesize that the geometry of profiles will influence checking of profiled decking. Our results show that rib profiles with narrow and deep grooves were better than profiles with wide or shallow grooves at restricting checking of all three species. Furthermore, our numerical model explains why a rib profile with deep grooves was more effective than a rib profile with shallow grooves at restricting checking of profiled spruce deckboards.

2. Materials and Methods

2.1. Manufacture of Profiled Decking

Six plain-sawn Douglas fir, western hemlock and white spruce boards, approximately $40 \times 140 \times 4877$ mm^3 in size were purchased from Northern Building Supplies (Vancouver, BC, Canada), Teal Jones Group (Surrey, BC, Canada), and Home Depot (Richmond, BC, Canada), respectively. The boards were stored in a conditioning room at 20 ± 1 °C and 65 ± 5% relative humidity for one month. The growth ring widths and grain angles of the six boards for each wood species were measured using a ruler and protractor, as described previously [27]. The densities of separate matched wood samples cut from parent boards were measured by water displacement and oven-drying overnight at 105 ± 5 °C (Table 1).

The six parent boards for each wood species were cross-cut using a pendulum saw (Stromab ps 50/f, Campagnola Emilia, Italy) to produce 12 samples, each 400 mm in length. Each sample was planed to a thickness of 35 mm using a European rotary planer (Martin T44, Otto Martin Maschinenbau, Ottobeuren, Germany). Six samples from each parent board for each wood species were selected at random and assigned to the six different profile types, including the flat unprofiled control (Table 2). The six profile types were a subset of those we described previously [19].

Table 1. Wood properties of Douglas fir (D. Fir), western hemlock (Hem) and white spruce boards.

Board	Growth Ring Widths (mm)			Grain Angle (°)			Densities (g/cm^3)		
	D. Fir	Hem	Spruce	D. Fir	Hem	Spruce	D. Fir	Hem	Spruce
1	3.7	4.8	0.8	1.9	3.1	1.4	0.42	0.49	0.38
2	7.9	1.7	3.4	2.1	2.6	1.2	0.53	0.42	0.34
3	4.4	1.1	3.1	1.8	1.9	0.9	0.36	0.41	0.39
4	7.8	3.8	3.7	2.7	3.3	2.2	0.47	0.44	0.35
5	4.3	4.2	1.2	3.4	2.8	1.8	0.46	0.50	0.38
6	3.3	2.9	0.9	1.5	2.2	2.3	0.43	0.40	0.31
Average	**5.2**	**3.0**	**2.2**	**2.2**	**2.6**	**1.6**	**0.445**	**0.44**	**0.36**

The rib profiles had very narrow grooves and hemispherical peaks (Table 2). The wavy (ribble and ripple) profiles had wider grooves (Table 2). Within the rib profile type there were three grooves depths: 1, 1.5 mm (short rib); 2, 2.0 mm (rib); 3, 2.5 mm (tall rib) (Table 2). The widths of peaks in all samples except the flat controls were 5.0 mm.

Table 2. Dimensions of the designed profiles used to manufacture profiled deckboard samples from Douglas fir, western hemlock and white spruce.

Profile type	Groove Depth (mm)	Groove Radius (mm)	Peak Radius (mm)
Rib	2.0	0.16	2.4
Tall rib	2.5	0.15	2.2
Short rib	1.5	0.16	2.4
Ribble	2.0	0.65	1.3
Ripple	2.0	1.0	1.2
Flat	-	-	-

Numbers of peaks per 15 cm (groove frequency) was 30 for all profiles except flat samples.

The method used to machine profiled deckboards is exactly the same as that described in our previous paper [19], except samples were machined using a shaper (Martin T26, Otto Martin Maschinenbau, Ottobeuren, Germany) rather than a molding machine. The first decking sample was fed into the shaper by hand and machined at a spindle speed of 6000 rpm to produce the selected profile. The remaining two (species) samples selected at random were then profiled. The whole process was repeated for each assigned profile and so on until all 18 samples (6 profiles × 3 species) from the first parent board for all three species were profiled. Then, samples from the second parent board for each species were profiled as above, followed by samples from boards 3, 4, 5 and 6 until all 108 samples (6 boards × 6 samples [profile type] × 3 species) had been machined. The final dimensions of the profiled boards were 400 (length) × 140 (width) × 35 mm^3 (thickness). Decking samples were air-dried in a conditioning room at 20 ± 1 °C and 65 ± 5% r.h. (relative humidity) for four months. Each sample was placed on a flat surface against a steel fence and planer deviation (cupping) was measured in three places using a dial gauge micrometer attached to a precision-machined steel square, as described previously [19]. The ends of the samples were brush-coated with a sealer (ZINSSER Bulls Eye 1, 2, 3 acrylic-latex undercoat, primer, sealer and stain blocker, Rust-Oleum Co., Vernon Hills, Illinois, USA) at the recommended rate (10 m^2/L), and samples were allowed to air dry overnight. The ends of the samples were re-coated with the sealer and samples were conditioned as above for a further two months and weighed using a digital balance (Mettler Toledo PG5002-S, Mississauga, ON, Canada). Sealing of the end-grain of samples was done to reduce preservative uptake via end-grain and to prevent checks from developing in end-grain.

