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RESEARCH ARTICLE

Toward understanding ignition vulnerabilities to firebrand showers using reduced-scale experiments

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Summary

Over the past few years, the large outdoor fire problem has been a growing concern throughout the world. It is recommended to clear the combustibles around homes and within communities to avoid potential loss of properties, as firebrand shower ignition is a dangerous threat. One of the common combustibles around homes is mulching materials. A reduced-scale experimental protocol was developed to study ignition of mulching materials by firebrands and resulting impact to adjunct wall assemblies. Reduced-scale experimental results were compared with full-scale experimental results. Specifically, two trends were of interest in the comparisons. First, the ranking of the ease of ignition for various mulch types from exposure to firebrand showers. Second, if a given mulch type ignited from exposure to firebrand showers, was the resulting mulch bed fire able to ignite the adjacent wall assembly. The reduced-scale experimental results captured some of these trends observed from full-scale experiments but not completely. The findings still suggest that the reduced-scale experiments may give insights into how easily different mulch beds may be ignited by firebrands, as compared to much more costly and time-consuming full-scale experiments. While it is interesting to conduct full-scale experiments, this is very expensive and not always practical, so the authors are devising far cheaper reduced-scale experiments to provide more in-depth scientific understanding of firebrand shower ignition of construction components.

KEYWORDS

embers, firebrands, ignition, large outdoor fires, wildland urban interface fires

1 | INTRODUCTION

Wildfires threaten eco-systems, various property types, and people every year.[1-4] Once a wildfire reaches developed areas, these fires are called wildland-urban interface (WUI) fires.[5] Studies indicate burned areas, and the suppression costs are increasing.[6,7]

During the 2018 Camp Fire, one of the most destructive WUI fires in California's history, more than 18 000 buildings were destroyed, with some 50 000 people evacuated.[8,9] During 2019-2020 Australia bushfire season, another example of WUI fires, more than 9000 buildings were lost, and 26 062 plant species were impacted.[10,11] Washington, Oregon, and California suffered tremendously during the 2020 fire season. In Japan, while the amount of destruction is smaller than California or Australia, wildland fires or forest fires reached communities and resulted in loss of properties or evacuation orders.[12,13] To be able to make communities resilient to WUI fires, it is important to understand the ignition risk around and within communities.[14,15]

WUI fires spread via three paths: flame contact, radiant heat, and firebrands. While the terms ember and firebrand are often used interchangeably, firebrands refer to hot objects in flight that may ignite other fuels. The term ember only refers to a hot object.[16] Flame contact and radiant heat exposures are easier to handle, but firebrand showers remain a complex problem. Naturally, firebrands contribute largely to rapid fire spread. Under strong wind, firebrands can fly far, even more than several kilometers (long-distance spotting).[17]

To reduce home ignition in the WUI, the concept of home ignition zone (HIZ) was developed and promoted.[18-20] Under these policies, combustibles should be removed or reduced within a certain distance from a home. Yet, it is difficult to implement in practice.[5,21] Firebrand showers only further complicate the concept of a HIZ.

Mulching materials are often seen around houses for landscaping purposes. Mulch, due to its widespread use, and suspected ease of ignition in WUI fires, has been widely studied in the past.[22-38] One of the most common mulching materials in the United States, pine straw, has been the main focus of many studies.[23,24,27,33,34] Pine straw is easy to collect and widely used. Pine straw is not the only common mulching material selected by homeowners. Pine bark nuggets, shredded hardwood, and cypress wood chips are also common in the United States.[22]

When investigating the potential for firebrands to ignite common mulch types, different approaches have been used to simulate firebrands.[33-36] This makes it hard to compare ignitability by firebrands and evaluate the dangers of various mulching materials accordingly. For studies that have used a single firebrand, it is possible to ignite dry shredded hardwood mulch, but it is difficult to ignite mulch types that are not oven dried (eg, with only 11% moisture content-MC, dry basis). Accumulation of firebrands, in contrast, was able to ignite shredded hardwood mulch of higher MCs.[37]

