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Ignition of Mulch Beds Exposed to Continuous Wind-Driven Firebrand Showers

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Abstract. A series of experiments were conducted to examine ignition of mulch beds to continuous, wind-driven firebrand showers. Shredded hardwood mulch, fitted in beds 1.2 m by 1.2 m with a thickness of 51 mm, was attached to a non-combustible reentrant corner assembly. The mulch/reentrant corner assembly was then exposed to continuous, wind-driven firebrand bombardment generated by the NIST full-scale Continuous Feed Firebrand Generator installed in the Fire Research Wind Tunnel Facility at the Building Research Institute in Japan. These experiments have determined ignition behavior of mulch beds installed in realistic building configurations under wind-driven firebrand showers. Experiments were performed by varying the wind speed and moisture content (MC) of the mulch beds. It was observed that continuous application of small wind-driven firebrands, with sizes similar to those observed in actual wildland–urban interface fires in California and Texas, resulted in flaming ignition of mulch beds held at MC up to 83% under wind speeds of 8 m/s. The accumulation of firebrands was a key factor to produce ignition.

Keywords: Wildland–Urban Interface (WUI) fire, Firebrand, Ignition, Firebrand Generator, Mulch

1. Introduction

Wildland–urban interface (WUI) fires have caused significant destruction to communities throughout the world [1]. WUI fires continue to burn in the USA; most recently in Texas in 2011, Colorado and California in 2012, and Arizona, Colorado, and California in 2013.

Post-fire damage studies have suggested that firebrands are a significant cause of structure ignition in WUI fires [2–4], yet for over four decades, firebrand studies have focused on understanding how far firebrands fly [5–8]. Few studies have

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examined firebrand generation [9–11] and the ultimate ignition of materials by firebrands or metal particles [12–17]. Prior firebrand studies are of limited help to harden structures to firebrand showers.

Developing the scientific-basis necessary to support test methods for firebrand resistant building elements is a key component required to reduce the WUI fire problem, as it is a structure ignition issue. Yet, in the WUI, buildings are often surrounded by vegetation that, when ignited, can produce intense, localized firebrand showers, and provide direct flame contact onto building elements, leading to ignition of buildings. The creation of defensible space around structures is a common mitigation strategy, yet in many areas the requirement for the creation of defensible space is either not popular due to resistance to modify the natural environment and landscaping around structures, or not practical due to limited lot size.

Of particular concern are landscape mulches located adjacent to buildings. While there have been some studies of mulch ignition in the literature [18, 19], none of these studies have investigated the ignition of mulch installed in realistic building configurations exposed to wind-driven firebrand showers; conditions seen in real WUI fires.

As result, a series of experiments were conducted to examine ignition of mulch beds to continuous, wind-driven firebrand showers. Shredded hardwood mulch, fitted in beds 1.2 m by 1.2 m with a thickness of 51 mm, was attached to a non-combustible reentrant corner assembly. The mulch/reentrant corner assembly was then exposed to continuous, wind-driven firebrand bombardment generated by the NIST full-scale Continuous Feed Firebrand Generator (aka the NIST full-scale Continuous Feed Dragon) installed in the Fire Research Wind Tunnel Facility (FRWTF) at the Building Research Institute (BRI). The NIST full-scale Continuous Feed Dragon, an improvement over the original NIST Dragon, can generate continuous wind-driven firebrand showers when installed in BRI's FRWTF. To investigate ignition of mulch beds exposed to firebrand showers requires the capability to generate firebrand showers of varying duration. The time to reach sustained flaming ignition (FI) of shredded hardwood mulch beds exposed to continuous wind-driven firebrand showers was determined as function of mulch bed moisture content (MC), and applied wind speed.

2. Experimental Description

Experiments were performed by using the full-scale Continuous Feed Firebrand Generator (see Fig. 1). The device has been described in prior publications, so only a brief description is provided here, and the interested reader is referred elsewhere [20, 21]. This version of the device is modified from the NIST Dragon [22] and consisted of two parts: the main body and continuous feeding component. The feeding system was connected to the main body and was equipped with two gates to prevent fire spread (described in more detail below). A blower was connected to the main body and the purpose of the blower is also described below. A major challenge when constructing this device was designing a completely contained feeding system shielded from the wind tunnel flow.

Figure 1. Picture of the full-scale Continuous Feed Firebrand Generator.