All decking samples were treated with a 1.8% alkaline copper quaternary (ACQ type C) preservative solution containing copper oxide (66.7%) and alkyldimethylbenzyl-ammonium chloride (33.3%) in a commercial pressure-treatment plant operated by Stella-Jones Inc. and located in Carseland, AB, Canada (50°51′7.2″ N, 113°28′12″ W). The pressure treatment cycle consisted of 30 min under a vacuum of −74.5 kPa, 85 min at a pressure of 958 kPa, and 120 min under a vacuum of −74.5 kPa. Treated decking samples were weighed and preservative retentions of samples were calculated. Preservative retentions of Douglas fir, western hemlock and white spruce samples were 3.7 kg/m^3 (min = 1.1; max = 6.1; SD = 1.1), 6.9 kg/m^3 (min = 3.5; max = 8.7; SD = 1.1) and 2.4 kg/m^3 (min = 0.4; max = 5.0; SD = 1.3), respectively. Differences in preservative retentions of Douglas fir, western hemlock and white spruce samples were statistically significant ($p < 0.001$), whereas there was no significant ($p = 0.479$) effect of profiling on preservative retention of treated samples. After treatment, samples were air-dried in a conditioning room at 20 ± 1 °C and 65 ± 5% r.h. for two months, reweighed and their cupping was re-measured, as above.

2.2. Outdoor Weathering and Statistical Analysis of Data

Profiled samples and the matching flat controls cut from each of the six parent boards for each species were screwed to separate wooden sub-frames made from pressure-treated 2 × 4 lumber to create six mini-decks. Each mini-deck was 2.9 m long, 35 cm wide and 47 cm high. Boards were fastened at each corner to the sub-frames using 34 mm long, 3.1 mm wide galvanized decking screws applied using the CAMO® Edge Deck Fastening System (Grand Rapids, MI, USA, https://www.camofasteners.com/). A gap of 10 mm was left between each of the 18 boards in each rack. Unprofiled spruce boards, measuring 360 × 90 × 40 mm^3 were screwed to each end of the row of 18 boards on each rack to prevent the edges of samples at the ends of the racks from being exposed to the weather. The weathering racks were exposed outdoors in Vancouver at FPInnovation's test site (49.257, −123.244) for six months from 1st May 2017 to 31st October 2017. All samples were removed from racks after 14 weeks on 7 August and cupping of samples was re-measured as described above. Samples were returned to the racks on 11 August. The weather conditions during the exposure trial are summarized in Table 3. At the end of the trial, weathered samples were removed from the racks, conditioned at 20 ± 1°C and 65 ± 5% r.h. for two months and the length and width of visible checks were measured using a transparent plastic ruler and calibrated optical loupe (Carson LumiLoupe 10× Power Stand Magnifier, Carson Optical, Inc., Ronkonkoma, NY, USA), as described previously [19].

Table 3. Weather conditions in Vancouver, British Columbia, Canada during the six-month exposure trial (1st May to 31st October 2017).

Month	Temperature (°C)			Total Precipitation (mm)
	Mean	Maximum [1]	Minimum [1]	
May	12.8	16.8 (25.9)	8.7 (3.8)	102.2
June	15.6	19.6 (26.2)	11.5 (8.3)	46.4
July	18.3	22.9 (25.7)	13.7 (10.4)	1.8
August	18.8	23.3 (29.5)	14.3 (10.9)	5.0
September	16.0	20.1 (26.6)	11.8 (6.8)	29.4
October	8.2	12.8 (16.8)	6.0 (0.6)	114.3

[1] Mean minimum and maximum temperatures (with extremes in parentheses). Data are for Vancouver International Airport (49.196, −123.182), http://climate.weather.gc.ca/historical_data/search_historic_data_e.html.

Our experiment was a randomized block design. Each of the six weathering racks contained 18 deckboard samples (five profiled samples and the flat control for each of the species) and represents a block. The factors of interest (wood species and profile type) were fully replicated in each block.

Analysis of variance (ANOVA) of the effect of wood species and sample type (profiled and flat samples) on the following numerical indicators of checking and cupping were analyzed: (1) total area of all visible checks ([length × width] × n); (2) average width of the five largest checks in each sample; (3) average area of the largest check in each sample; and (4) difference in cupping measured in three places in samples before and after 14 weeks of weathering. ANOVA was also used to examine the effects of wood species and profiling on the preservative retention of treated samples. The factorial design of the experiment allowed data to be averaged across non-significant ($p > 0.05$) effects, giving the experiment greater precision. All statistical computation including model checking was performed using Genstat (v. 19) [27]. As a result of such checks, data for the area of the largest check in each sample were transformed into natural logarithms before final analysis. Results describing the effects of profiling on the checking and cupping of deckboards are presented in graphs and error bars on each graph (± standard error of difference, $p < 0.05$), can be used to estimate whether the differences between individual means are statistically significant [28].

2.3. Numerical Modeling

Finite element analysis (modeling) was performed to explore the effect of groove depth on the moisture-induced stresses generated by wetting and drying profiled spruce deckboard samples. Moisture diffusion in wood has been widely modeled using Fick's second law [29,30], which can be expressed using Equation (1) [31]:

$$\frac{\partial M}{\partial t} = \left\{ D_x \frac{\partial^2 M}{\partial x^2}, D_y \frac{\partial^2 M}{\partial y^2}, D_z \frac{\partial^2 M}{\partial z^2} \right\}, \quad (1)$$

where M is the local moisture concentration (kg/kg), t is time (s), and Dx, Dy, and Dz represent the coefficient of moisture diffusivity of wood in x (tangential), y (radial) and z (longitudinal) directions, respectively. Our FEA software did not have a moisture diffusion simulation module, but there is similarity between the governing equations for moisture diffusion and thermal diffusion [32]. Thermal diffusion (transient heat conduction) can be described using Equation (2) [31]:

$$\frac{\partial T}{\partial t} = \left\{ \alpha_{Tx} \frac{\partial^2 T}{\partial x^2}, \alpha_{Ty} \frac{\partial^2 T}{\partial y^2}, \alpha_{Tz} \frac{\partial^2 T}{\partial z^2} \right\}, \quad (2)$$

where T stands for local temperature (°C), t is time (s), and α_{Tx} is thermal diffusivity (m^2/s) in x-direction and can be defined as $\alpha_{Tx} = K_x/(\rho Cp)$ where K_x is thermal conductivity in x-direction (W/m·°C), ρ is density (kg/m^3), and C_p is specific heat (J/kg·°C). The similarity between thermal and moisture-diffusion equations makes it possible to use the thermal diffusion simulation module in the FEA software ANSYS Multiphysics to simulate moisture diffusion [33]. On the other hand, hygroscopic strain, ε_h, induced by moisture diffusion into the material can be defined using Equation (3) in which β_x, β_y and β_z are coefficient of moisture expansion in the x, y, and z directions, respectively.