In order to recreate flying firebrands, the firebrand generator (the NIST Dragon) was developed.[39] The NIST Dragon has the capability to produce a shower of firebrands. The size of firebrands is matched with firebrand data from burning trees or burning structures by changing feeding materials.[40,41]

The NIST Dragon has experimentally revealed the vulnerabilities around houses in full-scale experiments considering "flying firebrands"[37-39,42-47] previously seen in postfire survey.[48-51] The experimental results from the NIST Dragon were used to revise the California Building Code Chapter 7A and develop ASTM test methods.[52,53] In prior experiments, common mulching materials were exposed to firebrand showers, and the impact to a surrogate building, an adjacent re-entrant corner assembly (size of 1.22 m × 1. 22 m × 2.44 m × 2), was investigated.[37,38] Results were useful to understand the vulnerability of mulching materials and the impact to the re-entrant corner assemblies, yet smaller scale experiments that are capable to recreate full-scale experiments are desired. Some advantages of smaller scale experiments are the ability to study broad parameter spaces as well as translate such methods into standardized test methods to enable more ignition-resistant communities.

In this study, a reduced-scale experimental method to evaluate combustibles around a mock structure was developed to study the vulnerabilities of mulching materials to firebrand showers. Results also were compared with the full-scale experiments to see if the developed bench-scale method may recreate the full-scale experimental results.

2 | EXPERIMENTS

The reduced-scale experimental settings are similar with those reported elsewhere.[54] The reduced-scale firebrand generator (the NIST baby Dragon) with a continuous feed system, was used for

FIGURE 2 Vertical separation distance between the surface of mulching materials and the bottom of vinyl sidings

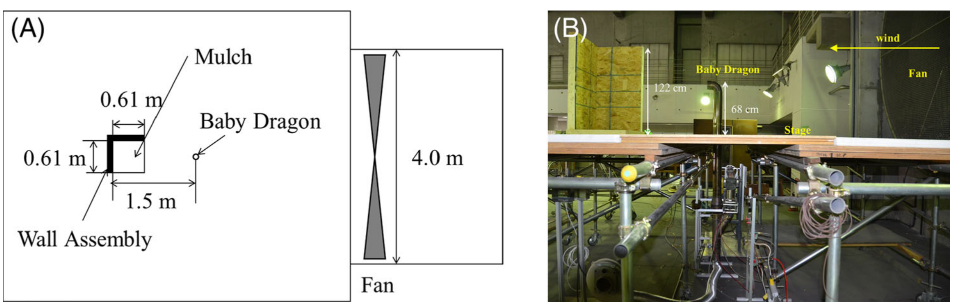

FIGURE 1 Reduced-scale experimental setting, (A) top view (schematics) and (B) side view

experiments to simulate the firebrand shower seen in real WUI fires. The description of the continuous-feed system and the NIST baby Dragon is described in detail elsewhere.[54] Douglas-fir wood pieces were cut into the size of 7.9 mm × 7.9 mm × 12.5 mm (before combustion) to produce desired firebrands. In this experimental series, the size and the mass of firebrands are similar to those from vegetation.[41]

The size of re-entrant corner assembly was 61 cm × 61 cm × 122 cm (inside), and the size of fuel beds (mulching materials) was 61 cm × 61 cm × 5.1 cm. The location of mulching bed is 89–150 cm from the exit of the NIST baby Dragon shown in Figure 1A (top view) B (side view). This is the one quarter of the size (half the length and half the width) of previous experimental series in full scale.[37,38]