The feeding system consisted of a pneumatic cylinder coupled to a cylindrical container where wood pieces were stored (see Fig. 2). The pneumatic cylinder was contained inside a metal sleeve. Inside the metal sleeve, the sliding rod of the pneumatic cylinder was connected to a plate that allowed the volume of wood contained within the sleeve to be varied. This volume was set precisely to allow a specific mass of wood pieces to fall into this volume. When the air pressure was applied, the sliding rod of the pneumatic cylinder moved forward, forcing the wood pieces within the volume of the metal sleeve to the first gate, where they are then dropped into the second gate that leads to the Dragon where they are ignited (see Fig. 3). The gate system was required to contain the fire from spreading from the Dragon to the feed system and each gate was driven by pneumatic cylinders as well. For all tests, Douglas-fir wood pieces machined to dimensions of 7.9 mm (H) by 7.9 mm (W) by 12.7 mm (L) were used to produce firebrands. The same-size wood pieces were used to feed the bench-scale continuous Firebrand Generator in past studies and have been shown to be commensurate with sizes measured from full-scale burning trees, as well size distributions obtained from actual WUI fires [11, 23].

When the blower was set to provide an average velocity below 3.0 m/s measured at the exit of the Dragon when no wood pieces were loaded, insufficient air was supplied for combustion and this resulted in a great deal of smoke being generated in addition to firebrands. At blower velocities above 3.0 m/s, smoke

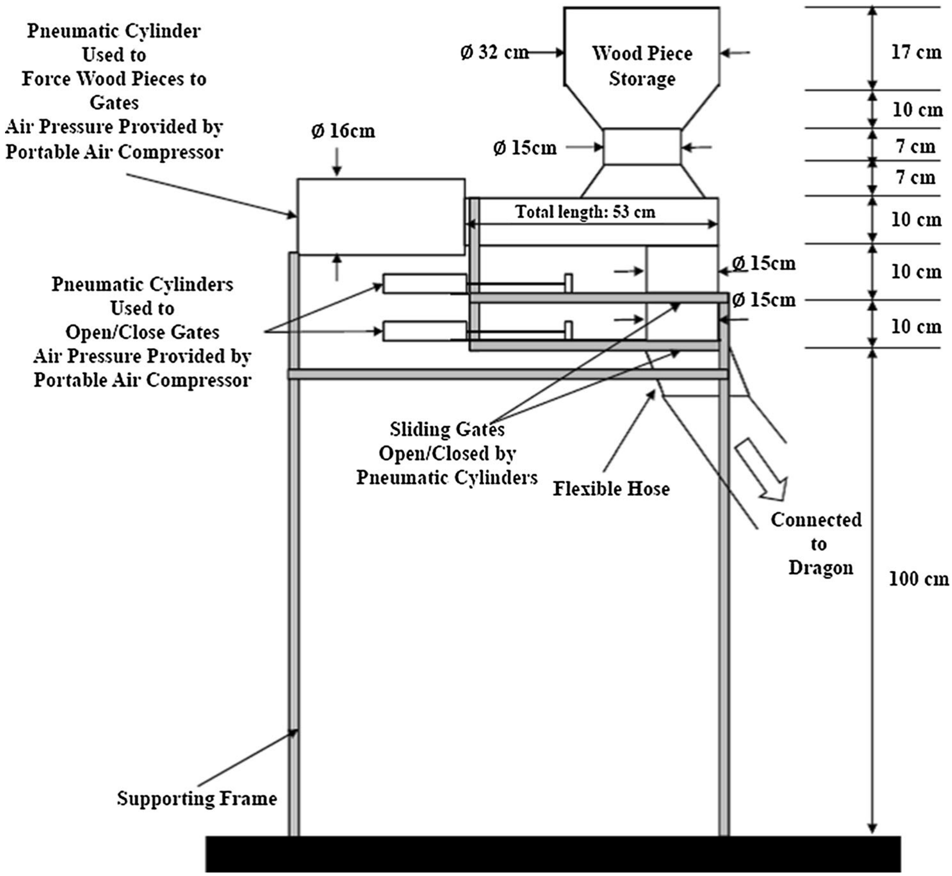

Figure 2. Schematic of the feeding system for the full-scale Continuous Feed Firebrand Generator.

production was mitigated, but many firebrands produced were in a state of flaming combustion as opposed to glowing combustion. It has been suggested that firebrands fall at or near their terminal settling velocity. As such, when firebrands contact ignitable fuel beds, they are most likely in a state of glowing combustion, not flaming [6]. It is possible for firebrands to remain in a flaming state under an air flow and, it is reasonable to assume that some firebrands may still be in a state of flaming combustion upon impact. The purpose of this device is to simulate firebrand showers observed in long-range spotting and therefore glowing firebrands were desired.

As in prior experiments using the NIST Dragon, the new experimental device was installed inside the test section of the Building Research Institute's Fire Research Wind Tunnel Facility (see Fig. 4). The facility was equipped with a 4.0 m diameter fan to produce the wind field. The cross section of the FRWTF is 5.0 m wide by 4.0 m high.