$$\{\varepsilon_{hx}, \varepsilon_{hy}, \varepsilon_{hz}\} = \{\beta_x M, \beta_y M, \beta_z M\} \quad (3)$$

Table 4 shows the mechanical properties of spruce (*Picea* spp.) [33], and Table 5 shows the moisture diffusion and hygroscopic swelling properties of spruce. Moisture diffusion coefficients, D, and coefficients of moisture expansion, β, were taken from the literature [34,35].

Table 4. Mechanical properties of spruce.

E_x (MPa)	E_y (MPa)	E_z (MPa)	G_{xy} (MPa)	G_{xz} (MPa)	G_{yz} (MPa)	v_{xy}	v_{xz}	v_{yz}
464	842	10800	30	640	690	0.31	0.023	0.026

E_x, E_y and E_z = elastic moduli in x, y and z directions, respectively; G_{xy} = longitudinal shear modulus; G_{xz} and G_{yz} = transverse shear moduli; v_{xy} = longitudinal Poisson's ratio; v_{xz} and v_{yz} = transverse Poisson's ratios.

Table 5. Moisture diffusion and hygroscopic swelling properties of spruce *.

D_x (m^2/s)	D_y (m^2/s)	D_z (m^2/s)	β_x	β_y	β_z
52×10^{-12}	52×10^{-12}	1000×10^{-12}	0.17	0.308	0.001

* See text for meaning of parameters.

To simulate moisture diffusion into wood, the surface moisture contents of grooved wood samples needed to be estimated. Therefore, an experiment was carried out to measure the moisture content of peaks and grooves in spruce wood samples with either 2.5 mm deep (tall rib) or 1.5 mm deep (short rib) profiles (Table 2). Each sample was sprayed with a fine mist of water (15 g per sample) and allowed to dry under two 500 W lamps (Shopro L002716, Burnaby, BC, Canada) for 90 min. The surface moisture contents of the peaks and grooves were measured every 2 min using a pin-type moisture meter (Delmhorst RDM3, Towaco, NJ, USA). Surface moisture contents were used as starting values to simulate moisture diffusion in the grooved wood substrates. Moisture diffusion was modeled using the thermal transient module in ANSYS. The initial time step for this analysis was 60 s with minimum and maximum time steps of 10 and 120 s, respectively. Due to the symmetry of profiled deckboard samples only half of each profiled sample was modeled, as shown in Figure 1. Sensitivity analysis was performed to find an appropriate element type and size for FEA. Elements with tetrahedral shape and a maximum size of 1 mm were used to mesh wood profiles. As a result of this simulation, moisture content contours of the wood substrates were known at any time. Then, the transient thermal module was linked with the transient structural module in ANSYS to simulate the hygroscopic behavior of the samples. Finally, the moisture-induced stresses and strains were determined for profiles with deep (tall rib) or shallow (short rib) grooves.

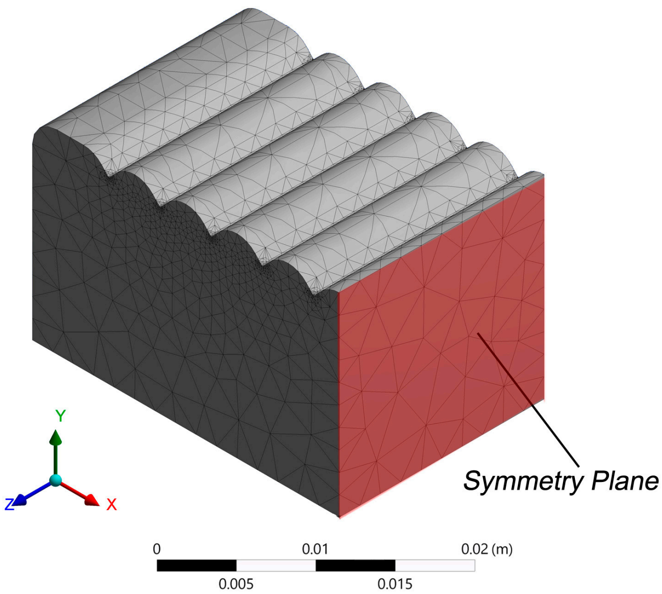

Figure 1. A finite element model of a profiled short rib board with shallow grooves and its symmetry plane.

All numerical modeling was carried out on a high-end laptop (Lenovo Ideapad Y700, 17″, Lenovo Canada, Markham, ON, Canada) with an Intel® Core™ i7-6700HQ CPU at 2.6 GHz and 16 GB of RAM.

3. Results

3.1. Effects of Profiling on Checking and Cupping of Deckboards

There were significant ($p < 0.001$) effects of wood species and sample type (profiled and flat deckboards) on checking of samples, but there were no significant ($p > 0.05$) interactions of species $\times$ sample type on checking. In other words, the effect of profiling was consistent across the Douglas fir, western hemlock and white spruce samples. The total area of checks in profiled samples was significantly ($p < 0.05$) smaller than the area of checks in unprofiled (flat) deckboard samples (Figure 2). There were also significant ($p < 0.05$) differences in the total area of checks that developed in the different profiled samples (Figure 2). The profiles with narrow and deep grooves (tall rib and rib) were significantly ($p < 0.05$) better at restricting checking than the other profiles, including the short rib profile (Figure 2).