Experiments were performed in NRIFD's wind facility where a 4 m-diameter fan is used to provide laminar flow 2 m × 2 m area with uncertainty of 10%. The time to smoldering ignition and flaming ignition was measured via a video recording, and in the case of flaming ignition, experiments were continued to see if flaming mulching materials were able to ignite the re-entrant corner assembly. The re-entrant corner assembly was either bare oriented strand board (OSB), OSB with gypsum sheet lined (inside), or vinyl siding applied with 10.2 cm (4 in.) or 20.3 cm (8 in.) separation distance (between the surface of mulching materials and the bottom of vinyl sidings) shown in Figure 2. The separation distance was the same distance to our previous full-scale experiments.[38] It is considered the most difficult to ignite vinyl sidings with 20.3 cm-separation distance. If ignition for a "more difficult case" was observed, some of conditions were not simply conducted. For example, if ignition of vinyl sidings with 20.3 cm-separation distance was observed for Japanese cypress woodchip mulch, experiments with vinyl sidings with 10.2 cm-separation distance were not conducted.

Experiments were performed with four different mulching materials—shredded hardwood mulch, Japanese cypress woodchip mulch, pine bark nuggets, and mini pine bark nuggets (see Figure 3). The first three materials were also used in the past studies at full scale.[38] The bulk densities of those mulch materials are matched with[38] namely, shredded hardwood mulch (0.25 g/cm^3), Japanese cypress woodchip mulch (0.14 g/cm^3), pine bark nuggets (0.17 g/cm^3), and mini pine bark nuggets (0.16 g/cm^3). Two wind speeds were selected to match the full-scale experiments, namely, 6 m/s and 8 m/s. In this study, ignitability of mulching materials as well as impact to nearby re-entrant corner assemblies of mulch materials was of interest. All mulching materials were oven-dried and cooled down in the ambient before experiments.

Separate experiments were conducted to check the repeatability of produced firebrands. Firebrands from the NIST baby Dragon were collected using water pans. Water is needed to quench the combustion as it is important to have firebrands within the same mass and size range upon landing the fuel beds. After the collection, firebrands were dried at 104°C for at least 48 hours until a pan weight stabilized. The mass was measured with the scale with 0.0001 g, and the projected area was calculated based on pictures of firebrands with a scale. Size and projected area of firebrands at reduced-scale Dragon are considered within the size and projected area of firebrands from full-scale experiments as shown in Figure 4.

FIGURE 3 Mulching materials for experimental series

3 | RESULTS AND DISCUSSION

Some of reduced-scale experimental images and comparison with full-scale experiments are shown in Figure 5. Smoldering ignition (SI) and flaming ignition (FI) were observed in all experiments with exceptions of those with pine bark nuggets (described later). The data were also compared with the full-scale experimental data.