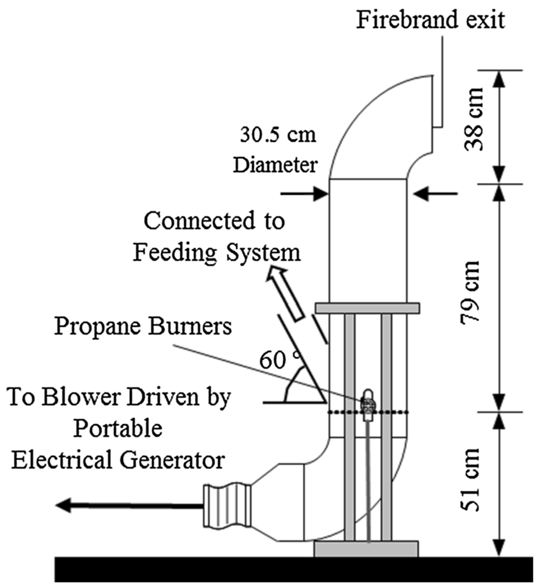

Figure 3. Side view of the main body (or Dragon) of the full-scale Continuous Feed Firebrand Generator. The location where the feeding system provided wood pieces into the device is shown.

Mulch beds were installed in front of a reentrant corner assembly to attempt to simulate mulch application in front of actual structures. The distance of the reentrant corner assembly from the Continuous Feed Firebrand Generator, as well as its orientation in the wind tunnel, was based on prior work [21]. Specifically, a parametric study was conducted to determine the influence of various configurations to be able to have the greatest number flux/mass flux of firebrands arrive at the front of a reentrant corner assembly in order to simulate worst-case conditions [21]. As a result of that work [21], the reentrant corner was placed at a distance of 3.25 m downstream of the full-scale Continuous Feed Firebrand Generator. The dimensions of the reentrant corner assembly were 1.2 m wide by 2.44 m high on each side. The walls of the reentrant corner were lined with gypsum board since these experiments were focused on mulch ignition, not the ignition of the wall assembly itself. Each of the mulch beds was installed inside the reentrant corner assembly at the base (ground level). In all experiments, the mulch beds were 1.2 m by 1.2 m. Shredded hardwood was used and the thickness was fixed at 51 mm; a commonly recommended mulch thickness. The base of container used to house the mulch beds was lined with gypsum board. This was done to mitigate any ignition of the mulch bed container.

A typical experiment was conducted in the following manner. The mulch bed was installed inside the reentrant corner. The wind tunnel speed was set to the desired level (e.g. 6 m/s or 8 m/s). Not only were these particular wind speeds selected based on prior work, discussed above [21], but test methods for roofing