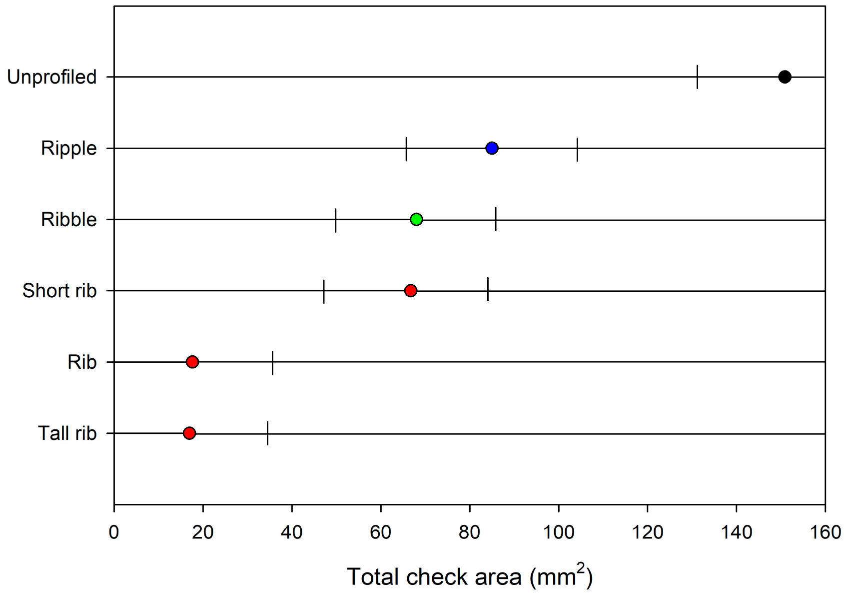

Figure 2. Total area of visible checks in profiled deckboard samples exposed to natural weathering is significantly lower than that in similarly exposed flat (unprofiled) samples. Results are averaged across all three species (Douglas fir, western hemlock and white spruce).

Wide checks are easier to see than narrower ones, and influence the appearance of deckboards to a greater extent than narrow checks [18]. Checks were significantly ($p < 0.05$) narrower in profiled boards than in unprofiled (flat) deckboard samples (Figure 3).

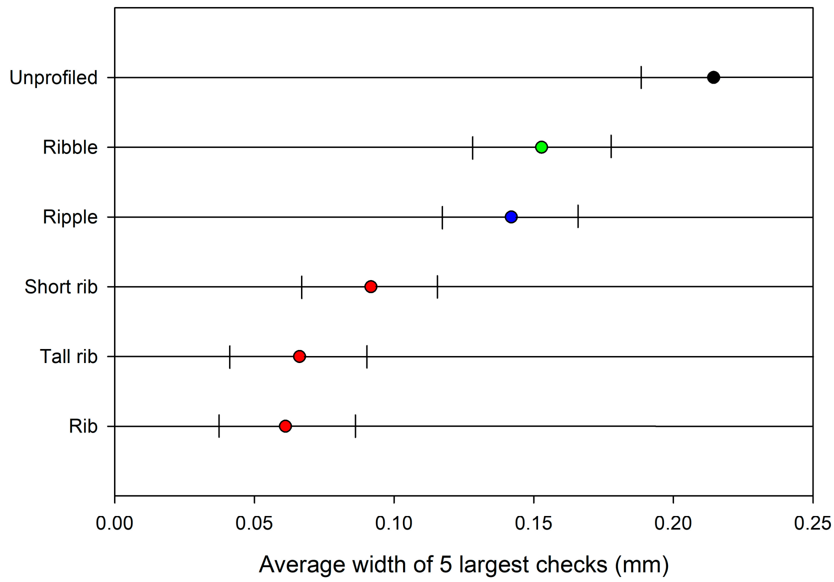

Figure 3. Average width of five largest checks in profiled deckboard samples exposed to natural weathering is significantly lower than that in similarly exposed flat (unprofiled) samples. Results are averaged across all three species (Douglas fir, western hemlock and white spruce).

Profiles with narrower grooves (rib profiles), including the short rib profile, were significantly ($p < 0.05$) more effective than profiles with wider grooves (ribble and ripple profiles) at restricting checks from becoming wider when profiled deckboards were exposed outside for six months (Figure 3). Furthermore, the largest check in profiled samples was significantly ($p < 0.001$) smaller than those in unprofiled (flat) deckboard samples (Figure 4). There were also significant ($p < 0.05$) differences in the area of the largest check that developed in the different profiled boards (Figure 4). The largest check in samples with narrow and deep grooves (tall rib and rib) was significantly ($p < 0.05$) smaller than those in other profiled samples including samples with the short rib profile (Figure 4).