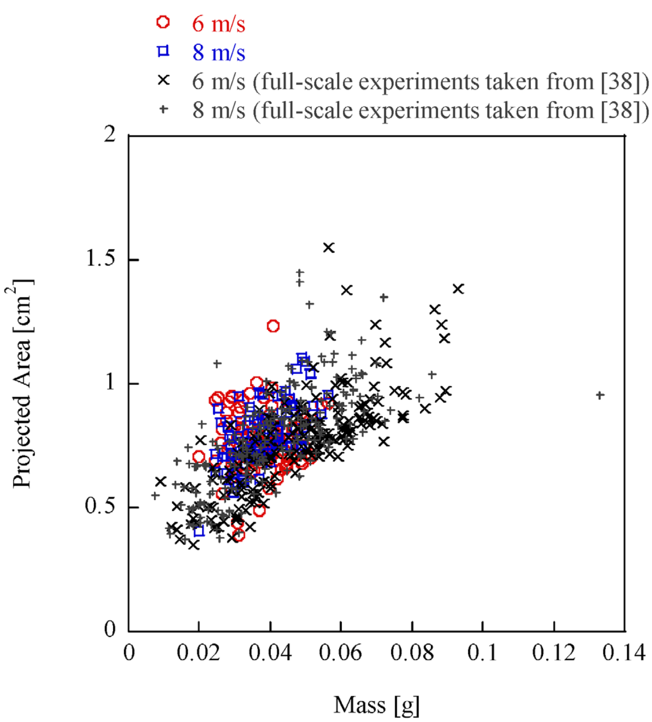

FIGURE 4 Characteristics of firebrands for experiments

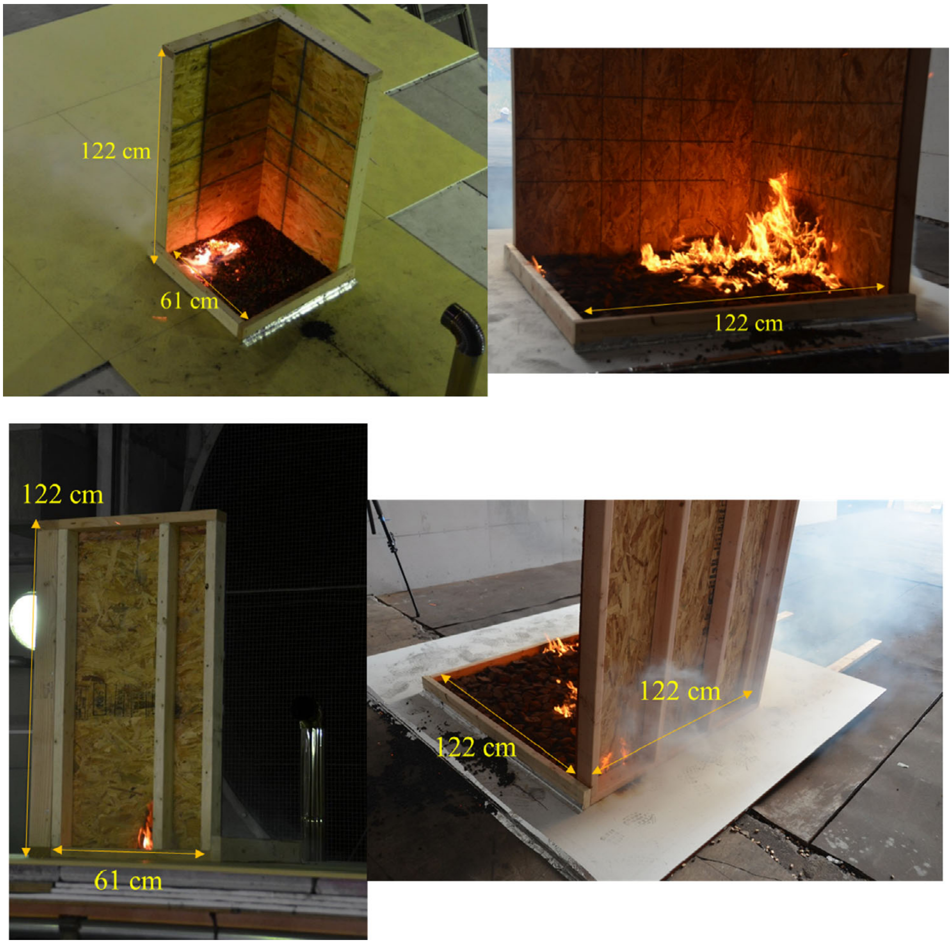

FIGURE 5 Images of experiments at a reduced-scale (left) and a full-scale (right). Top images show ignition in mulching materials, and bottom images show subsequent wall ignition

3.1 | Time to ignition

Time to SI and FI was measured via video recordings. Time to ignition was calculated based on repeated experiments. The ignition experiments were conducted at least three times under the same condition (a fuel bed and a wind speed). The data from pine bark nuggets under 6 m/s are not provided here as only one out of five experiments showed ignition after 40 min of a firebrand shower. It should be noted that the number flux of arriving firebrands on a fuel bed under 6 and 8 m/s are different—3.8 and 4.7/m^{2}s, respectively. So instead of time to ignition, the number of firebrands required for ignition/m^2 is used for comparison.