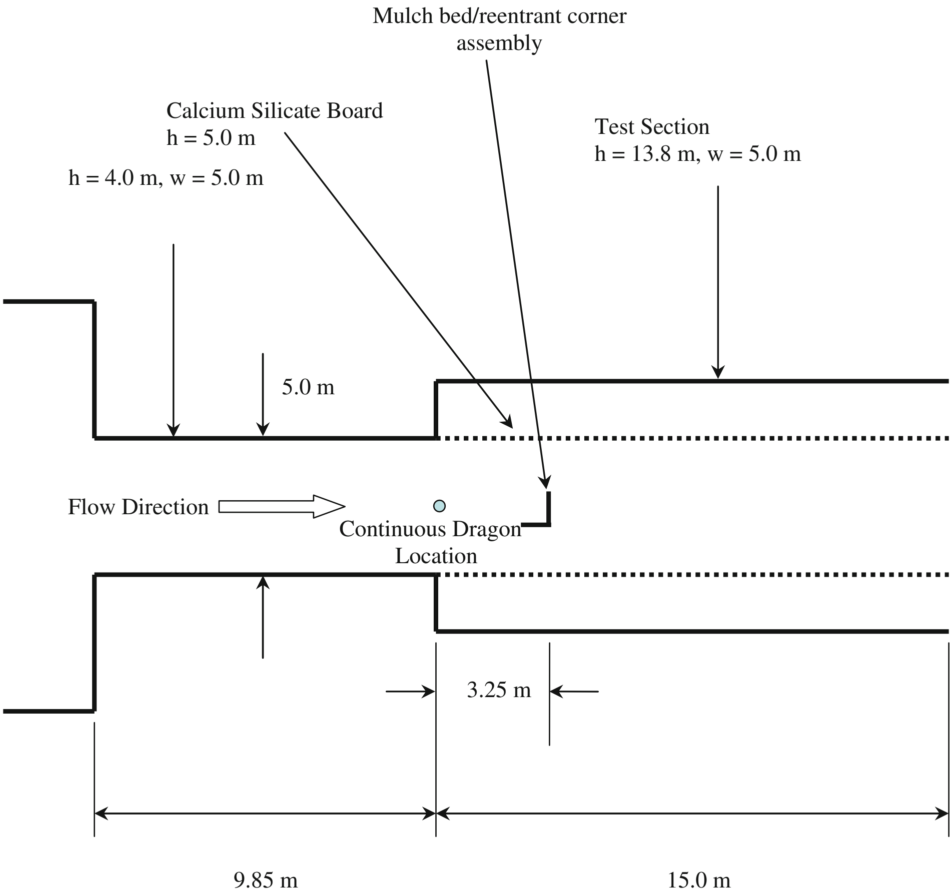

Figure 4. Schematic of the Fire Research Wind Tunnel Facility at Building Research Institute. Locations of the full-scale Continuous Feed Firebrand Generator and reentrant corner/mulch bed assembly are shown.

assemblies and decking assemblies are also within this range (again see the discussion in [21]). Wood pieces were first loaded into the cylinder storage container and the air compressor needed to provide compressed air for the pneumatic cylinder and gate system was switched on (air compressor pressure was set to 0.7 MPa). The blower was set at 3.0 m/s and two propane burners were ignited and inserted into the side of the device. The propane burners were operated continuously during the experiment. The pneumatic piston was then activated and the sliding rod was positioned to allow wood pieces to enter the volume in the metal sleeve. The sliding rod was moved to push the wood pieces (200 g) to the first gate. The gate was opened, closed, and the second gate was then opened, and the wood fell into the Dragon. The feeding was varied to determine the optimal conditions for continuous firebrand showers. It was observed that 200 g, fed into the Dragon every

15 s provided an adequate firebrand generation rate to ignite building materials [21].

The number flux (number of firebrands generated/m^2s), at the exit of the device, was measured at a feeding rate of 200 g every 15 s (800 g/min). To determine the number flux, the number of firebrands was counted at every frame of the video recording, summed every second, and then summed again at every ten seconds [24]. Based on the analysis, the number flux, at the exit of the device, reached a steady value of 342.0 $m^{-2}s^{-1}$ 300 s after feeding began. The first firebrands began to be generated ~100 s after feeding was commenced.

Mass flux data (mass of firebrands generated/m^2s) were calculated by multiplying the number flux and the average mass of each firebrand at a feed rate of 200 g every 15 s. To measure the firebrand mass, another set of experiments was conducted using a series of water pans placed downstream of the NIST full-scale Continuous Feed Firebrand Generator. Water pans were required in order to quench combustion of the firebrands. If the water pans were not used, the firebrands would continue to burn and by the time collection was completed; only ash remained. After the experiment was finished, the pans were collected and the firebrands were filtered from the water, using a series of fine-mesh filters. Firebrands were dried in an oven, at 104°C, for 16 h. As in previous work, the mass versus drying time was monitored to determine the duration need to completely dry the firebrands. The mass and dimension of each firebrand were measured using precision calipers (1/100 mm resolution) and a precision balance (0.001 g resolution). The mean mass and standard deviation of each firebrand were obtained and observed to be 0.05 ± 0.02 g. Therefore, the mass flux of generated firebrands was calculated to be 17.1 g/m^2s.

The total number/mass flux of firebrands generated from the full-scale Continuous Feed Firebrand Generator was determined, and did not vary with wind speed. However, all of the generated firebrands that depart the mouth of the Dragon did not land within the mulch bed. The total number of firebrands arriving on the surface of the mulch bed was determined as function of applied wind speed. Based on this analysis, approximately 42% at 6 m/s, and 36% at 8 m/s, of the firebrands generated from the Dragon were able to land on the surface of the mulch bed. These differences are believed to be due to the enhanced flow recirculation observed as the wind speed was increased, which made it more difficult for firebrands to arrive on the mulch bed surface with attendant increases in wind speed. The number fluxes of firebrands that arrived at mulch surface were 7.36 $m^{-2}s^{-1}$ and 6.18 $m^{-2}s^{-1}$ under 6 m/s and 8 m/s wind respectively, and corresponded to 0.368 g/m^2s and 0.309 g/m^2s for the mass flux deposited on the mulch bed surface. These are summarized in Table 1.

A very important characteristic of the NIST Dragon is that the firebrand size and mass produced using the device can be tailored to those measured from full-scale tree burns [11], and actual WUI fires [23]. In collaboration with the California Department of Forestry and Fire Protection (CALFIRE), NIST quantified firebrand distributions from a real WUI fire (2007 Angora Fire) for the first time [23]. The most salient result reported in [23] was the documentation of the consistently small size of firebrands (<0.5 cm^2) and the close correlation of these results

Table 1
Number and Mass Flux of Firebrands Arriving on the Surface of Mulch Bed via Applied Wind Speed

Wind speed (m/s)	Number flux (m^{-2} s^{-1})	Mass flux (g/m^2 s)
6	7.36	0.368
8	6.18	0.309

with the sizes of experimentally generated firebrands from the NIST Dragon. The Texas Forest Service has used this methodology to collect firebrand size distributions from the recent Texas Bastrop Complex fires in 2011, as well, and reported similar findings to the 2007 Angora fire [25].