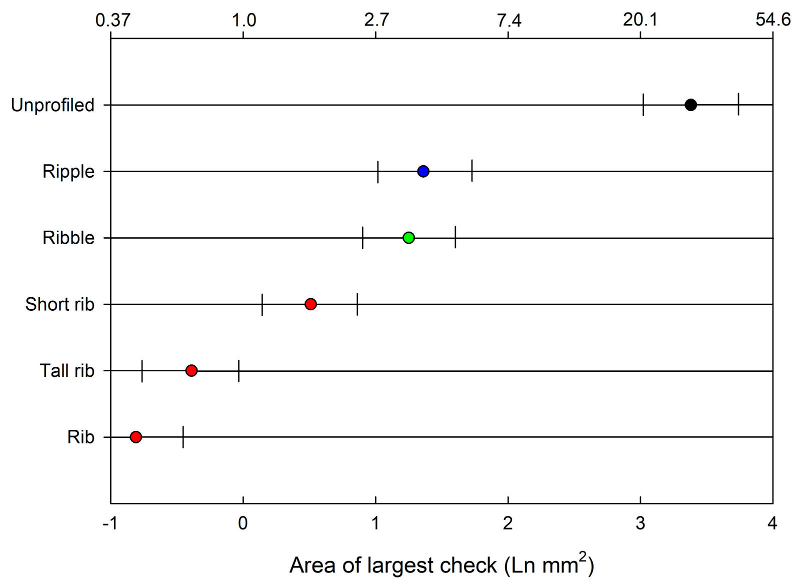

Figure 4. Average area of the largest individual check that developed in profiled deckboard samples exposed to natural weathering is significantly lower than that in similarly exposed flat (unprofiled) samples. Results are averaged across all three species (Douglas fir, western hemlock and white spruce). Values on *X*-axis represent natural logarithms, but back-transformed (e^x) values on natural scale can be found on the *X*2-axis.

In addition to the effects of profiling on checking of deckboards, there were significant ($p < 0.01$) effects of 'species' on checking, as mentioned above, although there were no significant ($p > 0.05$) species × profiling interactions on checking. The significant effects of species on checking occurred because checks in western hemlock boards were always more numerous and larger than those in spruce boards, and there were also significant differences in the severity of checking in western hemlock vs. Douglas fir samples and Douglas fir vs. spruce samples (Table 6).

Table 6. Checking of profiled Douglas fir, western hemlock and white spruce boards exposed to natural weathering. Results are averaged across all profiled samples.

Species	Check Parameters		
	Total Check Area (mm^2) *	Width of 5 Largest Checks (mm) †	Largest Check Area ($\ln mm^2$) ‡,**
Hem	97.5 ^{a}	0.156 ^{a}	1.33 ^{a} (3.78) **
D. fir	68.8 ^{b}	0.111 ^{b}	0.93 ^{a} (2.53)
Spruce	36.2 ^{c}	0.097 ^{b}	0.39 ^{b} (1.47)

* $p < 0.001$; † $p = 0.001$; ‡ $p < 0.001$; ** back-transformed values (e^x) in parentheses. Means in each column sharing the same superscripted letter (a, b, c) are not significantly ($p > 0.05$) different from each other.

There were significant effects of species ($p < 0.001$) and sample type (profiled and flat, $p = 0.038$) on the cupping of samples during natural weathering, expressed as the difference in cupping of samples before and after weathering. Western hemlock samples cupped (0.35 mm) significantly ($p < 0.05$) more than spruce (0.25) or Douglas fir (0.09) samples during weathering, and the difference in cupping of spruce and Douglas fir samples was also statistically significant ($p < 0.05$). Cupping of unprofiled (flat) samples was significantly ($p < 0.05$) less than those of profiled samples except for samples with narrow and deep grooves (tall rib) (Figure 5).

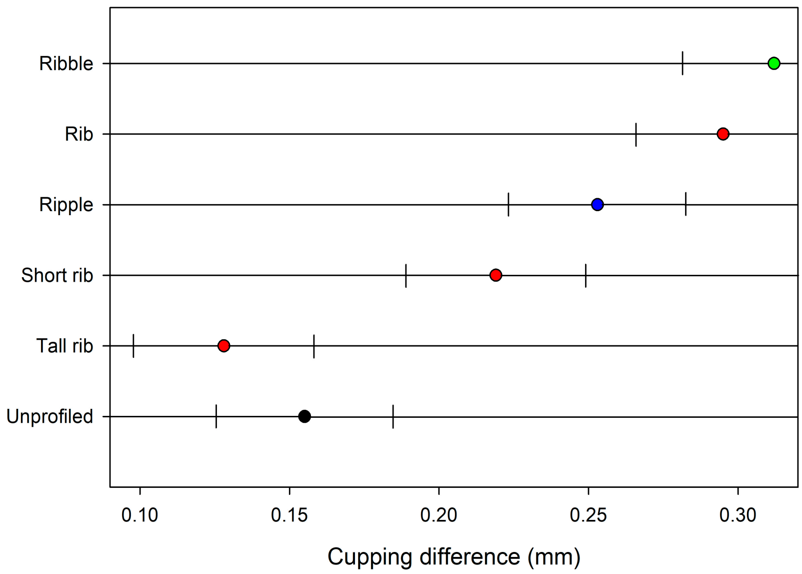

Figure 5. Difference in cupping of deckboard samples before and after they were exposed to natural weathering.

3.2. Numerical Modeling of the Effects of Groove Depth on Stress

Figure 6 shows the moisture contents of the grooves and peaks in profiled spruce samples with narrow (rib) and either deep (tall) or shallow (short) grooves. The moisture contents in the grooves and peaks of the two types of profiled samples are initially similar, and higher in grooves than in the peaks. The samples with the shallow grooves (short rib profile) dry more rapidly than samples with deeper grooves (tall rib profile), and moisture contents of grooves and peaks in the former samples converge more rapidly than those of samples with deeper grooves.