Figure 6 shows the number of firebrands required for SI and FI, respectively, for different mulching materials. Shredded hardwood mulch was the quickest for firebrand showers to ignite, followed by Japanese cypress woodchip mulch and mini-pine bark nuggets in the case of 6 m/s. It was not possible to ignite pine bark nuggets in four out of five experiments under 6 m/s; this is due to pine bark nuggets having the largest empty spaces among them due to its size and shape. Those empty spaces would result in transfer of heat to the ambient from firebrands not to fuel beds. Firebrands extinguished before reaching an ignition.

When comparing with full-scale experiments under 6 m/s, Japanese cypress woodchip mulch had the shortest average time to

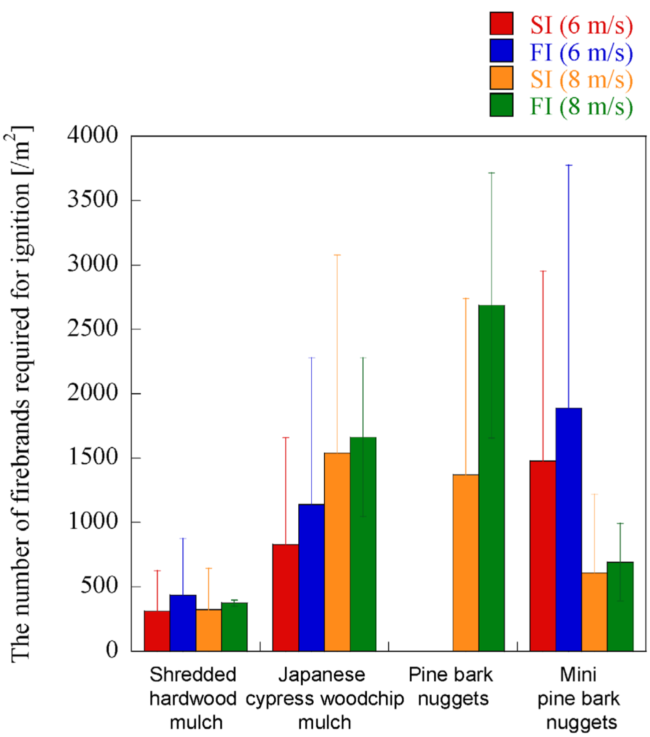

FIGURE 6 The number of firebrands required for ignition for different mulching materials at reduced-scale experiments

sustained FI among three mulching materials tested, followed by shredded hardwood mulch (slightly shorter) and then Pine bark nuggets.[38] Given the uncertainties for experiments, the time to ignition (the number of firebrands required for ignition) for shredded hardwood mulch and Japanese cypress might be not much different. In full-scale experiments, it was possible to ignite pine bark nuggets due to larger firebrand flux (7.4/m^2s (full-scale) vs. 3.8 /m^2s (bench-scale), thus, firebrands did not extinguish before reaching an ignition.

Under 8 m/s wind, firebrand showers were able to ignite all mulches tested. The number of firebrands required for SI or FI under 8 m/s beds was similar to the 6 m/s in the case for shredded hardwood mulch beds. For pine bark nuggets and mini pine bark nuggets, the smaller numbers of firebrands required for SI or FI were required under 8 m/s. An interesting point here is mini pine bark nuggets required much less firebrands than pine bark nuggets, even though both are made from the same materials.

As shown in Figure 3, size is quite different while bulk density is similar. Pine bark nuggets bulk density (0.17 g/cm^3) versus mini pine bark nuggets bulk density (0.16 g/cm^3). As discussed, the fuel beds of pine bark nuggets have large empty spaces between them due to the size of nuggets, thus firebrands transferring heat to the ambient, rather than to the fuel beds, resulting in longer time to ignition. The increase in the number of firebrands required for SI or FI in Japanese cypress chips was observed under 8 m/s. Close observation revealed that Japanese cypress woodchip mulch were moving under high wind speeds, which makes it difficult to contact firebrands and resulted in loss of heat.