3. Results and Discussion

Figure 5 displays a typical experiment to expose the mulch beds to continuous wind-driven firebrand showers. In this image, the wind tunnel speed was 6 m/s and the mulch bed MC was 11%. In all the experiments, the firebrand number, and mass flux, *directed* at the mulch bed/re-entrant corner assembly was fixed, but as described below the firebrand number, and mass flux that arrived at the mulch bed location was dependent on the applied wind speed. The mulch bed MC was defined as:

$$Moisture\ Content = \frac{M_{wet} - M_{dry}}{M_{dry}} \times 100$$

where M_{wet} and M_{dry} represent the mulch mass before and after oven drying, respectively. For fixed wind tunnel speed (set to either 6 m/s or 8 m/s), and fixed firebrand number/mass flux generated from the Continuous Feed Dragon, three experiments were conducted at three different MC levels. These included: (1) oven dried, (2) 9% to 25%, and (3) 25% to 83%. Oven dried conditions were intended to represent a worst-case scenario. Mulch bed MC up to 25% were intended as intermediate fuel moisture levels, and were also conducted to be able to compare results to available literature studies [18, 19, 26]. For the higher MC levels, these were intended to represent very wet mulch and determine if continuous firebrand showers could still produce ignition events under such 'wet' conditions. The rationale behind such tests was based on using water as wetting agent to potentially mitigate ignition; so called fuel pre-wetting. For wind speeds of 6 m/s and 8 m/s, three experiments were performed for mulch beds held at (1) oven dried MC, and (2) 9% to 25% MC. For MC level of (3) 25% to 83%, one experiment under 6 m/s, and two experiments at 8 m/s were performed. In total, 15 full-scale experiments were performed. A summary of experimental conditions are show in Table 2.

For the mulch beds, smoldering ignition (SI) was first observed, and SI was observed to transition to FI. The presence of SI was noted by intense smoke gen-

Figure 5. Image of 1.2 m by 1.2 m by 51 mm (depth) shredded hardwood mulch bed at 11% MC exposed to continuous wind-driven firebrand showers. The reentrant corner, with dimensions of 1.2 m by 1.2 m by 2.44 m high, was lined with gypsum board to investigate the ignition of the mulch bed itself; the ability of the mulch bed to ignite the wall assembly was not considered. Sustained FI was observed.

Table 2
Summary of Experimental Conditions

Wind speed	Moisture content	
6	(1) Oven dried	
8		
6	(2) 9% to 25%	9
		9
		11
8		9
		11
		25
6	(3) 25% to 83%	74
8		71
		83

eration and glowing combustion in the mulch bed. If FI was observed, the time for sustained FI to be reached was determined. The time was defined as the time for *sustained* FI was observed within the mulch bed less the time the first firebrand landed on the mulch bed surface. The average time for sustained FI under 6 m/s, which corresponds to a firebrand number flux that arrive at the mulch surface 7.36 $m^{-2}s^{-1}$, was 172 ± 62 s (average ± standard deviation), and 187 ± 26 s for dried mulch beds, and 9% to 25% MC, mulch beds respectively. The average time for sustained FI under 8 m/s, which corresponded to which corresponds to a firebrand number flux that arrive at the mulch surface of 6.18 $m^{-2}s^{-1}$, was 180 ± 37 s for dried mulch beds, 170 ± 49 s for 9% to 25% MC mulch beds, and 314 ± 108 s for 25% to 83% MC mulch beds. Under 8 m/s, continuous firebrand application ignited very wet mulch beds. Typically, several ignitions were observed during each experiment. Experiments were conducted until the entire mulch bed was ignited in most cases (Fig. 6). For the experiments with MCs above 74% under 6 m/s, the experiments were stopped after 20 min of firebrand showers. Even though several FI were observed during those 20 min, such FI were never sustained, thus these ignitions were not considered as FI in this study. Experiments were stopped after 20 min since the mulch beds were covered with firebrands and it was not easy to distinguish firebrands from the surface of the mulch beds anymore.

The relationship between the total numbers of firebrands required to reach sustained FI as a function of applied wind speed, and mulch bed MC, is shown in Fig. 7. Figure 8 displays the influence of the total firebrand mass need to reach sustained FI. In Fig. 7-8, the number/mass of firebrands required to reach sustained FI were counted/calculated based on the firebrands that arrived on the surface of the mulch bed. Figure 7-8 indicate that fewer firebrands, and therefore less mass, were required to reach sustained FI as the wind speed was increased, for the dried and 9% to 25% MC cases. *Plausible* reasons for these observations are described in detail below.