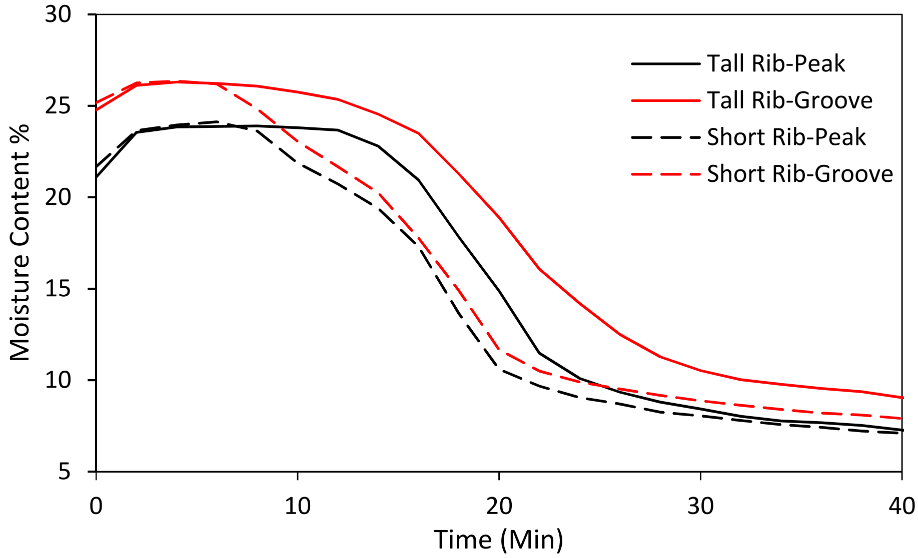

Figure 6. Moisture contents of grooves and peaks in profiled spruce samples with deep (tall rib) or shallow grooves (short rib) during a drying cycle.

Figure 7 shows the normal stress in x-direction in profiled samples with deep (tall rib) or shallow grooves (short rib). The maximum compressive stress in the first 15 min of the drying cycle, when the wood was still wet is higher for the sample with shallow grooves compared to that in the sample with deeper grooves (Figure 7). Moreover, later in the drying period, the tensile stress in the former sample is higher than that in the sample with deeper grooves (Figure 7).

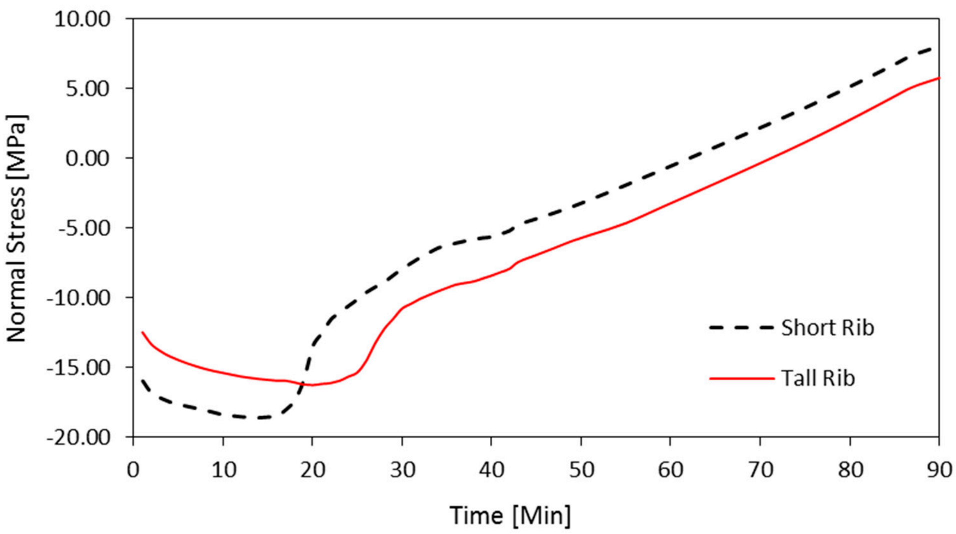

Figure 7. Normal stress in x-direction in the grooves of samples with 2.5 mm deep grooves (tall rib) vs. 1.5 mm deep (short rib) grooves.

Figures 8 and 9 show the induced normal stresses in x-direction for samples with shallow (short rib) and deep (tall rib) grooves, respectively. It can be observed that in the sample with shallower (1.5 mm deep) grooves the number of areas with high stress is greater than those in a sample with 2.5 mm deep grooves (tall rib profile).