Reduced-scale experimental results are compared with full-scale experimental data from.[38] Caution is needed to discuss pine bark nuggets and Japanese cypress chip under 8 m/s, as the full-scale experiment was not repeated. The number flux of arriving firebrands is different among experimental conditions (wind speeds and full-scale/bench-scale experiments), and adjustments (based on firebrand arrival flux) are made to plot Figure 7 for comparison. The number of firebrands required for ignition decreased both at reduced-scale experiments and at full-scale experiments with shredded hardwood mulch and pine bark nuggets as the wind speed increased from 6 m/s to 8 m/s. Both experiments with Japanese cypress woodchips showed the number of firebrands required for ignition increased (or remained similar) as the wind increased. This suggests that the reduced-scale experiments may give insights into how easily different mulch beds may be ignited by firebrands, as compared to much more costly and time-consuming full-scale experiments.

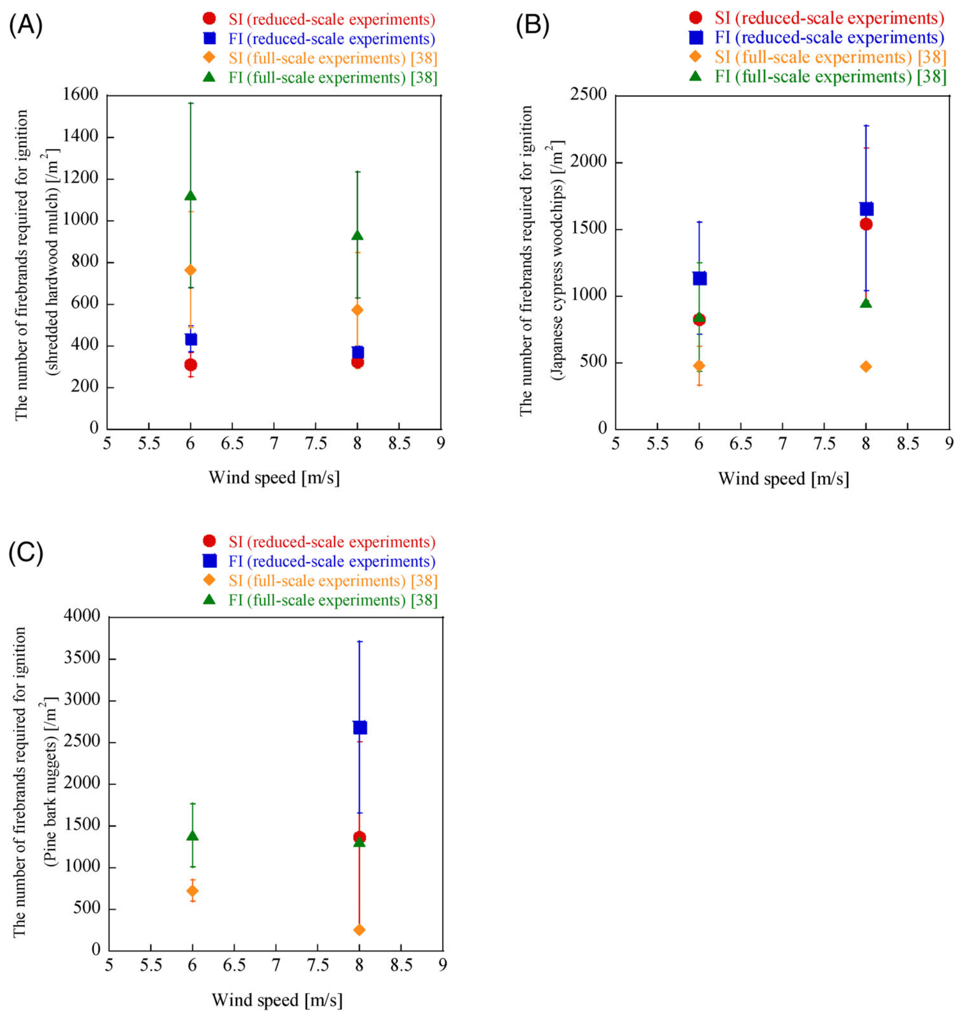

FIGURE 7 Comparison of the number of firebrands required for shredded hardwood mulch ignition under different wind speeds and scale (full-scale vs. reduced-scale); (A) shredded hardwood mulch, (B) Japanese cypress woodchip mulch, and (C) pine bark nuggets