Figure 6. Images of mulch ignitions at 2 min, 3 min, 4 min and 6 min after a first firebrand landed (11% MC, 8 m/s). After the first ignition at 2 min, flame spread was observed from several ignitions.

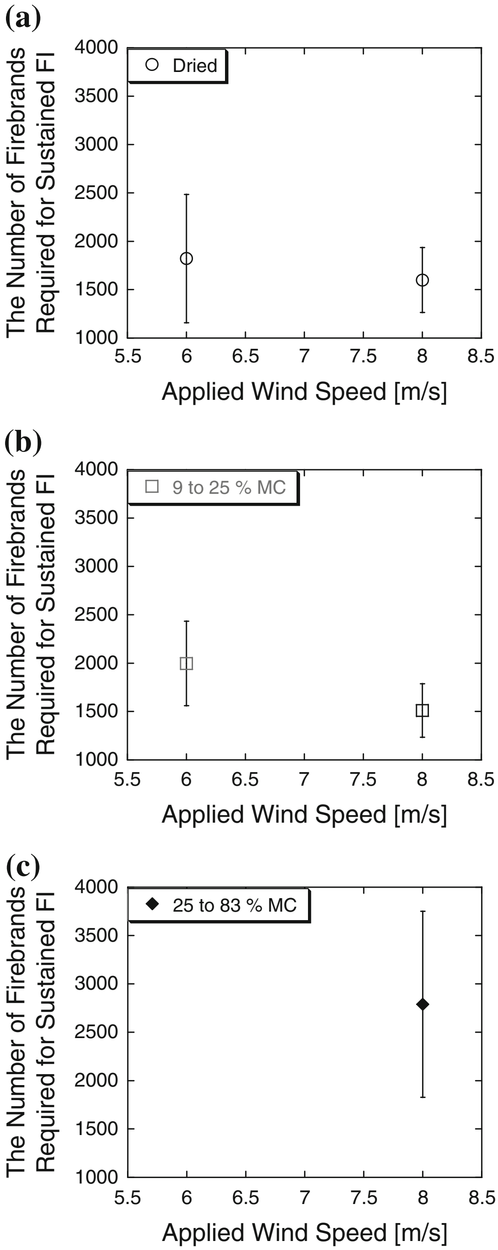

Figure 7. Relationship between the numbers of firebrands required for sustained FI and the applied wind speed, with different moisture content. The number of firebrands was counted based on the firebrands that arrived on the surface of the mulch bed. (a) oven dried condition, (b) 9% to 25% MC condition, (c) 25% to 83% MC condition.

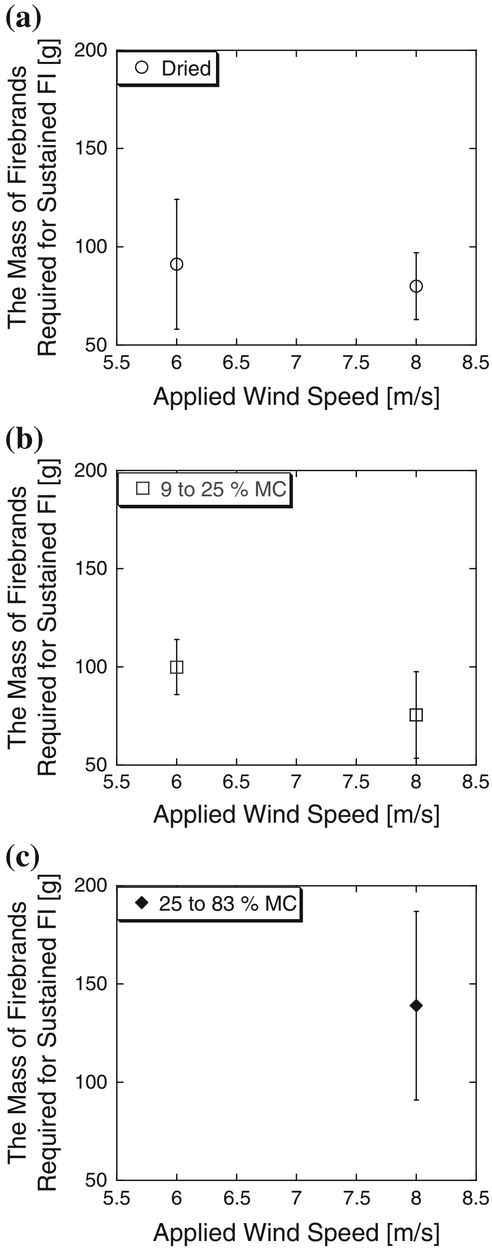

Figure 8. Relationship between the mass of firebrands required for sustained FI and the applied wind speed, with different moisture content. The mass of firebrands was calculated based on the firebrands that arrived on the surface of the mulch bed. (a) oven dried condition, (b) 9% to 25% MC condition, (c) 25% to 83% MC condition.