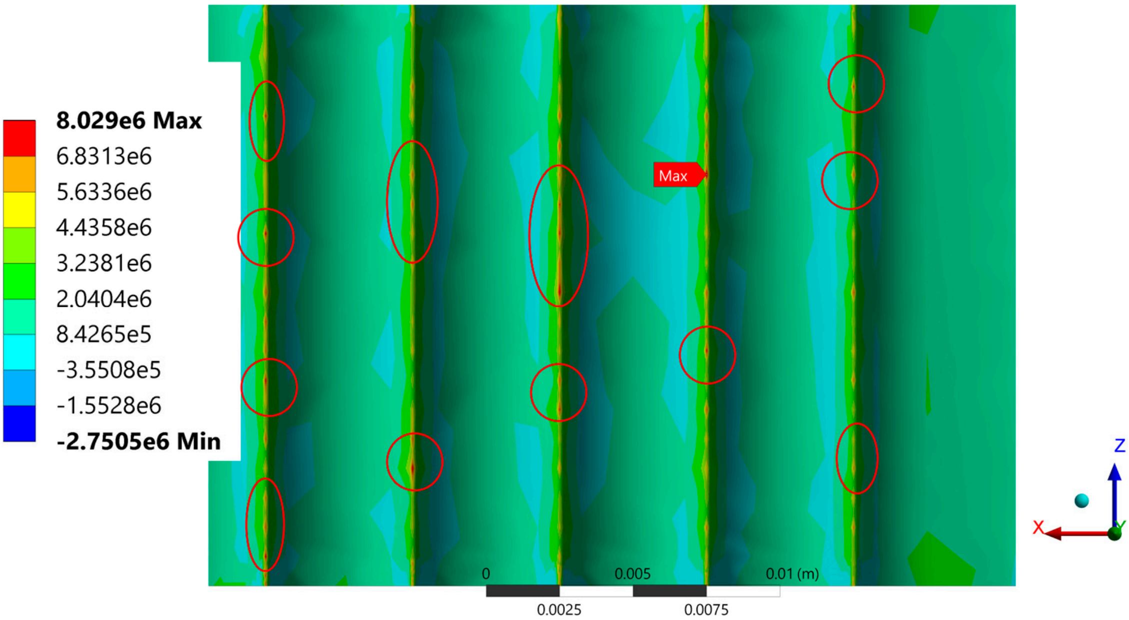

Figure 8. Normal stress in x-direction at the surface of a sample with 1.5 mm deep (short rib) grooves at the end of drying period (the areas with high stress are circled).

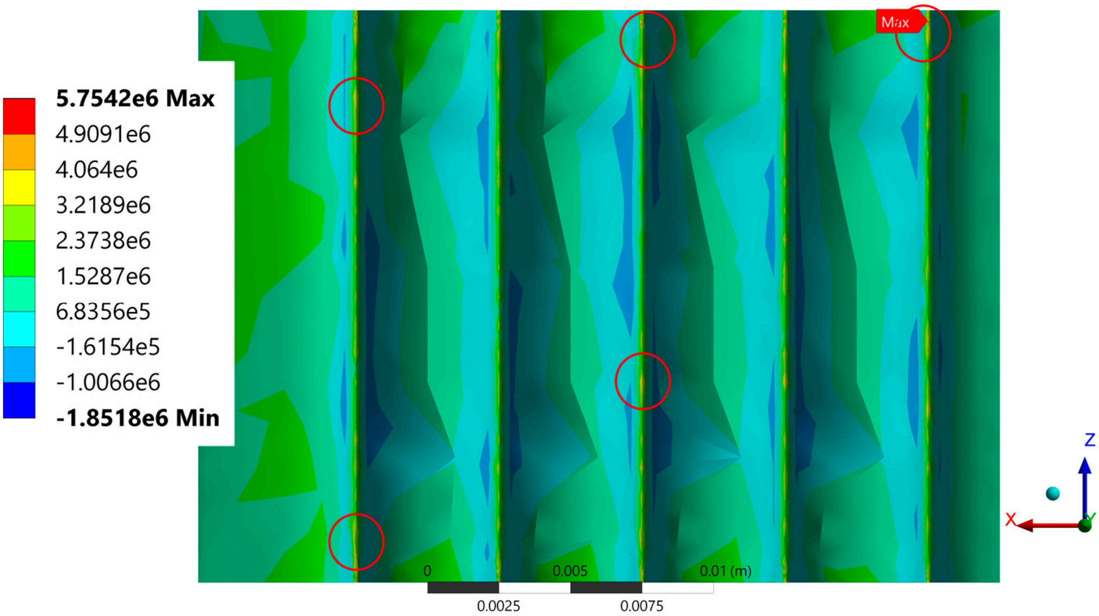

Figure 9. Normal stress in x-direction at the surface of a sample with 2.5 mm deep (tall rib) grooves at the end of drying period (the areas with high stress are circled).

4. Discussion

Profiling of deckboards is a good way of reducing the negative effect of surface checking on the appearance of deckboards exposed outdoors, and profiled deckboards are common in Asia, Australia, Europe and New Zealand, as mentioned above [7,8]. They are not common in North America. Interest in manufacturing profiled wooden deckboards in North America is increasing, but profiling has only been tested on a handful of wood species [12–19]. Previous results suggested that rib profiles with narrow grooves were better than profiles with wider grooves (ribble or ripple profiles) at reducing the checking of amabilis fir [19], but studies have also shown that the effectiveness of different profiles varies with wood species, as mentioned in the introduction [13,15]. Therefore, it has been difficult to recommend the best profile for the manufacture of profiled decking from North American softwood species, apart from amabilis fir or southern pine. Softwoods such as Douglas fir, western hemlock and white spruce are more commercially important than amabilis fir [36], and results here suggest that a profile with narrow grooves (rib profile) is better than wavy profiles (ribble or ripple) at reducing the checking of these three species. This finding accords with previous research that optimized surface profiling for amabilis fir deckboards [13,15,19]. Our finding that tensile stresses are greater in grooves of rib samples also accords with findings that tensile strains during drying are highest in the grooves of deckboards with wavy profiles [37], and observations that checks are mainly located in grooves of profiled deckboards [4,12,13].

In addition to the effect of groove width on checking (rib vs. ribble or ripple) we also observed that groove depth in boards with narrow grooves (rib profiles) had a significant effect on two measures of checking. Our previous research on the effect of profile geometry on the checking of amabilis fir suggested that groove depth influenced checking, but the relationship between groove depth and check parameters was not strong [19]. Our current experimental findings are more convincing and our model of the effect of groove depth on checking suggests why ribbed boards with deeper grooves (2 or 2.5 mm) check less than boards with shallower grooves (1.5 mm). In particular, we found that stresses, which cause checking at wood surfaces during drying [38], were greater in ribbed spruce samples with shallow grooves (1.5 mm deep) compared to samples with deeper grooves (2.5 mm deep). Furthermore, the former samples contained more areas with high stress. Rib samples with shallow grooves dried more rapidly than samples with deeper grooves, which may explain the pattern of stress development in the two types of samples. Accordingly, treatments such as coatings that restrict the rate of drying of profiled deckboards may further reduce checking. In accord with this suggestion, Akhtari and Nicholas [17] found that coatings containing zinc oxide or titanium dioxide particles reduced the checking of ribbed southern pine deckboards exposed to artificial accelerated weathering by approximately fifty percent [17].