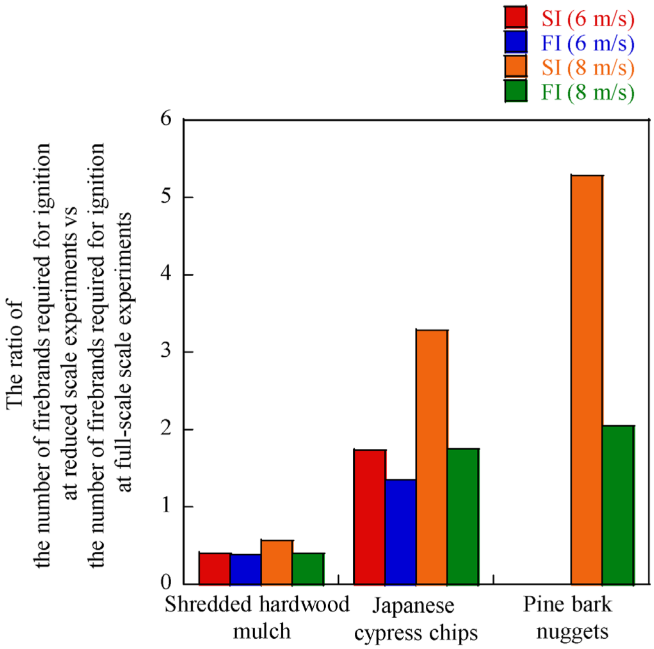

FIGURE 8 Ratio of the number of firebrands required for ignition at reduced-scale versus full-scale

FIGURE 9 Image of vinyl siding ignition (separation distance 20.3 cm)

Figure 8 shows the ratio of the number of firebrands required for ignition of each mulching material. Pine bark nuggets and Japanese cypress woodchip mulch required more firebrands at reduced-scale experiments than at full-scale experiments as the ratio is over 1. This is the opposite to shredded hardwood mulch. The ratio is

TABLE 1 Impact to re-entrant corner assemblies (wood studs/OSB/moisture barrier/vinyl siding) when located adjacent to different mulching materials with 10.2 and 20.3 cm separation distance

Reduced-scale experiments																
Wind speed	Shredded hardwood mulch				Japanese cypress woodchip mulch				Pine bark nuggets				Mini pine bark nuggets			
			Separation Distance				Separation Distance				Separation Distance				Separation Distance	
	OSB	Gypsum	10.2 (cm)	20.3 (cm)	OSB	Gypsum	10.2 (cm)	20.3 (cm)	OSB	Gypsum	10.2 (cm)	20.3 (cm)	OSB	Gypsum	10.2 (cm)	20.3 (cm)
6 (m/s)	NT	WI	NWI	NWI	NT	WI	WI	WI	WI	NI	NI	NI	NT	NT	NT	WI
8 (m/s)	NT	NT	WI	WI	NT	NT	NT	NT	NT	NT	WI	WI	WI	NT	NT	NT
Full-scale experiments																
6 (m/s)	WI	NR	WI	NWI	WI	NR	NT	WI	WI	NR	NT	WI	NT	NT	NT	NT
8 (m/s)	WI	NR	NR	WI	WI	NR	NT	NT	WI	NR	NT	NT	NT	NT	NT	NT