Manzello et al. [18, 26] performed firebrand ignition studies using a bench-scale ignition apparatus capable of depositing up to 4 firebrands for shredded hardwood mulch (fuel bed size of 23 cm by 23 cm with the depth of 5.1 cm, moisture content varied from dry to 11%). For dried shredded hardwood mulch beds, using glowing cylindrical shaped firebrands, a minimum mass of 2.68 g (four 10 mm diameter cylinders) was required for ignition as compared to 6.0 g (four 50 mm disks) of glowing disk shaped firebrands. The results from two different fuel beds suggest that glowing cylindrical shaped firebrands produced ignition events using about half the mass required when glowing disk shaped firebrands were used. Since these experiments were conducted under identical wind speeds (1.0 m/s), in the same testing apparatus, it was expected that the firebrand temperatures were similar. As a result, differences in contact surface area were able to explain these observations. Even though the mass of cylindrical shaped firebrands was less than half of the mass of disk shaped firebrands necessary to produce ignition in the same fuel bed, the actual glowing surface area in contact with the fuel beds was the same for both shapes under conditions of ignition. Those results suggested that the contact glowing surface area, due to accumulation of firebrands, may be an important parameter to determine ignition of fuel beds, not just the overall mass deposited.

For a given wind speed, the present work clearly shows that the accumulation of firebrands were important to produce ignition in mulch beds. Images of the detailed ignition phenomena are displayed in Fig. 9, and demonstrate that it was the ability of glowing firebrands to accumulate as the key to producing ignition. In recent experiments using decks exposed to continuous wind-driven firebrand showers using the same experimental apparatus in this work, accumulation of firebrands was the key factor to producing ignition as well. Due to the nature of the mulch beds, all of the firebrands deposited did not accumulate into one large area, as was observed for decking tests exposed to continuous firebrand showers [21]. For these mulch bed experiments, as the generator continually supplied firebrands to the mulch beds, more and more firebrands are deposited, leading to an increased likelihood that firebrands will eventually accumulate in a specific location and produce ignition. As can be seen, it only required a few of these small firebrands to eventually produce ignition at given location. The number of accumulated firebrand necessary to produce ignition increased as the mulch bed MC increased.

As indicated above, as the wind speed increased, the total number, and mass of firebrands required to produce sustained FI within the mulch beds for the two lower MC levels decreased. This is most likely due to the fact that when firebrands accumulated onto the mulch beds at higher wind speeds, the firebrand temperatures were higher. To support this supposition, Manzello et al. [27] quantitatively showed that the surface temperature of glowing firebrands increased as the applied airflow was increased. Building materials were observed to ignite under higher applied airflows, as compared to no ignition observed for lower applied airflows. Specifically, firebrand temperatures were observed to increase from 550°C at an applied wind speed of 1.3 m/s to 675°C when the wind speed was increased to 2.4 m/s [27]. This may also explain why wet mulch beds ignited at 8 m/s and not 6 m/s.