Ribbed boards with grooves that exceed 2 mm in depth are manufactured commercially [7]. For example, our survey of the topography of profiled deckboards manufactured around the world found that six of the 19 ribbed boards we analyzed had grooves that were deeper than 2 mm [7]. Boards with profiles that are very similar to our standard rib profile with a groove depth of 2 mm are manufactured commercially from radiata pine (*Pinus radiata* D. Don) or European larch (*Larix decidua* Mill.) [7]. Pre-commercial trials of profiled Douglas fir decking have been established in the USA based on our initial finding that rib profiles were better than wavy profiles at restricting the checking of amabilis fir decking [19]. The profile that was chosen for these trials was our standard rib profile with a groove depth of 2.0 mm. Results here support the choice of this standard rib profile for the profiled Douglas fir deckboards used for these pre-commercial trials [26].

The positive effects of profiling on the checking of deckboards exposed to the weather are clouded by results from some previous studies showing that profiling increases the undesirable cupping of amabilis fir deckboards exposed to the weather [13,19]. Cupping of profiled plywood siding exposed to the weather is also more pronounced than that of flat plywood siding [6,39]. In contrast, other studies have shown that profiling reduces the cupping and distortion of southern pine deckboards exposed to the weather [16,17]. Our results here for Douglas fir, western hemlock and white spruce deckboards accord with the results of our previous study that showed that profiling increased the cupping of amabilis fir deckboards exposed to the weather [19]. Previously we suggested that grooves or saw kerfs that are machined into the undersides of deck or flooring boards might reduce the tendency of profiled deckboards to cup when they are exposed outdoors [40,41]. We have carried out a study to examine whether this approach can reduce the cupping of profiled Douglas fir, western hemlock and white spruce boards cut from the same parent boards as those used here. Our results have successfully demonstrated the efficacy of this approach and they will be reported in a separate paper that is being prepared for publication.

In addition to the effects of profiling on the checking and cupping of deckboards, we also observed a significant wood species effect on checking and cupping of deckboards. Our finding that western hemlock deckboards checked more than Douglas fir or white spruce boards accords with the results of two previous studies that compared the checking of decking made from different softwood species [23,42]. One of these studies noted that softwood species that checked less than other species were ones that were dimensionally stable or impermeable such as western red cedar (*Thuja plicata* Donn ex D.Don), yellow cedar (*Cupressus nootkatensis* D.Don 1824) and white spruce [42]. White spruce deckboards here also cupped less than western hemlock deckboards. Norway spruce (*Picea abies* (L.) Karst), which is similar to white spruce, is preferred for exterior house siding in Europe because it cups and checks less than Scots pine (*Pinus sylvestris* L.) siding [43,44]. This desirable property of spruce has been attributed to its impermeability resulting from high percentages of blocked (aspirated) bordered pits and small proportion of ray tracheids [44,45]. Accordingly, it is possible that the lower checking and cupping of white spruce deckboards than western hemlock boards could be due to the lower permeability of the former species compared to western hemlock. Douglas fir is also less permeable than western hemlock, which may account for why Douglas fir deckboards checked and cupped less than western hemlock deckboards. However, Douglas fir deckboards cupped less than spruce deckboards even though they were more permeable than white spruce boards. Hence, differences in the permeability of the three wood species used to make deckboards cannot fully explain the variation in cupping of deckboards exposed to natural weathering.

The Douglas fir, western hemlock and white spruce samples tested here were treated with the preservative chemical ACQ (alkaline copper quaternary). This feature of our experimentation accords with commercial practice, but on the other hand decking boards are expected to maintain their appearance for several years, whereas we assessed checking after only six months' exposure. Nevertheless, Morris and Ingram [18] found that a rib profile significantly reduced the surface checking of subalpine fir (*Abies lasiocarpa* (Hooker) Nuttall) decking after six, 17, 36, 60, and 120 months' exposure. The difference in checking of unprofiled and ribbed decking became smaller, particularly after five years' exposure, but the authors concluded that 'profiling significantly reduced the checking of deckboards exposed to the weather for 10 years, and 'checks in ribbed boards were very difficult to see at standing height' [18]. Therefore, we suggest that our results on the effectiveness of rib profiles at reducing the checking of Douglas fir, western hemlock and white spruce are promising, but further research, similar to that carried out by Morris and Ingram [18], is needed to examine the long-term effectiveness of the profiles at reducing the checking of all three species, and to determine whether profiling affects the decay resistance of deckboards [18,19].

5. Conclusions

Our experimental results provide strong evidence that machined profiles with deep narrow grooves (tall rib profiles) are more effective than profiles with wider (ribble or ripple profiles) or shallower grooves (short rib profile) at restricting checking of ACQ-treated Douglas fir, western hemlock and white spruce deckboards exposed to natural weathering. Our numerical model explains why tall rib profiles with deeper grooves were more effective than short rib profiles with shallower grooves at restricting checking of profiled spruce deckboards. We conclude that current pre-commercial trials of profiled Douglas fir deckboards have selected a good profile (2 mm deep rib) to reduce the negative effects of checking on the appearance of deckboards exposed outdoors. However, this profile increased the undesirable cupping of deckboards exposed outdoors, and research is needed to solve this problem before the profiles developed here can be used commercially.

Author Contributions: P.D.E. conceived and designed the experiments. S.H. performed all experimental work. M.S.M. developed the analytical model. P.D.E. analyzed all data and wrote the first draft of the paper. All authors discussed and commented on the results and contributed to the final submitted and published manuscript.

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