Note: Wall ignition (WI) was defined a flame propagation to the back-side of the wall. Not tested (NT); no wall ignition (NWI); no ignition (NI); not reported (NR) (for full-scale experiments). Information on full-scale experiments were taken from[38] bigger at pine bark nuggets than at Japanese cypress woodchips. It was more difficult to ignite the pine bark nuggets at reduced-scale experiments and the fact ignition occurred only once out of five experiments with pine bark nuggets. As also mentioned above, close observation on mulch beds at reduced-scale experiments revealed that Japanese cypress woodchips were moving under higher wind speeds (8 m/s), which resulted in loss of heat and longer time for ignition. Due to the lack of more extensive video records, these issues, unfortunately, cannot be confirmed with full-scale experiments. The smaller amount of mulch beds and the lower firebrand arrival flux may have resulted in less "adequate spots" for firebrand accumulation. The advantage of shredded hardwood mulch is nonuniformity compared to Japanese cypress woodchips and pine bark nuggets, as seen in Figure 3. In addition, the surface of shredded hardwood mulch beds is more uneven compared to Japanese cypress woodchips, thus potentially making it easier for firebrands to accumulate.

3.2 | Impact to re-entrant corner assembly

Experimental results were shown in Table 1. Under 6 m/s wind, mini pine bark nuggets, as well as Japanese cypress woodchip mulch, were able to ignite re-entrant corner beyond 20.3 cm separation distance (Figure 9) while pine bark nuggets and shredded hardwood mulch were unable to do so. As full-scale experiment showed the fire become stronger as the wind speed increases from 6 to 8 m/s,[38] this series of experiments under 8 m/s was mainly focused to see if mulch beds ignited by firebrands might be able to ignite re-entrant corner assembly beyond 20.3 cm separation distance. Compared with full-scale experiments, the impact to the re-entrant corner assembly showed similar results. Due to the size of fuel beds (quarter of full-scale experiments), the total amount of heat produced from fuel bed combustion is less, and there was not enough heat to ignite the bottom of siding if the separation distance was too large. While the results do not match completely, reduced-scale experiments can be used to rank the dangerous of different mulch types adjacent to wall assemblies. Japanese cypress woodchip mulch and mini pine bark nuggets showed their dangers to the re-entrant corner assemblies even at reduced-scale experiments.

Naturally, more experiments (both full-scale and reduced-scale) with different mulch beds would be needed to improve and implement the proposed reduced-scale methods for practical use. The challenge would be how to control characteristics of mulch beds, as the mulch beds itself are naturally not uniform. These issues with the various mulch types resulted in many uncertainties.

One more important factor to be considered in the future would be the effect of the fuel MC (mulch in these experiments). The mulch beds in the current experimental series were all oven-dried; therefore, MC was not varied. MC is one of the important factors influencing ignition, as well as flame spread of fuel beds. In a real housing community, most of the fuels present would not be "oven-dried." It would be important that eventual test standards would include the different levels of MC for fuels that be exposed to firebrand showers in actual housing communities.

4 | SUMMARY

A reduced-scale experimental protocol was developed to study ignition of mulching materials by firebrands and resulting impact to adjunct wall assemblies. Experiments were performed at 6 and 8 m/s, with four different mulching materials. Mulching materials were attacked by firebrand showers, and ignition was observed. Due to the low arrival flux of firebrands, the reduced-scale experiments showed a clear difference of vulnerabilities to firebrands among mulching materials. The impact to wall assemblies was also studied.

The development of a reduced-scale experiment to be better help understand the complex problem of firebrand ignition for practical construction configurations is needed. Comparison with full-scale experiments is of course important, yet this is not the only objective of this study. While it is exciting to conduct full-scale experiments, this is simply too expensive and not practical, so the authors are devising far cheaper reduced-scale experiments to provide more in-depth scientific understanding of needed for the firebrand ignition problem. In this case, the fuel beds used were mulch, but other fuel types found near homes in communities could be considered in future work.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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