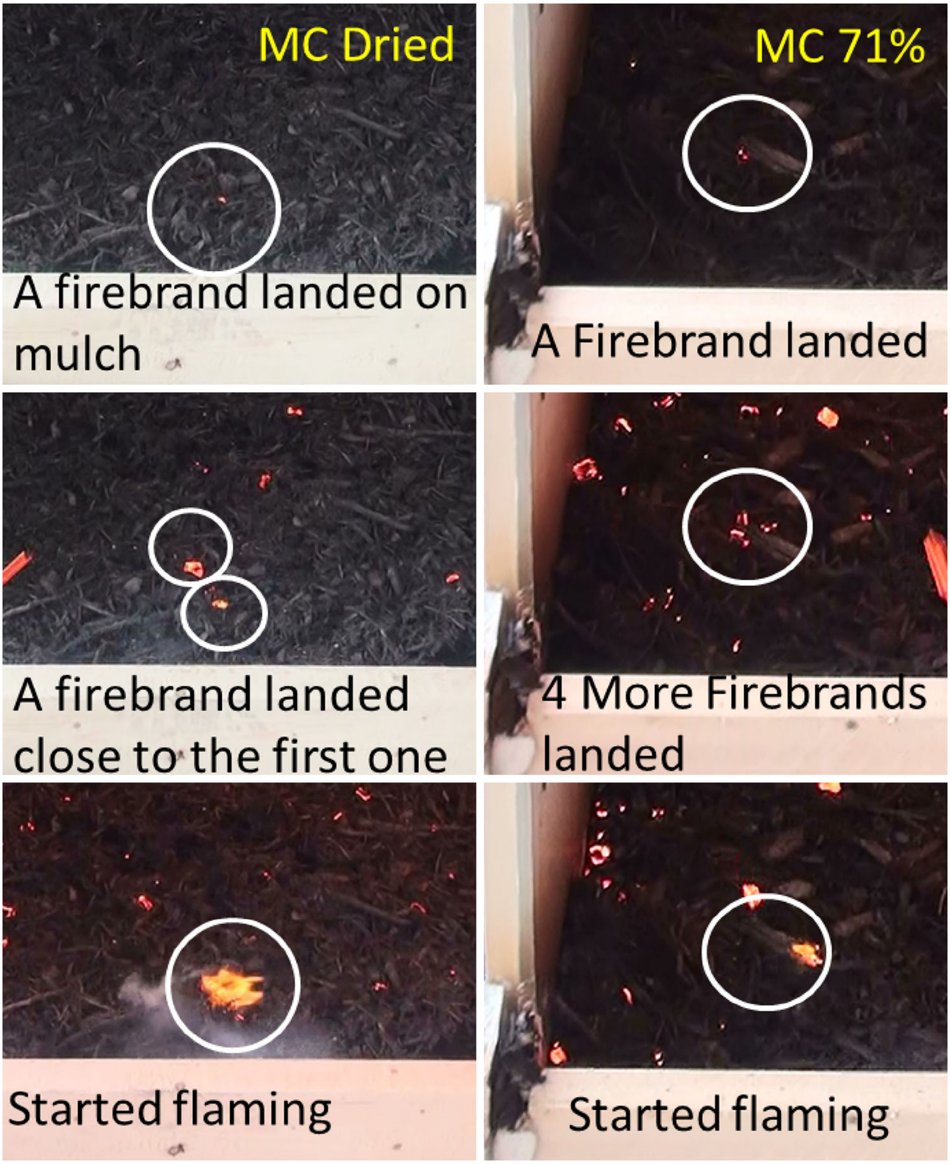

Figure 9. Images of the ignition process by firebrands under the condition of 8 m/s wind speed (*left* dried shredded hardwood mulch, *right* 71% MC shredded hardwood mulch) 71% MC mulch required a minimum of 6 firebrands while dried mulch required only 2 firebrands for FI.

As a final comparison, Beyler et al. [19] is the only work to systematically investigate mulch ignition on realistic scales. The mulch beds were contained in 0.6 m square containers. In their work, shredded hard mulch was held at 13.3% MC, and the mulch depth was fixed at 76 mm. Different wood cribs, so called Class A, B, C, 0.5 C, and 0.25 C, were used to simulate firebrands. They observed it was possible to only produce FI in shredded hardwood mulch at 13.3% MC when using a Class A flaming firebrand. In their work, FI was defined as whether spread of visible flame front propagation after firebrand (crib) deposition was observed. For the reader not familiar with a Class A firebrand, this is a very large wood crib (30.48 cm $\times$ 30.48 cm x 5.715 cm). None of the smaller sized firebrands used could produce flaming ignition. No wind speed was applied in these experiments, and in WUI fires, wind is known to be critical for WUI fire spread.

In the present study, continuous application of small wind-driven firebrands, with sizes similar to those observed in actual WUI fires in California and Texas, (average projected area of each firebrand in this study was 0.77 ± 0.2 cm^2), could produce FI of mulch beds held at MC substantially higher than 13.3%. As shown in Fig. 6, FI observed in this study demonstrated fire spread in the mulch. As Beyler et al. [19] clearly indicate, their test method is intended to show *relative* mulch performance and does not intend to represent a worst possible case for mulch performance. Nevertheless, both of these studies have begun to investigate mulch ignition on realistic scales, and are useful for the development of scientifically-based mulch test methods.

4. Conclusions

A series of experiments were conducted to examine ignition of mulch beds to continuous, wind-driven firebrand showers under varying applied wind speed, and moisture content. In this study, continuous application of small wind-driven firebrands, with sizes similar to those observed in actual WUI fires in California and Texas, resulted in FI of mulch beds held at MC up to 83% under wind speeds of 8 m/s. For the two lower MC levels, the number/mass of firebrands required for FI were found to decrease as the wind speed increased. It was observed that showers of wind-driven firebrands were able to ignite mulch beds, and the accumulation of firebrands is a key factor to produce ignition.

Additional experiments, using various mulch types, as well as different firebrand size and mass distributions, are also planned. Finally, future work must determine if ignited mulch beds may indeed ignite walls placed adjacent to them. To the authors' knowledge, detailed, systematic experiments that demonstrate if certain mulch types may ignite building elements fitted with various siding treatments have not been demonstrated.

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